sustainability

Sustainability and the Environmental Kuznets Curve Conjecture

Edited by
Bertrand Hamaide

Printed Edition of the Special Issue Published in *Sustainability*

www.mdpi.com/journal/sustainability

MDPI

Sustainability and the Environmental Kuznets Curve Conjecture

Sustainability and the Environmental Kuznets Curve Conjecture

Editor

Bertrand Hamaide

MDPI • Basel • Beijing • Wuhan • Barcelona • Belgrade • Manchester • Tokyo • Cluj • Tianjin

Editor
Bertrand Hamaide
Université
Saint-Louis—Bruxelles
Belgium

Editorial Office
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

This is a reprint of articles from the Special Issue published online in the open access journal *Sustainability* (ISSN 2071-1050) (available at: https://www.mdpi.com/journal/sustainability/special_issues/CurveConjecture).

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

LastName, A.A.; LastName, B.B.; LastName, C.C. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

ISBN 978-3-0365-4669-8 (Hbk)
ISBN 978-3-0365-4670-4 (PDF)

Contents

About the Editor . . . . **vii**

Bertrand Hamaide
Sustainability and the Environmental Kuznets Curve Conjecture: An Introduction
Reprinted from: *Sustainability* **2022**, *14*, 7372, doi:10.3390/su14127372 . . . . **1**

Pei-Zhi Liu, Seema Narayan, Yi-Shuai Ren, Yong Jiang, Konstantinos Baltas and Basil Sharp
Re-Examining the Income–CO_2 Emissions Nexus Using the New Kink Regression Model: Does the Kuznets Curve Exist in G7 Countries?
Reprinted from: *Sustainability* **2022**, *14*, 3955, doi:10.3390/su14073955 . . . . **5**

Yilmaz Bayar, Vladimir Smirnov, Marina Danilina and Natalia Kabanova
Impact of Institutions and Human Capital on CO_2 Emissions in EU Transition Economies
Reprinted from: *Sustainability* **2022**, *14*, 353, doi:10.3390/su14010353 . . . . **23**

Farrah Dina Abd Razak, Norlin Khalid and Mohd Helmi Ali
Asymmetric Impact of Institutional Quality on Environmental Degradation: Evidence of the Environmental Kuznets Curve
Reprinted from: *Sustainability* **2021**, *13*, 12507, doi:10.3390/su132212507 . . . . **35**

Paolo Maranzano, João Paulo Cerdeira Bento and Matteo Manera
The Role of Education and Income Inequality on Environmental Quality: A Panel Data Analysis of the EKC Hypothesis on OECD Countries
Reprinted from: *Sustainability* **2022**, *14*, 1622, doi:10.3390/su14031622 . . . . **59**

Pradyot Ranjan Jena, Babita Majhi and Ritanjali Majhi
Estimating Long-Run Relationship between Renewable Energy Use and CO_2 Emissions: A Radial Basis Function Neural Network (RBFNN) Approach
Reprinted from: *Sustainability* **2022**, *14*, 5260, doi:10.3390/su14095260 . . . . **83**

Runqing Zhu and Boqiang Lin
How Does the Carbon Tax Influence the Energy and Carbon Performance of China's Mining Industry?
Reprinted from: *Sustainability* **2022**, *14*, 3866, doi:10.3390/su14073866 . . . . **101**

Djula Borozan and Dubravka Pekanov Starcevic
Analysing the Pattern of Productivity Change in the European Energy Industry
Reprinted from: *Sustainability* **2021**, *13*, 11742, doi:10.3390/su132111742 . . . . **117**

About the Editor

Bertrand Hamaide

Bertrand Hamaide completed his Bachelor's and Master's Degrees in Economics at the University of Namur (Belgium), followed by a Master's Degree and a PhD in Systems Analysis and Economics for Public Decision Making at the School of Engineering (Department of Geography and Environmental Engineering) of Johns Hopkins University (USA). He is a Professor at the Université Saint-Louis, Bruxelles (and currently Vice-Rector of the University) and invited Professor at UCLouvain. His area of expertise is in environmental and ecological economics, mostly the economics of climate change and nature reserve selection and design.

sustainability

Editorial

Sustainability and the Environmental Kuznets Curve Conjecture: An Introduction

Bertrand Hamaide [1,2]

1 Department of Economics, Social, Political and Communication Sciences, CEREC, Université Saint-Louis, 1000 Brussels, Belgium; bertrand.hamaide@usaintlouis.be or bertrand.hamaide@uclouvain.be
2 ESPO (Department of Economics, Social and Political Sciences), Université Catholique de Louvain, 1340 Louvain-la-Neuve, Belgium

1. From Kuznets to the Environmental Kuznets Curve

In December 1954, Simon Kuznets delivered his Presidential Address at the American Economic Association about economic growth and income inequality. His talk was published a few months later by the American Economic Review [1], and that very paper laid the ground to what has been known as the Kuznets Curve.

In his seminal paper, Kuznets used data to see if inequality in the distribution of income increases or decreases with a country's economic growth. For being able to answer that question, he collected long-term data for the United States, the United Kingdom and Germany. Even though his research was meticulous and heavily documented, Kuznets was always careful to use words such as "conjecture", "hypothesis", "guess", etc. His conclusions were based on available data, available information, economic theory, statistical analysis and best guesses. With this precaution in mind, he stated that, for the countries studied, "One might thus assume a long swing in the inequality characterizing the secular income structure: widening in the early phases of economic growth when the transition from the pre-industrial to the industrial civilization was most rapid; becoming stabilized for a while; and then narrowing in the later phases" [1]. That is the essence of the Kuznets Curve: inequalities increase in earlier phases of development, then finally decrease until a certain income threshold has been reached, such that an inverted U-shaped relationship exists between inequalities and income.

This relationship cannot, however, be standardized across time and across nations. The timing of the turning point is indeed different for every country, and data showing a specific relation for one country does not ensure that all countries behave the same way. For the former point, Kuznets mentions the following: "No adequate empirical evidence is available for checking this conjecture of a long secular swing in income inequality; nor can the phases be dated precisely. However, to make it more specific, I would place the early phase in which income inequality might have been widening, from about 1780 to 1850 in England; from about 1840 to 1890, and particularly from 1870 on in the United States; and, from the 1840's to the 1890's in Germany. I would put the phase of narrowing income inequality somewhat later in the United States and Germany than in England-perhaps beginning with the first world war in the former and in the last quarter of the 19th century in the latter" [1]. For the latter issue, if the three developed countries under study were experiencing an inverted U-shaped relation between inequality and income at the time Kuznets wrote his paper, it remained to be seen if developing countries were following a similar path or were expected to follow such a path in the decades to come. Kuznets did not conclude with a strong affirmation but with a balanced opinion, mentioning that the widening inequality gaps in developing countries in the post-war period could be a sign that history repeats, but warning that swift conclusions may not always be advisable.

The inverted U-shaped relationship between inequality and income was rightfully treated as a conjecture, and not as "law", by Kuznets himself, as longer and more recent

Citation: Hamaide, B. Sustainability and the Environmental Kuznets Curve Conjecture: An Introduction. *Sustainability* **2022**, *14*, 7372. https://doi.org/10.3390/su14127372

Received: 31 May 2022
Accepted: 14 June 2022
Published: 16 June 2022

data showed that such a relation could not be generalized. For example, List and Gallet [2] collected data for many countries from the 1960s to the 1990s, and they found out that if lower-to-middle-developed countries do generally seem to follow an inverted U-shaped pattern, higher developed countries, however, see the relationship between income inequalities and per capita income become positive again. They explain this increasing trend, forming an N-shaped curve, as a shift from a manufacturing base towards a service base in advanced economies. This conclusion does not, of course, invalidate the interest of the Kuznets Curve but simply stresses that, as mentioned before, it is not a "law", nor is it a curve that is valid for all countries and at all periods of time.

A few decades after Kuznets' analysis, various researchers started studying the relation between environmental pollution (instead of inequalities) and economic growth. In 1991, Grossman and Krueger studied the impact of the NAFTA (North American Free Trade Agreement) on the environment, and for their analysis, they studied the relation between air quality and economic growth [3]. Two other important papers followed [4,5] before Grossman and Krueger again published their paper entitled 'Economic Growth and the Environment' in 1995 [6]. These researchers showed that an Environmental Kuznets Curve (EKC), that is, an inverted U-shaped relation between a measure of environmental damage and (per capita) income, could exist for various pollutants. At low levels of economic development, human behaviors are not imposing an excessive stress on natural capital. However, when the economy develops, natural resources are more and more impacted by human activities and environmental damages increase. Then, once a threshold is reached, after a certain level of development, environmental policies and individual preferences among others (e.g., agents give an additional value to a cleaner environment and are willing to invest part of their income in environmental conservation [7]), enabling them to reduce pollution.

Those studies were obviously limited to various pollutants and various countries. Grossman and Krueger [3] were the first to observe an inverted U-shape between urban air pollution (sulphur dioxide and dark matter) and income in the United States. Later on, a similar relationship was found between deforestation and national income [4] and between various air pollutants (sulfur dioxide, suspended particulate matter, nitrogen oxide and carbon monoxide) and per capita GDP [5]. In their seminal 1995 paper [6], Grossman and Krueger extended their analysis to several other countries and indicators related to air and water pollution and also found significant evidence of an EKC for most of their indicators.

For the past three decades, numerous papers have been published, whose studies concentrated on specific pollutants, on specific countries, on econometric estimates and on varying the ordinate (the type of environmental damage) and the abscissa (the measure of income) of the curve. The least than can be said is that the EKC is subject to much debate. If various local pollutants frequently exhibit an EKC, this is much more ambiguous for global pollutants, such as CO_2 emissions, for example. Results may also differ depending on the methodological approach used (time series, cross-country or panel data or more advanced methods, some of which are used in this Special Issue), on the country or group of countries used and on the time period. In one word, the EKC is not generalizable, and what Kuznets stressed for the relations between inequality and economic growth, that is, the need to use words of caution and to realize that the original inverted U-shaped relation between inequality and income is not a 'law' but a conjecture, is also valid here. Grossman and Krueger seem to be in line with this important cautionary note as they mention, for example, that "we find little evidence that environmental quality deteriorates steadily with economic growth" [6]. Hence, even though they find EKCs for most of the air and water pollutants studied, they do not claim that economic growth is the solution for tackling environmental issues. Rather, they suggest that economic growth might bring about pollution reduction for some pollutants (not all) after a threshold is reached.

2. CO_2, EKC and the Special Issue Articles

As climate change is the most pressing (long-term) environmental issue, what can we say about regional, national, international and global relations between CO_2 emissions and national income? As omitted variables and modeling formulations are significant drivers of the results obtained, what improvements can we propose for modeling techniques? Finally, what additional variables (on top of pollution and GDP) can we consider? Those and other questions are discussed in the articles of the Special Issue.

All papers of the Special Issue but one directly analyze the evolution of CO_2 emissions. The purpose here is not to undertake a literature review or go into the details of the debate about the EKC conjecture for CO_2 emissions, but it is interesting to pinpoint various issues and see how they are handled in this Special Issue.

A frequently cited shortcoming of the EKC is that it is generally not obtained for global pollutants such as CO_2. Some countries may show an inverted U-shaped relation while others follow an N-shaped pattern and others again seem to show a strictly positive correlation of emissions with growth. Hence, as the EKC is not generalized, its local existence may be (partly) due to stricter environmental regulations in some parts of the world that help reduce environmental damages. Concentrating their analysis on the G7 countries and using data spanning 150 years, Liu et al. [8] cannot confirm an EKC in most of these countries, even though the marginal propensity to emit CO_2 after a certain threshold is decreasing.

Over the years, many papers highlighted various econometrical flaws in the model formulations, arguing that issues such as, among others, cointegration or omitted variables render these models fragile. Concentrating on omitted variables and, more largely, additional variables, it is true that elements other than GDP (in)directly impact pollution. Bayar et al. [9] consider the impact of institutions and human capital on CO_2 emissions in 11 transition economies, and if they find mixed impacts for institutions, their results show a positive impact of human capital on CO_2 emission reductions in most countries in their sample. The importance of institutional quality is also highlighted by Razak et al. [10], as their models show that, in Malaysia, healthier governance (government stability, anti-corruption measures and law and order) allow for improvements in environmental quality, that is, a reduction in CO_2 emissions. Human capital is also considered as a crucial cornerstone in EKC modeling by Maranzano et al. [11]. Using data from 17 European countries and average years of schooling as a proxy for human capital, they were able to derive what they referred to as an 'Educational EKC' in various countries of their sample, controlling for income inequality, that is, an inverted U-shaped relationship between pollution and human capital.

Modeling techniques have also improved over time. Jena et al. [12] move away from linear regression models producing a single parameter estimate and propose a non-linear model with an adaptative process for estimating CO_2 emissions and possibly verifying the existence or inexistence of an EKC. They use a Radial Basis Function Neural Network applied to 19 countries representing 78% of global emissions with data spanning the last 60 years and found that renewable energy holds the key for future emission abatement. Liu et al. [8] also capture the non-linear characteristics without converting data into a quadratic (or cubic) form by using a kink (threshold effect) regression model. Razak et al. [10] employ various econometric techniques for Malaysia, among which is the non-linear autoregressive distributed lag model.

The final two papers aim at finding tools to reduce carbon emissions in specific countries and for specific sectors. Zhu and Lin [13] evaluate the impact of a carbon tax levied in China's mining industry to promote energy reforms and environmental improvements in traditional industries, while Borozan and Pekanov Starcevic [14] analyze the productivity gains in the European energy industry in light of the climate objectives.

Overall, the Special Issue provides useful insights on recent methodological developments, on the importance of additional variables to national income when estimating potential EKCs, on tools for promoting more sustainable policies and on applications to various parts of developed and the developing world for better understanding and grasping the complexity behind the Environmental Kuznets Curve.

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Kuznets, S. Economic Growth and Income Inequality. *Am. Econ. Rev.* **1955**, *45*, 1–28.
2. List, J.A.; Gallet, C.A. The Kuznets Curve: What Happens After the Inverted-U? *Rev. Dev. Econ.* **1999**, *3*, 200–206. [CrossRef]
3. Grossman, G.M.; Krueger, A.B. *Environmental Impacts of a North American Free Trade Agreement*; National Bureau of Economic Research: Cambridge, MA, USA, 1991; WP3914.
4. Shafik, N.; Bandyopadhyay, S. *Economic Growth and Environmental Quality: Time-Series and Cross-Country Evidence*; World Bank Publications: Washington, DC, USA, 1992; p. 904.
5. Selden, T.M.; Song, D. Environmental Quality and Development: Is There a Kuznets Curve for Air Pollution Emissions? *J. Environ. Econ. Manag.* **1994**, *27*, 147–162. [CrossRef]
6. Grossman, G.M.; Krueger, A.B. Economic Growth and the Environment. *Q. J. Econ.* **1995**, *110*, 353–377. [CrossRef]
7. Dinda, S. Environmental Kuznets Curve Hypothesis: A Survey. *Ecol. Econ.* **2004**, *49*, 431–455. [CrossRef]
8. Liu, P.-Z.; Narayan, S.; Ren, Y.-S.; Jiang, Y.; Baltas, K.; Sharp, B. Re-Examining the Income–CO_2 Emissions Nexus Using the New Kink Regression Model: Does the Kuznets Curve Exist in G7 Countries? *Sustainability* **2022**, *14*, 3955. [CrossRef]
9. Bayar, Y.; Smirnov, V.; Danilina, M.; Kabanova, N. Impact of Institutions and Human Capital on CO_2 Emissions in EU Transition Economies. *Sustainability* **2022**, *14*, 353. [CrossRef]
10. Abd Razak, F.D.; Khalid, N.; Ali, M.H. Asymmetric Impact of Institutional Quality on Environmental Degradation: Evidence of the Environmental Kuznets Curve. *Sustainability* **2021**, *13*, 12507. [CrossRef]
11. Maranzano, P.; Cerdeira Bento, J.P.; Manera, M. The Role of Education and Income Inequality on Environmental Quality: A Panel Data Analysis of the EKC Hypothesis on OECD Countries. *Sustainability* **2022**, *14*, 1622. [CrossRef]
12. Jena, P.R.; Majhi, B.; Majhi, R. Estimating Long-Run Relationship between Renewable Energy Use and CO_2 Emissions: A Radial Basis Function Neural Network (RBFNN) Approach. *Sustainability* **2022**, *14*, 5260. [CrossRef]
13. Zhu, R.; Lin, B. How Does the Carbon Tax Influence the Energy and Carbon Performance of China's Mining Industry? *Sustainability* **2022**, *14*, 3866. [CrossRef]
14. Borozan, D.; Pekanov Starcevic, D. Analysing the Pattern of Productivity Change in the European Energy Industry. *Sustainability* **2021**, *13*, 11742. [CrossRef]

sustainability

MDPI

Article

Re-Examining the Income–CO_2 Emissions Nexus Using the New Kink Regression Model: Does the Kuznets Curve Exist in G7 Countries?

Pei-Zhi Liu [1], Seema Narayan [2], Yi-Shuai Ren [3,4,5,6,*], Yong Jiang [7,*], Konstantinos Baltas [8] and Basil Sharp [6]

1 College of Finance and Statistics, Hunan University, Changsha 410006, China; liupeizhi@hnu.edu.cn
2 Independent Researcher, Melbourne 3806, Australia; swdhar27@gmail.com
3 School of Public Administration, Hunan University, Changsha 410082, China
4 Research Institute of Digital Society and BlockChain, Hunan University, Changsha 410082, China
5 Center for Resource and Environmental Management, Hunan University, Changsha 410082, China
6 The Energy Centre, University of Auckland, 12 Grafton Rd, Auckland 1010, New Zealand; b.sharp@auckland.ac.nz
7 School of Finance, Nanjing Audit University, Nanjing 211815, China
8 Essex Business School, University of Essex, Colchester CO4 3SQ, UK; k.baltas@essex.ac.uk
* Correspondence: renyishuai1989@126.com (Y.-S.R.); jiangziya.ok@163.com (Y.J.)

Abstract: More countries have made carbon neutral or net zero emission commitments since 2019. Within this context, re-examining the environmental Kuznets curve (EKC) hypothesis plays an essential role in sizing up the global economic development situation and realizing the global carbon emission reduction target. A methodological challenge in testing the EKC hypothesis, which states that increasing income makes CO_2 emissions begin to decline beyond a turning point, lies in determining if this benchmark point exists. The EKC hypothesis between income and CO_2 emissions is reassessed by applying a new kink regression model for the G7 countries from 1890 to 2015. Results reveal the inverted U-shaped nexus does not exist for US, Germany, Italy, Canada and Japan. For these five countries, the EKC curve has a turning point, but the positive impact of incomes on CO_2 emissions becomes significantly smaller after the turning point. We describe this relationship as a pseudo-EKC. K.U.K. and France are the only exceptions, fitting the EKC hypothesis. Further analysis indicates that the relationship between income and SO_2 emissions presents an inverted U-shaped curve. Moreover, we observe that the turning point occurs at different points in time for the different G7 countries. Therefore, environmental policies targeting pollutant emission reduction should consider the different characteristics of different pollutants and regions.

Keywords: environmental kuznets curve; kink regression model; G7 countries; CO_2 emissions

Citation: Liu, P.-Z.; Narayan, S.; Ren, Y.-S.; Jiang, Y.; Baltas, K.; Sharp, B. Re-Examining the Income–CO_2 Emissions Nexus Using the New Kink Regression Model: Does the Kuznets Curve Exist in G7 Countries? *Sustainability* **2022**, *14*, 3955. https://doi.org/10.3390/su14073955

Academic Editor: Bertrand Hamaide

Received: 21 February 2022
Accepted: 25 March 2022
Published: 27 March 2022

1. Introduction

With the global economy set for a growth relapse in recent years, a new round of carbon emission reduction planning has been on the agenda. The environmental Kuznets curve (EKC) debate was engendered by Grossman and Krueger (1991) [1]. It could date back to Kuznets (1955) [2], who put forward an inverted U-shaped relationship between income inequality and economic growth. Grossman and Krueger (1991) [1] proposed an inverted U-shaped path for pollution as a function of income, a frequently employed means for assessing the relationship between economic growth and environmental pollution. Subsequently, a large amount of literature on EKC has emerged [3]. Empirical results are generally mixed. Many studies show the existence of EKC [4]. However, some conclude there is no inverted U-shaped relationship between economic growth and environmental pollution [5].

The EKC hypothesis is important in understanding how to achieve a win–win situation in terms of economic development and enhancing environmental quality [6]. In the past, fossil fuels have contributed to economic growth and national prosperity, but these developments have come at the cost of environmental degradation. The EKC results suggest that economic growth can be compatible with environmental improvements if appropriate policies are adopted and a certain level of technology is achieved [7]. Before adopting policies, it is important to understand the relationship between economic growth and environmental quality [8]. In the current trend of low carbon economic development and environmental governance, the relevant question is: can economic growth play a positive role in achieving carbon emission reductions and improvements in air pollution problems, rather than at the expense of environmental quality? This has been the main motivation for empirical research into EKC [9]. Promoting a low carbon economy, improving the energy mix, and balancing economic growth with carbon reduction goals for sustainable development have received increasing attention from governments and scholars [10]. The results of this study are expected to add to the EKC literature and the literature on carbon mitigation and provide policymakers and practitioners with recommendations on sustainable development to mitigate climate risks and environmental pressures.

Despite a brief decline in carbon emissions within the context of the COVID-19 disease, the United Nations Environment Programme (UNEP)'s Annual Emissions Gap Report 2020 reveals that the world is still on the track, by the end of this century, to warm by more than 3 °C [11]. A growing number of G20 member countries have made carbon neutral or net zero emission commitments since 2019. In this context, re-examining the relationship between economic growth and carbon emissions plays an essential role in sizing up the global economic development situation and realizing the global carbon emission reduction target. As the earliest countries to initiate the industrial revolution, the G7 countries (U.S., UK, France, Germany, Japan, Italy and Canada) have played a great role in promoting and playing an important role in global carbon emission reduction. The G7 countries have rich experience in dealing with environmental challenges, are in a leading position in carbon emission reduction and provide a reference for the design of energy-saving and pollution reduction policies in developing countries. Therefore, it is quite necessary to research the EKC hypothesis between the incomes and CO_2 emissions of the G7 countries. The research objectives of this paper are twofold: firstly, have economies such as the G7 countries achieved sustainable development without damaging the environment? In other words, this paper proposes to re-examine the validity of the environmental EKC hypothesis using G7 countries as a sample. Secondly, given the EKC heterogeneity across pollutants and countries [12], this study proposes to examine the manifestation of EKC heterogeneity in the relationship between two pollutants (CO_2 and SO_2 emissions) and economic growth in different regions (G7 countries), respectively. These results will provide theoretical support and tailor made policy reference for subsequent pollution control and low carbon economic development.

The EKC literature, including both theoretical and empirical studies, is abundant. However, the existence of EKC among G7 countries is still a controversial issue. Therefore, after describing the general concept of the EKC hypothesis, this paper employs a new kink regression model with an unknown threshold proposed by Hansen (2017), to investigate the EKC hypothesis between the incomes and CO_2 emissions of the G7 countries [13]. The results show no EKC effect for the nexus for the US, Germany, Italy, Canada, and Japan, with the U.K. and France being exceptions. However, for those that do not fit the EKC hypothesis, the nexus still has a significant turning point; the contribution of incomes to CO_2 emissions becomes significantly smaller after the turning point. When income exceeds the threshold, the positive impact of income on CO_2 emissions becomes significantly smaller. We observe that the UK, France, Canada, Italy, the US, Germany, and Japan reached their turning points of the EKC curve in about 1972, 1969, 1899, 1891, 1912, 1914 and 1972. We describe this relationship as a pseudo-EKC and attempt to explain this phenomenon using the concept of the *free-rider* problem.

This study makes important contributions to the bulk of literature based on the scope of analysis and the econometric methodology employed. First, evidence of EKC is usually based on time series data that spans a period during which there is evidence of gains in environmental quality [14]. Previous literature focusing on relatively small datasets, spanning only a few decades, does not provide an effective way to directly estimate and test for the presence of an unknown turning point of income. We examine the EKC hypothesis of the G7 countries using a larger dataset that spans nearly 150 years. Second, we employ a new kink regression model with an unknown threshold. Consistent with a large set of theoretical models, this model can estimate and examine the existence of EKC and the presence of the unknown threshold value of income. It can test whether there exists an unknown threshold effect on carbon emissions and directly reveal the turning points of EKC. Third, we provide evidence that there are pseudo-EKC nexuses between incomes and CO_2 emissions for the five G7 countries.

The rest of our study is structured as follows. The relevant literature on the EKC hypothesis is discussed in Section 2. The methodology and data used in this study are described in the subsequent section. Section 4 presents the empirical findings and robustness analysis. In Section 5, the discussion and conclusions are provided.

2. Literature Review

2.1. Theoretical Explanations Supporting the EKC Hypothesis

Many scholars have made a detailed theoretical explanation of the formation of the traditional EKC theory, mainly from five perspectives: economic structure change, income inequality and demand preference, international trade, technological progress and policy guidance [9]. Shafic and Bandyopadhyay (1992) [15] point out that economic structure change, also known as industrial restructuring, is important for environmental quality. This refers to the adjustment from the development stage based on traditional energy intensive and heavy industry to the economic stage based on a technology intensive, information technology, and service industry [15]. In the first stage of development, the level of the byproducts of output, i.e., pollution, rises gradually with economic expansion, and economic growth is positively correlated with environmental pollution [16]. With the upgrading and restructuring of the industry structure, information technology industries and services would no longer bring more pollution and would, therefore, bring opportunities for environmental improvement, thus shifting the EKC curve to the second stage of negative correlation [7].

The second motivation for the EKC curve is income inequality and changes in demand preferences. With the improvement in the national income level, the population's income distribution would become more equitable [9]. An increase in residents' incomes will raise their preferences for environmental quality and increase people's awareness of environmental protection and spending on environmental protection research [17]. In addition, residents may pressure governments to implement stricter environmental regulations through activities such as marches and elections [18].

The third explanation comes from international trade. Countries use their comparative advantages to trade with each other. For this reason, developed countries are engaged in high technology industries, while developing countries are engaged in industries characterized by labor intensive industries and high pollution, for economic growth [19]. Developed countries tend to be more stringent in terms of environmental regulations, so these countries choose to move industries with high pollution to developing countries that pay less attention to environmental regulations. This transfer of polluting industries leads developed countries to the declining stage of the EKC curve [20].

Besides, the technological progress effect can also play an important role in the EKC curve. It consists of two aspects: first, technological progress increases productivity, such as improved energy efficiency. Namely, the same economic growth can be achieved by investing fewer resources. Second, the investment in clean technologies, such as new energy sources, leads to the gradual greening of production processes, thus combating the environmental pollution problem at the source [21,22]. Last but not least, when economic development reaches a certain high level, the government and people start to pay attention to the environmental pollution problem and take measures to protect the environment. By adopting market mechanisms, such as carbon trading mechanisms, sulfur trading mechanisms, carbon taxation and other price instruments [23], consumers and producers are motivated to pay attention to controlling environmental pollution and improving energy use and production efficiency [24]. Accordingly, some scholars argue that the downward phase of the EKC curve is not a result of increasing income but the government's initiative and policy guidance [25].

In general, the above studies have highlighted the importance of adding various influencing factors to study of the EKC hypothesis, such as income inequality, technological progress, and government regulation. These factor studies provide the basis for empirical research on EKC and thus better avoid omitted variables. However, a large number of empirical studies also find that the EKC hypothesis does not exist, and the theoretical explanation for this category of findings is still inadequate, by comparison.

2.2. Development and Debate of EKC Theory in Recent Years

In recent years, empirical research on EKC has remained a hot issue. Although many scholars have studied the EKC hypothesis, its research results have contradictory conclusions. Firstly, the relationship between economic growth and environmental degradation is highly sensitive to the choice of functional form and estimation method [26–28]. For example, in developed versus developing countries, importance should be attached to the distinction between the choice of a quadratic or cubic model of GDP per capita [17], since the explanatory power of the economic growth polynomial accounts for a much smaller proportion of the environmental improvement species in developed countries than in low and middle income countries [28,29]. Secondly, the variety in conclusions could come from the problem of omitted variables in the model [30]. Existing literature finds that the environmental impact per unit of economic activity is affected by income distribution [17,18], government regulation [23–25], scientific and technological progress [30,31], energy consumption [32–34] and many other factors. Thirdly, there are differences in selecting country samples and periods for various studies [17,35,36]. Until the early 2000s, most studies used cross-sectional data that included only one country [37]. The time dimension lacks long overlapping observations among panel data studies [38]. Therefore, it is important to extend the period to increase the overlap between countries [38,39]. This is particularly vital for analyses of carbon emissions, which originate from changes in energy use and should, therefore, be analyzed more from a long term perspective [40].

Concerning air pollution, one of the most representative EKC research objects, the academic debate about whether the relationship between air pollution and economic growth has a similar evolutionary law did not get a consistent conclusion. Table 1 summarizes some studies on EKC. Specifically, a classical inverted U-shaped relationship is represented by Grossman and Krugger (1991) [7], which confirms an inverted U-shaped curve relationship between per capita income and SO_2 pollution levels through the GLS method. In addition, a large number of empirical experiences support this conclusion from other country samples [30,31]. In addition to taking a cross country panel data sample, using a single country with provincial and municipal level panel data samples, Rafindadi (2016) [41] and Chang et al. (2021) [42] found that different regions in the same country, with differences in economic development levels, also have significant environmental Kuznets curve effects. However, Holtz-Eakin and Selden (1995) [43] found a positive relationship between economic growth and environmental pollution. Friedl and Getzner (2003) [44] and Shao et al. (2016) [45] found that economic growth and environmental pollution do not have an inverted U-shape, but rather an N-shape and U-shape. Besides, Baek (2015) [46] and Park and Lee (2011) [47] suggest there is no significant EKC relationship between environmental pollution and economic growth.

Table 1. Typical literature related to the EKC hypothesis.

Typical Literature	Sample	Period	Method	Main Results
Inverted U-shaped relationship				
Grossman and Krugger (1995)	A total of 42 countries	1977–1988	Generalized least squared (GLS) method	There is an inverted U-shaped curve relationship between per capita income and SO_2 pollution levels [1].
Farhani et al. (2014)	A total of 10 the Middle East and North African countries	1990–2010	OLS regression, standard linear EKC model	There is an inverse U-shaped relationship between environmental degradation and income [30].
Balado-Naves et al. (2018)	A total of 173 countries	1990–2014	OLS regression, log-linear EKC model; spatial models, SDEM (spatial Durbin error model)	Most regions support the standard EKC hypothesis; there is an inverted U-shaped relationship between national per capita emissions and per capita income in neighboring countries in Europe and Asia [32].
Churchill et al. (2018)	OECD countries	1870–2014	OLS regression, standard linear EKC model	Evidence of EKC exists in 9 of the 20 countries. Five countries exhibit an inverted U-shaped relationship, three countries exhibit an N-shaped relationship, and one exhibits an inverted N-shaped relationship [38].
Marbuah and Amuakwa-Mensah (2017)	Sweden	2005–2013	Spatial models	EKC is effective for all but one pollutant (carbon monoxide), and the distinguishing feature of this relationship is its spatial dependence [48].
Rafindadi (2016)	Japan	1961–2012	Standard linear EKC model	The EKC phenomenon remained in place during the energy disaster and the deterioration of revenues [41].
Chang et al. (2021)	China	2004–2015	First-order spatial dynamic panel model with fixed effects	An inverted U-shaped EKC is the nexus between air pollution and economic growth [42].
Churchill et al. (2020)	Australia	1990–2017	Nonparametric methods	An inverted U-shaped EKC, which peaks in 2010 [49].
A positive contribution relationship				
Holtz-Eakin and Selden (1995)	A total of 130 countries	1951–1986	Log quadratic models	There is a monotonic increasing relationship between economic growth and CO_2. As GDP per capita increases, the marginal tendency to emit CO_2 decreases [43].
Jaunky (2011)	A total of 36 countries with high income	1980–2005	OLS regression, standard linear EKC model	There is a positive linear correlation between GDP per capita and environmental degradation [50].
Fodha and Zaghdoud (2010)	Tunisia	1961–2004	OLS regression, cubic models	There is an inverted U-curve relationship between economic growth and SO_2 but a monotonically increasing relationship with CO_2 [51].
N-shape, U-shape relationship				
Friedl and Getzner (2003)	Austria	1960–1999	Linear, quadratic or cubic models	An N-shaped relationship exists between economic growth and CO_2 emission [44].
Shao et al. (2016)	China	1998–2012	Spatial models, generalized method of moments (GMM)	There is a significant U-shaped curve relationship between economic growth and haze [45].

Table 1. *Cont.*

Typical Literature	Sample	Period	Method	Main Results
		No significant evidence for the EKC hypothesis		
Baek (2015)	Arctic countries	1960–2010	Log quadratic and cubic models; Autoregressive distributed lag (ARDL) modelling approach	There is scant evidence of the existence of the EKC for the Arctic [46].
Nasr et al. (2015)	South Africa	1911–2010	OLS regression, standard linear EKC model	There is no support of the EKC for South Africa [52].
Park and Lee (2011)	Korea	1990–2005	A fixed-effects model, a random-effects model, and a random coefficient model	There is no single dominant shape of the EKC curves for SO_2 and NO_2. Environmental policies should consider different pollutants and regions [47].

In addition, there are also widespread disputes on the choice of models. Most current research regarding the EKC hypothesis uses a classical reduced form approach and linear econometric models, including primary, quadratic, and cubic linear models, resulting in multicollinearity problems [53]. With the development of methods and the improvement in data in recent years, more and more new methods are used to evaluate EKC theory, such as the fixed effect regression model with Driscoll–Kraay standard errors and the common correlated effects mean group (CCEMG) estimator [54]; the error correction based panel autoregressive distributed lag (ARDL) model augmented with cross-sectional averages [55]; and the moments quantile regression approach [56]. Particularly, a minority of the literature, such as Churchill et al. (2020) [49], avoids the issue of model form and uses nonparametric methods to test the EKC hypothesis. The use of panel data in EKC empirical studies assumes that the overall sample fits the EKC pattern, but not every country follows this pattern individually [22]. An individual country's turning points may differ significantly from those estimated for the overall sample. Therefore, empirical EKC studies should focus on each country separately [57–59] or use longer time series data [38,39].

Overall, there are many explanations for the reasons for EKC. From the above analysis of the causes of the EKC hypothesis, it is clear that, when there are large differences in income levels, economic development structures, national policies, international trade and scientific and technological progress, the EKC curves of different countries present different shapes. The relationship between environmental pollution and economic growth may exhibit forms other than the inverted U-shape, such as the U-shape and N-shape. The timing of the turning points will also be different with country and regional characteristics. Current studies have reached inconsistent conclusions about the EKC hypothesis. Therefore, it cannot be generalized to all pollutants and countries. In other words, it is not universally applicable. Collectively, the understanding of the EKC hypothesis is largely based on a number of empirical studies based on samples from countries around the world and over various periods. However, in those studies that do not conform to the inverted U-shaped performance of the EKC, there are relatively few theoretical explanations for the income–pollution relationship and why the EKC concept is no longer valid.

Considering that the inconsistency between all this evidence comes from different samples, Churchill et al. (2018) [38] and Shahbaz and Sinha (2019) [39] point to the importance of extending the period to increase the overlap between countries. This paper uses a long-time sample, from 1870–2015, to avoid misleading results. In addition, most previous studies have utilized classical linear econometric models to assess the EKC hypothesis. This paper used a threshold effects regression model proposed by Hansen (2017) [13] to analyze the EKC problem, which allows for a more precise grasp of the timing of the emergence of the turning point. Meanwhile, based on the finding that some countries do not conform to the EKC hypothesis, this paper attempts to further explain this phenomenon through the *free-rider* theory [60].

3. Methodology and Data

3.1. Methodology

EKC hypothesis argued that pollution tends to slow when income level exceeds a threshold. We employ a kink regression model with an unknown threshold to examine whether the G7 countries fit the EKC hypothesis. The regression kink model is a modification of the regression discontinuity model. The traditional regression discontinuity model assumes that the threshold is known, but it is unknown and must be estimated in some cases. This kink regression model with an unknown threshold was first proposed by Hansen (2017) [13], and can explain a nonlinear relationship between each independent variable and the dependent variable by threshold estimation. This model's function is continuous, but its slope discontinues at the kink or turning point. This model can be applied in a single time series that has the advantage of not imposing homogeneity. Meanwhile, this model extends the regression discontinuity model [61]. It is continuous but with a slope that produces a "kink" at the threshold. Hansen (2017) [13] used this model to study the nonlinear relationship between debt and economic growth based on long span time-series data from the United States of America. Since it is not known where the turning point of the relationship between economic growth and environmental quality will occur, this model allows us to estimate the model without knowing the specific threshold by the discontinuity, which provides a "kink" in its continuous regression function. Besides, this model can directly capture the nonlinear relationship between economic growth and environmental quality without converting the data into quadratic form, as is commonly performed in previous works. Maneejuk et al. (2020) [62] argued that estimating quadratic functions is associated with overly distorted data. In addition, the quadratic term model is accompanied by the problem of multicollinearity between the primary and secondary terms of GDP. The estimation results may not be well constructed for the relationship between economic growth and environmental quality [53]. Moreover, using this model proposed by Hansen (2017) [13] to examine the presence of EKC in the context of individual countries and each group of countries, enables us to examine the heterogeneity of the EKC effect, explore the threshold effect of economic growth on environmental improvement, and capture the jump characteristics of different developing countries in this relationship [63]. Many existing papers, such as Kaika and Zervas (2013) [59] and Al-Mulali et al. (2016) [53], have criticized the classical quadratic term models and econometric models used in studies on empirical EKC from the above literature review. There is no evidence that all countries follow a common inverted U-shaped environmental–economic relationship in their economic growth process, because this relationship can be affected by various factors, such as national income, technological progress, and severity of environmental regulations in different countries [9].

Generally, under this framework, the EKC hypothesis test for G7 countries can be formalized as a regression kink model, where the log per capita emissions is the dependent variable, and the log per capita GDP is the key regressor and threshold variable. If we estimate the threshold point of income and prove that when the income for a country exceeds the threshold then the estimated coefficients of the income–CO_2 emissions are negative, but it is positive before the threshold, it means this satisfies EKC hypothesis.

Based on the kink regression model with an unknown threshold, the EKC regression test model is [13]:

$$E_t = \beta_0 + \beta_1(y_t - \gamma)_- + \beta_2(y_t - \gamma)_+ + \mu_t \tag{1}$$

where E_t denotes the log per capita CO_2 emissions or SO_2 emissions, and y_t denotes the log per capita GDP for every G7 countries, $t = 1, \ldots, n$; μ_t is the disturbance. Function $(y_t - \gamma)_- = \min\,[y_t - \gamma;\ 0]$ and $(y_t - \gamma)_+ = \max\,[y_t - \gamma;\ 0]$ denote the "negative part" and "positive part" of $y - \gamma$, respectively; where γ is a cut off level of y_t, called the "threshold", β_0 is the intercept. The slope with respect to the variable y_t equals β_1 for log per capita

GDP less than γ; and the slope with respect to the variable y_t equals β_2 for log per capita GDP more than γ. In this paper, $H_0 : \beta_1 = \beta_2$ is rejected, and meanwhile if $\beta_1 > 0,\ \beta_2 < 0$, we claim that the EKC hypothesis is confirmed.

3.2. Variable

In this paper, we choose CO_2 emissions to measure environmental quality. EKC theory refers to the relationship between economic development and the degree of environmental pollution in a country. Antle and Heidebrink (1995) [64] pointed out that the concept of environmental quality has a broad conceptual and multidimensional nature. Environmental problems include air and water pollution and the growing issue of global warming, which is still the greatest global risk in 2022 according to the WEF's Global Risks Report 2022 [65]. The main contributor to greenhouse gas emissions and the gas that stays in the atmosphere the longest is CO_2 [31], and CO_2 emissions are also an indicator of air pollution [66]. As CO_2 emissions is a special case of environmental degradation with global effects [59], many studies have explored the EKC relationship between CO_2 emissions and economic growth, using greenhouse gas emissions as an indicator of environmental pollution [27,28,43,44,67–69]. Environmental stresses, such as extreme disasters caused by climate change, are increasing, directly linking carbon emissions and environmental degradation. This is why we choose CO_2 emissions as the measurement of environmental quality.

3.3. Data

Industrialization emerged around 1870, and we use 1870 as the starting point for our analysis. The data consist of annual information on per capita CO_2 emissions taken from the Carbon Dioxide Information Analysis Center, which provides us with a total sample size of 1050 observations consisting of 7 countries over the period 1870–2015 (Japan is 1950–2015 due to incomplete data); real GDP per capita data in constant USD, the base year 1985 were obtained from the Historical Statistics of the World Economy from 1870 to 2015 [70]. All the series are transformed into logs (natural logarithm) before empirical analysis.

Summary statistics of the variables are revealed in Table 2. Note that, during 1870–2015, the United States had the highest average per capita GDP, with a standard deviation of 0.7985. Italy's average per capita GDP is lowest, with the largest standard deviation, which is the largest standard deviation among G7, indicating that the Italian economy has great volatility. Regarding the per capita CO_2, the U.S. has the highest emissions among G7. Besides, note that the per capita CO_2 emissions for G7 are skewed to the left, and the real GDP per capita for G7 skewed to the right, with all the variables having excess kurtosis. The Jarque–Bera test overwhelmingly rejects the null of normality. This evidence of fat tails in the variables provides us with the preliminary motivation to use a nonlinear regression model rather than a standard linear regressions model based on the conditional mean.

We perform standard unit root tests to determine whether the series is stationary, since the kink regression model with an unknown threshold used in this paper assumed the variables have no unit root. Test results are reported in Table 3. According to results in Table 3, the augmented Dickey and Fuller (ADF) test by Dickey and Fuller (1979) [71] and the Phillips–Perron (P.P.) test by Phillips and Perron (1988) [72] reject the null hypothesis of nonstationarity for some series, but it cannot work for most. This result may be because ADF and P.P. tests have a major shortcoming in that they do not allow for the possibility of structural breaks. Therefore, we use the Zivot-Andrews unit root test proposed by Zivot-Andrews (1992) [73], which allows a break at an unknown location both on the trend and intercept for all variables. The results of the Zivot-Andrews unit root test and the estimated break date are also shown in Table 3. The Zivot-Andrews unit root test confirms that these series are stationary. There is a break for all countries' per capita CO_2 emissions and real GDP per capita. This finding of breakpoints in the variables indicates that the linear model based on mean estimation is not suitable to depict the relationship between them. Perhaps it is a nonlinear link.

Table 2. Summary statistics results.

Variables	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Jarque -Bera	Obs.
lnCanada_ CO_2	1.9759	2.3443	2.8688	−1.1272	1.0004	−1.6011	4.8018	82.1295 ***	146
lnCanada_SO_2	4.3175	4.6219	5.3798	2.1773	0.8608	−0.9528	2.9059	20.0204 ***	132
lnCanada_GDP	8.8254	8.8606	10.2709	7.4007	0.8711	0.0771	1.7209	10.0976 ***	146
lnFrance_ CO_2	1.4584	1.5787	2.2707	0.2744	0.4936	−0.4698	2.2695	8.6160 ***	146
lnFrance_SO_2	2.3402	2.3394	3.6446	0.9841	0.6830	0.0074	1.9896	5.6166 ***	132
lnFrance_GDP	8.6844	8.3922	10.0962	7.5367	0.8382	0.3557	1.6014	14.9774 ***	146
lnGermany_ CO_2	0.6873	0.8620	1.1540	−0.7276	0.4552	−1.3204	3.8485	46.8030 ***	146
lnGermany_SO_2	3.3378	3.4292	4.2191	1.3530	0.5627	−1.3647	5.2396	68.5570 ***	132
lnGermany_GDP	8.6586	8.4079	10.0761	7.5047	0.8189	0.3301	1.5980	14.6092 ***	146
lnItaly_ CO_2	0.2511	−0.0353	2.0997	−2.5360	1.4041	−0.0988	1.8003	8.9927 ***	146
lnItaly_SO_2	1.3760	1.0515	3.5049	−1.2313	1.1596	0.2691	2.0673	6.3774 ***	132
lnItaly_GDP	8.4493	8.1043	9.9723	7.2912	0.9316	0.3611	1.5991	15.1126 ***	146
lnJapan_ CO_2	1.7792	2.0708	2.2906	0.2028	0.6260	−1.2803	3.1125	18.0643 ***	66
lnJapan_SO_2	1.3214	1.6210	3.1709	−2.4197	1.1706	−1.2880	4.4436	47.9584 ***	132
lnJapan_GDP	9.3158	9.5604	10.1447	7.5605	0.7676	−0.8849	2.4661	9.3968 ***	66
lnUK_ CO_2	2.2588	2.2709	2.4699	1.6959	0.1278	−1.0910	5.1056	55.9347 ***	146
lnUK_SO_2	3.7023	3.7794	4.1926	2.2346	0.3570	−1.8152	7.7091	194.4561 ***	132
lnUK_GDP	8.9406	8.8248	10.2035	8.0679	0.6283	0.4826	1.9740	12.0703 ***	146
lnUS_CO_2	2.5260	2.7591	3.1140	0.8972	0.5662	−1.4011	3.8816	52.4952 ***	146
LnUS_SO_2	3.9452	4.0411	4.6404	2.7865	0.4422	−0.7508	2.8467	12.5293 ***	132
lnUS_GDP	9.0912	9.0955	10.4067	7.8017	0.7985	0.1295	1.7157	10.4416 ***	146

Notes: Std.Dev denotes standard deviation. *** denotes the rejection of the null of normality of the Jarque-Bera test at 1% significance level.

Table 3. Unit root test results.

	ADF		PP		Zivot-Andrews	
	C	C + T	C	C + T	C + T	Break Date
lnCanada_CO_2	−4.4384 ***(0)	−2.5252(0)	−4.6139(3) ***	−2.5361(3)	−3.1829 *	1899
lnCanada_SO_2	−2.8288 ***(0)	−0.6682(0)	−2.6527 *(6)	−0.5153(5)	−1.8375 **	1899
lnCanada_GDP	−0.0507(10)	−3.3355 *(1)	−0.2107(3)	−2.8840(1)	−5.4529 ***	1917
lnFrance_CO_2	−2.4402(0)	−1.7711(0)	−2.4361(5)	−1.8914(5)	−3.8106 *	1967
lnFrance_SO_2	−1.6726(0)	0.6143(0)	−1.7571(6)	0.3842(4)	−4.0846 *	1970
lnFrance_GDP	0.2427(6)	−1.8052(6)	−0.0704(4)	−2.2390(4)	−4.5760 ***	1954
lnGermany_CO_2	−3.9533 ***(6)	−1.7885(7)	−3.3369(1)**	−1.9015(2)	−3.0513 *	1992
lnGermany_SO_2	−0.1257(1)	1.0226(1)	−0.7866(5)	0.4649(1)	−4.5269 **	1981
lnGermany_GDP	−0.2236(2)	−2.7187(2)	−0.2409(5)	−2.6823(3)	−4.6415 ***	1955
lnItaly_CO_2	−1.5248(7)	−2.5061(7)	−1.4460(20)	−2.7335(12)	−3.9406 ***	1960
lnItaly_SO_2	−2.0121(1)	−2.3243(1)	−1.5739(5)	−2.0901(5)	−3.6241 ***	1960
lnItaly_GDP	0.1916(1)	−2.2673(1)	0.3387(2)	−2.1392(2)	−3.4489 ***	1957
lnJapan_CO_2	−3.0633 **(1)	−0.9758(0)	−3.8536 ***(4)	−1.0198(3)	−4.1607 **	1899
lnJapan_SO_2	−3.6578 **(1)	−2.2721(1)	−4.1074 ***(6)	−2.3226(5)	−3.5898 ***	1974
lnJapan_GDP	−3.4800 **(1)	−1.3310(1)	−5.9537 ***(4)	−1.5149(4)	−4.5932 ***	1886
lnUK_CO_2	−0.5902(4)	0.0501(4)	−3.7993 ***(2)	−3.6314***(3)	−2.5917 ***	1950
lnUK_SO_2	2.2388(1)	4.5620(4)	1.3912(3)	3.1428(5)	−0.3955 *	1974
lnUK_GDP	2.0266(4)	−1.1364(4)	2.5055(15)	−0.9298(13)	−5.0165 ***	1919
lnUS_CO_2	−2.7615 *(12)	−1.5156(12)	−3.8307 **(4)	−1.6471(5)	−2.8103 ***	1898
LnUS_SO_2	−2.1211 *(0)	−1.4132(0)	−2.1344(4)	−1.3613(2)	−2.9835 *	1908
lnUS_GDP	−0.0070(9)	−4.0856 ***(1)	−0.2742(10)	−3.4111*(5)	−5.6089 ***	1941

Notes: C denotes constant, T denotes trend; *, ** and *** indicate significance at the 10%, the 5% and 1% level, respectively. The numbers in parentheses are the optimal lag order in the ADF and P.P. test based on the Schwarz Info criterion and Newey–West bandwidth.

4. The Empirical Findings

4.1. Main Findings of CO_2 Emission

Table 4 and Figure 1 display the estimated results between log per capita GDP and log per capita CO_2 emissions for the G7 countries. There is no inverted U-shaped nexus between the income per capita and CO_2 emissions for the US, Germany, Italy, Canada, and Japan, except for the U.K. and France. Nevertheless, we find that income has a threshold effect for these countries that does not fit the traditional EKC hypothesis. When income exceeds this threshold, the estimated coefficients of the income–CO_2 emissions are positive but significantly smaller than before the threshold. Taking the U.S as an example, the F-test indicates the presence of a threshold at the 1% significance level. We also provide the R-squared as the goodness of fit for each regression, proving that each model is good. The estimated threshold value is 8.56. When GDP per capita is less than 8.56 (the low-income period), the regression coefficient of CO_2 emissions β_1 is 2.25 and is significant at the 5% level. When the income exceeds this threshold (the high-income period), the regression coefficient β_2 is 0.18, still greater than zero, but less than β_1. This implies that the positive impact of income on CO_2 emissions becomes much smaller with income increase. Economic growth and CO_2 emissions are positively correlated, but the marginal propensity to emit carbon dioxide decreases as GDP per capita increases. This finding is in line with Holtz-Eakin and Selden (1995) [43]. We define this relationship as the pseudo-EKC, and we suggest that a major factor causing this phenomenon is the *free-rider* problem [60]. Shafik (1994) [27], Galeotti and Lanza (2005) [74] and Aslanidis and Iranzo (2009) [75] also verified that the main explanation we may find is related to the *free-rider* problem. Shafik (1994) [27] and Aslanidis and Iranzo (2009) [75] believe that, because other regions bear all the costs of climate change, and, in most cases, the local benefits are very small in the short term, there is no significant cost of CO_2 emission locally. The *free-rider* problem is an economic phenomenon identified by Olson (2009) [76]. This issue arises in response to the world's public goods, which are characterized by their shared nature. Ethical standards require people to contribute to the use and maintenance of public goods. We propose the following mechanisms to explain this problem. Based on the perspective of supply and demand, the publicity of environmental protection related affairs may lead to insufficient supply of environmental protection commodities, which may further lead to market failure. This phenomenon is caused by the local government's "*free-rider*" problem, when the governments of neighboring countries strengthen environmental protection [77]. Besides, the transboundary nature of the air may encourage free-riding. Given the opportunity costs that could have been used to improve other economic indicators in the region, regional administrations and individuals lose the motivation to control their air pollution, which will lead most regions and individuals to take inaction and only wait for neighbors to take actions, making the "*free-rider*" problem more serious [78]. Last, in the context of global warming, the lack of incentives to internalize the negative effects of local economic activities is particularly strong. The public nature of global warming means that, once emissions are reduced, every country and everyone can equally enjoy the benefits of greenhouse gas emission reduction. Therefore, it is reasonable from a personal point of view to hitch a "*free-rider*" on the control projects being implemented in other countries [79].

Table 4. Kink regression with the unknown threshold for CO_2 emissions.

Country	β_0	β_1	β_2	γ	***F*-Test**	R^2
France	2.31 * (0.03)	0.94 * (0.04)	−0.85 * (0.06)	9.30 * (0.03)	432.31 *	0.83
UK	2.44 * (0.01)	0.23 * (0.02)	−0.45 * (−0.04)	9.31 * (0.03)	173.97 *	0.82
Germany	0.73 * (0.03)	2.47 * (0.18)	0.18 * (0.02)	8.02 * (0.03)	276.12 *	0.82
Japan	2.10 * (0.03)	1.10 * (0.02)	0.20 * (0.05)	9.30 * (0.03)	317.49 *	0.84
Italy	−1.10 * (0.07)	14.20 * (3.15)	1.30 * (0.04)	7.40 * (0.01)	50.18 *	0.79
Canada	1.90 * (0.05)	4.88 * (0.41)	0.45 * (0.03)	7.99 * (0.04)	941.29 *	0.76
US	2.67 * (0.02)	2.25 * (0.06)	0.18 * (0.02)	8.56 * (0.02)	1220.74 *	0.81

Notes: Numbers in parentheses denotes Std. Error. * denotes significant at the level of 5%.

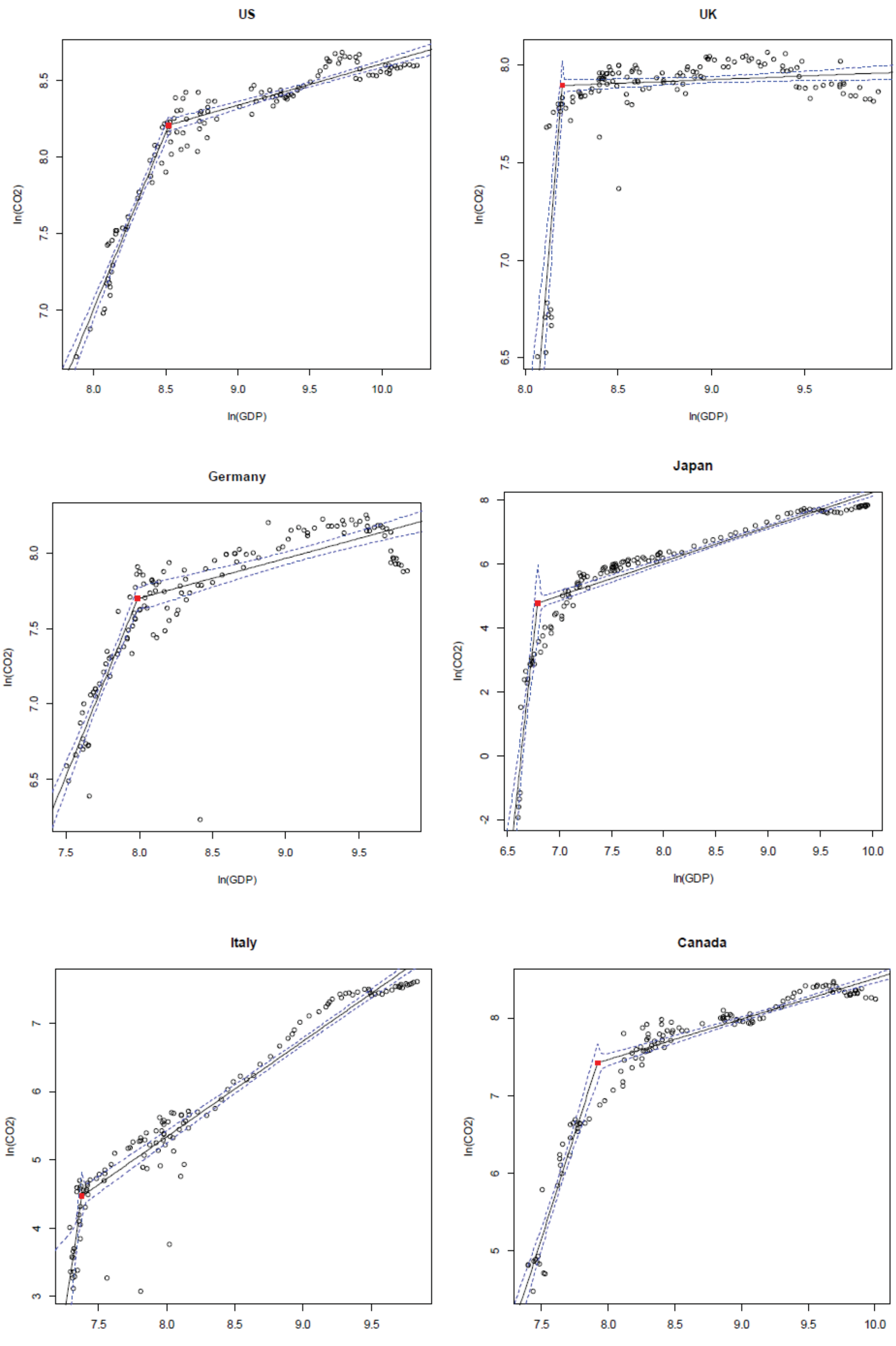


Figure 1. *Cont*.

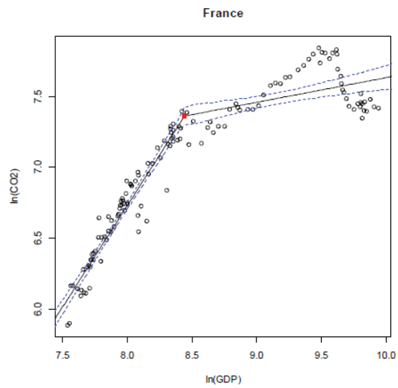


Figure 1. Scatter plot of real GDP and CO_2 emissions, with estimated kink regression model, and 95% confidence intervals. The dots show the pairs of observations of $\ln(GDP)$ and $\ln(CO_2)$. The red dot is the estimated threshold.

The issue of carbon reduction and combating climate change is a public good that all countries need to maintain. However, as long as one person contributes to maintaining the public good, others can enjoy the creation of that public good. At the same time, they quietly wait for others to contribute, thus achieving free-riding and unearned benefits. However, due to the goal of economic growth and rational considerations, there may be a strong tendency for countries to adopt a *free-rider* strategy, hoping that they can rely on others to complete the task of reducing carbon emissions. A Kuznets inverted U effect for U.K. and France is in line with Wagner (2015) [80]. For the other five countries that do not fit the EKC hypothesis, our US, Canada, and Italy results are similar to Onater-Isberk (2016) [81]. Our results for Germany and Japan are similar to Jaunky (2011) [50]. However, our result is different from the idea of some former research, which provided support for the EKC hypothesis in G7 countries [82,83]. Meanwhile, Chang (2015) [84] found that the G7 countries did not satisfy the environmental Kuznets curve hypothesis, but our point disagrees with the previous study results offered by Chang (2015) [84].

In contrast to models that indirectly get the turning points of the EKC curve, the threshold value directly identifies the historical time of the G7 countries' turning points on the EKC curve. Turning points in the U.K. and France approximately go back to 1972 and 1969, respectively, when CO_2 emissions declined rapidly with income growth. However, for Canada and Italy, their turning points are approximately 1899 and 1891, respectively. The turning point for US, Germany and Japan is later, approximately 1912, 1914 and 1972, respectively, and the effect of income on CO_2 emissions is still positive but smaller. The time difference of the turning point of the EKC curve in the G7 countries mainly results from their respective economic scale effect, population size effect, economic structure effect, technical progress effect, international trade effect and policy effect. Therefore, the specific situation of their turning point is completely different.

4.2. Robust Analysis about SO_2 Emission

To further verify, compare and check the robustness of the analysis, we now turn to SO_2 pollution. Meanwhile, for verifying that the sample periods have no impact on our study results, we select the SO_2 data of G7 countries over time from 1870 to 2001. We also carry on the unit root tests for the time series of SO_2 for G7 countries using the Zivot-Andrews unit root test. The results indicate that these series are stationary and fill the modelling conditions (see Table 3). Table 5 and Figure 2 display the estimated results between log per capita GDP and log per capita SO_2 emissions for the G7 countries. The F-test indicates the presence of a threshold at the 1% significance level. The regression coefficient of SO_2 emissions β_1 for all the G7 countries is positive, and the regression coefficient of SO_2 emissions β_2 for all the G7 countries is negative, which means the EKC hypothesis is confirmed. Our empirical results show that the EKC hypothesis is perfectly valid in G7 for the nexus between incomes and SO_2 emissions, which is in line with the classical literature [10,51,80,85]. These papers focused on the relationship between income and SO_2 emissions, and all identified an inverted U-shaped relationship in G7. However, our results are different than the study results offered by Park and Lee (2011) [47], who find that there is no identical shape of EKC for SO_2 emission in different regions.

Table 5. Kink regression with the unknown threshold for SO_2 emissions.

Country	β_0	β_1	β_2	γ	*F*-Test	R^2
France	3.80 * (0.05)	1.30 * (0.05)	−4.50 * (0.16)	9.50 * (0.02)	762.74 *	0.84
UK	4.24 * (0.02)	0.64 * (0.02)	−2.57 * (0.21)	9.27 * (0.02)	991.32 *	0.83
Germany	4.15 * (0.05)	0.56 * (0.04)	−16.54 * (1.17)	9.65 * (0.01)	569.81 *	0.78
Japan	2.08 * (0.06)	5.60 * (0.27)	−0.12 * (0.05)	7.26 * (0.02)	533.30 *	0.82
Italy	3.40 * (0.04)	1.60 * (0.04)	−3.50 * (0.23)	9.40 * (0.02)	116.36 *	0.8
Canada	5.60 * (0.03)	2.60 * (0.07)	−1.30 * (0.06)	8.60 * (0.02)	1673.94 *	0.79
US	4.50 * (0.04)	2.07 * (0.08)	−0.52 * (0.05)	8.59 * (0.02)	717.34 *	0.80

Notes: Numbers in parentheses denotes Std. Error. * denotes significant at the level of 5%.

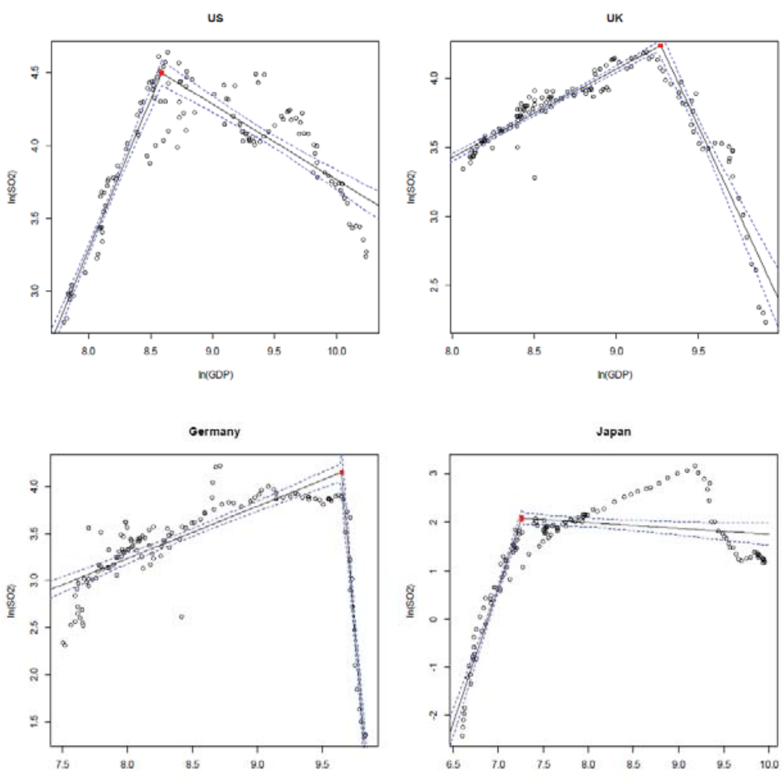


Figure 2. *Cont.*

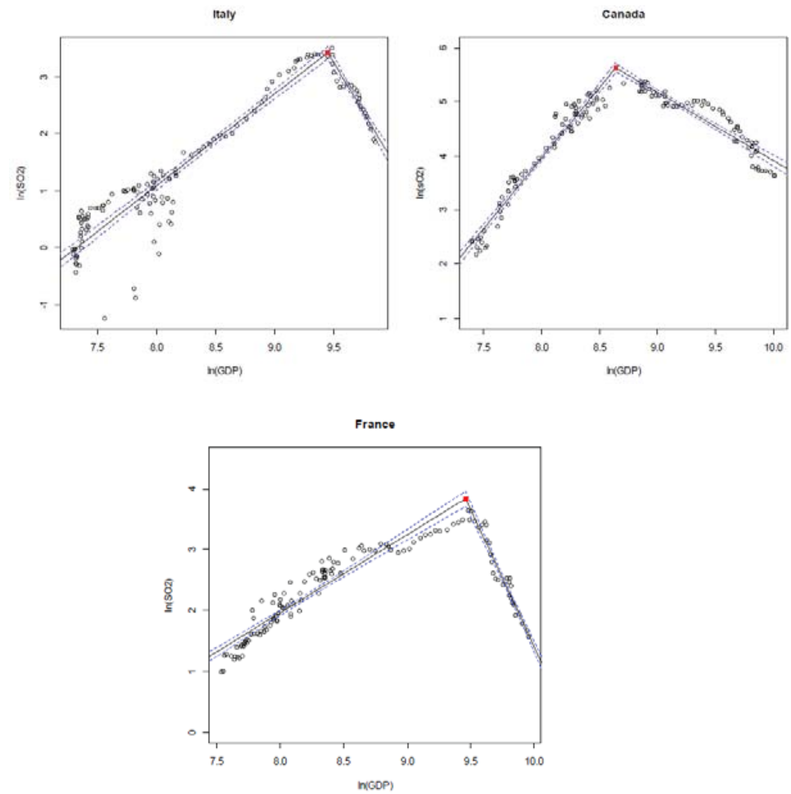


Figure 2. Scatter plot of real GDP and SO_2 emissions, with estimated regression kink model, and 95% confidence intervals. The dots show the pairs of observations of $\ln(GDP)$ and $\ln(SO_2)$. The red dot is the estimated threshold.

In summary, CO_2 emissions and SO_2 emissions have different relationships with income, possibly due to the following two reasons. On the one hand, the source range of CO_2 emissions is wider than SO_2 emissions. CO_2 emissions are produced in the industrial production activities and stem from the ordinary lives of residents. By comparison, the SO_2 emission source range is relatively narrow. On the other hand, with the growth in the economy and the improvement in income, the consumption of energy structure has been changing. Even in the same country, there is no single dominant shape of the EKC curves for the various pollutant, namely, SO_2 and CO_2. Further analysis of SO_2 emissions implies that environmental policies targeting pollutant emissions reduction should consider the different characteristics of different pollutants and regions.

5. Discussion and Conclusions

5.1. Conclusions

This paper re-examines the EKC hypothesis in the G7 countries based on CO_2 and SO_2 emissions data by employing a new kink regression model with an unknown threshold. The results show no inverted U-shaped nexus between the income per capita and CO_2 emissions for the US, Germany, Italy, Canada and Japan, except for U.K. and France. Nevertheless, we find that income has a threshold effect for these countries that not does fit the EKC hypothesis. We call this relationship a pseudo-EKC. The turning point of the EKC curve is evident for the UK, France, Canada, Italy, US, Germany and Japan, and occurs in 1972, 1969, 1899, 1891, 1912, 1914 and 1972, respectively. In addition, this paper finds that the relationship between CO_2 and economic growth is a "pseudo" EKC, while SO_2 exhibits an inverted U-shape, consistent with the EKC curve hypothesis. Therefore, the EKC hypothesis cannot be generalized to all pollutants and all countries.

5.2. Discussions and Policy Implications

According to the research conclusions, this paper puts forward the following policy suggestions: First, since the stage of negative correlation between economic growth for carbon emission reduction has not yet been reached in most countries, the government must take care to avoid contradictions between policies to control greenhouse gas emissions and economic development policies in the future [43]. Therefore, policymakers must strategically design and implement interventions to promote economic growth, improve environmental quality and promote sustainable development. For example, in the long run, for economic and environmental benefits, compatible green economic growth policies such as carbon pricing and increasing subsidies for green energy activities should be encouraged. Second, environmental policies need to be customized for each pollutant, rather than being standardized measures. In other words, governments should formulate relevant policies and take different measures to reduce air pollution according to the EKC characteristics of different air pollutants. Third, each country should formulate corresponding policy objectives according to the time of the turning point. As sustainable development is crucial to every G7 country, environmental pollution is an important obstacle to national sustainable development. Therefore, to reduce environmental pollution, we must raise public awareness and carry out necessary structural reform to make per capita GDP reach a turning point.

There are some limitations of our study in this paper, such as the data collection, analysis and interpretation that the modelling should further support. Meanwhile, many areas of the investigation remain for future studies. For example, we should further develop a framework to further analyze the reasons for the turning point of pollutant emissions in G7 countries at a certain historical point, which can help policymakers identify the correct mechanism to drive national carbon emission reduction. Second, we still need to build a model to further analyze why the evidence from SO_2 data indicates the existence of EKC, but the evidence from CO_2 data indicates that it does not exist. Third, the explanation of the *free-rider* effect in the main results proves the complexity of carbon emissions reductions across countries. It suggests that solving the problem of collective global action by a country and its government alone is inherently unworkable [86–88]. Therefore, effectively reducing the occurrence of the "*free-rider*" as much as possible is an important problem to be discussed in the future. Fourth, our current study does not analyze the heterogeneity of different G7 countries. Future research needs to increase comparative regional analysis to find the impact of carbon emissions in different countries and other economic conditions. In particular, to better understand environmental sustainability, future research can use other greenhouse gases, such as methane and nitrous oxide.

Author Contributions: Conceptualization, P.-Z.L., Y.-S.R. and Y.J.; methodology, P.-Z.L. and Y.J.; software, P.-Z.L. and Y.-S.R.; validation, P.-Z.L., Y.-S.R. and Y.J.; formal analysis, P.-Z.L., Y.-S.R. and Y.J.; investigation, Y.-S.R. and Y.J.; resources, Y.-S.R. and Y.J.; data curation, P.-Z.L. and Y.J.; writing—original draft preparation, P.-Z.L., Y.-S.R. and Y.J.; writing—review and editing, S.N., K.B. and B.S.; visualization, Y.J. and Y.-S.R.; supervision, Y.J., Y.-S.R., S.N., K.B. and B.S.; project administration, Y.-S.R. and Y.J.; funding acquisition, Y.-S.R. and Y.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 72104075; 72101120; 71850012, the National Office for Philosophy and Social Sciences Fund of China, grant number 19AZD014, the Hunan social science achievement review committee, grant number XSP21YBC087, Youth project of Jiangsu Social Science Foundation, grant number 21EYC001, The third phase of Applied Economics of Nanjing Audit University for advantageous disciplines in Colleges and universities in Jiangsu Province project, grant number [2014]37, and the Hunan University Youth Talent Program.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be available on request.

Acknowledgments: The authors would like to thank Hunan University for sponsoring this research. Meanwhile, the authors would like to thank the editor and anonymous reviewers for their patience and helpful comments on the earlier versions of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Grossman, G.M.; Krueger, A.B. Economic growth and the environment. *Q. J. Econ.* **1995**, *110*, 353–377. [CrossRef]
2. Kuznets, S. Economic Growth and Income Inequality. *Am. Econ. Rev.* **1955**, *45*, 1–28.
3. Özokcu, S.; Özdemir, Ö. Economic growth, energy, and environmental Kuznets curve. *Renew. Sustain. Energy Rev.* **2017**, *72*, 639–647. [CrossRef]
4. Jalil, A.; Feridun, M. The impact of growth, energy and financial development on the environment in China: A cointegration analysis. *Energy Econ.* **2011**, *33*, 284–291. [CrossRef]
5. Martinez-Zarzoso, I.; Bengochea-Morancho, A. Pooled mean group estimation of an Environmental Kuznets Curve for CO_2. *Econ. Lett.* **2004**, *82*, 121–126. [CrossRef]
6. Sarkodie, S.A.; Strezov, V. Empirical study of the Environmental Kuznets curve and Environmental Sustainability curve hypothesis for Australia, China, Ghana and USA. *J. Clean. Prod.* **2018**, *201*, 98–110. [CrossRef]
7. Grossman, G.M.; Krueger, A.B. *Environmental Impacts of a North American Free Trade Agreement*; National Bureau of Economic Research: Cambridge, MA, USA, 1991.
8. Coondoo, D.; Dinda, S. Causality between income and emission: A country group-specific econometric analysis. *Ecol. Econ.* **2002**, *40*, 351–367. [CrossRef]
9. Kaika, D.; Zervas, E. The Environmental Kuznets Curve (EKC) theory—Part A: Concept, causes and the CO_2 emissions case. *Energy Policy* **2013**, *62*, 1392–1402. [CrossRef]
10. Nieto, J.; Carpintero, Ó.; Miguel, L.J.; de Blas, I. Macroeconomic modelling under energy constraints: Global low carbon transition scenarios. *Energy Policy* **2020**, *137*, 111090. [CrossRef]
11. UNEP. *Emissions Gap Report 2020*; U.N. Environment Programme: Nairobi, Kenya, 2020.
12. He, L.; Zhang, X.; Yan, Y. Heterogeneity of the Environmental Kuznets Curve across Chinese cities: How to dance with 'shackles'? *Ecol. Indic.* **2021**, *130*, 108128. [CrossRef]
13. Hansen, B.E. Regression Kink with an Unknown Threshold. *J. Bus. Econ. Stat.* **2017**, *35*, 228–240. [CrossRef]
14. Chimeli, A.B. Growth and the environment: Are we looking at the right data? *Econ. Lett.* **2007**, *96*, 89–96. [CrossRef]
15. Shafic, N.; Bandyopadhyay, S. *Economic Growth and Environmental Quality. Time-Series and Cross Country Evidence. Policy Research Working Paper No. 904*; World Development Report 1992; The World Bank: Washington, DC, USA, 1992.
16. Panayotou, T. *Economic Growth and the Environment 2003. Economic Survey of Europe*; UNECE: Geneva, Switzerland, 2003; Volume 2, Chapter 2.
17. Magnani, E. The Environmental Kuznets Curve, environmental protection policy and income distribution. *Ecol. Econ.* **2000**, *32*, 431–443. [CrossRef]
18. Khanna, N. The income elasticity of non-point source air pollutants: Revisiting the environmental Kuznets curve. *Econ. Lett.* **2002**, *77*, 387–392. [CrossRef]
19. López, R. The Environment as a Factor of Production: The Effects of Economic Growth and Trade Liberalization. *J. Environ. Econ. Manag.* **1994**, *27*, 163–184. [CrossRef]
20. Suri, V.; Chapman, D. Economic growth, trade and energy: Implications for the environmental Kuznets curve. *Ecol. Econ.* **1998**, *25*, 195–208. [CrossRef]
21. Selden, T.M.; Song, D. Environmental quality and development: Is there a Kuznets curve for air pollution emissions? *J. Environ. Econ. Manag.* **1994**, *27*, 147–162. [CrossRef]
22. De Bruyn, S.M.; van den Bergh, J.C.J.M.; Opschoor, J.B. Economic growth and emissions: Reconsidering the empirical basis of Environmental Kuznets Curves. *Ecol. Econ.* **1998**, *25*, 161–175. [CrossRef]
23. Wara, M. Is the global carbon market working? *Nature* **2007**, *445*, 595–596. [CrossRef]
24. Fan, Y.; Wu, J.; Xia, Y.; Liu, J.-Y. How will a nationwide carbon market affect regional economies and efficiency of CO_2 emission reduction in China? *China Econ. Rev.* **2016**, *38*, 151–166. [CrossRef]
25. Panayotou, T. Demystifying the environmental Kuznets curve: Turning a black box into a policy tool. *Environ. Dev. Econ.* **1997**, *2*, 465–484. [CrossRef]
26. Grossman, G.M.; Krueger, A.B. Environment Impacts of a North American Free Trade Agreement. In *The Mexican-US Free Trade Agreement*; Garber, P.M., Ed.; MIT Press: Cambridge, UK, 1993; pp. 1–10.
27. Shafik, N. Economic Development and Environmental Quality: An Econometric Analysis. *Oxf. Econ. Pap.* **1994**, *46*, 757–773. [CrossRef]

28. Roberts, J.T.; Grimes, P.E. Carbon intensity and economic development 1962–1991. A brief exploration of the environmental Kuznets curve. *World Dev.* **1997**, *25*, 191–198. [CrossRef]
29. Magnani, E. The Environmental Kuznets Curve: Development path or policy result? *Environ. Model. Softw.* **2001**, *16*, 157–165. [CrossRef]
30. Farhani, S.; Mrizak, S.; Chaibi, A.; Rault, C. The environmental Kuznets curve and sustainability: A panel data analysis. *Energy Policy* **2014**, *71*, 189–198. [CrossRef]
31. Balado-Naves, R.; Baños-Pino, J.F.; Mayor, M. Do countries influence neighbouring pollution? A spatial analysis of the EKC for CO_2 emissions. *Energy Policy* **2018**, *123*, 266–279. [CrossRef]
32. Ang, J.B. CO_2 emissions, energy consumption, and output in France. *Energy Policy* **2007**, *35*, 4772–4778. [CrossRef]
33. Apergis, N.; Payne, J.E. The emissions, energy consumption, and growth nexus: Evidence from the commonwealth of independent states. *Energy Policy* **2010**, *38*, 650–655. [CrossRef]
34. Arouri, M.H.; Ben Youssef, A.; M'Henni, H.; Rault, C. Energy consumption, economic growth and CO_2 emissions in Middle East and North African countries. *Energy Policy* **2012**, *45*, 342–349. [CrossRef]
35. Stern, D.I.; Common, M.S. Is There an Environmental Kuznets Curve for Sulfur? *J. Environ. Econ. Manag.* **2001**, *41*, 162–178. [CrossRef]
36. Neve, M.; Hamaide, B. Environmental Kuznets curve with adjusted net savings as a trade-off between environment and development. *Aust. Econ. Pap.* **2017**, *56*, 39–58. [CrossRef]
37. Dinda, S. Environmental Kuznets Curve Hypothesis: A Survey. *Ecol. Econ.* **2004**, *49*, 431–455. [CrossRef]
38. Churchill, S.A.; Inekwe, J.; Ivanovski, K.; Smyth, R. The Environmental Kuznets Curve in the OECD: 1870–2014. *Energy Econ.* **2018**, *75*, 389–399. [CrossRef]
39. Shahbaz, M.; Sinha, A. Environmental Kuznets curve for CO_2 emissions: A literature survey. *J. Econ. Stud.* **2019**, *46*, 106–168. [CrossRef]
40. Piaggio, M.; Padilla, E.; Román, C. The long-term relationship between CO_2 emissions and economic activity in a small open economy: Uruguay 1882–2010. *Energy Econ.* **2017**, *65*, 271–282. [CrossRef]
41. Rafindadi, A.A. Revisiting the concept of environmental Kuznets curve in period of energy disaster and deteriorating income: Empirical evidence from Japan. *Energy Policy* **2016**, *94*, 274–284. [CrossRef]
42. Chang, H.-Y.; Wang, W.; Yu, J. Revisiting the environmental Kuznets curve in China: A spatial dynamic panel data approach. *Energy Econ.* **2021**, *104*, 105600. [CrossRef]
43. Holtz-Eakin, D.; Selden, T.M. Stoking the fires? CO_2 emissions and economic growth. *J. Public Econ.* **1995**, *57*, 85–101. [CrossRef]
44. Friedl, B.; Getzner, M. Determinants of CO_2 emissions in a small open economy. *Ecol. Econ.* **2003**, *45*, 133–148. [CrossRef]
45. Shao, S.; Li, X.; Cao, J.; Yang, L. China's Economic Policy Choices for Governing Smog Pollution Based on Spatial Spillover Effects. *Econ. Res.* **2016**, *51*, 73–88. (In Chinese)
46. Baek, J. Environmental Kuznets curve for CO_2 emissions: The case of Arctic countries. *Energy Econ.* **2015**, *50*, 13–17. [CrossRef]
47. Park, S.; Lee, Y. Regional model of EKC for air pollution: Evidence from the Republic of Korea. *Energy Policy* **2011**, *39*, 5840–5849. [CrossRef]
48. Marbuah, G.; Amuakwa-Mensah, F. Spatial analysis of emissions in Sweden. *Energy Econ.* **2017**, *68*, 383–394. [CrossRef]
49. Churchill, S.A.; Inekwe, J.; Ivanovski, K.; Smyth, R. The Environmental Kuznets Curve across Australian states and territories. *Energy Econ.* **2020**, *90*, 104869. [CrossRef]
50. Jaunky, V.C. The CO_2 emissions-income nexus: Evidence from rich countries. *Energy Policy* **2011**, *39*, 1228–1240. [CrossRef]
51. Fodha, M.; Zaghdoud, O. Economic growth and pollutant emissions in Tunisia: An empirical analysis of the environmental Kuznets curve. *Energy Policy* **2010**, *38*, 1150–1156. [CrossRef]
52. Nasr, A.B.; Gupta, R.; Sato, J.R. Is there an environmental Kuznets curve for South Africa? A co-summability approach using a century of data. *Energy Econ.* **2015**, *52*, 136–141. [CrossRef]
53. Al-Mulali, U.; Solarin, S.A.; Ozturk, I. Investigating the presence of the environmental Kuznets curve (EKC) hypothesis in Kenya: An autoregressive distributed lag (ARDL) approach. *Nat. Hazards* **2016**, *80*, 1729–1747. [CrossRef]
54. Isik, C.; Ongan, S.; Ozdemir, D.; Ahmad, M.; Irfan, M.; Alvarado, R.; Ongan, A. The increases and decreases of the environment Kuznets curve (EKC) for 8 OECD countries. *Environ. Sci. Pollut. Res.* **2021**, *28*, 28535–28543. [CrossRef]
55. Tenaw, D.; Beyene, A.D. Environmental sustainability and economic development in sub-Saharan Africa: A modified EKC hypothesis. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110897. [CrossRef]
56. Aziz, N.; Sharif, A.; Raza, A.; Jermsittiparsert, K. The role of natural resources, globalization, and renewable energy in testing the EKC hypothesis in MINT countries: New evidence from Method of Moments Quantile Regression approach. *Environ. Sci. Pollut. Res.* **2021**, *28*, 13454–13468. [CrossRef] [PubMed]
57. List, J.A.; Gallet, C.A. The environmental Kuznets curve: Does one size fit all? *Ecol. Econ.* **1999**, *31*, 409–423. [CrossRef]
58. Dijkgraaf, E.; Vollebergh, H.R.J. A Test for Parameter Homogeneity in CO_2 Panel EKC Estimations. *Environ. Resour. Econ.* **2005**, *32*, 229–239. [CrossRef]
59. Kaika, D.; Zervas, E. The environmental Kuznets curve (EKC) theory. Part B: Critical issues. *Energy Policy* **2013**, *62*, 1403–1411. [CrossRef]
60. Liu, X. Explaining the relationship between CO_2 emissions and national income—The role of energy consumption. *Econ. Lett.* **2005**, *87*, 325–328. [CrossRef]

61. Card, D.; Lee, D.S.; Pei, Z.; Weber, A. *Regression Kink Design: Theory and Practice*; Emerald Publishing Limited: Bentley, UK, 2017.
62. Maneejuk, N.; Ratchakom, S.; Maneejuk, P.; Yamaka, W. Does the environmental Kuznets curve exist? An international study. *Sustainability* **2020**, *12*, 9117. [CrossRef]
63. Yi, M.; Fang, X.; Wen, L.; Guang, F.; Zhang, Y. The heterogeneous effects of different environmental policy instruments on green technology innovation. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4660. [CrossRef]
64. Antle, J.M.; Heidebrink, G. Environment and Development: Theory and International Evidence. *Econ. Dev. Cult. Chang.* **1995**, *43*, 603–625. [CrossRef]
65. World Economic Forum. The Global Risks Report 2022. 2022. Available online: https://www.weforum.org/reports/global-risks-report-2022 (accessed on 11 January 2022).
66. Yilanci, V.; Pata, U.K. Investigating the EKC hypothesis for China: The role of economic complexity on ecological footprint. *Environ. Sci. Pollut. Res.* **2020**, *27*, 32683–32694. [CrossRef]
67. Galeotti, M.; Lanza, A. Richer and cleaner? A study on carbon dioxide emissions in developing countries. *Energy Policy* **1999**, *27*, 565–573. [CrossRef]
68. Halicioglu, F. An econometric study of CO_2 emissions, energy consumption, income and foreign trade in Turkey. *Energy Policy* **2009**, *37*, 1156–1164. [CrossRef]
69. Ertugrul, H.M.; Cetin, M.; Seker, F.; Dogan, E. The impact of trade openness on global carbon dioxide emissions: Evidence from the top ten emitters among developing countries. *Ecol. Indic.* **2016**, *67*, 543–555. [CrossRef]
70. Shahbaz, M.; Shafiullah, M.; Papavassiliou, V.G.; Hammoudeh, S. The CO_2—Growth nexus revisited: A nonparametric analysis for the G7 economies over nearly two centuries. *Energy Econ.* **2017**, *65*, 183–193. [CrossRef]
71. Dickey, D.A.; Fuller, W.A. Distribution of the estimators for autoregressive time series with a unit root. *J. Am. Stat. Assoc.* **1979**, *74*, 427–431.
72. Phillips, P.C.; Perron, P. Testing for a unit root in time series regression. *Biometrika* **1988**, *75*, 335–346. [CrossRef]
73. Zivot, E.; Andrews, D.W. Further Evidence on the Great Crash, the Oil-Price Shock, and the Unit-Root Hypothesis. *J. Bus. Econ. Stat.* **1992**, *10*, 251–270.
74. Galeotti, M.; Lanza, A. Desperately seeking environmental Kuznets. *Environ. Model. Softw.* **2005**, *20*, 1379–1388. [CrossRef]
75. Aslanidis, N.; Iranzo, S. Environment and development: Is there a Kuznets curve for CO_2 emissions? *Appl. Econ.* **2009**, *41*, 803–810. [CrossRef]
76. Olson, M. *The Logic of Collective Action*; Harvard University Press: Harvard, UK, 2009; Volume 124.
77. Grooms, K.K. Enforcing the Clean Water Act: The effect of state-level corruption on compliance. *J. Environ. Econ. Manag.* **2015**, *73*, 50–78. [CrossRef]
78. Guo, S.; Lu, J. Jurisdictional air pollution regulation in China: A tragedy of the regulatory anti-commons. *J. Clean. Prod.* **2019**, *212*, 1054–1061. [CrossRef]
79. Ansuategi, A.; Escapa, M. Economic growth and greenhouse gas emissions. *Ecol. Econ.* **2002**, *40*, 23–37. [CrossRef]
80. Wagner, M. The environmental Kuznets curve, cointegration and nonlinearity. *J. Appl. Econ.* **2015**, *30*, 948–967. [CrossRef]
81. Onater-Isberk, E. Environmental Kuznets curve under noncarbohydrate energy. *Renew. Sustain. Energy Rev.* **2016**, *64*, 338–347. [CrossRef]
82. Raza, S.A.; Shah, N. Testing environmental Kuznets curve hypothesis in G7 countries: The role of renewable energy consumption and trade. *Environ. Sci. Pollut. Res.* **2018**, *25*, 26965–26977. [CrossRef]
83. Nabaee, M.; Shakouri, G.H.; Tavakoli, O. Comparison of the Relationship Between CO_2, Energy USE, and GDP in G7 and Developing Countries: Is There Environmental Kuznets Curve for Those? In *Energy Systems and Management*; Bilge, A., Toy, A., Günay, M., Eds.; Springer Proceedings in Energy; Springer: Cham, Switzerland, 2015; pp. 229–239.
84. Chang, M.C. Room for improvement in low carbon economies of G7 and BRICS countries based on the analysis of energy efficiency and environmental Kuznets curves. *J. Clean. Prod.* **2015**, *99*, 140–151. [CrossRef]
85. Fosten, J.; Morley, B.; Taylor, T. Dynamic misspecification in the environmental Kuznets curve: Evidence from CO_2 and SO_2 emissions in the United Kingdom. *Ecol. Econ.* **2012**, *76*, 25–33. [CrossRef]
86. Ostrom, E. A Polycentric Approach For Coping With Climate Change. *Ann. Econ. Financ.* **2014**, *15*.
87. Ostrom, E. Polycentric systems for coping with collective action and global environmental change. *Glob. Environ. Chang.* **2010**, *20*, 550–557. [CrossRef]
88. Cole, D.H. Advantages of a polycentric approach to climate change policy. *Nat. Clim. Chang.* **2015**, *5*, 114–118. [CrossRef]

sustainability

MDPI

Article

Impact of Institutions and Human Capital on CO_2 Emissions in EU Transition Economies

Yilmaz Bayar [1,*], Vladimir Smirnov [2,3], Marina Danilina [2,3,4] and Natalia Kabanova [3]

1 Department of Public Finance, Faculty of Economics and Administrative Sciences, Bandirma Onyedi Eylul University, 10200 Bandirma-Balikesir, Turkey
2 Scientific Department, All-Russian Research Institute VNII of Labour, 123995 Moscow, Russia; vsmirnov@vcot.info (V.S.); marinadanilina@yandex.ru (M.D.)
3 Department of Economics, Finance University under the Government of the Russian Federation, 125167 Moscow, Russia; NKabanova@fa.ru
4 Department of Economics, Plekhanov Russian University of Economics (PRUE), 115093 Moscow, Russia
* Correspondence: yilmazbayar@yahoo.com

Abstract: Environmental degradation is one of the most significant problems of the globalized world. This paper explores the impact of institutional development and human capital on CO_2 emissions in 11 EU transition economies over the period of 2000–2018 through co-integration analysis. The co-integration analysis revealed that human capital negatively affected CO_2 emissions in Croatia, the Czech Republic, Hungary, and Slovenia, and that institutions had a negative impact on CO_2 emissions in the Czech Republic. However, both institutions and human capital positively affected CO_2 emissions in Latvia and Lithuania.

Keywords: institutional development; human capital; CO_2 emissions; co-integration analysis

Citation: Bayar, Y.; Smirnov, V.; Danilina, M.; Kabanova, N. Impact of Institutions and Human Capital on CO_2 Emissions in EU Transition Economies. *Sustainability* **2022**, *14*, 353. https://doi.org/10.3390/su14010353

Academic Editor: Bertrand Hamaide

Received: 19 November 2021
Accepted: 21 December 2021
Published: 29 December 2021

1. Introduction

The significant increase in industrialization, mass production, global population, and urbanization has deteriorated the environment over the past two centuries and has led to many environmental problems, including climate change, water, air, and soil pollution and degradation, waste-utilization problems, species extinction, and deforestation. Environmental degradation has become one of the most serious problems faced by human beings in terms of health and sustainable economic growth and development. Therefore, national (especially developed economies) and international authorities began to introduce measures for environmental sustainability. The 1972 United Nations Conference on the Environment was the first global organization to bring attention to environmental problems [1]. As a result, the United Nations Environment Program (UNEP), governed by the United Nations Environment Assembly as a global body, was established in 1972 to set environmental agendas and organize environmental policies on a global scale [2]. Furthermore, the Intergovernmental Panel on Climate Change (IPCC), which is the United Nations' body for climate change, was formed by the United Nations Environment Program (UN Environment) and the World Meteorological Organization (WMO) in 1988 [3].

The European Union (EU) has also struggled to bring attention to environmental sustainability since the first UN conference on the environment. The Single European Act of 1987 introduced the term "environment," which was the first legal basis for common environmental policies aimed at the preservation of environmental quality, human health, and the rational employment of human resources [4]. The EU environmental policy has been implemented by the Environment Action Program (EAPs) since the 1970s, and a 55% reduction in greenhouse-gas emissions to 1990 levels by 2030 is a target of the 2030 Climate Target Plan [5]. On the other hand, China, which has the largest energy consumption and CO_2 emissions, targets to maintain its international competitiveness and sustainable development through a national carbon-trading system [6].

Globally, environmental quality has significantly degraded, prompting scholars to explore the factors underlying environmental degradation and possible environmental measures to restore the environment. In this context, economic growth, industrialization, urbanization, population, residential heating systems, energy consumption, industrialization, deforestation, trade openness, FDI inflows, and globalization have been documented as the main causes of environmental degradation in the related literature [7–19]. Furthermore, an extensive number of studies in the related literature have tested the validity of the Environmental Kuznets Curve (EKC) hypothesis, which suggests the interaction between environmental and economic development levels for different countries, and have reached mixed findings [20–23].

Legislative environmental measures such as environmental regulations and standards, as well as market-based environmental policy instruments such as environment tax, transferable emissions permit, and government subsidy reductions have been developed in order to mitigate and restore earth systems from environmental degradation [24]. Furthermore, renewable energy and efficiency through new and cleaner technologies have been observed to significantly mitigate environmental degradation [25–27].

Both institutions and human capital are significant players in the implementation of the appropriate and prudent environmental policies. In this context, the role of institutions and their effect on the environment is shown in the literature in many direct and indirect examples. It is extremely likely that strong and efficient institutions can maintain environmental quality by ensuring the efficient functioning of local and global environmental regulations, rather than being perceived to encourage corruption and the shadow economy [28]. Institutional quality may negatively affect the environment by fostering economic growth [29]; however, increasing overall income can raise the environmental awareness of the population [28]. We suggest that the net effect of institutions can change depending on which factors are dominant. Alternatively, human beings have been shown to have a significant impact on the global environment through their consumption and production activities. Therefore, we suggest that local populations with higher environmental awareness through education and training can have a positive impact on environmental quality, but human capital is also a significant determinant of economic growth. Similarly, the net effect of human capital on the environment can change depending on which channels are dominant.

The determinants of environmental degradation or CO_2 emissions have been extensively explored, while the environmental effects of both institutions and human capital have been relatively less explored, as can be seen from the empirical literature review. Therefore, in this study, we focus on institutions and human development in a sample of EU transition economies that are experiencing structural change in institutions and human capital with the contribution of transition and EU membership processes. The scores of institutions and human capital of the EU transition economies are presented in Table 1. Table 1 shows that Czechia, Latvia, and Lithuania made significant improvements to their institutions, whereas only Hungary experienced deteriorations in its institutions. On the other hand, Bulgaria, Czechia, Estonia, Poland, Slovakia, and Slovenia experienced considerable progress in human capital, but the other countries experienced relatively fewer improvements to human capital.

Table 1. Development of institutions and human capital in EU transition members.

Countries	Year	Institutions Score	Human-Capital Score
Bulgaria	2000	57.8042	51.68337
Bulgaria	2018	59.52434	58.98156
Croatia	2000	58.9135	55.54833
Croatia	2018	64.41148	58.57758
Czechia	2000	67.81401	56.78816
Czechia	2018	76.75671	67.39377
Estonia	2000	75.44497	54.6999
Estonia	2018	82.69684	64.02946
Hungary	2000	77.0254	55.07496
Hungary	2018	64.25326	61.61617
Latvia	2000	63.85738	53.05329
Latvia	2018	73.83265	55.76249
Lithuania	2000	65.66885	55.9387
Lithuania	2018	77.38173	59.91948
Poland	2000	70.91636	54.6009
Poland	2018	72.25084	61.12796
Romania	2000	44.02271	47.67062
Romania	2018	51.5108	52.06732
Slovakia	2000	67.19018	53.83563
Slovakia	2018	72.15298	60.84067
Slovenia	2000	75.2741	61.48158
Slovenia	2018	76.24501	71.8252

Source: UNCTAD [30].

We aim to make a contribution to the empirical literature in three ways. In the related empirical literature, scholars have generally proxied the institutions by worldwide governance indicators of the World Bank. Therefore, the first contribution of the study is to use the institutions index by UNCTAD (United Nations Conference on Trade and Development) in view of the related literature. Secondly, this study is targeted to be one of the first to analyze the interaction among institutions, human capital and CO_2 emissions in a sample of EU transition economies. Thirdly, the employment of a second generation co-integration test, which also produces robust findings for small samples, was evaluated in order to raise the reliability of the findings. The general framework of our research is as follows: The theoretical and empirical literature summary is presented in Section 2, then the data and methods are described, the results and discussion are given in Section 4, and finishes with the conclusions.

2. Empirical Literature Review

The environmental degradation has become a critical problem for the globalized world. Therefore, institutional and economic determinants of environmental degradation have been extensively explored in the related literature. The related literature has documented institutional quality, human capital, economic growth, population, energy consumption, industrialization, urbanization, export, FDI inflows, trade, and financial openness [7–19].

In this study, we focused on the impact of institutions and human capital on the environmental quality proxied by CO_2 emissions by considering the limited literature and the significant role of institutions and human capital in the design and implementation of environmental policies. In the empirical literature, most scholars have determined that a higher institutional quality has raised the environmental quality, as can be seen from the following empirical literature review.

Tamazian and Rao [31] explored the impact of institutional quality on environmental quality in transition economies over 1993–2004 through dynamic regression analysis and revealed that strong institutions was a significant determinant of environmental quality. On the other hand, Lau et al. [32] also explored the effect of institutions on CO_2 emissions in

Malaysia over 1984–2008 through the ARDL co-integration test and determined a decreasing effect of institutions on CO_2 emissions.

Gill et al. [33] explored the effect of public governance on CO_2 emissions in South-Eastern Asian countries over 1980–2014 and revealed the worldwide governance indicators as the significant determinants of CO_2 emissions. On the other hand, Baloch and Wang [34] explored the effect of governance on CO_2 emissions in BRICS economies over 1996–2017 through the Westerlund co-integration test and determined that a higher governance level decreased the CO_2 emissions. Ali et al. [35] also explored the impact of institutions proxied by a variable derived from corruption, rule of law, and bureaucratic quality of the International Country Risk Guide on CO_2 emissions in 47 developing countries through dynamic regression analysis and determined a negative effect of institutional quality on CO_2 emissions.

Ahmed et al. [36] explored the effect of institutional quality proxied by an index calculated from worldwide governance indicators and some economic variables on the environment in Pakistan over 1996–2018 through the ARDL co-integration approach and determined the ultimately negative impact of institutional quality on CO_2 emissions. Nkengfack et al. [37] also explored the impact of public governance proxied by worldwide governance indicators on environmental quality in the Economic Community of Central African States over 1996–2014 and found that public governance had a positive effect on the environmental quality.

Simionescu et al. [38] analyzed the effect of worldwide governance indicators on GHG emissions in Central and Eastern European states over 2006–2019 through estimators of panel dynamic OLS and panel autoregressive distributed lag and determined that public governance indicators decreased GHG emissions. On the other hand, Wu and Madni [28] researched the institutional development proxied by an index formed from 12 institutional indicators from the International Country Risk Guide on the environmental quality in One Belt, One Road countries over 1986–2017 through a panel threshold regression analysis and discovered that institutional quality decreased the environmental degradation after a threshold level of institutional quality.

Sah [39] explored the impact of institutional development proxied by an index derived from worldwide governance indicators on CO_2 emissions in the Economic and Monetary Community of Central African countries over 1996–2017 through a first generation co-integration analysis and discovered a negative impact of institutional development on CO_2 emissions.

These few studies have determined a positive impact of institutional development on CO_2 emissions in the empirical literature on environmental institutions. Cole [40] explored the impact of corruption on CO_2 and sulfur dioxide emissions in 94 countries over 1987–2000 and revealed the increasing impact of corruption on both emissions. Goel et al. [41] explored the impact of institutional quality proxied by corruption and the shadow economy in a panel consisting of over 100 countries over 2004–2007 and revealed that countries with more corruption and shadow economy experienced lower emissions, but higher emissions in MENA countries. Nguyen et al. [29] explored the impact of institutions on CO_2 emissions in 36 emerging countries over 2002–2015 through dynamic regression analysis and determined a positive impact of institutional development on CO_2 emissions.

The empirical literature on the impact of human capital on the environment has mainly revealed a positive impact of human capital on environmental quality. In this context, Bano et al. [42] explored the effect of human capital on CO_2 emissions in Pakistan over 1971–2014 through ARDL co-integration and revealed the ultimately decreased effect of human-capital improvement on CO_2 emissions. Mahmood et al. [43] also researched the effect of human capital on CO_2 emissions in Pakistan over 1980–2014 through regression analysis and discovered a negative effect of human capital on CO_2 emissions. On the other hand, Li and Ouyang [44] analyzed the effect of human development and some economic variables on CO_2 emissions in China over 1978–2015 through ARDL co-integration and revealed an inverted N-shaped interaction between human capital and CO_2 emissions, which suggested that human-capital improvement decreased CO_2 emission intensity and raised emissions in the short term while decreasing them in the long term.

Yao et al. [45] explored the effect of human capital on CO_2 emissions in 20 OECD economies over 1870–2014 and determined that human-capital development decreased the CO_2 emissions in the long run, but the non-parametric estimations revealed that the interaction between human capital and CO_2 emissions became negative in the 1950s and then the negative impact became stronger.

Zhang et al. [46] explored the effect of human capital on CO_2 emissions in Pakistan over 1985–2018 by employing dynamic ARDL co-integration and discovered that human capital decreased the CO_2 emissions in the long term, but raised them in the short term. Wang and Xu [47] also explored the effect of human capital together with internet usage on CO_2 emissions in 70 economies over 1995–2018 through regression analysis and found that human capital was a significant determinant of economic development with a low carbon footprint.

Lin et al. [48] explored the effect of innovative human capital on CO_2 emissions in 30 Chinese provinces over 2003–2007 through static and dynamic regression analyses and determined a decreasing effect of human capital on CO_2 emissions. Joof and Isiksal [49] explored the effect of human capital on CO_2 emissions in Mexico, Indonesia, Nigeria, and Turkey over 1975–2010 through a pooled mean group estimator and determined a negative effect of human capital on CO_2 emissions. Xiao and You [50] analyzed the effect of human capital on green total factor productivity in 30 Chinese provinces over 2001–2018 through regression analysis and revealed a positive effect of human capital on green total factor productivity.

3. Data and Method

This study explored the impact of institutions and human capital on CO_2 emissions in EU transition members over 2000–2018 through co-integration analysis. In the empirical analysis, carbon dioxide emissions were proxied by carbon dioxide emissions (metric tons per capita). On the other hand, institutions and human capital were represented by scores of institutions and human capital between 0 and 100 (higher values mean better institutions and human capital) of UNCTAD [51]. The institutions score was calculated by considering political stability, regulatory quality, effectiveness, success in fighting corruption, criminality and terrorism, and freedom of expression and association [30]. The human-capital score reflected the education, skills and health conditions of each country's population, their research and development integration and their gender dimension [51]. The data of CO_2 emissions was obtained from the World Bank database [52], and the institution and human-capital scores were provided from the UNCTAD [30] database. All series are annual and the study covered 2000–2018 (see Table 2). The logarithmic forms of the variables were used in the econometric analyses.

Table 2. Dataset definition.

Variable	Abbreviation	Data Source
Carbon dioxide emissions (metric tons per capita)	*CO*	World Bank [52]
Institutions index	*INST*	UNCTAD [30]
Human-capital index	*HUMAN*	UNCTAD [30]

The following econometric model was formed in order to explore the impact of institutions and human capital on CO_2 emissions in a country i (i = 1, . . . , 11), in year t (t = 2000, . . . , 2018).

$$CO_{it} = f(INST_{it}, HUMAN_{it}) \tag{1}$$

The EU transition economies consist of Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia and Slovenia. The key characteristics of the series are displayed in Table 3. The average CO_2 emissions in terms of metric tons per capita were about 6.5762 and the average institutions and human-capital scores were, respectively, 69.3187 and 58.8173. However, the quality of institutions and human capital significantly changed from country to country as seen in Table 3.

Table 3. Descriptive statistics of the dataset.

	Characteristics	***CO***	***INST***	***HUMAN***
Countries	Mean	6.5762	69.3187	58.8173
	Maximum	14.8059	82.9772	74.7581
	Minimum	2.9270	44.0227	47.6706
	Std. Dev.	2.8798	8.4476	5.1028
Bulgaria	Mean	6.0796	59.5356	55.1254
	Maximum	6.9738	60.9912	59.4539
	Minimum	5.3034	57.8042	51.6833
	Std. Dev.	0.4353	0.92939	2.58111
Croatia	Mean	4.4981	63.6732	57.0224
	Maximum	5.3106	65.4378	58.6673
	Minimum	3.8552	58.9135	54.91431
	Std. Dev.	0.4576	1.66797	1.305984
Czechia	Mean	10.8933	74.9831	63.1774
	Maximum	12.1054	76.7895	68.5973
	Minimum	9.4771	67.8140	56.7881
	Std. Dev.	1.0186	2.13930	4.02976
Estonia	Mean	12.5179	79.4459	61.4329
	Maximum	14.8059	82.9772	67.4835
	Minimum	10.6085	75.4449	54.6999
	Std. Dev.	1.2544	2.36094	4.04260
Hungary	Mean	4.9839	72.2871	59.56935
	Maximum	5.7485	78.8646	62.5481
	Minimum	4.1179	64.2532	55.0749
	Std. Dev.	0.5322	4.81834	2.17034
Latvia	Mean	3.5827	70.4504	55.5037
	Maximum	4.0618	73.8326	56.9494
	Minimum	2.9270	63.8573	53.0532
	Std. Dev.	0.2937	2.5979	1.2450
Lithuania	Mean	3.7539	72.6050	59.1822
	Maximum	4.1370	77.3817	61.2563
	Minimum	3.0032	65.6688	55.9387
	Std. Dev.	0.3386	3.16905	1.61321
Poland	Mean	7.9241	71.3075	57.6828
	Maximum	8.2470	75.0620	61.1279
	Minimum	7.5144	66.1412	54.6009
	Std. Dev.	0.2520	2.72999	2.17127
Romania	Mean	4.11540	50.1872	51.5218
	Maximum	4.6683	54.3944	53.3686
	Minimum	3.5868	44.0227	47.6706
	Std. Dev.	0.3903	3.01943	1.70976
Slovak Republic	Mean	6.5278	71.4208	58.1412
	Maximum	7.1725	73.5764	61.8875
	Minimum	5.6194	67.1901	53.8356
	Std. Dev.	0.5566	1.69027	2.75126
Slovenia	Mean	7.4612	76.61015	68.6316
	Maximum	8.6033	78.5454	74.7581
	Minimum	6.3822	74.9362	61.4815
	Std. Dev.	0.6131	1.12124	4.33385

In the econometric analysis section of this paper, the *LM* bootstrap co-integration test by Westerlund and Edgerton [53] was employed to explore the effect of institutions and human capital on CO_2 emissions. The *LM* bootstrap co-integration test was chosen because it allows for autocorrelation and heteroscedasticity and produces more robust results for small samples. Furthermore, the co-integration coefficients were estimated by the AMG (Augmented Mean Group) estimator of Eberhardt and Bond [54] and Eberhardt and Teal [55] in view of their heterogeneity and cross-sectional dependency.

The co-integration relationship among institutions, human capital, and CO_2 emissions was examined by the *LM* bootstrap co-integration test of Westerlund and Edgerton [53]. The *LM* bootstrap co-integration test considers the cross-sectional dependency. The Westerlund and Edgerton [53] *LM* bootstrap co-integration test is based on the Lagrange multiplier test of McCoskey and Kao [56]. The *LM* bootstrap co-integration test produces biased results in the case of cross-sectional dependency and a standard normal distribution is also very susceptible to serial correlation. Therefore, the bootstrap approach is used instead of the standard normal distribution in order to overcome these problems.

4. Results and Discussions

The check for cross-sectional dependency and heterogeneity among the series employed in the study is important for the specification of further econometric tests such as the unit root and co-integration tests. Therefore, cross-sectional dependence was investigated using tests of *LM*, $LM_{adj.}$ and *LM* CD developed by Breusch and Pagan [57], Pesaran [58], and Pesaran et al. [59], respectively, and the tests' results are shown in Table 4. The null hypothesis of cross-sectional independency was reduced at 1% in light of all three tests and in turn we determined that there existed cross-sectional dependency among the three series.

Table 4. Cross-sectional-dependence tests' results.

Test	Test Statistic	*p*-Value
LM	212.1	0.0000
LM CD *	13.22	0.0000
LM_{adj} *	31.92	0.0000

* two-sided test.

The presence of homogeneity was checked by the homogeneity tests of Pesaran and Yamagata [60] after cross-sectional dependency, and both test results are shown in Table 5. The null hypothesis of homogeneity was reduced at 1%. Therefore, the co-integrating coefficients were discovered to be heterogeneous.

Table 5. Homogeneity tests' results.

Test	Test Statistic	*p*-Value
$\widetilde{\Delta}$	12.612	0.000
$\widetilde{\Delta}_{adj.}$	14.194	0.000

The presence of a unit root in the series was checked with the CIPS (Cross-Sectional IPS) [61] unit test by Pesaran [62] due to the existence of cross-sectional dependence among the variables, and the test findings are shown in Table 6. The test results indicated that the series of *LNCO, LNINST,* and *LNHUMAN* were I (1).

Table 6. Panel CIPS unit root test's results.

Variables	Level		First Differences	
	Constant	Constant + Trend	Constant	Constant + Trend
LNCO	1.706	−0.900	−6.180 ***	−5.366 ***
LNINST	−1.714	0.065	−4.307 ***	−3.087 ***
LNHUMAN	−0.925	1.230	−3.307 ***	−2.860 ***

*** It is significant at 5% significance level.

The co-integration relationship among institutions, human capital, and CO_2 emissions was analyzed through the *LM* bootstrap co-integration test by Westerlund and Edgerton [53] in view of the existence of cross-sectional dependency and heterogeneity, and the test findings are shown in Table 7. The test findings verified the importance of the second-generation co-integration test, because the bootstrap probability values were considered in case of cross-sectional dependency. Therefore, the null hypothesis of significant co-integration among the three series was accepted and we reached a significant co-integration relationship among the three variables.

Table 7. Westerlund and Edgerton [53] *LM* Bootstrap co-integration test results.

	Constant			Constant + Trend		
$LM_N{}^+$	Test statistic	Asymptotic *p*-value	Bootstrap *p*-value	Test statistic	Asymptotic *p*-value	Bootstrap *p*-value
	1.292	0.098	0.846	4.045	0.000	0.990

Note: Bootstrap probability values were derived from 10.000 repetitions, while asymptotic probability values were obtained from standard normal distribution. Lag and lead values were taken as 2.

The co-integration coefficients were estimated by the AMG estimator of Eberhardt and Teal [55] and the CCEMG (Common Correlated Effects Mean Group) estimator of Pesaran [63] in view of the cross-sectional dependency, heterogeneity, and robustness of the findings. The estimations of the AMG estimator are presented in Table 8, because similar coefficients were estimated by the two estimators. The co-integration coefficients revealed that institutions had a negative impact on CO_2 emissions only in Czech Republic, but a significant positive impact on CO_2 emissions in Latvia and Lithuania, and no significant impact in the other countries. On the other hand, the results indicated that human capital had a considerable decreasing impact on CO_2 emissions in Croatia, Czech Republic, Hungary, and Slovenia, but a positive impact on CO_2 emissions in Latvia and Lithuania.

Table 8. Estimation results of co-integration coefficients.

Countries	*LNINST*	*LNHUMAN*
Bulgaria	−0.7209	0.3208
Croatia	0.6043	−2.8286 ***
Czechia	−0.2793 *	−1.2560 ***
Estonia	0.2447	0.6377
Hungary	−0.1082	−2.7003 ***
Latvia	0.7497 ***	2.2568 ***
Lithuania	0.6726 **	1.7027 ***
Poland	−0.0855	0.3368
Romania	−0.1769	−1.6254
Slovak Republic	−0.1156	−1.5807
Slovenia	1.2169	−0.5567 ***
Panel	0.1819	−0.4811

***, **, * indicates that it is respectively significant at 1%, 5%, and 10%.

Institutions and human capital play a critical role in the design, implementation, and control of environmental policies, because environmental policies are mainly carried out and controlled by institutions and human capital. On the other hand, institutions and human capital are also significant determinants of economic growth. In this regard, the net effect of institutions and human capital on the environment can be varied depending on the current economic-development level of the countries in the sample, according to the EKC hypothesis. However, most scholars have revealed a positive impact of institutions and human capital on environmental quality in the related literature. Additionally, the findings of the co-integration analysis about the institution–environment nexus contradicted the findings of most of the studies in the related empirical literature, because most of the scholars such as Tamazian and Rao [31], Lau et al. [32], Gill et al. [33], Ahmed et al. [36], Nkengfack et al. [37], Simionescu et al. [38], Wu and Madni [28], and Sah [39] revealed a negative effect of institutions on CO_2 emissions. However, we revealed a decreasing effect of institutions on CO_2 emissions only in Czechia. On the other hand, we revealed that institutions raised the CO_2 emissions in Latvia and Lithuania, which was in agreement with Cole [40], Goel et al. [41] and Nguyen et al. [29]. The rising impact of institutions on CO_2 emissions indicated that the growth effect of institutional development dominated the environmental effects of institutions.

On the other hand, the findings of the co-integration analysis about the human capital–environment nexus were compatible with the theoretical and empirical findings of Bano et al. [42], Li and Ouyang [44], Yao et al. [45], Zhang et al. [46], and Joof and Isiksal [49]. However, human capital considerably raised the CO_2 emissions in Latvia and Lithuania. We evaluated that this effect could have resulted from the environment-deteriorating effect of human capital outweighing its positive environmental effect in these two countries.

5. Conclusions and Policy Implications

The globalized world is encountering the serious environmental problems of air pollution, climate change, deforestation, species extinction, soil degradation, overpopulation. Environmental quality is important not only for health, but also for sustainable economic growth and development. Therefore, extensive studies have been conducted in order to reveal the factors underlying the environmental degradation and to develop measures for improvements to environmental quality. In this context, many institutional and economic factors have been documented as possible determinants of environmental degradation, mainly proxied by CO_2 emissions. Furthermore, legal and market-based instruments have been developed to raise the environmental quality.

In this study, we focused on the ultimate environmental effects of institutions and human capital in a sample of EU transition economies, in view of their critical roles in the design, implementation and control of environmental policies, and the related limited empirical literature. The related empirical studies have generally proxied institutions by using worldwide governance indicators of the World Bank, but we proxied institutions using the institution score of UNCTAD, unlike the related literature. Furthermore, we employed a second-generation co-integration test and estimator that considered the presence of cross-sectional dependence and heterogeneity in the dataset, and country-level coefficients were also obtained. However, a limitation in this study was the limited period of 2000–2018, because the data of institutions and human capital only refer to this time, which should not be considered in the context of this research.

The co-integration analysis showed that institutional development decreased the CO_2 emissions only in Czechia, which made a significant institutional improvement during the study period, similar to most of the empirical findings. However, institutions raised the CO_2 emissions in Latvia and Lithuania and may have resulted from the growth effect of institutions outweighing their environmental effects. The findings also indicated that most of the countries have not reached their threshold level to experience the improvements to environmental quality through institutions.

On the other hand, human capital had a considerable decreasing impact on CO_2 emissions in Croatia, Czechia, Hungary, and Slovenia, in agreement with the theoretical and empirical findings. However, human capital raised the CO_2 emissions in Latvia and Lithuania. The EU transitions have generally experienced significant improvements to human capital, but the improvements to institutions lagged behind during the study period. Furthermore, the findings also indicated that the countries have not reached their threshold level of economic development to experience the improvements to environmental quality in view of the EKC hypothesis

The related theoretical considerations and empirical literature pointed out that both institutions and human capital have critical roles in achieving the improvements to environmental quality, and our findings partially verified these considerations because some countries in the sample still need to make progress in terms of their institutions and human capital. However, both institutions and human capital are significant determinants of economic growth and development. In this context, the countries can yield environmental gains from improvements to institutions and human capital after reaching the threshold referred to by the environmental Kuznets curve. Future studies can be conducted with a panel consisting of low-, middle- and high-income countries in order to see the effect of country-specific characteristics on the interaction among institutions, human capital, and CO_2 emissions.

Author Contributions: The authors contributed equally to this paper. Y.B., V.S., N.K. and M.D. described the context of the analysis and conducted the literature review. Y.B., V.S., N.K. and M.D. developed the research approach and performed the empirical analyses. Y.B., V.S., N.K. and M.D. formulated and discussed the main conclusions. Y.B. and M.D. edited the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: https://unctadstat.unctad.org/wds/ (accessed on 14 July 2021). and https://data.worldbank.org/indicator/EN.ATM.CO2E.PC (accessed on 14 July 2021).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. United Nations. United Nations Conference on the Human Environment, 5–16 June 1972. Available online: Stockholmhttps://www.un.org/en/conferences/environment/stockholm1972 (accessed on 13 June 2021).
2. UNEP. About UN Environment Programme. Available online: https://www.unep.org/about-un-environment (accessed on 13 June 2021).
3. IPCC. The Intergovernmental Panel on Climate Change. Available online: https://www.ipcc.ch/ (accessed on 13 June 2021).
4. European Parliament. Environment Policy: General Principles and Basic Framework. Available online: https://www.europarl.europa.eu/factsheets/en/sheet/71/environment-policy-general-principles-and-basic-framework (accessed on 13 June 2021).
5. European Commission. 2030 Climate Target Plan. Available online: https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-plan_en (accessed on 14 June 2021).
6. Zeng, S.; Nan, X.; Liu, C.; Chen, J. The Response of the Beijing Carbon Emissions Allowance Price (BJC) to Macroeconomic and Energy Price Indices. *Energy Policy* **2017**, *106*, 111–121. [CrossRef]
7. Sharma, S.S. Determinants of carbon dioxide emissions: Empirical evidence from 69 countries. *Appl. Energy* **2011**, *88*, 376–382. [CrossRef]
8. Gatto, A.; Busato, F. Energy Vulnerability around the World: The Global Energy Vulnerability Index (GEVI). *J. Clean. Prod.* **2020**, *253*, 118691. [CrossRef]
9. Shaheen, A.; Sheng, J.; Arshad, S.; Muhammad, H.; Salam, S. Forecasting the Determinants of Environmental Degradation: A Gray Modeling Approach. *Energy Sources Part A Recovery. Util. Environ. Eff.* **2020**. [CrossRef]
10. Laureti, T.; Benedetti, I. Analysing Energy-saving Behaviours in Italian Households. *Stud. Appl. Econ.* **2021**, *39*. [CrossRef]
11. Singh, G.; Singh, B. Deforestation and its Impact on Environment. *Int. J. Adv. Res. Sci. Eng.* **2017**, *6*, 262–268.
12. Wang, L.; Vo, X.V.; Shahbaz, M.; Ak, A. Globalization and Carbon Emissions: Is There any Role of Agriculture Value-added, Financial Development, and Natural Resource rent in the Aftermath of COP21? *J. Environ. Manag.* **2020**, *268*, 110712. [CrossRef] [PubMed]
13. Mahmood, H.; Alkhateeb, T.T.Y.; Furqan, M. Exports, Imports, Foreign Direct Investment and CO_2 Emissions in North Africa: Spatial Analysis. *Energy Rep.* **2020**, *6*, 2403–2409. [CrossRef]
14. Qiao, H.; Zheng, F.; Jiang, H.; Dong, K. The greenhouse effect of the agriculture-economic growth-renewable energy nexus: Evidence from G20 countries. *Sci. Total Environ.* **2019**, *671*, 722–731. [CrossRef]
15. Shao, Y. Does FDI Affect Carbon Intensity? New Evidence from Dynamic Panel Analysis. *Int. J. Clim. Change Strateg. Manag.* **2018**, *10*, 27–42. [CrossRef]
16. Rehman, H.U.; Zeb, S. Determinants of Environmental Degradation in Economy of Pakistan. *Empir. Econ. Rev.* **2020**, *3*, 85–109.
17. Aghasafari, H.; Aminizadeh, M.; Karbasi, A.; Calisti, R. CO_2 emissions, export and foreign direct investment: Empirical evidence from Middle East and North Africa Region. *J. Int. Trade Econ. Dev.* **2021**, *30*, 1054–1076. [CrossRef]
18. Salahuddin, M.; Gow, J.; Ali, I.; Hossain, R.; Al-Azami, K.S.; Akbar, D.; Gedikli, A. Urbanization-Globalization-CO_2 Emissions Nexus Revisited: Empirical Evidence from South Africa. *Heliyon* **2019**, *5*, e01974. [CrossRef] [PubMed]
19. Vlahinic Lenz, N.; Fajdetic, B. Globalization and GHG Emissions in the EU: Do We Need a New Development Paradigm? *Sustainability* **2021**, *13*, 9936. [CrossRef]
20. Zhang, J. Environmental Kuznets Curve Hypothesis on CO_2 Emissions: Evidence for China. *J. Risk Financ. Manag.* **2021**, *14*, 93. [CrossRef]
21. Karsch, N.M. Examining the Validity of the Environmental Kuznets Curve. *Consilience* **2019**, *21*, 32–50.
22. Tachega, M.A.; Yao, X.; Liu, Y.; Ahmed, D.; Ackaah, W.; Gabir, M.; Gyimah, J. Income Heterogeneity and the Environmental Kuznets Curve Turning Points: Evidence from Africa. *Sustainability* **2021**, *13*, 5634. [CrossRef]
23. Ozcan, B.; Tzeremes, P.G.; Tzeremes, N.G. Energy Consumption, Economic Growth and Environmental Degradation in OECD Countries. *Econ. Model.* **2020**, *84*, 203–213. [CrossRef]

24. Stavins, R.N. Market-Based Environmental Policies. Resources for the Future Discussion Paper. 1998. Available online: https://media.rff.org/documents/RFF-DP-98-26.pdf (accessed on 10 June 2021).
25. Sun, M.; Wang, Y.; Shi, L.; Klemeš, J.J. Uncovering Energy Use, Carbon Emissions and Environmental Burdens of Pulp and Paper Industry: A Systematic Review and Meta-analysis. *Renew. Sustain. Energy Rev.* **2018**, *92*, 823–833. [CrossRef]
26. Zeng, S.; Jiang, C.; Ma, C.; Su, B. Investment efficiency of the new energy industry in China. *Energy Econ.* **2018**, *70*, 536–544. [CrossRef]
27. Bilan, Y.; Streimikiene, D.; Vasylieva, T.; Lyulyov, O.; Pimonenko, T.; Pavlyk, A. Linking between Renewable Energy, CO_2 Emissions, and Economic Growth: Challenges for Candidates and Potential Candidates for the EU Membership. *Sustainability* **2019**, *11*, 1528. [CrossRef]
28. Wu, Q.; Madni, G.R. Environmental Protection in Selected One Belt One Road Economies through Institutional Quality: Prospering Transportation and Industrialization. *PLoS ONE* **2021**, *16*, e0240851. [CrossRef]
29. Nguyen, C.P.; Nguyen, N.A.; Schinckus, C.; Su, T.D. The Ambivalent Role of Institutions in the CO_2 Emissions: The Case of Emerging Countries. *Int. J. Energy Econ. Policy* **2018**, *8*, 7–17.
30. UNCTAD. Productive capacities. 2021. Available online: https://unctadstat.unctad.org/wds/ (accessed on 14 July 2021).
31. Tamazian, A.; Rao, B.B. Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies. *Energy Econ.* **2010**, *32*, 137–145. [CrossRef]
32. Lau, L.S.; Choong, C.K.; Eng, Y.K. Carbon dioxide emission, institutional quality, and economic growth: Empirical evidence in Malaysia. *Renew. Energy* **2014**, *68*, 276–281. [CrossRef]
33. Gill, A.R.; Hassan, S.; Viswanathan, K.K. Is Democracy Enough to Get Early Turn of the Environmental Kuznets Curve in ASEAN Countries? *Energy Environ.* **2019**, *30*, 1491–1505. [CrossRef]
34. Baloch, M.A.; Wang, B. Analyzing the Role of Governance in CO_2 Emissions Mitigation: The BRICS Experience. *Struct. Change Econ. Dyn.* **2019**, *51*, 119–125.
35. Ali, H.S.; Zeqiraj, V.; Lin, W.L.; Law, S.H.; Yusop, Z.; Bare, U.A.A.; Chin, L. Does Quality Institutions Promote Environmental Quality? *Environ. Sci. Pollut. Res.* **2019**, *26*, 10446–10456. [CrossRef]
36. Ahmed, F.; Kousar, S.; Pervaiz, A.; Ramos-Requena, J.P. Financial Development, Institutional Quality, and Environmental Degradation Nexus: New Evidence from Asymmetric ARDL Co-Integration Approach. *Sustainability* **2020**, *12*, 7812. [CrossRef]
37. Nkengfack, H.; Temkeng Djoudji, S.; KaffoFotio, H. Gouvernance, Institutions et Protection de L'environnement dans les Pays de la CEEAC. *Économierurale* **2020**, *371*, 5–22. [CrossRef]
38. Simionescu, M.; Răileanu Szeles, M.; Gavurova, B.; Mentel, U. The Impact of Quality of Governance, Renewable Energy and Foreign Direct Investment on Sustainable Development in CEE Countries. *Front. Environ. Sci.* **2021**, *9*, 765927. [CrossRef]
39. Sah, M.R. Effects of Institutional Quality on Environmental Protection in CEMAC Countries. *Mod. Econ.* **2021**, *12*, 903–918. [CrossRef]
40. Cole, M.A. Corruption, income and the environment: An empirical analysis. *Ecol. Econ.* **2007**, *62*, 637–647. [CrossRef]
41. Goel, R.K.; Herrala, R.; Mazhar, U. Institutional quality and environmental pollution: MENA countries versus the rest of the world. *Econ. Syst.* **2013**, *37*, 508–521. [CrossRef]
42. Bano, S.; Zhao, Y.; Ahmad, A.; Wang, S.; Liu, Y. Identifying the Impacts of Human Capital on Carbon Emissions in Pakistan. *J. Clean. Prod.* **2018**, *183*, 1082–1092. [CrossRef]
43. Mahmood, N.; Wang, Z.; Hassan, S.T. Renewable Energy, Economic Growth, Human Capital, and CO_2 Emission: An Empirical Analysis. *Environ. Sci. Pollut. Res.* **2019**, *26*, 20619–20630. [CrossRef]
44. Li, P.; Ouyang, Y. The Dynamic Impacts of Financial Development and Human Capital on CO_2 Emission Intensity in China: An ARDL Approach. *J. Bus. Econ. Manag.* **2019**, *20*, 939–957. [CrossRef]
45. Yao, Y.; Ivanovski, K.; Inekwe, J.; Smyth, R. Human Capital and CO_2 Emissions in the Long Run. *Energy Econ.* **2020**, *91*, 104907. [CrossRef]
46. Zhang, L.; Godil, D.I.; Bibi, M.; Khan, M.K. Caring for the Environment: How Human Capital, Natural Resources, and Economic Growth Interact with Environmental Degradation in Pakistan? A Dynamic ARDL Approach. *Sci. Total Environ.* **2021**, *774*, 145553. [CrossRef]
47. Wang, J.; Xu, Y. Internet Usage, Human Capital and CO_2 Emissions: A Global Perspective. *Sustainability* **2021**, *13*, 8268. [CrossRef]
48. Lin, X.; Zhao, Y.; Ahmad, M.; Ahmed, Z.; Rjoub, H.; Adebayo, T.S. Linking Innovative Human Capital, Economic Growth, and CO_2 Emissions: An Empirical Study Based on Chinese Provincial Panel Data. *Int. J. Environ. Res. Public Health* **2021**, *18*, 8503. [CrossRef] [PubMed]
49. Joof, F.; Isiksal, A.Z. Do Human Capital and Export Diversification Decline or Augment CO_2 Emissions? Empirical Evidence from the MINT Countries. *J. Environ. Account. Manag.* **2021**, *9*, 111–125. [CrossRef]
50. Xiao, H.; You, J. The Heterogeneous Impacts of Human Capital on Green Total Factor Productivity: Regional Diversity Perspective. *Front. Environ. Sci.* **2021**, *9*, 713562. [CrossRef]
51. UNCTAD. *UNCTAD Productive Capacities Index: Methodological Approach and Results*; United Nations: New York, NY, USA, 2021.
52. World Bank. CO_2 Emissions (Metric Tons per Capita). Available online: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC (accessed on 14 July 2021).
53. Westerlund, J.; Edgerton, D.L. A Panel Bootstrap Cointegration Test. *Econ. Lett.* **2007**, *97*, 185–190. [CrossRef]

54. Eberhart, M.; Bond, S.R. Cross-sectional Dependence in Non-stationary Panel Models: A Novel Estimator. In Proceedings of the 5th Nordic Econometric Meetings, Lund, Sweden, 29–31 October 2009.
55. Eberhart, M.; Teal, F. *Productivity Analysis in the Global Manufacturing Production*; Department of Economics, University of Oxford: Oxford, UK, 2010.
56. McCoskey, S.; Kao, C. A Residual-Based Test of the Null of Cointegration in Panel Data. *Econom. Rev.* **1998**, *17*, 57–84. [CrossRef]
57. Breusch, T.S.; Pagan, A.R. The Lagrange multiplier test and its applications to model specification tests in econometrics. *Rev. Econ. Stud.* **1980**, *47*, 239–253. [CrossRef]
58. Pesaran, M.H. *General Diagnostic Tests for Cross Section Dependence in Panels*; Working Paper, CWPE 0435; University of Cambridge: Cambridge, UK, 2004.
59. Pesaran, M.H.; Ullah, A.; Yamagata, T.A. A bias-Adjusted LM test of error cross-section independence. *Econom. J.* **2008**, *11*, 105–127. [CrossRef]
60. Pesaran, M.H.; Yamagata, T. Testing slope homogeneity in large panels. *J. Econom.* **2008**, *142*, 50–93. [CrossRef]
61. Im, K.S.; Pesaran, M.H.; Shin, Y. Testing for unit roots in heterogeneous panels. *J. Econom.* **2003**, *115*, 53–74. [CrossRef]
62. Pesaran, M.H. A simple panel unit root test in the presence of cross-section dependence. *J. Appl. Econom.* **2007**, *22*, 265–312. [CrossRef]
63. Pesaran, M.H. Estimation and Inference in Large Heterogeneous Panels with a Multifactor Error Structure. *Econometrica* **2006**, *74*, 967–1012. [CrossRef]

sustainability

MDPI

Article

Asymmetric Impact of Institutional Quality on Environmental Degradation: Evidence of the Environmental Kuznets Curve

Farrah Dina Abd Razak [1], Norlin Khalid [2,*] and Mohd Helmi Ali [3]

[1] Faculty of Business and Management, Universiti Teknologi MARA, Tapah 35400, Malaysia; farra104@uitm.edu.my
[2] Faculty of Economics and Management, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia
[3] Graduate School of Business, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia; mohdhelmiali@ukm.edu.my
* Correspondence: nrlin@ukm.edu.my

Abstract: This paper aims to discover the asymmetry impacts and co-integration between gross domestic product, financial development, energy use and environmental degradation by featuring institutional quality covering the Malaysia economy during the period from 1984 until 2017 using a nonlinear auto-regressive distributed lag model. The results confirm the existence of the Environmental Kuznets Curve hypothesis for both linear and nonlinear analyses, thus verifying the relevance of symmetric and asymmetric EKC hypotheses for Malaysia. Further, this study verifies the attributes of financial development and institutional quality that mitigates the concern on CO_2 emissions, but contradicting results were produced on energy use. The implication of this finding provides new guidelines for Malaysia authorities to consider the asymmetries in formulating environment-related policies to maintain environmental quality and achieve their sustainable development goals.

Keywords: Environmental Kuznets Curve; carbon dioxide emissions; environmental degradation; financial development; energy use; institutional quality

Citation: Abd Razak, F.D.; Khalid, N.; Ali, M.H. Asymmetric Impact of Institutional Quality on Environmental Degradation: Evidence of the Environmental Kuznets Curve. *Sustainability* **2021**, *13*, 12507. https://doi.org/10.3390/su132212507

Academic Editor: Bertrand Hamaide

Received: 19 October 2021
Accepted: 8 November 2021
Published: 12 November 2021

1. Introduction

Economic growth is the crucial objective of developing countries because it is the greatest indicator for eradicating poverty and in increasing the quality of life. The challenge for countries is to combine economic growth policies with sustainable development strategies. Much emerging evidence has revealed significant positive relationships between economic growth and environmental deterioration, especially in developing countries [1]. According to the Environmental Kuznets Curve (EKC) hypothesis, developing countries are at the beginning of the development stage and offer cheap labour, transportation, and trading cost, which together with lenient environmental standards tends to create a pollution haven [2]. The impact of environmental deterioration may only decrease with economic growth. Energy use is considered to be a necessary feature of economic growth in developing countries, where almost 89% of cumulative energy needs are fulfilled by non-renewable energy such as petroleum and natural gas. The development trend poses a serious threat to sustainable development because of its contribution to greenhouse gases (GHG) emissions.

Over the last 30 years, Malaysia has experienced robust economic growth rates and an extraordinary level of financial development among the developing countries. Unfortunately, Malaysia is paying the cost for these tremendous economic and financial development activities in the form of environmental deterioration. For instance, the annual growth rate of carbon emission has gone up at least 6% from 2000 until 2019, thus making the country highly prone to the dangers of climate change and pollution. The growth of GDP and carbon emissions per capita in Malaysia for the year 1960 to 2020 is shown in Figure 1. Both indicators appear to move in tandem over that period, and both similarly showed a marked decline in 2020 due to the Coronavirus pandemic [3]. In the Paris Agreement of 2015, Malaysia has pledged to cut 45% of its GHG emissions intensity against the GDP by 2030, as compared to the emission intensity and GDP in 2005. This transition requires not only wider implementation of greener technologies but also substantial financial, institutional, and behavioural changes.

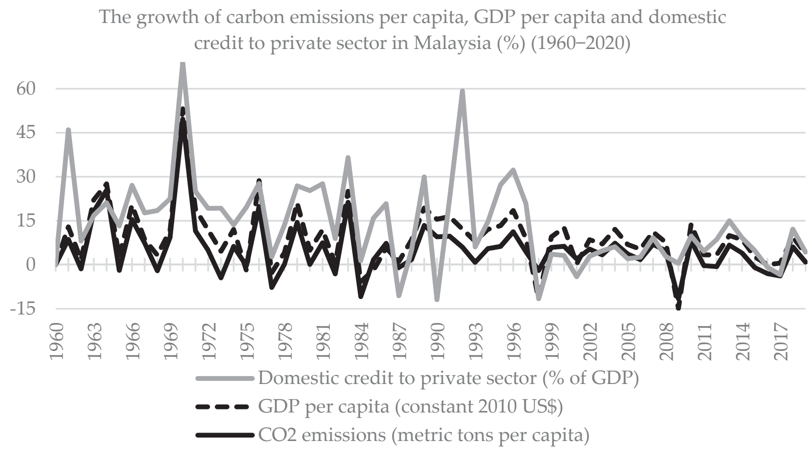


Figure 1. Annual growth rate of CO_2 emission per capita, GDP per capita and domestic credit to private sector (1960–2020); Source: Author's own calculation based on data from World Bank.

Amidst the danger of global warming, numerous possible solutions have been identified, including the development of the financial system, uncompromising government regulations, adoption of technological innovation, renewable energy and increasing efficiency. The development of the financial sector can harmonize pollution abatement efforts and affect the dynamics of environmental quality through mobilization and utilization of funds. A healthy financial system provides better access to financial services, and this will decrease the cost of doing business. A stable financial system is essential for smooth transaction in economic activities and facilitates trading activities which lead to greater economic growth. Numerous empirical researches have highlighted the significance of financial development in preserving the environment through judicious allocation of financial resources, especially on improving research and development and eco-friendly projects. Moreover, financial development has been reported, supported by empirical evidence, to play a significant role in adoption of greener technologies, thus mitigating the environmental impacts of economic growth in the case of China [4], Japan, Korea, Singapore [5], and several developing countries [6]. Similarly, the importance of financial development has also been highlighted; namely, in nurturing good governance in encouraging firms to adopt environmentally friendly projects that can simultaneously reduce pollution [7]. It is also important to emphasise that in the development of the financial sector, the consequent enhancement of economic growth harbours potential capability to cause irrevocable harm to the environment. Adopting a systematic financial system will ease the liquidity process that may lead to higher investment opportunities and low borrowing costs which consequently encourage firms to increase production, hence resulting in high energy demand and eventually increased rate of carbon emission [8].

Second is the role of institutional quality which has been more widely emphasized in the context of the analysis factors influencing financial development but not in the framework of finance-emission nexus. Institutional quality constitutes a key determinant of a country's economic and financial development as it ensures capital allocation to the most efficient investment especially in environmentally friendly development projects. High quality institutions create an ecosystem where all parties have the capacity to effectively play their role in protecting the environment. For example, environmental quality can be expected when local governments are able to implement environmental regulations effectively. In other words, a high institutional quality, comprised of sturdy corporate governance, effective control of corruption, strong monitoring of a stable banking system and easily accessible financial information, is expected to set an environmentally friendly standard for financial development. The Environmental Performance Index (EPI) is used to measure the proximity of a country to establishing environmental policy targets and the country's achievement in addressing environmental pollution [9]. In 2020, Malaysia ranked 68th from 180 countries on the EPI ranking and 53rd out of 61 countries on greenhouse gas (GHG) emissions by the Climate Change Performance Index (CCPI) [10]. From this, perspective policy space is considered important in the overall effort to alleviate pollution.

This study investigates the impact of economic growth, financial development, institutional quality, and energy use on carbon emissions in the case of Malaysia for the year 1984 until 2017. Based on the EKC hypothesis, there is a nonlinear relationship between economic growth and carbon emissions, and it can be illustrated by an inverted U-shaped curve. This hypothesis has been backed up by numerous numbers of scholars [1,2,4–6,11–13]; hence, it motivates this study to validate the presence of the same hypothesis in Malaysia. Moreover, as seen in Figure 1, there were similar trends of growth between economic growth and carbon emissions in Malaysia. Since 1984, Malaysia's annual economic growth is at five percent on average, and it endured uninterrupted except for financial crises that hurt the country in 1999 and 2009, and recently in 2020–2021 with the shocks of the coronavirus pandemic. Nevertheless, there is a clash between these two objectives—increasing economic growth against lowering carbon emissions—and this conflict is exacerbated when it concerns energy use as it acts as an engine of growth. In this condition, countries will be hesitant to mitigate carbon emissions and moderate energy use for the sake of economic growth. Therefore, scholars and authority have been discovering attributes to achieve these two objectives without deteriorating the environment. Malaysia also is a common example of this condition because its energy consumption is from non-renewable energy sources, especially petroleum and natural gas, while maintaining its persistent economic growth.

As has been discussed above, financial development and institutional quality have been identified to curb carbon emissions in the literature review. An apparent reason for this study to use financial development as a significant attribute in describing carbon emissions is that the occurrence of healthy and stable financial sectors may support in the financing of environmentally friendly technologies, attracting economic agents to participate in environmentally friendly projects, hence helping the country to embracing a cleaner energy consumption system [4–8]. In the utmost pertinent literature to this study, Lv and Li [4] have utilized data from developing countries, and they brightly claim that healthy financial sectors lead to a lower carbon emission. This finding inspires this study to obtain 'domestic knowledge' systematically on how financial development can mitigate carbon emissions in the case of Malaysia by considering the strong growth in Malaysian financial systems. However, the strong financial system needs to be supported by healthy government institutions. As claims by Khan et al. [7], institutional quality plays a dynamic role in affecting financial development and environmental quality as it prevents the misuse of resource allocations. Furthermore, a weak government might dampen economic growth and the implementation of environmental policies. Thus, these arguments have motivated this study to validate the integration of carbon emissions, economic growth, energy use, financial development, and institutional quality in the case of Malaysia.

This study addressed a few knowledge gaps in the literature on the implication of financial development on carbon emissions. First, this study contributes to the literature on the finance–emissions nexus by incorporating the interaction of institutional quality. With reference to the past literature, this study contends that financial development alone is insufficient to promise a better quality of environment unless it is complemented with a sound quality of the relevant institutions. Compared to earlier reports, this study exclusively focuses on Malaysia where empirical literature on drivers of environmental deterioration is notably lacking. Likewise, literature that deliberates on carbon emission is equally limited in the Malaysia context, thus rendering the support for the EKC hypothesis inconclusive. Second, Malaysia's institutional quality may be able to shed its lights in explaining the performance of the domestic financial system in the environmental context. Third, this study is proposing a fresh dimension in the political economic perspectives regarding the finance–emissions nexus. The Non-Linear Autoregressive Distributed Lag (NARDL) was employed to confirm the effects of carbon emissions, financial development, institutional quality, and energy use, either as causality or as asymmetric influence. In this respect, the NARDL method on either a short- or long-term basis may be able to investigate the asymmetric impacts of finance–emissions, especially on a developing country like Malaysia. Furthermore, the classic EKC hypothesis may lead to a biased outcome because it focuses only on economic factors but overlooks the institutional elements which are widely considered as the pillars of economic development. From the indeterminate nature of findings in the literature, information on the effect of different proxies of institutional quality on the nexus of finance–emissions is decidedly scarce. Fourth, this motivates in-depth analyses of individual countries, such as Malaysia, rather than as multiple countries, thus enabling a more feasible outcome in contributing to the development of national policies.

This paper is organised as follows: Part 1 provides the introduction. Part 2 reviews the related literature and deals with development of hypotheses. Part 3 discusses the estimation models and Part 4 deals with the source of data, variables, and the estimations. Part 5 deliberates on the empirical results and Part 6 presents the conclusions and policy implications.

2. Literature Review

The relationship between economic growth, financial development, institutional quality, and energy use with carbon emissions is investigated in the study. The four sections of the extant literature and relationship between variables organized in this section on the review are as follows: (1) carbon emission and economic growth, (2) carbon emission and financial development, (3) institutional quality and emission nexus, and (4) carbon emissions and energy use. Additionally, the literature analysis will focus on the Malaysia setting as a developing country.

Fundamentally, the EKC hypothesis stands for the following: At first, an increase in income per capita of a country will deteriorate environmental quality, and after that, any further increase in income per capita will improve environmental quality. This mixed relationship between income per capita and environment quality has been validated by a mushrooming number of studies by applied econometricians that mirrors the pioneer study of Grossman and Krueger [14]. Even though these studies aim to validate the EKC hypothesis, the results are deferred due to the methodologic approaches, selection of the data and variables, location of studies, and time. There are two types of analysis that are commonly used, which are time series analysis and panel data analysis. Time series analysis is referring to investigations on individual country, and panel data analysis is referring to investigation of multiple countries with similar characteristics. Based on Table 1, the methodologic approaches have an extensive variety—for instance, and Fully Modified OLS (FMOLS) [6], Autoregressive Distributed Lag (ARDL) [15–17], Vector Error Correction Method (VECM) [16,17], and Dynamic Ordinary Least Square (DOLS) [18,19], This study employs ARDL as it is beneficial for the analysis of long-term relationships from the dynamics of short-term.

Table 1. Summary of the literature on finance–emissions nexus.

References	Country/Period	Empirical Model/Methods	Financial Development Proxies	Results	EKC Hypothesis
[6]	34 upper middle-income developing countries	FMOLS, Kao cointegration	Domestic credit provided by the financial sector. Domestic credit to the private sector by banks.	**Long-run:** FD on RE (positive effect) GDP on RE (negative effect) CP on RE (no effect)	Not tested
[15]	China (1994–2016)	ARDL-ECM	Sum of total assets and liabilities in foreign countries as a share of GDP.	**Short-run:** FD and GDP on CO_2 (positive effect) URB on CO_2 (negative effect) **Long-run:** FD and GDP on CO_2 (positive effect) URB on CO_2 (negative effect)	No
[16]	United Arab Emirates (1975–2011)	ARDL, VECM, Granger causality	Domestic credit to private sector	FD, ELC, URB, TRD improves EQ	Yes
[17]	India (1990–2018)	ARDL, VECM, Gregory-Hansen cointegration	Domestic credit to the private sector as a GDP share	**Short-run:** ELC and GDP on CO_2 (positive effect) FD on CO_2 (no effect) **Long-run:** FD on CO_2 (negative effect) EC on CO_2 (positive effect) ELC and GDP on CO_2 (positive effect) GDP^2 and ICT on CO_2 (negative effect)	Yes

Notes: EQ (Environmental Quality), SO_2 (Sulphur Dioxide Emissions), CO_2 (Carbon Dioxide Emissions), FD (Financial Development), RD (Research and Development), SUR (Seemingly Unrelated Regression), GDP (Per Capita GDP), TRD (Trade Openness), URB (Urbanization), ELC (Electricity consumption), ICT (Information Communication Technology), RE (Renewable energy), CP (Consumer Price), ARDL (Autoregressive Distributed Lag), ECM (Error Correction Method), VECM (Vector Error Correction Method), FMOLS (Fully Modified Ordinary Least Square).

2.1. Carbon Emission and Economic Growth

Based on the EKC hypothesis, economic growth and the environment is a dual dichotomous nature in which at the beginning, growth will deteriorate the environment quality but will subsequently improve it upon reaching and surpassing a certain threshold level. Most recently, Noda [20] conducted an inclusive literature survey and concluded that the results of EKC empirical research is rather mixed and contradictory due to differences in explanatory variables, the choice of models and time. This implies that in the context of the EKC hypothesis, one size does not fit all. Numerous scholars have supported the EKC hypothesis [21] while others did not [22,23]. The EKC literature commonly treated income per capita as a proxy for economic growth and in the form of either linear, quadratic, or cubic relationship. He and Lin [24] and Shahbaz [25] have utilized the ARDL approach to confirm the EKC hypothesis with an inverted U-shaped curve because the linear and quadratic forms of income have significant corresponding positive and negative parameter estimates. On the contrary, the literatures have also recorded that the economic growth and emission nexus is rather an N-shaped curve [26,27]. The report argued that carbon emission will continue to increase in the future and will not decrease with further economic growth thus indicating that the EKC hypothesis is inconclusive, especially in the findings from developing countries. For example, Laverde-Rojas et al. [28] used VECM in their analysis and maintained that the EKC does not exist in Colombia because the country is facing challenges in overcoming institutional constraints in its approach to derive environmental benefits. Similarly, Kurniawan [1] conducted a pooled mean group estimator analysis sourced from 140 developing countries and reported no evidence to support the EKC but conversely produced empirical evidence of a long-run relationship between economic growth and carbon emission. In Malaysia, Suki, Sharif and Afshan utilize the Quantile Autoregressive Distributed Lag (QARDL) method, and others [29–31] showed evidence to validate the EKC hypothesis, while in contrast some scholars like Ali and Rahman [32] disproved it. The positive impact of economic growth on carbon emission over the last 30 years is shown in Figure 1.

2.2. Carbon Emission and Financial Development

The discussion on mechanism and channels through which the impact of financial development on economic growth affects the environment is rather limited even in specialised literature, especially in the developing economies. As depicted in Table 1, findings on the impact of financial development on carbon emissions are quite mixed and contradictory. In general, there are records of positive effects or relatively negative impacts, and even no impact at all of financial development on carbon emissions. In a nutshell, the perplexing findings signify ambiguous results from city level data financial development [33], varying financial scale and efficiency involving other factors [34] and conducted over different time scopes.

The relationship between financial developments on carbon emissions, which describes an inverted U-shaped curve, is still debatable. For instance, Yin et al. [35] adopted the Seemingly Unrelated Regression (SUR) model in the context of China and concluded that financial development is helpful in improving water quality but may incur more emissions. Government regulations play a critical role in improving environmental quality together with the joint effect of financial development. Some studies considered the two dimensions of financial development, namely financial depth and financial breadth, as better proxies in representing the overall financial development and structure [36]. Firstly, financial depth reflects the quality of financial development that can support local economic development. It is measured from the percentage of total amount of securities on GDP, domestic credit provided by the financial sector, and domestic credit advanced to the private sector by banks (both in percentage of GDP). Secondly, financial breadth reflects the soundness of banking institutions and scale of finance that can be measured using the number of financial institutions involved, number of domestically listed companies and number of financial employees. Most researchers, however, found that financial depth, rather than financial breadth, exerts significantly greater influence on environment quality, and this consequently supports the EKC hypothesis [37].

Development in the financial sector should hypothetically reduce carbon emission due to the following reasons: First, a well-developed financial system will assist the efficient allocation of credit for environment-friendly technologies [38]. Schumpeter regarded finance as a root cause that can spark innovation [39]. Integration of innovation into all phases of development will involve an introduction to a whole new or modified process of production, practices or systems which benefit the environment [40]. In addition, improving a greener production process has potential to lower emissions through increased efficiency in energy consumption. Second, a manageable and sophisticated financial sector can lead to low borrowing costs that will motivate local and national governments as well as local producers to participate in environmental projects [41]. Hence, this will help countries to adopt and convert into a cleaner energy consumption structure.

2.3. Institutional Quality-Emission Nexus

Salman et al. [42] classified the context of institutions into two: (1) informal constitutional limitations reflected by authorizations, societies, and customs, and (2) formal procedures that can be reflected by means of institutional quality index, i.e., accountability, corruption control, government effectiveness and rule of law. This study is focused on the latter with greater attention centering institutional quality impact on the environment. In general, high-quality institutions enable all parties to effectively contribute to environmental protection. Local governments soundly implementing environmental regulations will improve environmental quality [43]. In the scope of the EKC hypothesis, the environment tends to improve as better and more effective institutions reduce environmental cost of high economic growth. Stringent policies and healthier law and regulation enable countries to flatten the EKC curve and decrease pollution whilst achieving economic growth. Thus, institutional quality can be the key factor for pollution control and is complementary to the finance–emissions nexus. Ali et al. [44] who measured institutional quality using corruption, rule of law, and bureaucratic quality had highlighted reduced carbon emission in developing countries, as consistent with findings by Salman [42] and Lau [45]. Hunjra [46] demonstrated a negative moderate effect of institutional quality on the finance–emissions nexus for selected five South Asian countries. The study suggested that better governance reduces the trade-off impacts of financial development on the environment because stronger financial structure provides more capital on environmentally friendly projects.

Theoretically, a country with a higher institutional quality index will be successful in reducing carbon emissions because of the increase in government effectiveness. The first reason for this is that better governance with high control of corruption and higher score of rules of law will directly improve effectiveness in the implementation of environment-related policies. This will leave local producers and citizens with only one choice, that is to obey the rules by using greener production and consumption methods. Second, a more honest local and national government can credibly moderate the negative impact of financial development on the environment. In the prevalence of better governance, financial sectors are more convinced into allocating capital to environmentally friendly projects [4]. Furthermore, the presence of a more translucent political system is beneficial for environmentally friendly projects because it will enforce smooth contracts and decrease uncertainty and the risk of expropriation [47]. In the case of Africa, Ibrahim and Sare [48] discovered that the reasons behind an underdeveloped financial sector are weak governance, poor political and economic stability altogether with lack of institutional quality.

2.4. Carbon Emissions and Energy Use

The relationship between energy use and CO_2 emissions under various research methodologies is amply reported in the literature. Studies on the nexus between these two attributes have produced consistent conclusions where energy consumption is the main contributor to the rise in CO_2 emissions. For instance, Wasti and Zaidi [49] proxied as an indicator the kilogram of oil equivalent per capita for energy use and provided evidence of bi-directional causality between energy use and CO_2 emissions in Kuwait. Recent studies by Shaari et al. [13] for OIC countries and by Yuping et al. [33] in Argentina claimed that energy use boosts CO_2 emissions both in the short- and long-term. A similar effect was recorded by Aftab et al. [34] in a study in Pakistan. They highlighted that energy use promotes CO_2 emissions in the long-term.

3. Research Methodology

This part presents the data, research design, empirical specification, and estimation strategy to estimate finance–emission nexus.

3.1. Model Specifications

This study endeavours to validate the EKC hypothesis using data spanning 1984 to 2017 and to investigate the nexus between CO_2 emissions and other variables which include financial development, institutional quality, and energy use in the Malaysian context. Informed by the EKC hypothesis, the first model is developed as shown below:

$$CO_2 = f\left(GDP_t, GDP_t^2, FD_t,\ ENERGY_t,\ IQ_t\right) \quad (1)$$

CO_2 = carbon dioxide emissions per capita,
GDP = Gross Domestic Product per capita,
FD = financial development,

ENERGY = energy use,
IQ = institutional quality, and
t = the year.
Note: *GDP* and GDP^2 were introduced into the model as independent variables along with financial development, institutional quality, and energy use.

All variables were transformed to natural logarithm form to omit the problem of heteroscedasticity. In summary, a long-run model of CO_2 emissions is presented in the Equation (2):

$$lnCO_2 = \alpha_0 + \beta_1 lnGDP_t + \beta_2 lnGDP_t^2 + \beta_3 lnFD_t + \beta_4 lnENERGY_t + \beta_5 lnIQ_t + \varepsilon_t \quad (2)$$

$lnCO_2$ = logarithm of carbon dioxide emissions per capita,
lnGDP = logarithm of Gross Domestic Product per capita,
$lnGDP^2$ = logarithm of the square Gross Domestic Product per capita,
lnFD = logarithm of financial development,
lnENERGY = logarithm of energy use,
lnIQ = logarithm of institutional quality, and
ε_t = noise errors.

To accept the EKC hypothesis in the Malaysia context, the conditions that need to be met are (1) the coefficient of β_1 is positive and (2) the coefficient of β_2 is negative.

3.2. Data Description

As shown in Table 2, all data were compiled from the World Bank database, except data for institutional quality which were obtained from the International Country Risk Guide database for the period of 1984–2017. All measurements follow precedence in the existing literature, specifically the following: (1) For CO_2 emissions, the amount per capita was used [50]; (2) financial development used domestic credit to the private sector [6,16,17]; and (3) institutional quality applied government stability, corruption, and law and order [18,19]. All data covered the period 1984–2017, with sourcing restricted by data availability. The descriptive statistics of the attributes of this study are shown in Table 3.

Table 2. Data information.

Variable Code	Variable Name and Details	Unit	Source
CO_2	CO_2 emissions	Metric tons per capita	World Bank
GDP	Gross Domestic Product	constant 2010 US$ per capita	World Bank
GDP^2	Square of Gross Domestic Product	constant 2010 US$	World Bank
FD	Financial development: Domestic credit to the private sector	% of GDP	World Bank
ENERGY	Energy use	kg of oil equivalent per capita	World Bank
IQ	Government' ability to implement declared projects. It is the sum of three subcomponents: popular support, government unity and legislative strength [51].	Scored from zero to twelve. A low rating represents very high risk, and a higher rating represents very low risk.	International Country Risk Guide
COR	Corruption (COR): Corruption in the form of favouritism, job reservations, and questionably close connexions between business and politics [51].	Scored from zero to six. A low rating represents the highest possible level of corruption, and a high rating indicates a lower level of corruption.	International Country Risk Guide
LO	Law and Order (LO): Law signifies the forte of the legal system and, Order represents compliance on the law [51].	Scored from zero to six points. A low rating represents a high crime rate where the law is routinely ignored, and high rating represents public respect for the law.	International Country Risk Guide

Table 3. Descriptive statistics.

	LCO2PC	LGDPPC	LGDPPC2	LFD	LN ENERGY	GS	COR	LO
Mean	1.533	8.770	77.019	4.690	7.535	8.083	3.335	3.981
Median	1.596	8.838	78.108	4.687	7.633	9.000	3.000	4.000
Max.	2.049	9.261	85.774	5.066	8.008	11.000	5.000	5.000
Min.	0.826	8.218	67.542	4.240	6.904	2.000	2.375	3.000
Std dev.	0.399	0.323	5.621	0.205	0.356	2.320	0.841	0.750
Skewness	−0.442	−0.366	−0.322	−0.233	−0.476	−0.972	0.317	0.055
Kurtosis	1.862	1.936	1.921	2.893	1.902	3.621	1.736	1.760

3.3. Research Methodology

This study conducted a series of econometric techniques to identify symmetric and asymmetric relationships amongst selected attributes. The first step was the unit root test and stationary testing using several analyses comprising Augmented Dicker–Fuller (ADF), Phillips–Perron (PP), Lee–Strazicich (LEE) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) Test. The second step was to identify the linear and nonlinear relationships between all attributes using symmetric and asymmetric cointegration tests which included the Autoregressive Distributed Lag Model (ARDL) by Pesaran et al. [52] and the Non-Linear Autoregressive Distributed Lag Model (NARDL) by Shin et al. [53]. Finally, a diagnostic and stability test was carried out to verify whether the ARDL and NARDL models were stable and reliable.

3.3.1. Research Hypotheses

This study proposes to examine the symmetric and asymmetric relationship of carbon emissions, economic growth, energy use, financial development, and institutional quality. Hence, to statistically prove the theoretical predictions, this study empirically tests the following hypotheses using the case of Malaysia.

Hypothesis 1 (H1). *There is a symmetric relationship between economic growth and carbon emissions.*

Hypothesis 2 (H2). *There is an asymmetric relationship between economic growth and carbon emissions.*

Hypothesis 3 (H3). *There is a symmetric relationship between financial development and carbon emissions.*

Hypothesis 4 (H4). *There is an asymmetric relationship between financial development and carbon emissions.*

Hypothesis 5 (H5). *There is a symmetric relationship between institutional quality and carbon emissions.*

Hypothesis 6 (H6). *There is an asymmetric relationship between institutional quality and carbon emissions.*

Hypothesis 7 (H7). *There is a symmetric relationship between energy use and carbon emissions.*

Hypothesis 8 (H8). *There is an asymmetric relationship between energy use and carbon emissions.*

3.3.2. Autoregressive Distributed Lag Model (ARDL)

The ARDL was employed as the estimation procedure which included three series of econometric steps: first, investigation of stationarity by employing unit root test analysis; second, bound tests to confirm the presence of cointegration; third, diagnostic and stability tests via autoregressive conditional heteroscedastic (ARCH) for heteroscedasticity, Jarque–Bera for normality test, and Breusch–Godfrey for serial correlation. It was followed by CUSUM and CUSUMSQ tests in confirming the stability of these models.

The prevailing method of ARDL was used in this study to estimate the symmetric relationships between CO_2 emissions, GDP, financial development, energy use, and institutional quality, as follows:

$$\begin{aligned}\Delta lnCO_2 = \; & \alpha_0 + \sum_{i=1}^{n} \varnothing \Delta lnCO2_{t-i} + \sum_{i=0}^{n} \alpha_1 \Delta lnGDP_{t-i} + \sum_{i=0}^{n} \alpha_2 \Delta lnGDP^2_{t-i} + \sum_{i=0}^{n} \alpha_3 \Delta lnFD_{t-i} \\ & + \sum_{i=0}^{n} \alpha_4 \Delta lnENERGY_{t-i} + \sum_{i=0}^{n} \alpha_5 \Delta lnIQ_{t-i} + \gamma lnCO2_{t-1} + \beta_1 lnGDP_{t-1} \\ & + \beta_2 lnGDP^2_{t-1} + \beta_3 lnFD_{t-1} + \beta_4 lnENERGY_{t-1} + \beta_5 lnIQ_{t-1} + \varepsilon_t \end{aligned} \tag{3}$$

ΔCO_2, ΔGDP, ΔGDP^2, ΔFD, ΔIQ, $\Delta ENERGY$ = respective difference values.
$\varnothing$ and α_1 to α_5 = short term dynamic relationship
γ, β_5 to β_5 = long-run dynamic relationship.
n = lag period of the explained variable and explanatory variable.

A joint significance test, Wald and F-statistic will be used to determine whether there is a cointegration relationship under the following hypothesis: H_0: $\varnothing = \alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = 0$, and H_1: $\varnothing = \alpha_1 \neq \alpha_2 \neq \alpha_3 \neq \alpha_4 \neq \alpha_5 \neq 0$. The null hypothesis is rejected under condition where cointegration exists. The next step was the investigation of causality. The lagged error correction term was derived from the cointegration equation as follows:

$$\begin{aligned} lnCO_2 = \alpha_0 + \sum_{i=1}^{n} \varnothing \Delta lnCO2_{t-i} + \sum_{i=0}^{n} \alpha_1 lnGDP_{t-i} + \sum_{i=0}^{n} \alpha_2 lnGDP^2_{t-i} + \sum_{i=0}^{n} \alpha_3 lnFD_{t-i} + \sum_{i=0}^{n} \alpha_4 lnENERGY_{t-i} \\ + \sum_{i=0}^{n} \alpha_5 lnIQ_{t-i} + \varepsilon_t \end{aligned} \tag{4}$$

Finally, the short-run coefficients were estimated using the error correction model (ECM) per the ARDL method:

$$\begin{aligned} \Delta lnCO_2 = \alpha_0 + \sum_{i=1}^{n} \varnothing \Delta lnCO2_{t-i} + \alpha_1 \sum_{i=0}^{n} \Delta lnGDP_{t-i} + \alpha_2 \sum_{i=0}^{n} \Delta lnGDP^2_{t-i} + \alpha_3 \sum_{i=0}^{n} \Delta lnFD_{t-i} \\ + \alpha_4 \sum_{i=0}^{n} \Delta lnENERGY_{t-i} + \alpha_5 \sum_{i=0}^{n} \Delta lnIQ_{t-i} + + \varnothing lnCO2_{t-1} + \beta_1 lnGDP_{t-1} \\ + \beta_2 lnGDP^2_{t-1} + \beta_3 lnFD_{t-1} + \beta_4 lnENERGY_{t-1} + \beta_5 lnIQ_{t-1} + \eta ECT_{t-i} + \varepsilon_t \end{aligned} \tag{5}$$

where η denotes the error correction term coefficient, implying the dependent attribute's speed of adjustment after a change in the other attributes in the short-term. It indicates how fast the dependent attributes return to the long-run equilibrium following shocks to the other attributes in the short-run.

3.3.3. Non-Linear Autoregressive Distributed Lag Model (NARDL)

The asymmetric impacts of the independent variables were tested using NARDL version conditional error correction that was reformulated from the ARDL model. Equation (6) was formulated to capture the nonlinear relationship amongst the selected attributes. This study employed the NARDL for bound test approach as proposed by Shin et al. [53].

$$\begin{aligned} \Delta lnCO_2 = \alpha_0 + \sum_{i=1}^{n} \varnothing \Delta lnCO2_{t-i} + \sum_{i=0}^{n} \alpha_1 \Delta lnGDP_{t-i} + \sum_{i=0}^{n} \alpha_2 \Delta lnGDP^2_{t-i} + \sum_{i=0}^{n} \alpha_3 \Delta lnFD_{t-i} \\ + \sum_{i=0}^{n} \alpha_4 \Delta lnENERGY_{t-i} + \sum_{i=0}^{n} \alpha_5^{+} \Delta lnIQ^{+}_{t-1} + \sum_{i=0}^{n} \alpha_5^{-} \Delta lnIQ^{-}_{t-1} + \gamma lnCO2_{t-1} + \beta_1 lnGDP_{t-1} \\ + \beta_2 lnGDP^2_{t-1} + \beta_3 lnFD_{t-1} + \beta_4 lnENERGY_{t-1} + \beta_5^{+} lnIQ^{+}_{t-1} + \beta_5^{-} lnIQ^{-}_{t-1} + \varepsilon_t \end{aligned} \tag{6}$$

From Equation (6), the term (+) and (−) respectively represents the asymmetric impacts of the variable related to *IQ* for CO_2 emissions. The variable related to *IQ* takes the notation (+) and (−) which, respectively, represent the partial sum of positive and negative changes. Positive and negative values of attributes of *IQ* were formulated in Equations (7) and (8) and measured as follows:

$$lnIQ_{t-1}^{+} = \sum_{k=1}^{t} \Delta lnIQ_{k}^{+} = \max(\Delta IQ_{k},\ 0) \tag{7}$$

$$lnIQ_{t-1}^{-} = \sum_{k=1}^{t} \Delta lnIQ_{k}^{-} = \min(\Delta IQ_{k},\ 0) \tag{8}$$

where IQ^{+} represents the partial sum for positive change in IQ, while IQ^{-} represents the partial sum for negative change in IQ. IQ-CO_2 emissions impacts can be considered to be asymmetric in the condition of changes of the positive or negative results in IQ inflows. Bound testing was employed using the F-statistic to test the long-run cointegration between attributes with the null hypothesis of no cointegration: H_0: $Ø = \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$ and H_1: $Ø \neq \beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq 0$. Further, in testing the possibilities of a long-run relationship, this study analysed the null hypothesis of long-run symmetry $\beta = \beta^{+} = \beta^{-}$ and $\alpha = \alpha^{+} = \alpha^{-}$ for CO_2 emissions using standard Wald test. The NARDL estimation and the test for diagnostic and stability testing were carried out, similar to the testing applied in the ARDL model to verify stability, reliability and freedom from any estimation bias.

4. Results and Discussion

4.1. Unit Root and Stationarity Tests

In regard to ascertaining the order of integration of each variable, the time series properties were examined by utilizing Augmented Dickey–Fuller (ADF) test, Phillips–Perron (PP) test, and Lee–Strazicich (LEE) test. These three-unit root tests describe that the attributes contain a unit root as its null hypothesis. The null hypothesis of nonstationary is produced at the 1, 5 and 10% significance level correspondingly. Table 4 displays the outcomes of unit root tests, and all the attributes have undergone the stationary test with constant and time trends. The outcomes of the tests demonstrate that all the data series are nonstationary at level. However, the outcomes of the ADF tests on the first difference clearly stands that all data series are stationary after the first difference at the 1, 5 and 10% significance level correspondingly, thus rejecting the null hypothesis. Thus, the overall outcomes of the ADF tests explain that all the attributes' series were integrated series of order I (1). The outcomes of ADF, PP, and LEE unit root tests have been verified by employing another related test which is Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test. The null hypothesis for the KPSS test is that attributes have no unit root. The results for the KPSS test revealed that all attributes are significant at level I (0) except for the attributes of government stability and law and order. By these outcomes of the unit root tests, it implies that the attributes' series were an integrated series of only order I (0) and I (1). Hence, the requirement for the application of the ARDL approach is assured where none of the attributes are integrated at I (2).

Table 4. Unit root tests.

Methodology	ADF	PP	KPSS	LEE	
Attribute	**t-Stat.**	**t-Stat.**	**t-Stat.**	**t-Stat.**	**Break-Years**
			At Level I (0)		
LCO2PC	0.180	0.180	0.935 ***	−2.013	1995, 2003
LGDPPC	−1.703	−1.648	0.972 ***	−4.552	1983, 1991
LGDPPC2	−1.127	−1.010	0.975 ***	−4.485	1983, 1991
LFD	−2.836 *	−2.749 *	0.835 ***	−4.900	1981, 2001
LNENERGY	−1.059	−1.586	0.829 ***	−4.337	1965, 1988
GS	−2.214	−2.236	0.182	−6.444	1966, 1983
COR	−2.058	−2.040	0.624 ***	−5.178	1968, 1976
LO	−2.100	−2.379	0.090	−4.766	1967, 1976
			At First Difference I (1)		
LCO2PC	−9.053 ***	−9.053 ***	0.134	−8.936 ***	2004, 2008
LGDPPC	−6.044 ***	−5.992 ***	0.278	−5.974	1983, 1996
LGDPPC2	−6.129 ***	−6.140 ***	0.142	−6.234 *	1983, 1996
LFD	−2.991 **	−6.974 ***	0.527 **	−6.801 **	1965, 1997
LENERGY	−6.944 ***	−7.266 ***	0.204	−7.715 ***	1964, 1968
GS	−4.596 ***	−5.069 ***	0.172	−11.854 ***	1965, 1985
COR	−5.107 ***	−5.130 ***	0.225	−6.466 ***	1964, 1976
LO	−8.156 ***	−3.682 ***	0.062	−5.627	1966, 1974

Note: ***, ** and * show significance at the 1, 5 and 10% level respectively. Null hypothesis for ADF test: Attribute has a unit root. Null hypothesis for PP test: Attribute has a unit root. Null hypothesis for KPSS test: Attribute has no unit root. Null hypothesis for LEE test: Attribute has a unit root.

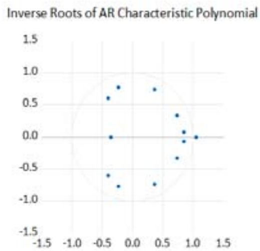
4.2. Autoregressive Distributed Lag (ARDL) Methodology

In selecting the optimum number of lags, five lag selection criteria were followed: (1) sequential modified (LR), (2) Final Prediction Error (FPE), (3) Akaike Information Criteria (AIC), (4) Schwarz Information Criterion (SC) and (5) Hannan–Quinn Information Criteria (HQ). The optimum number of lags will capture the dynamic of the series. The result of different selection criteria is shown in Table 5 where the two-lag length is identified as the desirable condition for cointegration testing. This lag selection under vector autoregressive (VAR) is confirmed as illustrated in the polynomial graph in Figure 2. All the dots are within the circle (except for one dot for government stability (GS) and law and order (LO)), which therefore signify the appropriateness of lag length two for decision and policy reliability.

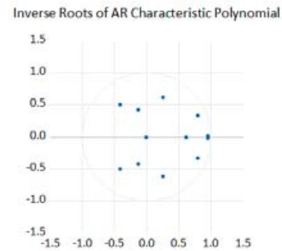
Table 5. Lag Selection for the ARDL model.

	Lag	LogL	LR	FPE	AIC	SC	HQ
GS	0	138.378	NA	4.37×10^{-12}	−9.129	−8.846	−9.040
	1	322.978	280.082	1.64×10^{-16}	−19.377	−17.397	−18.757
	2	398.377	83.198 *	1.54×10^{-17} *	−22.094 *	−18.417 *	−20.943 *
COR	0	141.663	NA	3.48×10^{-12}	−9.356	−9.073	−9.267
	1	324.058	276.736	1.52×10^{-16}	−19.452	−17.472 *	−18.832
	2	379.518	61.197 *	5.66×10^{-17} *	−20.794 *	−17.116	−19.642 *
LO	0	115.092	NA	2.18×10^{-11}	−7.523	−7.240	−7.435
	1	304.250	286.997	5.97×10^{-16}	−18.086	−16.106 *	−17.466
	2	355.117	56.129 *	3.05×10^{-16} *	−19.111 *	−15.434	−17.959 *

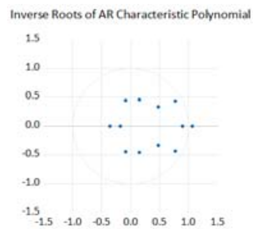
Note: * = lag order selected by the criterion. LR (sequential modified LR test statistics), FPE (Final Prediction Error), AIC (Akaike Information Criteria), SC (Schwarz Information Criterion), HQ (Hannan–Quinn Information Criteria).



Lag selection criteria under VAR in a polynomial graph (GS)



Lag selection criteria under VAR in a polynomial graph (COR)



Lag selection criteria under VAR in a polynomial graph (LO)

Figure 2. Lag selection criteria under VAR in a polynomial graph, created by author.

The bound F-test was conducted between the attributes of Model 1, Model 2, and Model 3 for the cointegration test, and the results are given in Table 6. The F-statistic of Model 1 (7.4835), the F-statistic of Model 2 (15.5718), and the F-statistic of Model 3 (9.1436) exceed the 10% upper bound critical value. With reference to Narayan [54], these results confirm that there exists a significant long-run relationship between the attributes in Model 1, Model 2, and Model 3. Once cointegration evidence has been found, the long-term and short-term ARDL coefficients for the three models, with significant cointegration, are estimated. Table 6 reports the long-run coefficients of the ARDL estimates, while Table 7 reports the short-run coefficients. The coefficients of the lagged Error Correction Term (ECT_{t-1}) for all the three models are negative and statistically significant, implying a highly stable long-run relationship between attributes in all the three models. Moreover, this coefficient is used to measure the speed of adjustment from short-run fluctuations to the long-run equilibrium. The result specifies that the deviation of variables from the short-run to the long-run equilibrium is regulated by 53.81% per year in Model 1, 10.80% per year in Model 2 and 81.04% annually in Model 3.

Table 6. The ARDL long-run results.

Attributes	Model 1	Model 2	Model 3
LGDPC	11.34187 ** (4.5003)	5.1373 *** (1.299)	5.6820 *** (1.9534)
LGDPPC2	−0.6671 ** (0.2669)	−0.2636 *** (0.0719)	−0.3037 ** (0.1099)
LFD	−0.0440 (0.0763)	−0.1058 *** (0.0320)	−0.1632 *** (0.0540)
LENERGY	1.2911 *** (0.0763)	0.4689 *** (0.1056)	0.7377 *** (0.1342)
GS	−0.1855 ** (0.2824)		
COR		−0.0717 *** (0.0124)	
LO			−0.0105 (0.0111)
Selection Model	1,1,1,1,1,0	1,1,1,0,0,0	1,1,1,1,1,0
R-square	0.997	0.997	0.997
Adjusted R-square	0.996	0.996	0.996
F-stat.	729.443	1044.437	750.442
ARDL Bound Test Estimate			
F-stat.	7.483465 *	15.57181 *	9.143613 *

Table 6. *Cont.*

Attributes	Model 1		Model 2		Model 3	
Narayan (2005) Critical Values						
	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
10% Significance Level	4.537	6.370	4.537	6.370	4.537	6.370
5% Significance Level	3.125	4.608	3.125	4.608	3.125	4.608
1% Significance Level	4.537	6.370	4.537	6.370	4.537	6.370
Diagnostic Testing						
Normality	0.000 ***		0.803		0.939	
Serial correlation	0.162		0.763		0.072	
Heteroscedasticity (BPG)	0.939		0.897		0.669	
ARCH	0.865		0.803		0.803	
CUSUM	Stable		Stable		Stable	

Note: *** = significant at 1%, ** = significant at 5% and * = significant at 10%. Standard errors are presented in brackets. Jarque–Bera (normality) test; Breusch–Godfrey LM serial correlation test; Breusch–Pagan–Godfrey heteroscedasticity test; LM-ARCH heteroscedasticity test; Cumulative sum (CUSUM) stability test; Cumulative sum of square (CUSUM-SQ.) stability test.

Table 7. The ARDL short-run results.

Attributes	Model 1	Model 2	Model 3
C	−29.9669 *** (3.9817)	−28.1023 *** (2.6256)	−24.0215 *** (2.8877)
D (LGDPPC)	−22.3680 *** (3.8751)	−7.0390 *** (2.4580)	−13.0812 *** (2.9251)
D (LGDPPC2)	1.2821 *** (0.2189)	0.4165 *** (0.1415)	0.7581 *** (0.1664)
D (LFD)	−0.0811 ** (0.0365)		−0.2001 *** (0.0405)
D (GS)	−0.03649 *** (0.0715)		
D (LO)			−0.0438 *** (0.0974)
ECT (−1)	−0.5381 *** (0.0715)	−0.1080 *** (0.1009)	−0.8104 *** (0.0974)

Note: *** = significant at 1%, and ** = significant at 5%. Standard errors are in brackets.

The ARDL long-run relationship between economic growth (LGDPPC) and CO_2 emissions is positive and significant in the Malaysian context for Model 1 (at 5% significance level), Models 2 and 3 (at 5% significance level respectively). It indicates that any 1% increase in GDP will increase CO_2 emissions by 11.34% for Model 1, 5.14% for Model 2 and 5.68% for Model 3. For the square term of per capita income, denoted by LGDPPC2, negative and significant coefficient results are found for the long-run, hence verifying the existence of the EKC hypothesis for the case of Malaysia in all the three models. Consequently, this validates the occurrence of an inverted U-shaped curve because the CO_2 emissions in Malaysia are affected positively by linear GDP and influenced negatively by the quadratic GDP. However, a contrary result is depicted in the short-run as it recorded a relatively negative and significant relationship between linear GDP and CO_2 emissions and a relatively positive and significant relationship between quadratic GDP and CO_2 emissions in all the three models. Therefore, an inverted U-shaped curve is not found in the short-run, which thus validates the EKC hypothesis as a long-run occurrence for Malaysia.

In the short-run, the result shows that energy use has no significant effect on CO_2 emissions, but for the long-run, it recorded a significant and positive relationship in all the three models. As per the result, a 1% increase in energy use in the long-run will increase CO_2 emissions by 1.29%, 0.47% and 0.74% for Model 1, 2 and 3, respectively. This result supports the finding by Aftab et al. [34], Wada et al. [55], Nathaniel and Adeleye [56], and Atsu and Adams [57] that energy use is the significant contributor to the rise in CO_2 emissions.

This study focused on the relationship between institutional quality and CO_2 emissions and utilized more than a few measures of institutional variables. However, of these, only government stability, corruption and law of order demonstrated consistent and significant coefficients in the case of Malaysia. Thus, in line with the literature, only these three attributes will be analysed for the relationship between institutional quality and CO_2 emissions. Referring to Model 1, government stability (GS) was shown to generate a significantly negative impact on CO_2 emissions both in the long- and short-run. Corruption (COR), which was included in Model 2, indicates a significantly negative effect on CO_2 emissions but only in the long-run. In Model 3, however, law and order (LO) proved to negatively influence CO_2 emissions only in the short-run. As predicted, institutional quality is thus verified to be the vital indicator to the reduction in CO_2 emissions in Malaysia. These outcomes are consistent with Salman [42], Lau [45], and Hunjra [46] who suggest that a country with high institutional quality is successful in monitoring and mitigating CO_2 emissions.

The influence of financial development on CO_2 emissions produced mixed results. These were subsequently incorporated as different institutional quality attributes into the model, but the sign of the coefficients was still negative. In the long-run, financial development relationships with CO_2 emissions were found to be significantly negative if only the attributes of corruption and law and order were included, as shown in Model 2 and Model 3, respectively. Nevertheless, financial development non significantly influenced CO_2 emissions in the long-run as government stability was incorporated in Model 1. This is contrary to the short-run result. For every 1% increase in financial development will decrease CO_2 emissions by 0.08% as specified by Model 1. Similarly, a significant negative short-run relationship is detected in Model 3, when the law-and-order attribute was incorporated into the model. To recapitulate, financial development was validated to be one of the attributes that may decrease CO_2 emissions in the country. This finding is consistent with Khan et al. [7], Sahoo et al. [17], Dauda et al. [40], and Ahmed et al. [41], which suggests that a developed financial system might assist firms in alleviating financial constraint, which in turn would enable them to adopt environmentally friendly technologies with which to decrease CO_2 emissions.

The diagnostic test results for the ARDL model are shown in the lower part of Table 6. The probability chi-square values for the Breusch–Pagan–Godfrey heteroscedasticity test and ARCH test were found to be not significant, hence the null hypothesis of homoscedasticity was retained. Further, the probability of chi-square values for normality test were found significant, suggesting normality in the model. However, from the Breusch–Godfrey Serial, the probability of chi-square values from the Correlation LM test were not significant because no such serial correlation in the model was detected. The robustness and dynamic stability of the models were further tested through cumulative sum of recursive residuals (CUSUM) and cumulative sum of recursive residuals square (CUSUMSQ). From Figure 3, it is clear that the residual values are all positioned between the confidence lines, which thus implies the stability of our ARDL models.

Figure 3. ARDL CUSUM and CUSUMSQ graphs, created by author.

4.3. Nonlinear Autoregressive Distributed Lag Methodology (NARDL)

This study adopted the NARDL approach by Shin et al. [53] to explore asymmetry issues that might exist between the attributes employed. The F-statistic value of Model 1 (8.4090), the F-statistic of Model 2 (8.9723), and the F-statistic of Model 3 (10.545) exceed the 10% upper bound critical value. According to Narayan [54], these results confirm that there exists a significant long-run relationship between the attributes in Model 1, Model 2 and Model 3. Therefore, this study consequently proceeded with the long-run and the short-run NARDL estimation on all the three models.

Tables 8 and 9 indicate the NARDL estimates in the short- and long-run, with CO_2 emissions as the dependent variable. It was established that economic growth, financial development, and energy use—including institutional quality attributes such as government stability, corruption, and law and order—are important variables in explaining CO_2 emissions in Malaysia. The positive and significant coefficients of GDP and energy use denote that an increase in these factors will deteriorate the environment in the country. Conversely, however, an increase in financial development, government stability, corruption, and law and order improve environment quality. Some fascinating results from more sophisticated asymmetric analyses are given below:

1. The GDP and CO_2 emissions relationship is positive but only in the long-run, hence providing support to the argument that economic growth will increase environmental degradation in Malaysia. Specifically, in the long-run, the increase in GDP will proliferate CO_2 emissions to 15.30% on average. However, the square term of GDP is negative and similarly influences CO_2 emissions in the long-run. This finding shows that the EKC hypothesis is true only in the long-run in the country, and the results are similar to that of the ARDL. At the early stage of development, the environment is strongly subjected to pressure due to increasing economic activities and rising income. The pressure will, however, ease beyond a certain threshold of development.
2. Financial development is negatively associated with CO_2 emissions in the long-run. On average, 0.10% decline in CO_2 emissions is caused by financial development in the long-run. This result is analogous to the findings of Sahoo et al. [17], Zaidi [58], and Liu with Song [59], who established that the development in the financial sector might help decrease CO_2 emissions. This could reflect the ability of Malaysian financial institutions to lure industries to invest in environmental sustainability projects, implement environmentally friendly technologies and finance environmental sustainability projects at lower cost, hence resulting in lower environmental pollution.
3. Energy use is positively associated with CO_2 emissions in the short- and long-run in Malaysia. In the short-run, 0.51% rise in CO_2 emissions is caused by the increase in energy use. On average, the increase of energy use will increase by 0.67% CO_2 emissions in the long-run. The ARDL model highlighted the positive influence of energy use on CO_2 emissions. Despite its importance in the development process, energy is causing environmental impact through pollution, global warming, and climate change. These results are parallel with research by Ridzuan et al. [11], Begum et al. [12], and Shaari et al. [13], that claim energy use provides a negative effect to Malaysia environment quality.
4. The results show that government stability does affect CO_2 emissions only in the long-run, and it applies to both positive and negative shocks. The effects of both shocks on CO_2 emissions are negative (-0.1903 and -0.1875, respectively). Specifically, an increase in government stability will decrease CO_2 emissions by 0.19%, and conversely the decrease in government stability will increase it by 0.18%.
5. The influence of corruption on CO_2 emissions is also asymmetric, but only through its negative shocks. The positive shocks of corruption are not effective in decreasing CO_2 emissions in Malaysia under all conditions. The estimated long-run coefficients of negative shocks were measured at -0.08, which implied that a more severe level of corruption may lead to an increase in CO_2 emissions. These results are similar to Khan [7] and Hunjra [46] who posited that a country led by a clean government with integrity may be able improve environment quality.
6. The impact of law and order on CO_2 emissions was shown to be asymmetric both in the short- and long-run. In the long-run, CO_2 emissions were only affected by negative shock, while in the short-run, both positive and negative shocks were influential. In the long-run, the impact of negative shocks is negative at -0.03, implying that a 1% decrease in law-and-order results in 0.03% increase in CO_2 emissions. In the short-run, the impact of both positive and negative shocks is negative. A 1% increase in law and order thus results in 0.04% decrease in CO_2 emissions and a 1% decrease results in 0.06% increase in CO_2 emissions. In summary, the impact of law and order indicates that positive shocks do not affect CO_2 emissions in the long-run, and the impact of negative shocks is greater in the short-run than in the long-run. This finding is consistent with Lau et al. [46] who maintained that respectable institutional quality is imperative for monitoring CO_2 emissions.

Table 8. The NARDL long-run results.

Attributes	**Model 1**		**Model 2**		**Model 3**	
LGDPPC	15.2952 *** (4.838)		6.6406 *** (1.5417)		4.0873 ** (1.5342)	
LGDPPC2	−0.8940 *** (0.2864)		−0.3489 *** (0.0882)		−0.2175 ** (0.0840)	
LFD	−0.0874 (0.0850)		−0.0981 ** (0.0345)		−0.1589 *** (0.0392)	
LENERGY	1.2384 *** (0.2904)		0.3944 *** (0.1017)		0.6625 *** (0.1059)	
GS_POS	−0.1903 ** (0.0706)					
GS_NEG	−0.1875 * (0.0914)					
COR_POS			−0.0248 (0.0467)			
COR_NEG			−0.0806 *** (0.0126)			
LO_POS					0.0117 (0.0126)	
LO_NEG					−0.0295 *** (0.0090)	
R-squared	0.998		0.997		0.999	
Adjusted R-square	0.996		0.996		0.997	
F-stat.	752.081		711.738		924.573	
NARDL Bound Test Estimate						
F-stat.	8.4090 ***		8.9723 ***		10.5451 ***	
Narayan (2005) Critical Values						
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
10% Significance Level	2.457	3.797	2.457	3.797	2.457	3.797
5% Significance Level	2.970	4.449	2.970	4.449	2.970	4.449
1% Significance Level	4.270	6.211	4.270	6.211	4.270	6.211
Diagnostic Testing						
Normality	0.247		0.824		0.483	
Serial correlation	0.0628 *		0.831		0.720	
Heteroscedasticity (BPG)	0.872		0.771		0.954	
ARCH	0.469		0.741		0.404	
CUSUM	Stable		Stable		Stable	
CUSUM-SQ	Stable		Stable		Stable	

Note: *** = significant at 1%, ** = significant at 5% and * = significant at 10%. Jarque–Bera (normality) test; Breusch–Godfrey LM serial correlation test; Breusch–Pagan–Godfrey heteroscedasticity test; LM-ARCH heteroscedasticity test; Cumulative sum (CUSUM) stability test; Cumulative sum of square (CUSUMSQ) stability test. Standard errors are in brackets.

Table 9. The NARDL short-run results.

Attributes	**Model 1**	**Model 2**	**Model 3**
D (LGDPPC)	−33.1551 *** (4.1935)	−10.4366 *** (2.7202)	−10.4366 *** (2.7165)
D (LGDPPC2)	1.8936 *** (0.2361)	0.6059 *** (0.1545)	0.6059 *** (0.6059)
D (LENERGY)			0.5130 *** (0.0658)
D (GS_POS)	0.0147 (0.0200)		
D (COR_POS)		0.04606 (0.1299)	
D (LO_POS)			−0.0370 *** (0.0123)
D (LO_NEG)			−0.0552 *** (0.0092)
C	−39.8999 *** (4.1665)	−38.6419 *** (4.2243)	−25.2182 *** (2.5040)
ECT (−1)	−0.5079 *** (0.0573)	−1.1896 *** (0.1299)	−1.1517 *** (0.1143)

Note: *** = significant at 1%. Standard errors are in brackets.

The Wald test statistics suggest mixed findings, namely that the asymmetry between corruption and CO_2 emissions is significant only in the long-run, whereas its asymmetry with government stability and law and order are both for the short- and long-run. As shown in Table 10, the diagnostic test specifies no evidence on issues of heteroscedasticity, normality, and serial correlation issues. Additionally, Figure 4 demonstrates that the residual values shown in the graphs are all positioned between the confidence lines, thus implying the stability of our NARDL models.

Table 10. The NARDL Wald test results.

Models	Exogenous Attribute	Short-Run		Long-Run	
		F-Stat.	Probability	F-Stat.	Probability
Model 1	GS	11.544 ***	0.003	4.297 **	0.014
Model 2	COR	1.525	0.233	9.031 ***	0.002
Model 3	LO	5.816 **	0.013	12.720 ***	0.001

Note: *** = significant at 1%, ** = significant at 5%.

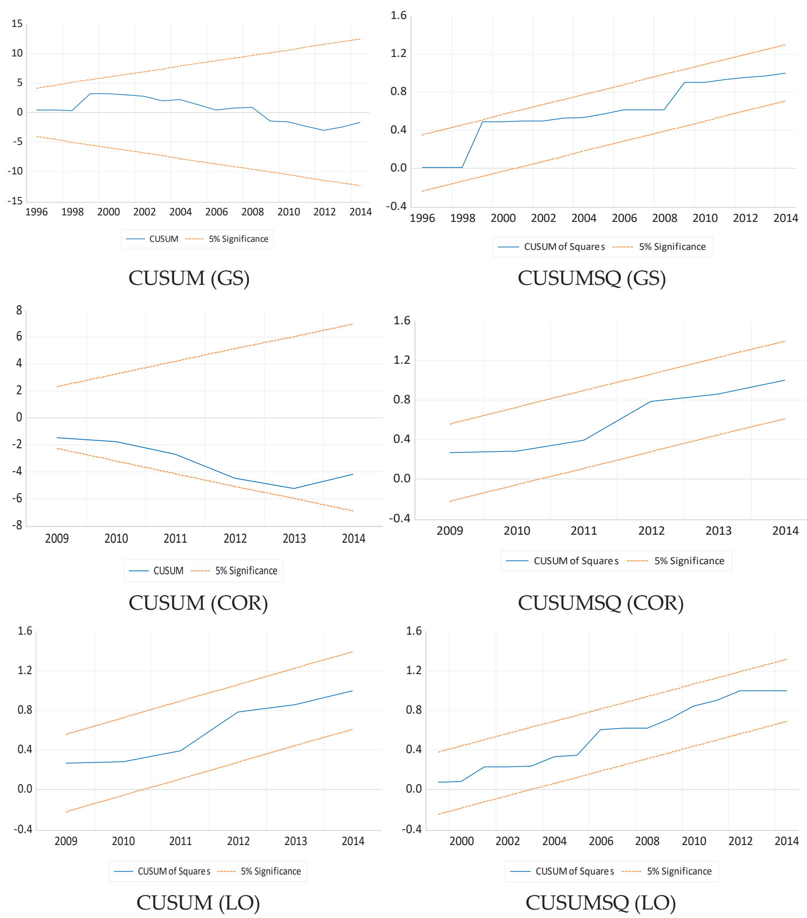
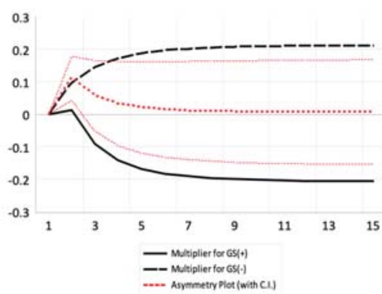
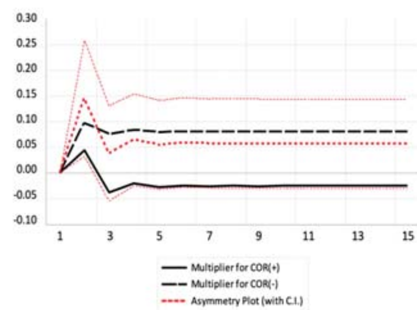


Figure 4. NARDL CUSUM and CUSUMSQ graphs, created by author.

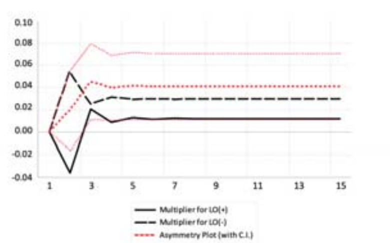
In summary to the NARDL estimation, the asymmetric dynamic multiplier was conducted to illustrate the adjustment pattern of the attributes to their new long-run equilibrium following shocks in the short-run. Figure 5 illustrates the asymmetric dynamic multipliers assessed on Model 1–3, showing patterns of adjustment of CO_2 emissions to their new long-run equilibrium in response to positive and negative shocks on explanatory attributes, namely government stability, corruption and law and order. The fine dotted red lines in the graphics represent the lower and upper bands, indicating symmetry at the 95% confidence interval. The positive change curves (the continuous black line) provide information on the asymmetric adjustments of the dependent attribute (CO_2 emissions) to positive shocks on the explanatory attributes, and similarly the negative change curves (dashed black lines) show the asymmetric adjustment patterns of the dependent attribute (CO_2 emissions) to negative shocks on the explanatory attributes. The asymmetry curve is presented by the difference between the positive component and negative component curves, showing the linear mixture of the dynamic multipliers linked with positive and negative shocks on the explanatory attributes.



Dynamic multiplier graph: GS



Dynamic multiplier graph: COR



Dynamic multiplier graph: LO

Figure 5. NARDL dynamic multiplier effect graphs, created by author.

5. Conclusions

This study analyses the symmetric and asymmetric nexuses of GDP per capita, financial development, energy use, and institutional quality with CO_2 emissions by using information sourced in Malaysia from 1984 to 2017. The Autoregressive Distributed Lag (ARDL) and the Non-Linear Autoregressive Distributed Lag (ARDL) methodologies were utilized to discover the short- and long-term nexuses amongst the attributes of the study. This study is quite dissimilar from those reported in the existing literature concerning Malaysia because it is among the first to incorporate and examine the individual effect of selected institutional quality attributes—namely government stability, corruption, and law and order—on CO_2 emissions in a single investigation. These three proxies for institutional quality have provided consistent and significant coefficients in the Malaysian context. The main objective of this study was to validate the EKC hypothesis in the context of Malaysia under both symmetric and asymmetric approaches. This has been achieved. In the former approach, economic growth and energy use were shown to intensify CO_2 emissions only in the long-term and financial development, and institutional quality attributes mitigate this in the long- and short-term. Results from the asymmetric test were similar for economic growth and institutional quality in intensifying CO_2 emissions. Differences, however, were shown for effects of energy use (long- and short-term) and financial development (not influential in the long-term).

The test on Model 1 established that economic growth, energy use, institutional quality, and CO_2 emissions were statistically cointegrated when government stability was used as a proxy for institutional quality. However, financial development proved not significant in the long run for both the ARDL and NARDL models. This finding further strengthened the arguments by Acheampong and Boateng [8] who concluded that financial development has no direct impact on CO_2 emissions. The test on Model 2 revealed that economic growth, financial development, and energy use, in both symmetric and asymmetric approaches, significantly influenced CO_2 emissions when corruption was used as a proxy for institutional quality in the long- and short-run. However, a positive shock from corruption did not influence CO_2 emissions. This indicates that for any successful measures in controlling corruption, its effect on CO_2 emissions can only be captured in the longer term. Finally, in Model 3, law and order was cointegrated as attributes to institutional quality. The variables in ARDL and NARDL employed for the model—namely financial development, energy use, law and order—were proven statistically significant in both the long- and short-term, excluding the positive shocks for law and order. Therefore, for institutional quality to strongly influence CO_2 emissions, the country needs to strengthen its law and order. The bigger rating indicates higher public respect for the law especially on environment related issues, which translates into stronger mitigation on CO_2 emissions.

In these concerns, several policy implications can be suggested to Malaysian authorities. First, The Malaysian government should work together with private financial providers to develop a policy that can ease financial constraints through having residents, firms, and the industries to contribute to environmentally friendly technologies such as installing renewable energy sources. This may also reduce government burden on energy demand pressure whilst aiming for reduction in CO_2 emissions. Further, the study made it clear that to decrease CO_2 emission, intervention from a clean government is requisite especially on aspects of government stability, reducing corruption, and effective execution of law and order. The healthier governance thus allows for the country to deliver appropriate laws, rules, and regulations to end corruption, exclusively on environmental related projects, for consequent improvement on environmental quality.

This study contributes to the literature on environmental related areas ranging from economics, science, engineering, and energy use aspects. These above-mentioned research areas have one resemblance which is digging approaches to achieve sustainable development goals. In the path of achieving sustainable development goals, a strong policy framework is needed to continuously support the development of green technologies and less carbon-intensive economics activities. Furthermore, this development of green technology can indeed be achieved by receiving help from a stable financial system and a sound institutional quality especially in developing countries [7]. This is validated by the finding of this study that financial development and institutional quality were proven statistically significant in both the long- and short-term in mitigating carbon emissions in Malaysia. This study on an individual country apparently benefits in country-oriented implications; however, the limitation of the study is that its findings cannot be generalized for other developing countries because this study utilized a time series data on an individual country, Malaysia. Apparently, this study leaves space for future research particularly in the light considering other attributes that may influence carbon emissions such as innovation, urbanization, trade openness or population which cannot be covered in this study due to data limitations. Furthermore, the current histrionic worldwide health tragedy which is the COVID-19 pandemic has now been an international debate regarding its negative effects on economic growth, social fabric, and human mobility [60,61]. Hence, it is worth considering this issue as one of the crucial elements in research fields of environmental economics and sustainable development. Regarding interconnection between economic and financial development, the literature can be extent by employing a fresh approach introduced by Diebold and Yilmaz [62] to measure the volatility spillover on global financial crisis. This is an interesting topic related to environmental economics because the global financial crisis has a long-term externalities effect not only on economic growth, but also for the environmental quality especially in developing countries [63].

Author Contributions: Conceptualization, F.D.A.R. and N.K.; methodology, F.D.A.R. and N.K.; software, N.K.; validation, N.K.; formal analysis, F.D.A.R., N.K. and M.H.A.; investigation, F.D.A.R., N.K. and M.H.A.; resources, F.D.A.R. and N.K.; data curation, F.D.A.R. and N.K.; writing—original draft preparation, F.D.A.R., N.K. and M.H.A.; writing—review and editing, F.D.A.R., N.K. and M.H.A.; visualization, N.K.; supervision, N.K. and M.H.A.; project administration, F.D.A.R., N.K. and M.H.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by UNIVERSITI KEBANGSAAN MALAYSIA, grant number EP-2019-010.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from sources as indicated in Table 2.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kurniawan, R.; Sugiawan, Y.; Managi, S. Economic growth–environment nexus: An analysis based on natural capital component of inclusive wealth. *Ecol. Indic.* **2021**, *120*, 106982. [CrossRef]
2. Singhania, M.; Saini, N. Demystifying pollution haven hypothesis: Role of FDI. *J. Bus. Res.* **2021**, *123*, 516–528. [CrossRef]
3. Global Energy Review 2020. Available online: https://doi.org/10.1787/a60abbf2-en (accessed on 11 October 2021).
4. Lv, Z.; Li, S. How financial development affects CO_2 emissions: A spatial econometric analysis. *J. Environ. Manag.* **2021**, *277*, 111397. [CrossRef]
5. Ibrahim, M.; Vo, X.V. Exploring the relationships among innovation, financial sector development and environmental pollution in selected industrialized countries. *J. Environ. Manag.* **2021**, *284*, 112057. [CrossRef]
6. Shahbaz, M.; Topcu, B.A.; Sarıgül, S.S.; Vo, X.V. The effect of financial development on renewable energy demand: The case of developing countries. *Renew. Energy* **2021**, *178*, 1370–1380. [CrossRef]
7. Khan, M.A.; Abdulahi, M.E.; Liaqat, I.; Shah, S.S.H. Institutional quality and financial development: The United States perspective. *J. Multinatl. Financ. Manag.* **2019**, *49*, 67–80. [CrossRef]
8. Acheampong, A.; Amponsah, M.; Boateng, E. Does financial development mitigate carbon emissions? Evidence from heterogeneous financial economies. *Energy Econ.* **2020**, *88*, 104768. [CrossRef]
9. Wendling, Z.A.; Emerson, J.W.; de Sherbinin, A.; Esty, D.C.; Hoving, K.; Jacob, M. *2020 Environmental Performance Index*; Yale Center for Environmental Law & Policy: New Haven, CT, USA, 2020; Available online: epi.yale.edu (accessed on 11 October 2021).
10. Burck, J.; Hagen, U.; Bals, C.; Höhne, N.A.; Nascimento, L. Climate Change Performance Index. 2021. Available online: https://www.germanwatch.org/en/CCPI (accessed on 30 October 2021).
11. Ridzuan, N.H.A.M.; Marwan, N.F.; Khalid, N.; Ali, M.H.; Tseng, M.-L. Effects of agriculture, renewable energy, and economic growth on carbon dioxide emissions: Evidence of the environmental Kuznets curve. *Resour. Conserv. Recycl.* **2020**, *160*, 104879. [CrossRef]
12. Begum, R.A.; Sohag, K.; Abdullah, S.M.S.; Jaafar, M. CO_2 emissions, energy consumption, economic and population growth in Malaysia. *Renew. Sustain. Energy Rev.* **2015**, *41*, 594–601. [CrossRef]
13. Shaari, M.S.; Karim, Z.A.; Abidin, N.Z. The Effects of Energy Consumption and National Output on CO_2 Emissions: New Evidence from OIC Countries Using a Panel ARDL Analysis. *Sustainability* **2020**, *12*, 3312. [CrossRef]
14. Grossman, G.M.; Krueger, A.B. *Economic Growth and the Environment*; NBER Working Paper No. W4364; National Bureau of Economic Research: Cambridge, MA, USA, 1994.
15. Fang, Z.; Gao, X.; Sun, C. Do financial development, urbanization and trade affect environmental quality? Evidence from China. *J. Clean. Prod.* **2020**, *259*, 120892. [CrossRef]

16. Charfeddine, L.; Ben Khediri, K. Financial development and environmental quality in UAE: Cointegration with structural breaks. *Renew. Sustain. Energy Rev.* **2016**, *55*, 1322–1335. [CrossRef]
17. Sahoo, M.; Gupta, M.; Srivastava, P. Does information and communication technology and financial development lead to environmental sustainability in India? An empirical insight. *Telemat. Inform.* **2021**, *60*, 101598. [CrossRef]
18. Law, S.H.; Azman-Saini, W.N.W.; Tan, H.B. Economic Globalization and Financial Development in East Asia: A Panel Cointegration and Causality Analysis. *Emerg. Mark. Financ. Trade* **2014**, *50*, 210–225. [CrossRef]
19. Su, Z.-W.; Umar, M.; Kirikkaleli, D.; Adebayo, T.S. Role of political risk to achieve carbon neutrality: Evidence from Brazil. *J. Environ. Manag.* **2021**, *298*, 113463. [CrossRef]
20. Noda, H.; Kano, S. Environmental economic modeling of sustainable growth and consumption in a zero-emission society. *J. Clean. Prod.* **2021**, *299*, 126691. [CrossRef]
21. Muhammad, S.; Long, X. Rule of law and CO_2 emissions: A comparative analysis across 65 belt and road initiative (BRI) countries. *J. Clean. Prod.* **2021**, *279*, 123539. [CrossRef]
22. Zoundi, Z. CO_2 emissions, renewable energy and the Environmental Kuznets Curve, a panel cointegration approach. *Renew. Sustain. Energy Rev.* **2017**, *72*, 1067–1075. [CrossRef]
23. Zambrano-Monserrate, M.A.; Silva, C.A.; Davalos-Penafiel, J.L.; Zambrano-Monserrate, A.; Ruano, M.A. Testing environmental Kuznets curve hypothesis in Peru: The role of renewable electricity, petroleum and dry natural gas. *Renew. Sustain. Energy Rev.* **2018**, *82*, 4170–4178. [CrossRef]
24. He, Y.; Lin, B. Investigating environmental Kuznets curve from an energy intensity perspective: Empirical evidence from China. *J. Clean. Prod.* **2019**, *234*, 1013–1022. [CrossRef]
25. Shahbaz, M.; Nasir, M.A.; Hille, E.; Mahalik, M.K. UK's net-zero carbon emissions target: Investigating the potential role of economic growth, financial development, and R&D expenditures based on historical data (1870–2017). *Technol. Forecast. Soc. Chang.* **2020**, *161*, 120255. [CrossRef]
26. Tarazkar, M.H.; Dehbidi, N.K.; Ansari, R.A.; Pourghasemi, H.R. Factors affecting methane emissions in OPEC member countries: Does the agricultural production matter? *Environ. Dev. Sustain.* **2021**, *23*, 6734–6748. [CrossRef]
27. Xu, X.; Hu, X.; Wang, T.; Sun, M.; Wang, L.; Zhang, L. Non-inverted U-shaped challenges to regional sustainability: The health risk of soil heavy metals in coastal China. *J. Clean. Prod.* **2021**, *279*, 123746. [CrossRef]
28. Laverde-Rojas, H.; Guevara-Fletcher, D.A.; Camacho-Murillo, A. Economic growth, economic complexity, and carbon dioxide emissions: The case of Colombia. *Heliyon* **2021**, *7*, e07188. [CrossRef]
29. Suki, N.M.; Sharif, A.; Afshan, S. Revisiting the Environmental Kuznets Curve in Malaysia: The role of globalization in sustainable environment. *J. Clean. Prod.* **2020**, *264*, 121669. [CrossRef]
30. Karsh, N.M. Examining the Validity of the Environmental Kuznets Curve. *Cons. J. Sustain. Dev.* **2019**, *21*, 32–50.
31. Saqib, M.; Benhmad, F. Updated meta-analysis of environmental Kuznets curve: Where do we stand? *Environ. Impact Assess. Rev.* **2020**, *86*, 106503. [CrossRef]
32. Ali, W.; Rahman, I.U.; Zahid, M.; Khan, M.A.; Kumail, T. Do technology and structural changes favour environment in Malaysia: An ARDL-based evidence for environmental Kuznets curve. *Environ. Dev. Sustain.* **2020**, *22*, 7927–7950. [CrossRef]
33. Yuping, L.; Ramzan, M.; Xincheng, L.; Murshed, M.; Awosusi, A.A.; Bah, S.I.; Adebayo, T.S. Determinants of carbon emissions in Argentina: The roles of renewable energy consumption and globalization. *Energy Rep.* **2021**, *7*, 4747–4760. [CrossRef]
34. Aftab, S.; Ahmed, A.; Chandio, A.A.; Korankye, B.A.; Ali, A.; Fang, W. Modeling the nexus between carbon emissions, energy consumption, and economic progress in Pakistan: Evidence from cointegration and causality analysis. *Energy Rep.* **2021**, *7*, 4642–4658. [CrossRef]
35. Yin, W.; Kirkulak-Uludag, B.; Zhang, S. Is financial development in China green? Evidence from city level data. *J. Clean. Prod.* **2019**, *211*, 247–256. [CrossRef]
36. Chen, W.; Lu, H.; Liu, X.; Li, D. Financial depth or breadth: What really matters for fighting air pollution in China? *Chin. J. Popul. Resour. Environ.* **2020**, *18*, 331–341. [CrossRef]
37. Zhao, J.; Zhao, Z.; Zhang, H. The impact of growth, energy and financial development on environmental pollution in China: New evidence from a spatial econometric analysis. *Energy Econ.* **2021**, *93*, 104506. [CrossRef]
38. Khan, M.; Ozturk, I. Examining the direct and indirect effects of financial development on CO_2 emissions for 88 developing countries. *J. Environ. Manag.* **2021**, *293*, 112812. [CrossRef]
39. Schumpeter, J.A. *Capitalism, Socialism, and Democracy*; Harper & Row: New York, NY, USA, 1962.
40. Dauda, L.; Long, X.; Mensah, C.N.; Salman, M.; Boamah, K.B.; Ampon-Wireko, S.; Dogbe, C.S.K. Innovation, trade openness and CO_2 emissions in selected countries in Africa. *J. Clean. Prod.* **2021**, *281*, 125143. [CrossRef]
41. Ahmed, K.; Jahanzeb, A. Does financial development spur environmental and energy-related innovation in Brazil? *Int. J. Financ. Econ.* **2021**, *26*, 1706–1723. [CrossRef]
42. Salman, M.; Long, X.; Dauda, L.; Mensah, C.N. The impact of institutional quality on economic growth and carbon emissions: Evidence from Indonesia, South Korea, and Thailand. *J. Clean. Prod.* **2019**, *241*, 118331. [CrossRef]
43. Khan, Z.; Ali, S.; Dong, K.; Li, R.Y.M. How does fiscal decentralization affect CO_2 emissions? The roles of institutions and human capital. *Energy Econ.* **2021**, *94*, 105060. [CrossRef]
44. Ali, H.S.; Zeqiraj, V.; Lin, W.L.; Law, S.H.; Yusop, Z.; Bare, U.A.A.; Chin, L. Does quality institutions promote environmental quality? *Environ. Sci. Pollut. Res.* **2019**, *26*, 10446–10456. [CrossRef]

45. Lau, L.-S.; Choong, C.K.; Eng, Y.-K. Carbon dioxide emission, institutional quality, and economic growth: Empirical evidence in Malaysia. *Renew. Energy* **2014**, *68*, 276–281. [CrossRef]
46. Hunjra, A.I.; Tayachi, T.; Chani, M.I.; Verhoeven, P.; Mehmood, A. The Moderating Effect of Institutional Quality on the Financial Development and Environmental Quality Nexus. *Sustainability* **2020**, *12*, 3805. [CrossRef]
47. Alfalih, A.A.; Hadj, T.B. Asymmetric effects of foreign direct investment on employment in an oil producing country: Do human capital, institutions and oil rents matter? *Resour. Policy* **2021**, *70*, 101919. [CrossRef]
48. Ibrahim, M.; Sare, Y.A. Determinants of financial development in Africa: How robust is the interactive effect of trade openness and human capital? *Econ. Anal. Policy* **2018**, *60*, 18–26. [CrossRef]
49. Wasti, S.K.A.; Zaidi, S.W. An empirical investigation between CO_2 emission, energy consumption, trade liberalization and economic growth: A case of Kuwait. *J. Build. Eng.* **2020**, *28*, 101104. [CrossRef]
50. Baltagi, B.; Demetriades, P.O.; Law, S.H. Financial development and openness: Evidence from panel data. *J. Dev. Econ.* **2009**, *89*, 285–296. [CrossRef]
51. Howell, L.D. International Country Risk Guide Methodology. 2011. Available online: https://www.prsgroup.com/ (accessed on 15 October 2021).
52. Pesaran, M.H.; Shin, Y. An Autoregressive Distributed Lag Modelling Approach to Cointegration Analysis. In *Econometrics and Economic Theory in the 20th Century: The Ragnar Frisch Centennial Symposium*; Strøm, S., Ed.; Cambridge University Press: Cambridge, UK, 1999.
53. Shin, Y.; Yu, B.; Greenwood-Nimmo, M. Modelling Asymmetric Cointegration and Dynamic Multipliers in a Nonlinear ARDL Framework. In *The Festschrift in Honor of Peter Schmidt: Econometric Methods and Applications*; Horrace, W., Sickles, R., Eds.; Springer: New York, NY, USA, 2014; pp. 281–314. [CrossRef]
54. Narayan, S.; Doytch, N. An investigation of renewable and non-renewable energy consumption and economic growth nexus using industrial and residential energy consumption. *Energy Econ.* **2017**, *68*, 160–176. [CrossRef]
55. Wada, I.; Faizulayev, A.; Bekun, F.V. Exploring the role of conventional energy consumption on environmental quality in Brazil: Evidence from cointegration and conditional causality. *Gondwana Res.* **2021**, *98*, 244–256. [CrossRef]
56. Nathaniel, S.P.; Adeleye, N. Environmental preservation amidst carbon emissions, energy consumption, and urbanization in selected African countries: Implication for sustainability. *J. Clean. Prod.* **2021**, *285*, 125409. [CrossRef]
57. Atsu, F.; Adams, S. Energy consumption, finance, and climate change: Does policy uncertainty matter? *Econ. Anal. Policy* **2021**, *70*, 490–501. [CrossRef]
58. Zaidi, S.A.H.; Hussain, M.; Zaman, Q.U. Dynamic linkages between financial inclusion and carbon emissions: Evidence from selected OECD countries. *Resour. Environ. Sustain.* **2021**, *4*, 100022. [CrossRef]
59. Liu, H.; Song, Y. Financial development, and carbon emissions in China since the recent world financial crisis: Evidence from a spatial-temporal analysis and a spatial Durbin model. *Sci. Total Environ.* **2020**, *715*, 136771. [CrossRef]
60. Spelta, A.; Pagnottoni, P. Mobility-based real-time economic monitoring amid the COVID-19 pandemic. *Sci. Rep.* **2021**, *11*, 13069. [CrossRef]
61. Pagnottoni, P.; Spelta, A.; Pecora, N.; Flori, A.; Pammolli, F. Financial earthquakes: SARS-CoV-2 news shock propagation in stock and sovereign bond markets. *Phys. A Stat. Mech. Its Appl.* **2021**, *582*, 126240. [CrossRef]
62. Diebold, F.X.; Yilmaz, K. Better to give than to receive: Predictive directional measurement of volatility spillovers. *Int. J. Forecast.* **2012**, *28*, 57–66. [CrossRef]
63. Alsamara, M.; Mimouni, K.; Mrabet, Z.; Temimi, A. Do economic downturns affect air pollution? Evidence from the global financial crisis. *Appl. Econ.* **2021**, *53*, 4059–4079. [CrossRef]

sustainability

MDPI

Article

The Role of Education and Income Inequality on Environmental Quality: A Panel Data Analysis of the EKC Hypothesis on OECD Countries

Paolo Maranzano [1,*], João Paulo Cerdeira Bento [2] and Matteo Manera [1,3]

[1] Department of Economics, Management and Statistics (DEMS), University of Milano-Bicocca, Piazza dell'Ateneo Nuovo, 1, 20126 Milano, Italy; matteo.manera@unimib.it
[2] Department of Economics, Management, Industrial Engineering and Tourism (DEGEIT), Campus Universitário de Santiago, University of Aveiro, 3810-193 Aveiro, Portugal; jpbento@ua.pt
[3] Fondazione Eni Enrico Mattei (FEEM), Corso Magenta, 63, 20126 Milano, Italy
* Correspondence: paolo.maranzano@unimib.it

Abstract: This study examines the impact of education on the pollution–income relationship, controlling for income inequality in 17 European OECD countries over the period 1950–2015. We developed a novel two-stage algorithm, whose first step consists in applying clustering techniques to group countries according to the income inequality temporal pattern. In the second step, we estimate the educational-mitigated EKC hypothesis (Educational EKC) by employing panel regression techniques accounting for endogeneity issues. The clustering findings suggest the existence of high variability in income inequality levels across countries and heterogeneous development patterns. Empirical estimates highlight that, for high income inequality countries, the Educational EKC hypothesis holds, and that the emissions–income elasticity appears to decline when including the schooling level. In the low income inequality cluster, these effects are not clear-cut. For these countries, we propose a different specification of the EKC, which substitutes the income per capita term with the years of schooling. The new specification is statistically validated for both high income inequality and low income inequality countries. In conclusion, we can state that education should be addressed as a crucial cornerstone to shaping the EKC curve.

Keywords: pollution-income; Environmental Kunzets Curve; education; income-inequality; Europe; panel data; clustering

JEL Classification: Q56; I24-25; C51-52; O15; O44

Citation: Maranzano, P.; Cerdeira Bento, J.P.; Manera, M. The Role of Education and Income Inequality on Environmental Quality: A Panel Data Analysis of the EKC Hypothesis on OECD Countries. *Sustainability* **2022**, *14*, 1622. https://doi.org/10.3390/su14031622

Academic Editor: Bertrand Hamaide

Received: 10 January 2022
Accepted: 27 January 2022
Published: 30 January 2022

1. Introduction

The literature on the debate over growth and environmental issues is vast. Most studies refer to the evidence that there is a relationship between environmental quality and income, of the kind that environmental quality worsens at early periods of economic development and improves at later periods, as the economy develops. The literature on this relationship focuses on testing the Environmental Kuznets Curve, hereafter EKC, hypothesis [1,2].

This paper focuses on the importance of including education in the EKC modeling. We will use the average years of schooling as a proxy of human capital. Included in the panel dataset are all the OECD member states and we use a parabolic specification to model the EKC relationship. This paper discusses the role played by education and schooling in long-term development and its impact on the environment. The rationale is that the literature on the EKC has often debated on control variables to avoid omission bias, and has also modeled external factors that can negatively influence the quality of the environment, but rarely included any issue related to the role of human capital. Nevertheless, there is a study for Australia that has focused on how the educational level may affect the level of emissions within the EKC framework in the period from 1950 to 2015 [3]. Its finding is that education has played an essential role in economic development in the long run and, therefore, cannot be ignored within the pollution–income relationship.

What is expected from the empirical results on the relationship between pollution and schooling is the identification of a concave quadratic curve that grows in the initial phase and then decreases once the turning point has been passed. Analytically, the expectations lead to an inverted-U shape in addition to the main hypothesis underlying the EKC model. We refer to this result as the *Educational EKC*, which will be opposed to the economically driven specification commonly known as the *Standard EKC*. The concave shape can be justified interpreting education as a process moving along with the long-run economic development of countries. Historically, at an early stage of development, countries exhibit low levels of education and economic production. In the short run, the productive system invests in intensive industrial production, often supported by eco-unfriendly technologies and resources. Sustainable economic development requires a parallel and balanced strengthening of physical capital, technology, knowledge, and human capital to generate an extra boosting effect on the economy without wasting natural resources. In this phase, the economy needs to override the technological improvements brought about by knowledge. The turning point is reached when the educational system offers people the skills to develop efficient and environmentally compatible technologies and social instruments to adopt sustainable lifestyles. Hence, the human capital will push the economy towards more sustainable behaviors able to increase wealth and collective well-being simultaneously. Virtuous examples of these mechanisms are the countries of Central and Northern Europe, which show simultaneously very high levels of human capital and wealth.

As a further contribution, we consider as a discriminant factor the income inequality affecting the countries in the panel, as suggested by [4]. Using the Gini Index as a proxy of the social inequality, we aim at assessing whether the level of income inequality across countries affects the relationship between income, pollution, and level of schooling. First, we want to check if the estimated coefficients associated with income and education change in magnitude and statistical significance by considering countries all together and divided into groups based on their level of income inequality. Second, we assess whether the education variable has the same effect on environmental degradation in high income and low income inequality countries.

The remainder of the paper is structured as follows. In Section 2, we introduce the empirical specification of the EKC, augmented by the effect of the educational level, pointing out our expectations regarding the parameter values and their interpretation. In Section 3, we describe the available data and their sources. In Section 4, we describe the statistical methodologies implemented to test the research questions. In particular, we focus on the two-stage approach developed to estimate the effect of income inequality and schooling on CO_2 emissions. In Section 5, we comment on the empirical results based on the OECD panel. In Section 6, we critically discuss the interpretation of the empirical evidence relative to the existing econometric literature and provide some suggestions for policymakers. Lastly, Section 7 sums up the contents of the paper.

2. Specification of Standard and Educational EKC

The specification of the *Standard EKC* model sets the per capita emission levels in a quadratic relationship with the per capita income, augmented by a set of control variables that capture indirect and external factors affecting the quality of the environment. Extending the proposal of Balaguer and Cantavella [3], in this paper we propose a panel specification of the *Educational EKC* which expresses the environmental quality as a quadratic function of both the per capita income and the educational level. According to a log-log panel specification, the model can be expressed as follows:

$$log(CO_{2,it}/Pop_{it}) = \beta_0 + \beta_1 log(GDP_{it}/Pop_{it}) + \beta_2 log(GDP_{it}/Pop_{it})^2 + \beta_3 log(Sch_{it}) + \beta_4 log(Sch_{it})^2 + \Theta Z_{it} + \varepsilon_{it} \quad (1)$$

where $CO_{2,it}/Pop_{it}$ refers to the per capita CO_2 emission levels, GDP_{it}/Pop_{it} is the per capita income, Sch_{it} is the educational level, measured as the average number of schooling years, Z_{it} is the set of control variables, and ε_{it} is the error term.

The *Standard EKC* hypothesis is supported by the data if $\beta_1 > 0$, $\beta_2 < 0$ and the turning point $TP_{inc} = exp(-\frac{\beta_1}{2\beta_2})$ belongs to the observed range of per capita income values. The coefficients can be interpreted as elasticities since all the variables are expressed in a logarithmic scale. The empirical relationship between environmental quality and the level of education is modeled through a quadratic specification with coefficients β_3 and β_4. The expected relationship between these variables is a quadratic inverted-U shape form, whose coefficients must respect the same sign constraints of the EKC hypothesis, i.e., $\beta_3 > 0$ and $\beta_4 < 0$. The empirical turning point $TP_{EDU} = exp(-\frac{\beta_3}{2\beta_4})$ identifies the minimum years of schooling such that pollution begins to decrease. In other words, it can be interpreted as the educational level that must be reached in order to guarantee long-term sustainable development.

The *Kuznets Curve* has been proposed by Simon Kuznets and is a hypothetical curve that graphs income inequality against income per capita over the course of the society's urbanization and industrialization [5]. This relation has led to the development of the EKC [1,6]. As income increases, environmental pressure also grows to a certain point, and from that point the relationship becomes negative [7]. Moreover, as social welfare increases, people are more willing to use certified products and services complying with many environmental standards. The improvement in the quality of life leads society to put pressure on national authorities and governments to take appropriate measures for encouraging ecological best practices. Moreover, the availability of more information about products and production processes, the innovations introduced in those same processes, and the increased pressure on companies to favor products that meet the ecological standards further encourage the introduction of "greener" products and practices fostering environmental awareness. These attitudes explain why and how environmental quality is deteriorating in the early stages of economic development, and then in a second stage, it improves over time, generating an inverted-U relationship between emissions and income.

Several studies have tested other forms of this relationship, namely, the N-form [8]. According to these studies, there could be a third stage where the economy begins to experience increases in obsolescence, and at a certain point, a positive relationship re-emerges between per capita environmental degradation and income. In addition, these studies seem to indicate that growth may be compatible with environmental improvement if appropriate anticipating policies that tackle environmental issues are followed [9]. The EKC hypothesis have been criticized due to the sensitivity of the empirical findings presented in the literature [10,11]. The variables used to measure the impact of economic activity on the environmental quality have generated some doubts about the effectiveness of the EKC approach as a way to assess the impact of economic variable on the environment. Along with this, as a reaction, new tests and more robust methodologies have been proposed [12].

In particular, one of the main criticisms of the EKC models is the assumption that environment and growth are not interrelated. This view posits that the EKC hypothesis assumes no feedback between income and the pollution of the environment [13]. It has also been argued that the empirical robustness of the EKC relation depends on the reliability of the data used [14]. Another problem is the little attention that has been paid to the statistical properties of the variables used to investigate the validity of the EKC. Major econometric problems that affect the empirical EKC literature are also related to the use of nonlinear transformations of integrated regressors and, in a panel context, to cross-sectional dependence in the data [15]. These econometric issues could invalidate the EKC results. Therefore, researchers should carefully apply the available statistical methods and interpret their findings with care [16].

Nevertheless, despite there being many issues around the modeling of the EKC, the analysis of the relationship between income and environmental quality has been attracting great attention from researchers, who, from the 1990s, have been devoting themselves to theoretical and empirical studies investigating the effects of growth on the environment, analyzing each phase of the economic development process. Consequently, it is essential to understand the use of a quadratic function as an appropriate mathematical model to represent the EKC. Researchers must have a clear structured methodology for determining the preferred EKC specification and hence the shape of the estimated EKC model. Concavity should be assessed based upon the sign and statistical significance of the estimated coefficients of the leading terms, the location of turning point(s), and the sign and statistical significance of the estimated elasticities [17].

3. Data and Sources

In order to perform the empirical analysis for the selected OECD panel, we gathered annual data from 1950 to 2015 from various data sources. Data on income, population, average years of schooling, and international trade were collected from the Penn World Table (PWT) version 9.0 [18]. Data on pollutant emissions were provided by the Carbon Dioxide Information Analysis Center (CDIAC) of the US Department of Energy, while energy use data were collected from The Shift Project database (TSP). Information regarding income inequality was collected from the Standardized World Income Inequality Database (SWIID) [19]. SWIID gathers data about Gini Index from institutional sources, i.e., World Bank, Eurostat, Federal Reserve, and standardizes data on income inequality. Despite its completeness and extension, SWIID contains missing values and starts from 1960. Table 1 provides summary descriptive statistics of the selected countries between 1950 and 2015.

Table 1. Descriptive statistics for the considered variables.

Variable Name	Measure Unit	Mean	Std.Dev.	Min	Max
CO_2 per capita	CO_2 emissions (metric tons per capita)	7.955	5.42	0.46	41.04
Income per capita	GDP per capita (constant 2011 US$)	24,912.46	14,390.29	3375.50	84,417.24
Education	Average years of schooling (population 15–64 years)	8.61	2.74	0.98	13.55
Energy use	Renewable energy production over total energy production (percentage)	26%	29%	0%	99%
Trade openness	Sum of imports and exports over GDP (percentage)	65%	47%	1%	286%

3.1. Emissions

According to their research interests, EKC studies use alternative model specifications of the dependent variable. *Standard EKC* literature, such as [13], uses the level of carbon dioxide or sulfur dioxide and the concentration of particulate matters $PM_{2.5}$ and PM_{10} as a proxy of environmental quality. Some papers introduce new indicators to proxy environmental quality, such as the yearly amount of CO_2 produced by a country and measured in thousand metric tons divided by the total population. Other studies have selected alternative pollutants to compare with CO_2 emissions. Rasli et al. [20] used local pollutants, such as nitrous oxide emissions (N_2O), carbon monoxide (CO) or total nitrogen oxides (NO_x), on a panel of 36 countries, both developed and developing, during the period 1995–2013. The reason we have selected CO_2 as an environmental degradation indicator among a series of other possible pollutants is that human emissions of carbon dioxide and other greenhouse gases are a primary driver of climate change and present one of the world's most pressing challenges linking emissions to global temperatures and greenhouse gas concentrations. Overall, CO_2 emissions are a gaseous compound that is capable of absorbing and emitting infrared radiation, thereby allowing less heat to escape back to space and 'trapping' it in the earth's atmosphere. Since more than 80% of the world's current primary energy consumption is met by fossil fuels, CO_2 is considered a major greenhouse gas in Earth's atmosphere, which contributes to climate change with potentially adverse effects on the world economy as well.

Alternatively, more recent strands of research have attempted to investigate the EKC hypothesis by employing new environmental indices of sustainability as dependent variable instead of using carbon dioxide emissions per capita. See for example the ecological footprint indicator used by [21] as proxy of environmental quality. This indicator measures how fast a population consumes resources and produces waste with respect to how fast the natural environment can absorb resource exploitation and regenerate itself. Conclusions about this approach support the existence of EKC in developed countries, while it is not validated for developing countries. The substantial advantage in using alternative indices of environmental sustainability is their capacity to resume multi-dimensional aspects of sustainable development considering the complexity of the reality.

Here, we consider the CO_2 per capita emissions stored by the Carbon Dioxide Information Analysis Center (CDIAC) of the US Department of Energy as proxy of environmental degradation. The variable is measured as yearly per capita metric tons of CO_2 produced by each country.

3.2. Income

The EKC hypothesis is usually tested using per capita gross domestic product or income as a proxy for economic development. Usually, the EKC is tested with income data in per capita terms and valued at constant prices [22]. We decided to use the real GDP measured in constant 2011 millions of US dollars divided by the total population to account for possible errors in measuring national income or biases generated by inflation.

The EKC hypothesis has been tested for a large variety of countries and regions, but the conclusions about the validity of the EKC are very different and strongly depend on the considered cross-sectional units or periods. For example, whereas the EKC conjecture is validated for Malaysia if the regression includes disaggregated energy sources, the hypothesis is not validated with aggregated data [23]. Instead, for OECD countries, the conclusions are more robust [24–27].

3.3. Education

One of the key points of this paper is that we aim to assess the mitigating effect that education generates on the standard income–pollution-based specification of the EKC. The level of education in the EKC has been measured in different ways, such as the ratio of secondary school enrolment [28], the average years of schooling in the population aged over 25 [28,29], or the total number of students at the graduate and postgraduate levels of education [3]. In our case, we exploit the potential contained in the Penn World Tables to quantify the degree of human capital since 1950 through the average years of schooling as a proxy for the education in the countries under consideration. In support of our choice, it is well known in the literature that average years of schooling have become the most popular and commonly used specification of the human capital stock (see, on this regard, [30–38]).

3.4. Energy

The debate over the role that energy consumption and production play in the relationship between environment and economic development is extensive and multifaceted. Many contributions include energy consumption as the primary driver of emissions in EKC specifications. The EKC literature often distinguishes between energy production (consumption) generated by renewables and energy production (consumption) generated by non-renewable sources. See, for example the contribution of [39], which evaluates the mitigating effects of renewable energy sources by separating the shares of hydroelectricity energy consumption and alternative energy sources (e.g., solar, thermal and nuclear) from the non-renewable energy consumption. Somewhat similarly, ref. [40] explores the effect of energy consumption from renewable and non-renewable sources on the EKC hypothesis. Using Pakistan data from 1970 to 2012 as a case study, the authors show that renewable energy can generate strong environmental benefits by reducing emissions, while consumption of fossil fuels significantly increases the amount. Using the aggregate value of consumption rather than separating the effect of energy sources, the effect that energy generates on the environment is negative. In fact, an increase in energy consumption leads to further airborne pollutant emissions both in the long run and in the short run [41–43]. However, a recent paper by [44] argues that the inclusion of energy consumption among the determinants of the EKC hypothesis can lead to systematic volatility in the estimated coefficients, leading to potential changes in their magnitudes and signs, and to misleads in cointegration tests. The main reason is that data on CO_2 emissions and energy consumption are derived from the same source, namely, fossil energy consumption. Many studies have looked at the relationship between energy consumption and economic growth and have demonstrated that energy consumption has a direct impact on the level of pollution [45]. Other studies have shown that there is a relationship between income, pollution, and energy consumption [46,47]. In addition, when differentiating between non-renewable and renewable sources of energy, gas and petroleum consumption have positive effects on CO_2 emissions, while electricity consumption from renewable sources has a negative one [48]. Moreover, the empirical results fully support the existence of an EKC when using control variables such as oil reserves and the Gini Index [49].

For the reasons outlined above, we define the *energy use* variable used in our paper as composed by both renewable energy and non-renewable energy sources, allowing us to control for distinct effects on the environment. Renewable and non-renewable energy production are measured in thousand tons of oil equivalent (TOE). The amount of renewable energy is given by the sum of hydro, wind, solar, and geothermal energy production, while non-renewable energy production includes fossil fuel sources such as oil, gas, coal, and nuclear. The variable *energy use* is then computed as the ratio of renewable energy production over the total energy production, given by the sum of both renewable and non-renewable production of energy [44,50,51].

3.5. Trade Openness

International trade and logistics impact directly on the environment through human activities. Trade activities and investment in physical capital can increase or decrease significantly the quantity of pollutant emissions generated by each country and those imported by other economies. The *Pollution Haven Hypothesis* states that trade can move pollutant activities from economies with strong environmental standards to countries with less restrictive laws, increasing pollution production of the latter and reducing that of the former. Conversely, the *Pollution Halo Hypothesis* states that trade can reduce global environmental degradation through efficient and environment-friendly investments carried on by multinationals all over the world. Including *trade openness* is crucial within the EKC framework because it avoids econometric issues such as the omitted variable bias. Studies using the augmented version of the EKC where additional regressors have been introduced to control for omitted variable bias show that significant unidirectional relationships from trade indicators to pollutant emissions are identified [52]. In this paper we control for logistic and international exchanges by computing the *trade openness* index as the sum of exports and imports divided by the gross domestic product. Data on trade were collected from the PWT database.

3.6. Income Inequality

The concept of inequality can assume different meanings and interpretations. Inequality can be defined as the income distribution gap between different workers, and it affects production through structural changes [5]. Differences in income across countries can be explained by investments in physical and human capital and technological differences [53,54]. There are many measures of income inequality across countries [55], each based on different methodologies assessing how wealth is distributed among the population [56]. According to the macroeconomic literature, the most important and popular measure of income inequality is the Gini Index [57]. Recent contributions have investigated the process of income distribution and inequality at a global level. After the financial crisis of 2008, particular attention has been given to developed countries [58]. These studies aimed to establish new relationships between inequality measures and socio-economic factors, explaining the social consequences and causes affecting the level of inequalities. All these contributions show positive evidence and increasing trends of income inequalities within developed countries, which are even more intense due to the 2008–2011 economic and sovereign-debt crises. The trilateral relationship between environmental degradation, income inequality, and economic growth has been studied, for example, by augmenting the EKC with the Gini Index for Chinese provinces [59]. Results suggest that the income gap doubled due to the unbalanced development of regional economies, causing a general slowdown in the central government's commitment to improve environmental quality.

Usually, EKC studies include income inequality as an exogenous control variable and test the causal relationship between income inequality and environmental degradation. Several studies report that income inequality creates gaps between countries that reduce their willingness to pay for environmental protection [29,60]. Recent contributions have employed the distribution of income inequality [59] and the institutional framework as factors to explain differences in pollutant emissions across countries [61]. Research has shown that environmental innovations and inequality depend on per capita income and that excessive income distribution inequality harms innovation in green technology, despite new green products providing benefits to the whole society [62]. Moreover, income inequality has been recently used in the EKC framework by [4] as a discriminant factor for identifying the impact of foreign direct investments on environmental quality. In particular, this study splits the full sample of Latin American countries into two groups based on the income level and estimate the *Standard EKC* using panel data models. According to its findings, using income inequality measures as grouping factors can improve the estimation of economic effect and contribute to the literature extending the debate on sustainable development to income distribution issues.

The SWIID database offers various inequality measures, including the Gini Index measured on disposable income (after taxes) or income at market values. The OECD countries analyzed in our paper present a strong variability in income levels, adopt different fiscal policies, and have social protection mechanisms that are not always comparable. This has led us to employ the Gini Index on disposable income as a measure of the distribution of income inequality across countries. The indicator is used to cluster countries based on the values of social inequality observed between 1987 and 2015. This exercise aims to assess whether the level of income inequality across countries affects the relationship between income, pollution, and level of schooling. Specifically, we are interested in testing whether: (1) the regression coefficients change in magnitude and significance by considering a single large panel or by separating countries according to their income inequalities, (2) the education variable has the same effect on environmental degradation in high inequality and low inequality countries.

Figure 1 shows the temporal evolution of the average Gini Index and its variability within the sample of countries between 1987 and 2015. The plot clearly highlights a generalized increase in income inequality levels among the considered OECD countries. However, as it will be shown in the following sections, the increase is associated with some particular countries, while others have experienced noticeable reductions in income inequality.

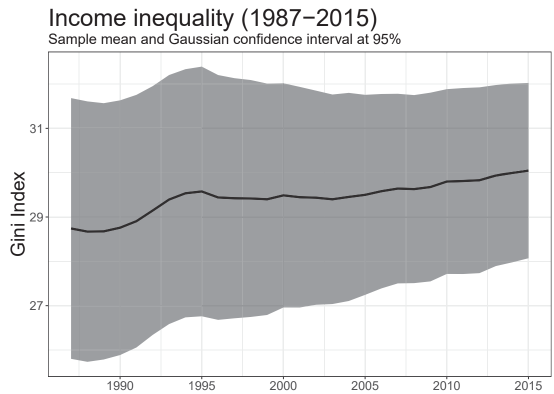


Figure 1. Income inequality trend in the OECD sample (1987–2015). The solid black line represents the sample mean of Gini Index on disposable income by year and the gray area is the approximate Gaussian confidence interval at 95% for the sample mean. Values are expressed in percentage.

4. Econometric Methods and Statistical Approaches

This section describes the research design, which consists of two steps, namely, a statistical clustering analysis followed by the econometric estimation of our EKC models. We employ this two-step statistical procedure to evaluate the role of education in mitigating the income–pollution relationship according to the income inequality levels. The first stage of the two-step statistical method investigates the evolutionary path of socio-economic inequality in the selected panel of countries by identifying homogeneous groups of countries with similar temporal trajectories. In the second stage, we estimate EKC models for both the full sample and the sub-samples. In this stage, we estimate the EKC augmented by the direct contribution of education (years of schooling) by employing panel data regression methods. We complement the econometric analysis by several preliminary tests, such as unit root testing, endogeneity, and cointegration testing in a panel context.

4.1. K-Means Clustering Using Income Inequality

As stated in Section 3.6, the use of income inequality measures in the EKC framework allows to properly identify the impact of economic variables on environmental quality and contributes to the debate on the role of income distribution [4]. For this reason, we use clustering analysis to gain some valuable insights into our data set by separating countries into groups according to their level of income inequality across the last decades. This study applies an innovative approach to country grouping based on the temporal evolution of income inequality and uses as clustering variables the annual values of the Gini Index on disposable income from 1987 to 2015. This approach partitions the countries according to their cross-sectional distances, obtaining groups of countries that share a "common evolutionary path" of income inequality. The use of socio-economic indicators to aggregate countries or regions and evaluate comparative performances has been considered in the literature. For example, the clustering of more than 150 countries based on Human Well-Being indicators of the Social Society Indices has been used [59,63], while composite indicators to generate a ranking of EU countries according to their sustainability in terms of lifestyle, environment, and social issues have also been calculated [64].

Cluster analysis techniques, such as K-means, are multivariate statistical methods used to obtain groups of observations based on their similarity to a set of specific features X. The K-means algorithm has the objective to partition n observations into k clusters, assigning each observation to the group with the nearest mean value and retaining the maximum inter-group and the minimum intra-group heterogeneity. The literature offers various examples of studies using clustering techniques based on inequality measures to classify countries [65]. Findings show structural differences between groups of countries in terms of social indicators, particularly about income inequality measures, with a reduced dynamicity from one group to another along time.

Our study seeks to classify the countries in the panel data set through the K-means algorithm using the information on income inequality, setting as grouping variables the yearly values of the Gini Index on disposable income from 1987 to 2015. Formally, the set of cluster features available for each country $i = 1, 2, \ldots, 17$ can be expressed as $X_i = X_{i,1987}, X_{i,1988}, \ldots, X_{i,t}, \ldots, X_{i,2014}, X_{i,2015}$, where $t = 1987, \ldots, 2015$ and X_{it} represents the observed Gini Index for country i at time t.

Since we study the impact of the level of education on the environment–growth relationship by controlling for income inequality, we have decided to use the most straightforward classification strategy with $K = 2$ potential groups. Given the small number of cross-sectional units (17 countries), a clustering algorithm with a larger number of groups would harm the robustness of the panel regression analysis. In addition, from an interpretative perspective, this assumption allows identifying two distinguished groups of European OECD countries, characterized by common temporal patterns that can be traced back to historical events that occurred during the period 1950 to 2015.

4.2. Panel Data Analysis

All EKC models are tested using panel data techniques [66] with fixed-effects (FE) and random-effects (RE) model specifications. The FE model assumes that the individual effects are fixed parameters to be estimated and the disturbances are I.ID. with zero mean and constant variance. The RE specification allows the individual effects to be random and I.ID. distributed with zero mean and constant variance. FE and RE are compared using a Hausman's specification test [67,68]. The software Stata 16 [69] is used to estimate the FE and RE specifications and to compute all the diagnostic tests, including cross-sectional dependence, unit-root, and cointegration. Data management, cluster analysis, and graphical analysis are performed using the software R [70].

5. Empirical Results

5.1. Cluster of the Income Inequality Trajectories

The K-means procedure identified two distinct groups of 7 and 10 countries, respectively. The smaller group is composed by countries that share a common high income inequality path with a decreasing trend, therefore appointed as 'High income inequality cluster'. In comparison, the larger group is composed of countries with a generally lower income inequality with increasing perspectives, named 'Low income inequality cluster'.

The high income inequality group (dark gray) includes Mediterranean countries, the United Kingdom, Ireland, and Turkey, while the low income inequality block (light gray) includes Central and Northern Europe economies. Table 2 reports the list of countries belonging to each group. Figure 2 shows the geographical partition of the selected countries among the two groups.

Table 2. K-means cluster results: countries by group.

Cluster	Member Countries
Low income-inequality (10 countries)	Austria, Belgium, Denmark, Finland, France, Germany Netherlands, Norway, Sweden, and Switzerland
High income-inequality (7 countries)	Greece, Ireland, Italy, Portugal Spain, Turkey, and UK

The two temporal patterns, represented in Figure 3, confirm previous expectations, namely, that OECD countries are strongly heterogeneous in terms of income distribution and run parallel paths that converge very slowly. Also, Figure 3 highlights two other crucial facts. The first is the remarkable increasing trend of income inequality for countries that initially had very low levels of the Gini Index. The second aspect is the convergence in terms of disparities among the two blocks. These results reflect both recent and historical events related to the development and growth of the area. Due to financial crises and general slowdowns of growth, in the last decades the distance among OECD countries in terms of income distribution and economic perspectives increased strongly and generated structural economic divergences as well as the rising of new social issues and demands about the growing inequalities. The strong growth of the low income inequality group and the consolidation of the high income inequity countries is symptomatic of an asymmetry in the long-term effects of these phenomena.

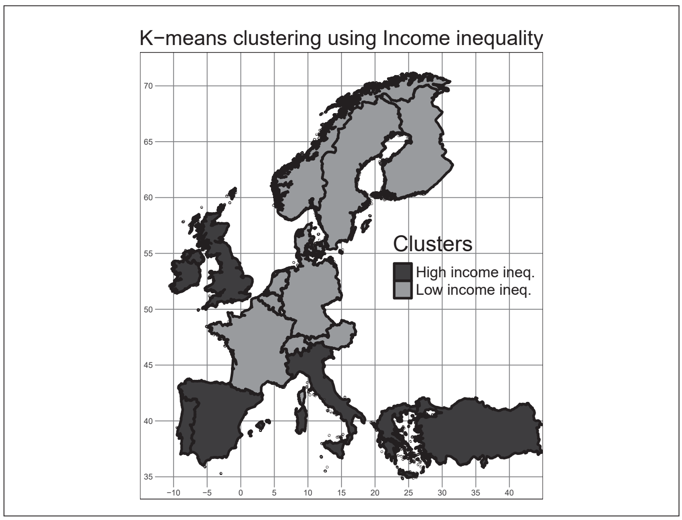


Figure 2. Map of the clusters for the sample OECD countries. Dark gray countries belong to the 'High income-inequality' cluster and the light gray countries belong to the 'Low income-inequality' cluster.

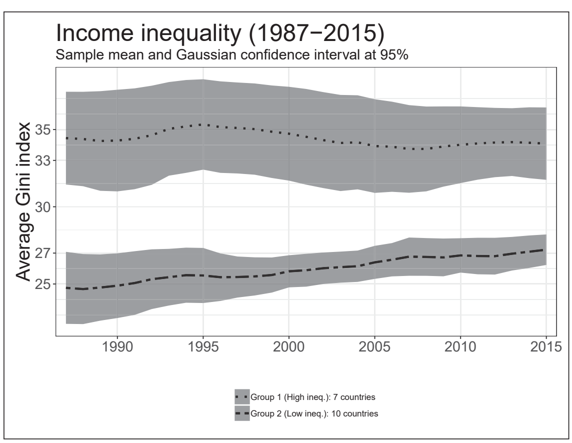


Figure 3. Income inequality trend in the two clusters (1987–2015). The dotted black line represents the average annual Gini Index observed in the first sub-sample ('High income-inequality') and the dot-dashed black line represents the average annual Gini index for the second sub-sample ('Low income-inequality'). Gray areas are the approximate Gaussian confidence interval at 95% for the sample mean. Values are expressed in percentage.

5.2. Panel Regression Analysis

5.2.1. Endogeneity Tests

The EKC literature has investigated endogeneity problems linking the environmental variables to many covariates. In this paper, we tested the hypothesis of endogeneity among the dependent variable and every regressor included in the models. In particular, endogeneity issues are related to the trade openness of countries and the amount of renewable energy consumption over the total. Intuitively, international trade exchanges are direct pollution sources due to logistics and transportation. However, there could be a reverse causality issue, since more polluting countries or regions may be less attractive for trading agreements and investments. In addition, energy production and consumption influence directly the amount of air pollution, according to their dual composition of sustainable and non-sustainable energy sources. Due to climate change and pollution excess, the growing legislation in defense of the environment has generated an innovative inverse causality-flow, which has increased the global demand for more sustainable and green energy sources and the exploitation of environment-friendly technologies.

To empirically test the endogeneity of the variables reported in Table 3, we performed the Davidson–Mackinnon test [71] by using as instrument for each variable its one-period lag. The Davidson–Mackinnon approach allows testing the null hypothesis of consistency of the OLS estimates for panel data against the alternative hypothesis that the OLS estimator is inconsistent and an instrumental variable technique is more appropriate. The rejection of the null hypothesis would suggest the presence of endogeneity of the considered regressors.

According to the results of the tests summarized in Table 3, the data do not provide enough statistical significance to reject the null hypothesis of exogeneity between the variables, except for *energy use*. Thus, to avoid inconsistency, instrumental variables estimation methods will be considered.

Table 3. Exogeneity test (Davidson–Mackinnon) for each variable.

Variable Name	F-Statistic	*p*-Value
Income per capita	2.474	0.116
Income per capita squared	2.411	0.121
Education	3.664	0.056
Education squared	0.016	0.898
Energy use	7.320	0.007
Trade openness	0.309	0.579

Hypothesis 0. *Exogenous regressor, alternative.*

Hypothesis 1. *Endogenous regressor.*

5.2.2. Unit Root and Cointegration Tests

Given the relevance of the time dimension in our panel, we analyze the stationarity and cointegration conditions of the system. Panel stationarity of each variable and its first difference transformation are investigated using the popular first-generation tests by Levin–Lin–Chu [72] and Im–Pesaran–Shin [73], with a time trend variable included. Empirical results of the panel stationary tests are available in Tables 4 and 5.

Table 4. Im–Pesaran–Shin (2003) panel unit root test results.

Variable Name	Statistic	*p*-Value	Decision
CO_2 per capita	2.136	0.984	Non-stationary
Δ CO_2 per capita	−22.113	0.000	Stationary
Income per capita	3.910	0.999	Non-stationary
Δ Income per capita	−17.338	0.000	Stationary
Income per capita squared	3.848	0.999	Non-stationary
Δ Income per capita squared	−17.627	0.000	Stationary
Education	3.949	0.999	Non-stationary
Δ Education	−3.3663	0.000	Stationary
Education squared	−1.6354	0.0510	Non-stationary
Δ Education squared	−3.0835	0.001	Stationary
Energy use	−0.487	0.313	Non-stationary
Δ Energy use	−22.076	0.000	Stationary
Trade openness	1.1534	0.8756	Stationary
Δ Trade openness	−23.328	0.000	Stationary

Note. All variables are log-transformed. Trend is included. Lag lengths are selected by Akaike Information Criterion (AIC).

Hypothesis 2. *All the panels contain unit roots.*

Hypothesis 3. *Some panels are stationary.*

Table 5. Levin–Lin–Chu (2002) panel unit root test results.

Variable Name	Statistic	*p*-Value	Decision
CO_2 per capita	−0.4400	0.3300	Non-stationary
Δ CO_2 per capita	−17.3616	0.000	Stationary
Income per capita	0.0419	0.5167	Non-stationary
Δ Income per capita	−16.0918	0.000	Stationary
Income per capita squared	0.8433	0.8005	Non-stationary
Δ Income per capita squared	−16.0173	0.000	Stationary
Education	0.2032	0.581	Non-stationary
Δ Education	−3.5700	0.000	Stationary
Education squared	−1.5479	0.0608	Non-stationary
Δ Education squared	−3.1864	0.000	Stationary
Energy use	0.2129	0.5843	Non-stationary
Δ Energy use	−18.934	0.000	Stationary
Trade openness	0.2720	0.607	Stationary
Δ Trade openness	−21.669	0.000	Stationary

Note. All variables are log-transformed. Trend is included. Lag lengths are selected by Akaike Information Criterion (AIC).

Hypothesis 4. *Panels contain unit roots.*

Hypothesis 5. *Panels are stationary.*

Considering the log-levels, CO_2 emissions, per capita income, education level, and energy use are non-stationary, but become stationary when considering their first differences. When a time trend is included in the analysis, both tests confirm that trade openness becomes stationary. While adding just a constant term, the tests do not reject the null hypothesis of unit-root in the panels. The overall picture becomes even more clouded if we use the CIPS test by Pesaran [74], which allows for cross-sectional dependence among different panel units (second-generation test). In this case, trade openness, energy use, and the square of per capita income are non-stationary, while for CO_2 emissions, per capita income, education, and its square, the test does not indicate the presence of unit roots (Table 6).

Table 6. Pesaran's CIPS panel unit root test (2007) in the presence of cross-section dependence.

Variable Name	Statistic	*p*-Value	Decision
CO_2 per capita	−2.865	<0.01	Stationary
Δ CO_2 per capita	−6.420	<0.01	Stationary
Income per capita	−2.595	<0.05	Stationary
Δ Income per capita	−5.872	<0.01	Stationary
Income per capita squared	−2.508	>0.10	Non-stationary
Δ Income per capita squared	−5.768	<0.01	Stationary
Education	−3.534	<0.01	Stationary
Δ Education	−2.410	>0.10	Non-stationary
Education squared	−3.417	<0.01	Stationary
Δ Education squared	−2.546	>0.10	Non-stationary
Energy use	−2.199	>0.10	Non-stationary
Δ Energy use	−5.584	<0.01	Stationary
Trade openness	−2.545	<0.10	Non-stationary
Δ Trade openness	−5.941	<0.01	Stationary

Note. All variables are log-transformed. Constant and trend are included. Lag lengths are selected by Akaike Information Criterion (AIC).

Hypothesis 6. *Homogeneous non-stationary panels.*

Hypothesis 7. *Stationary panels.*

The variability in the performance of the most commonly used panel unit root tests is well-known in the literature [75]. Moreover, their limited adequacy when requested to deal with non-linear transformations of integrated variables, such as squares of per capita income, is acknowledged [16,75,76]. In the light of the mixed evidence provided by those tests and the major aim of this paper, which is to provide further empirical evidence on the economic aspects and implications of the EKC hypothesis, we proceed to the analysis of cointegration, implicitly assuming that the series are integrated of order one, i.e., I(1). We employed the panel cointegration tests proposed by Pedroni [77,78] and Westerlund [79,80]. The results of Pedroni and Westerlund panel cointegration tests are reported in Tables 7–9.

Table 7. Pedroni (1999) panel cointegration test results.

Statistic	Value	*p*-Value	Decision
Panel non par. v (VR)	−0.9327	0.1755	No cointegration
Panel non par. ρ (PP)	−2.9529	0.0016	Cointegration
Panel non par. t (PP)	−6.8828	0.0000	Cointegration
Panel par. t (ADF)	−4.3549	0.0000	Cointegration
Group non par. ρ (PP)	−2.0061	0.0224	Cointegration
Group non par. t (PP)	−6.7938	0.0000	Cointegration
Group par. t (ADF)	−4.5235	0.0000	Cointegration

Note. Constant and trend are included. The test is performed using all the variables, including the quadratic terms of per capita GDP and years of schooling (in total 7 variables). Lag lengths are selected by Akaike Information Criterion (AIC). Cross-sectional means removed.

Hypothesis 8. *No cointegration.*

Hypothesis 9. *Cointegrated panel.*

Table 8. Westerlund (2005) variance-ratio cointegration test results, including quadratic terms.

Statistic	Value	*p*-Value	Decision
VR (some panels)	−2.4811	0.0065	Cointegration
VR (all panels)	−1.7994	0.0360	Cointegration

Note. The test is performed using all the variables, including the quadratic terms of per capita GDP and years of schooling (in total 7 variables). Trend is included.

Hypothesis 10. *No cointegration.*

Hypothesis 11. *Cointegration between some of the cross-sectional units (some panels) or Cointegration between all cross-sectional units (all panels).*

Table 9. Westerlund (2007) error correction based panel cointegration test results, including quadratic terms.

Statistic	Value	*p*-Value	Decision
Gt	−3.654	0.010	Cointegration
Ga	−13.632	0.680	No Cointegration
Pt	−12.814	0.030	Cointegration
Pa	−12.451	0.450	No Cointegration

Note. The test is performed using all the variables, including the quadratic terms of per capita GDP and years of schooling (in total 7 variables). Constant and trend are included. Robust *p*-value. Critical values are bootstrapped with 100 simulations.

Hypothesis 12. *No cointegration.*

Hypothesis 13. *Cointegration between at least one of the cross-sectional units (Gt and Ga) or Cointegration for panel as a whole (Pt and Pa).*

The data do not provide strong statistical evidence of cointegration relationships between the variables. Specifically, all seven Pedroni statistics contradict each other, both at the group and panel level, showing observed values close to the critical ones, while the Westerlund tests suggest the absence of cointegration. While cointegration tests suffer from the same problems of the unit root statistics, especially when non-linear transformations of variables are present [76], nevertheless the Augmented Dickey–Fuller versions of Pedroni's panel and group tests (tests four and seven in Table 7) exhibit a good performance in terms of size and power and are less severely affected by I(2) components and short-run cross-sectional correlation [81]. We have also included a dummy for capturing the structural breaks in the time series due to the 2008–2012 crisis. In this case, the previously cited tests provide minimal changes of *p*-values, without affecting our conclusions.

5.2.3. Estimates for the Full Sample

Both FE and RE models are estimated using the full sample from 1950 to 2015 and including *energy use* as an endogenous covariate. The estimation results are reported in Table 10.

Regarding the EKC model specification, both models provide statistically significant coefficients of per capita income and per capita income squared, and coherence of signs with respect to the expectations. Hence, the data lead to conclusions in favor of the EKC for the selected panel of OECD countries. Estimated turning points (TP) of per capita income for FE model and RE model are respectively TP_{FE} = USD 64,320 per capita and TP_{RE} = USD 55,157. Both values are included within the empirical range of the sample, strengthening the existence of the curve. Even the quadratic relationship between pollution and education is validated. All the related coefficients are statistically significant and respect the expected signs, leading to an inverted-U curve for increasing values of years of schooling. At the aggregate level, the educational turning points using FE and RE are calculated at 4.60 and 5.37 years of schooling, respectively. According to these results, it is possible to infer that data for the selected OECD countries support the empirical evidence of a *Standard EKC* and *Educational EKC*.

Table 10. Fixed and random effects estimation for the full sample.

Variable	Fixed Effects		Random Effects	
Income per capita	7.108	***	7.184	***
	(0.420)		(0.423)	
Income per capita squared	−0.321	***	−0.329	***
	(0.022)		(0.022)	
Education	1.331	***	1.285	***
	(0.120)		(0.120)	
Education squared	−0.436	***	−0.382	***
	(0.048)		(0.047)	
Energy use	−0.120	***	−0.121	***
	(0.008)		(0.007)	
Trade openness	0.012	.	0.027	.
	(0.031)		(0.029)	
Constant	−45.008	***	−45.125	***
	(1.998)		(2.016)	
R^2	0.719			
Observations	1088		1088	
Hausman FE vs. RE stat.		64.250 ***		

Note. Values in parenthesis are standard errors. Stars represent p-values: *** $p < 0.01$, $p > 0.10$.

We recall that we calculated *energy use* as the ratio of renewable energy production over total energy production, given by the sum of both renewable and non-renewable productions of energy. Then, we expect that the estimated coefficient is negative, meaning that an increase in renewable energy production corresponds to a reduction in atmospheric emissions. In both FE and RE estimators, the impact of energy production on CO_2 emissions is estimated with a negative sign and significant coefficients, consistent with expectations. In particular, both models suggest that a percentage increase in energy produced through renewable sources might reduce the CO_2 emissions by 0.12 percentage points. On the contrary, data do not support statistically significant coefficients for trade openness, whose impact is estimated to be positive but close to zero. To identify the more appropriate model specification, we use the Hausman's specification test, which compares the FE and RE estimators under the null hypothesis of uncorrelation between the regressors and error terms. The test statistic is equal to 64.25, providing enough statistical information to reject the null hypothesis and to conclude in favor of the FE estimator.

5.2.4. Estimates for the Grouped Samples

To reinforce the hypothesis of a significant effect of schooling on environmental degradation and to engage the social theme of wealth distribution, we developed a sensitivity analysis by re-estimating the panel regressions with fixed effects for each group identified using the clustering algorithm. As discussed above, the countries were divided into two clusters based on the temporal evolution of income inequality and characterized by widely different values of the Gini Index. Table 11 contains the FE estimates of the parameters for both groups of countries.

Table 11. Fixed effects estimation by income inequality level.

Variable	Low Income Inequality		High Income Inequality	
Income per capita	2.122	***	9.481	***
	(0.799)		(0.599)	
Income per capita squared	−0.041	.	−0.454	***
	(0.040)		(0.031)	
Education	5.530	***	0.596	***
	(1.454)		(0.129)	
Education squared	−1.750	***	−0.146	***
	(0.338)		(0.053)	
Energy use	−0.090	***	−0.130	***
	(0.009)		(0.013)	
Trade openness	−0.125	***	0.145	***
	(0.043)		(0.038)	
Constant	−25.941	***	−55.299	***
	(3.037)		(2.816)	
R^2	0.217		0.892	
Observations	640		448	

Note. Values in parenthesis are standard errors. Stars represent *p*-values: *** $p < 0.01$, $p > 0.10$.

Compared to the overall sample, the two groups differ considerably and present interesting features. The EKC hypothesis holds only for high income inequality countries, while the coefficient associated with the quadratic income term is no more statistically significant in the complementary group. The Educational EKC hypothesis is validated for both clusters, but the educational turning point of the high income inequality group, i.e., $TP_{Edu,High} = 1.002$, does not provide a meaningful economic interpretation. The estimates for both groups of countries show that energy production from renewable sources still plays a crucial role in mitigating airborne pollutant emissions. In both groups, its coefficient is negative and statistically significant. In fact, the estimate of the coefficient of energy use for countries with low income inequality is smaller than in the full sample, moving from −0.12 to −0.09 (a 1% increase in renewable production is associated with a reduction in CO_2 emissions of 0.09%), while for countries with greater levels of inequality the coefficient increases in absolute value to 0.13 (a 1% increase in renewable production is associated with a reduction in CO_2 emissions of 0.13%).

Moreover, trade openness becomes significant, and for each percentage of trade openness, low income inequality countries enjoy a reduction in emissions of 0.125%, hence validating the *pollution haven hypothesis*. On the contrary, high income inequality countries suffer from the opposite effect, namely, a 1% increase in international trade is associates with a 0.145% increase in CO_2 emissions, supporting the *pollution halo hypothesis*. According to these results, the clustering highlighted the presence of different effects of economic development and human capital on environmental quality differentiated by levels of income inequality within the countries.

6. Discussion

The lack of empirical verification of the EKC hypothesis for the set of countries with low levels of inequality and the simultaneous validation of the Educational EKC hypothesis deserve to be further investigated and open a debate on new adoptable functional forms. Moreover, some of those countries represent in empirical studies positive examples for the EKC theory [22,82,83]. The role of education in long-run development is crucial. Investments in strengthening educational systems and facilities, supported by other structural reforms of the labor market, companies, and taxation, can push growth and at the same time reduce the level of social inequality [84]. Countries with low income inequality show a very strong positive linear correlation between GDP and average years of schooling, greater than that observed in countries with higher inequality. Tables 12 and 13 provide the Pearson's correlation coefficients between per capita income, education, and pollution levels grouped by cluster.

Table 12. Linear correlation in low income inequality cluster.

	CO_2 per Capita	Income per Capita	Education
CO_2 per capita	1.000		
Income per capita	0.2683	1.000	
Education	0.2463	0.9008	1.000

Table 13. Linear correlation in high income inequality cluster.

	CO_2 per Capita	Income per Capita	Education
CO_2 per capita	1.000		
Income per capita	0.8606	1.000	
Education	0.8950	0.8306	1.000

In those countries where the level of income inequality is lower, the link between educational level and personal income, measured by their positive linear correlation, seems to be very strong and steady. This empirical evidence is consistent with many studies in the field of development economics that identify schooling and education as determinants of personal income and capital endowment of a country and, therefore, promoters of higher economic growth [32,85]. Furthermore, the linear correlation between per capita income and level of pollutants is very close to the linear correlation between education and pollutants. Both are very low and are symptoms of a non-linear relationship between the variables.

Given these facts, we propose a different specification of the EKC that employs the educational variable, i.e., years of schooling, as the primary driver of environmental degradation instead of personal income. From an econometric perspective, the simultaneous presence of average years of schooling and per capita income among the set of regressors could imply severe multicollinearity issues and generate inconsistent estimates. The new specification is applied to countries with high income inequality and countries with low income inequality. The specification which uses the years of schooling as a regressor is called *Educational EKC*, while the one with the level of income per capita remains the *Standard EKC*. For each group, the estimate of the *Educational EKC* is compared with the *Standard EKC* specification. Estimates for the alternative EKC specification are available in Table 14, which reports the estimated coefficients for the four models.

Considering low income inequality countries, renewable energy use and trade openness have negative signs and similar values in the models, i.e., an increase in renewable energy share of one percent can generate a reduction around 0.086% in pollution (CO_2) levels. In addition, international trade plays a role in emissions reduction: a percentage point increase in trade openness corresponds to a reduction of pollution levels between 0.1% and 0.3%. The estimated turning points for the two models are $TP_{Low,GDP} = 85.523\$$ and $TP_{Low,Edu} = 10.83$ years, respectively. None of the low income inequality countries reached the monetary turning point. The country with greater personal income is Norway, which registered a value of 84,417$ in 2007. On the contrary, the educational turning point is achieved by low income inequality countries: Switzerland (1967), Germany (1978), Norway (1985), Sweden (1989), Denmark (1990), Netherlands (1998), Finland (1999), Austria (2000), Belgium (2012), and France (2013). This fact confirms the robustness of the Educational EKC specification with respect the *Standard EKC* with quadratic terms. In Figure 4, we represent the observed relationship between years of schooling and CO_2 per capita (*Educational EKC*, left panel) and between income per capita and CO_2 per capita (*Standard EKC*, right panel) for low income inequality countries.

Table 14. Fixed effects estimates of Educational EKC and Environmental EKC by income inequality clusters.

Variable	Low Income-Inequality		High Income-Inequality	
	Educational	**Environmental**	**Educational**	**Environmental**
Income per capita		5.383 *** (0.579)		11.587 *** (0.012)
Income per capita squared		−0.237 *** (0.031)		−0.560 *** (0.022)
Education	9.412 *** (1.211)		1.809 *** (0.134)	
Education squared	−1.976 *** (0.276)		−0.228 *** (0.055)	
Energy use	−0.086 *** (0.011)	−0.087 *** (0.010)	−0.202 *** (0.019)	−0.107 *** (0.012)
Trade openness	−0.108 *** (0.049)	−0.277 *** (0.044)	0.357 *** (0.055)	0.149 *** (0.034)
Constant	−16.167 *** (0.416)	−35.406 *** (0.269)	−8.074 *** (0.192631)	−65.008 *** (2.055)
R^2	0.416	0.269	0.815	0.881
Observations	640	640	448	448
Number of groups	10	10	7	7

Note. Values in parenthesis are standard errors. Stars represent p-values: *** $p < 0.01$.

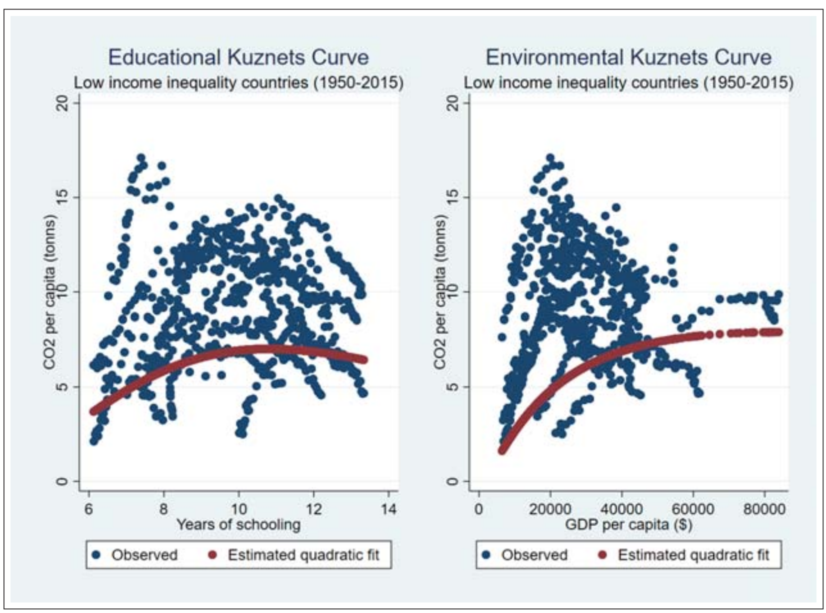


Figure 4. Environmental Kuznets Curve and Educational Kuznets Curve for low income inequality countries (panel fixed-effects estimator). Educational Kuznets Curve for low income inequality countries fitted using FE panel estimator (**left panel**) and Environmental Kuznets Curve for low income inequality countries fitted using FE panel estimator (**right panel**).

Independently from the cluster, all the estimated coefficients are statistically significant and have the expected signs. The *Standard EKC* and the *Educational EKC* are validated in the two samples.

In addition, as shown by the country-by-country plots provided in Appendix A, some countries properly match the inverted-U shape form of the EKC because they follow the same behavior of the aggregate EKC model closely, and other countries exhibit less similarities with the theoretical EKC pattern. In particular, both *Educational EKC* and *Standard EKC* specifications are better performing for the cluster of low income inequality countries. We infer from the graphs that low income inequality countries are more advanced economies and dispose of a large amount of resources to invest into environment-friendly technologies, accelerating the decarbonization process towards a cleaner production, which is less harmful to the environment.

7. Conclusions

The present paper has assessed the relationship between the role of education and income inequality on environmental quality using a panel data approach for 17 selected OECD and European countries, by taking into account the historical evolution of their income inequality pathways. The clustering analysis based on the Gini Index has highlighted structural differences in the paths of the sampled countries. The statistical approach has generated heterogeneous income inequality patterns and has led to different growth impacts on the natural environment. In addition, the variable modeling the role of education has been embedded in the models by augmenting the *Standard EKC* specification with a quadratic term for the average years of schooling. The research findings indicate clear results for the cluster of low income inequality countries and plausible turning points.

We have employed panel data models which provided statistically significant and acceptable estimates of the parameters, suggesting the existence of an inverted-U EKC curve both for the *Standard* and *Educational* specifications. The *Educational EKC* has underlined the non-linearity in the relationship between education and emissions, reflecting the dynamic change in economic and social development. Moreover, this study is not only grounded on statistical methods. Our findings have mainly highlighted the economic aspects and implications of the EKC research design. For this reason, we argue that the type of research methodology makes use of verifiable evidence in order to arrive at research outcomes. In fact, we have provided further evidence on the relationship between education and the environment which has been supported within the EKC framework.

We encourage researchers to replace the *Standard EKC* with an educational-based specification, namely, the *Educational EKC*. Further research should consider the level of schooling and inequality of countries as the main drivers of socio-economic development, along with other relevant variables and pollutant emissions, in the EKC framework.

Author Contributions: Conceptualization, P.M., J.P.C.B. and M.M.; methodology, P.M., J.P.C.B. and M.M.; software, P.M.; validation, P.M., J.P.C.B. and M.M.; formal analysis, P.M., J.P.C.B. and M.M.; investigation, P.M.; resources, P.M.; data curation, P.M.; writing—original draft preparation, P.M.; writing—review and editing, P.M., J.P.C.B. and M.M.; visualization, P.M., J.P.C.B. and M.M.; supervision, J.P.C.B. and M.M.; project administration, P.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data and codes can be requested by email to Paolo Maranzano (paolo.maranzano@unibg.it).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EKC	Environmental Kuznets Curve
Edu_EKC	Educational Environmental Kuznets Curve
TP	Turning point
PWT	Penn World Tables
FE	Fixed-effects model
RE	Random-effects model

Appendix A. Environmental and Educational EKC by Countries and Income Inequality Level

Appendix A.1. Low Income Inequality Countries

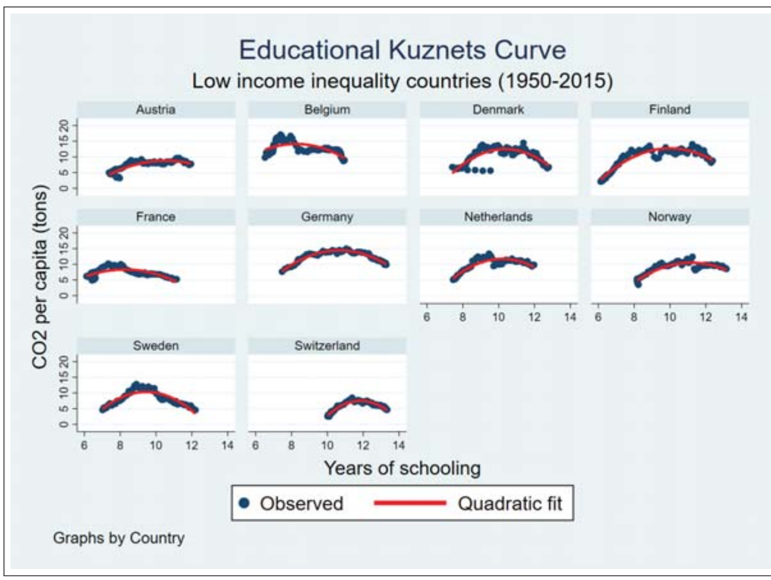


Figure A1. Educational Kuznets Curve for low income inequality countries. Blue points are the observed values, red curves are the quadratic fit for each country. Own elaboration based on our estimation results.

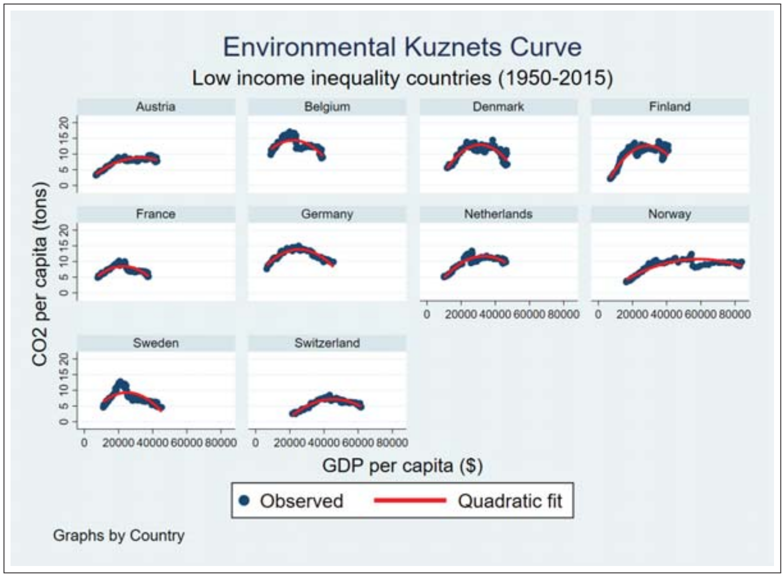


Figure A2. Environmental Kuznets Curve for low income inequality countries. Blue points are the observed values, red curves are the quadratic fit for each country. Own elaboration based on our estimation results.

Appendix A.2. High Income Inequality Countries

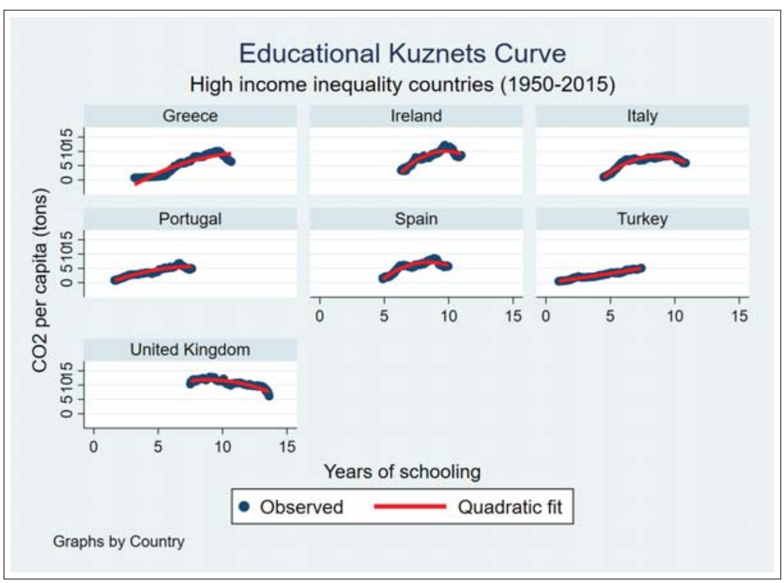


Figure A3. Educational Kuznets Curve for high income inequality countries. Blue points are the observed values, red curves are the quadratic fit for each country. Own elaboration based on our estimation results.

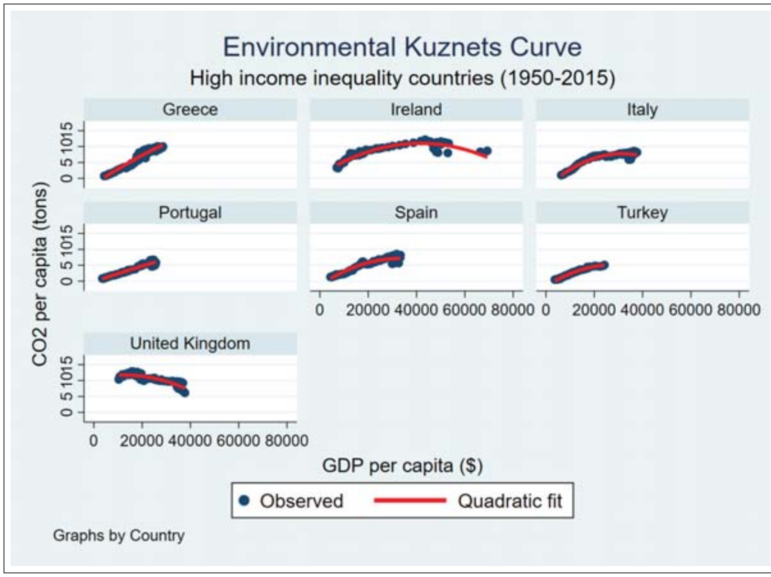


Figure A4. Environmental Kuznets Curve for high income inequality countries. Blue points are the observed values, red curves are the quadratic fit for each country. Own elaboration based on our estimation results.

References

1. Grossman, G.M.; Krueger, A.B. *Environmental Impacts of a North American Free Trade Agreement*; Technical Report; National Bureau of Economic Research: Cambridge, MA, USA, 1991.
2. Stern, D.I. The environmental Kuznets curve after 25 years. *J. Bioecon.* **2017**, *19*, 7–28. [CrossRef]
3. Balaguer, J.; Cantavella, M. The role of education in the Environmental Kuznets Curve. Evidence from Australian data. *Energy Econ.* **2018**, *70*, 289–296. [CrossRef]
4. Sapkota, P.; Bastola, U. Foreign direct investment, income, and environmental pollution in developing countries: Panel data analysis of Latin America. *Energy Econ.* **2017**, *64*, 206–212. [CrossRef]
5. Kuznets, S. Economic Growth and Income Inequality. *Am. Econ. Rev.* **1955**, *45*, 1–28.
6. Grossman, G.M.; Krueger, A.B. Economic Growth and the Environment*. *Q. J. Econ.* **1995**, *110*, 353–377. [CrossRef]
7. Cerdeira Bento, J.P.; Moutinho, V. CO_2 emissions, non-renewable and renewable electricity production, economic growth, and international trade in Italy. *Renew. Sustain. Energy Rev.* **2016**, *55*, 142–155. [CrossRef]
8. Alvarez-Herranz, A.; Balsalobre-Lorente, D.; Shahbaz, M.; Cantos, J.M. Energy innovation and renewable energy consumption in the correction of air pollution levels. *Energy Policy* **2017**, *105*, 386–397. [CrossRef]
9. Coondoo, D.; Dinda, S. Causality between income and emission: A country group-specific econometric analysis. *Ecol. Econ.* **2002**, *40*, 351–367. [CrossRef]
10. Stern, D.I. The rise and fall of the environmental Kuznets curve. *World Dev.* **2004**, *32*, 1419–1439. [CrossRef]
11. Stern, D.I. Progress on the environmental Kuznets curve? *Environ. Dev. Econ.* **2001**, *3*, 173–196. [CrossRef]
12. Gill, A.R.; Viswanathan, K.K.; Hassan, S. A test of environmental Kuznets curve (EKC) for carbon emission and potential of renewable energy to reduce green house gases (GHG) in Malaysia. *Environ. Dev. Sustain.* **2018**, *20*, 1103–1114. [CrossRef]
13. Dinda, S. Environmental Kuznets curve hypothesis: A survey. *Ecol. Econ.* **2004**, *49*, 431–455. [CrossRef]
14. Ekins, P. *Economic Growth and Environmental Sustainability: The Prospects for Green Growth*; Routledge: London, UK, 2002.
15. Wagner, M. The carbon Kuznets curve: A cloudy picture emitted by bad econometrics? *Resour. Energy Econ.* **2008**, *30*, 388–408. [CrossRef]
16. Müller-Fürstenberger, G.; Wagner, M. Exploring the environmental Kuznets hypothesis: Theoretical and econometric problems. *Ecol. Econ.* **2007**, *62*, 648–660. [CrossRef]
17. Hasanov, F.J.; Hunt, L.C.; Mikayilov, J.I. Estimating different order polynomial logarithmic environmental Kuznets curves. *Environ. Sci. Pollut. Res.* **2021**, *28*, 41965–41987. [CrossRef] [PubMed]
18. Feenstra, R.C.; Inklaar, R.; Timmer, M.P. The next generation of the Penn World Table. *Am. Econ. Rev.* **2015**, *105*, 3150–3182. [CrossRef]
19. Solt, F. The standardized world income inequality database. *Soc. Sci. Q.* **2016**, *97*, 1267–1281. [CrossRef]

20. Rasli, A.M.; Qureshi, M.I.; Isah-Chikaji, A.; Zaman, K.; Ahmad, M. New toxics, race to the bottom and revised environmental Kuznets curve: The case of local and global pollutants. *Renew. Sustain. Energy Rev.* **2018**, *81*, 3120–3130. [CrossRef]
21. Al-Mulali, U.; Weng-Wai, C.; Sheau-Ting, L.; Mohammed, A.H. Investigating the environmental Kuznets curve (EKC) hypothesis by utilizing the ecological footprint as an indicator of environmental degradation. *Ecol. Indic.* **2015**, *48*, 315–323. [CrossRef]
22. Iwata, H.; Okada, K.; Samreth, S. Empirical study on the determinants of CO_2 emissions: Evidence from OECD countries. *Appl. Econ.* **2012**, *44*, 3513–3519. [CrossRef]
23. Saboori, B.; Sulaiman, J. Environmental degradation, economic growth and energy consumption: Evidence of the environmental Kuznets curve in Malaysia. *Energy Policy* **2013**, *60*, 892–905. [CrossRef]
24. Galeotti, M.; Manera, M.; Lanza, A. On the Robustness of Robustness Checks of the Environmental Kuznets Curve Hypothesis. *Environ. Resour. Econ.* **2008**, *42*, 551. [CrossRef]
25. Beck, K.A.; Joshi, P. An analysis of the environmental Kuznets curve for carbon dioxide emissions: Evidence for OECD and Non-OECD countries. *Eur. J. Sustain. Dev.* **2015**, *4*, 33.
26. Churchill, S.A.; Inekwe, J.; Ivanovski, K.; Smyth, R. The environmental Kuznets curve in the OECD: 1870–2014. *Energy Econ.* **2018**, *75*, 389–399. [CrossRef]
27. Leal, P.H.; Marques, A.C. Rediscovering the EKC hypothesis for the 20 highest CO_2 emitters among OECD countries by level of globalization. *Int. Econ.* **2020**, *167*, 36–47. [CrossRef]
28. Ehrhardt-Martinez, K.; Crenshaw, E.M.; Jenkins, J.C. Deforestation and the environmental Kuznets curve: A cross-national investigation of intervening mechanisms. *Soc. Sci. Q.* **2002**, *83*, 226–243. [CrossRef]
29. Magnani, E. The Environmental Kuznets Curve, environmental protection policy and income distribution. *Ecol. Econ.* **2000**, *32*, 431–443. [CrossRef]
30. Sala-i Martin, X.X.; Barro, R.J. *Technological Diffusion, Convergence, and Growth*; Report, Center Discussion Paper; Center Discussion Paper No. 735; Yale University, Economic Growth Center: New Haven, CT, USA, 1995.
31. Barro, R.J. Human Capital and Growth in Cross-Country Regressions. Ph.D. Thesis, Harvard University, Cambridge, MA, USA, 1998.
32. Barro, R.J. Human capital and growth. *Am. Econ. Rev.* **2001**, *91*, 12–17. [CrossRef]
33. Benhabib, J.; Spiegel, M.M. The role of human capital in economic development evidence from aggregate cross-country data. *J. Monet. Econ.* **1994**, *34*, 143–173. [CrossRef]
34. Gundlach, E. The role of human capital in economic growth: New results and alternative interpretations. *Weltwirtschaftliches Arch.* **1995**, *131*, 383–402. [CrossRef]
35. Islam, N. Growth Empirics: A Panel Data Approach*. *Q. J. Econ.* **1995**, *110*, 1127–1170. [CrossRef]
36. Krueger, A.B.; Lindahl, M. Education for growth: Why and for whom? *J. Econ. Lit.* **2001**, *39*, 1101–1136. [CrossRef]
37. O'neill, D. Education and income growth: Implications for cross-country inequality. *J. Political Econ.* **1995**, *103*, 1289–1301. [CrossRef]
38. Temple, J.R. Generalizations that aren't? Evidence on education and growth. *Eur. Econ. Rev.* **2001**, *45*, 905–918. [CrossRef]
39. Pata, U.K. Renewable energy consumption, urbanization, financial development, income and CO_2 emissions in Turkey: Testing EKC hypothesis with structural breaks. *J. Clean. Prod.* **2018**, *187*, 770–779. [CrossRef]
40. Zhang, B.; Wang, B.; Wang, Z. Role of renewable energy and non-renewable energy consumption on EKC: Evidence from Pakistan. *J. Clean. Prod.* **2017**, *156*, 855–864. [CrossRef]
41. Usman, O.; Iorember, P.T.; Olanipekun, I.O. Revisiting the environmental Kuznets curve (EKC) hypothesis in India: The effects of energy consumption and democracy. *Environ. Sci. Pollut. Res.* **2019**, *26*, 13390–13400. [CrossRef]
42. Shahbaz, M.; Mutascu, M.; Azim, P. Environmental Kuznets curve in Romania and the role of energy consumption. *Renew. Sustain. Energy Rev.* **2013**, *18*, 165–173. [CrossRef]
43. Dogan, E.; Turkekul, B. CO_2 emissions, real output, energy consumption, trade, urbanization and financial development: Testing the EKC hypothesis for the USA. *Environ. Sci. Pollut. Res.* **2016**, *23*, 1203–1213. [CrossRef]
44. Jaforullah, M.; King, A. The econometric consequences of an energy consumption variable in a model of CO_2 emissions. *Energy Econ.* **2017**, *63*, 84–91. [CrossRef]
45. Ang, J.B. CO_2 emissions, energy consumption, and output in France. *Energy Policy* **2007**, *35*, 4772–4778. [CrossRef]
46. Apergis, N.; Payne, J.E. Renewable Energy, Output, Carbon Dioxide Emissions, and Oil Prices: Evidence from South America. *Energy Sources Part Econ. Plan. Policy* **2015**, *10*, 281–287. [CrossRef]
47. Dogan, E.; Seker, F. Determinants of CO_2 emissions in the European Union: The role of renewable and non-renewable energy. *Renew. Energy* **2016**, *94*, 429–439. [CrossRef]
48. Zambrano-Monserrate, M.A.; Silva-Zambrano, C.A.; Davalos-Penafiel, J.L.; Zambrano-Monserrate, A.; Ruano, M.A. Testing environmental Kuznets curve hypothesis in Peru: The role of renewable electricity, petroleum and dry natural gas. *Renew. Sustain. Energy Rev.* **2018**, *82*, 4170–4178. [CrossRef]
49. Esmaeili, A.; Abdollahzadeh, N. Oil exploitation and the environmental Kuznets curve. *Energy Policy* **2009**, *37*, 371–374. [CrossRef]
50. Burnett, J.W.; Bergstrom, J.C.; Wetzstein, M.E. Carbon dioxide emissions and economic growth in the U.S. *J. Policy Model.* **2013**, *35*, 1014–1028. [CrossRef]
51. Itkonen, J.V. Problems estimating the carbon Kuznets curve. *Energy* **2012**, *39*, 274–280. [CrossRef]

52. Jebli, M.B.; Youssef, S.B.; Ozturk, I. Testing environmental Kuznets curve hypothesis: The role of renewable and non-renewable energy consumption and trade in OECD countries. *Ecol. Indic.* **2016**, *60*, 824–831. [CrossRef]
53. Acemoglu, D.; Autor, D. What Does Human Capital Do? A Review of Goldin and Katz's The Race between Education and Technology. *J. Econ. Lit.* **2012**, *50*, 426–463. [CrossRef]
54. Acemoglu, D.; Gallego, F.A.; Robinson, J.A. Institutions, Human Capital, and Development. *Annu. Rev. Econ.* **2014**, *6*, 875–912. [CrossRef]
55. Atkinson, A.B. On the measurement of inequality. *J. Econ. Theory* **1970**, *2*, 244–263. [CrossRef]
56. De Maio, F.G. Income inequality measures. *J. Epidemiol. Community Health* **2007**, *61*, 849–852. [CrossRef] [PubMed]
57. Gini, C. Measurement of inequality of incomes. *Econ. J.* **1921**, *31*, 124–126. [CrossRef]
58. Pontusson, J.; Weisstanner, D. Macroeconomic conditions, inequality shocks and the politics of redistribution, 1990–2013. *J. Eur. Public Policy* **2018**, *25*, 31–58. [CrossRef]
59. Hao, Y.; Chen, H.; Zhang, Q. Will income inequality affect environmental quality? Analysis based on China's provincial panel data. *Ecol. Indic.* **2016**, *67*, 533–542. [CrossRef]
60. Heerink, N.; Mulatu, A.; Bulte, E. Income inequality and the environment: Aggregation bias in environmental Kuznets curves. *Ecol. Econ.* **2001**, *38*, 359–367. [CrossRef]
61. Ridzuan, S. Inequality and the environmental Kuznets curve. *J. Clean. Prod.* **2019**, *228*, 1472–1481. [CrossRef]
62. Vona, F.; Patriarca, F. Income inequality and the development of environmental technologies. *Ecol. Econ.* **2011**, *70*, 2201–2213. [CrossRef]
63. Akan, M.O.A.; Selam, A.A. Assessment of social sustainability using Social Society Index: A clustering application. *Eur. J. Sustain. Dev.* **2018**, *7*, 412–424. [CrossRef]
64. Luzzati, T.; Gucciardi, G. A non-simplistic approach to composite indicators and rankings: An illustration by comparing the sustainability of the EU Countries. *Ecol. Econ.* **2015**, *113*, 25–38. [CrossRef]
65. Neri, L.; D'Agostino, A.; Regoli, A.; Pulselli, F.M.; Coscieme, L. Evaluating dynamics of national economies through cluster analysis within the input-state-output sustainability framework. *Ecol. Indic.* **2017**, *72*, 77–90. [CrossRef]
66. Baltagi, B. *Econometric Analysis of Panel Data*; John Wiley & Sons: New York, NY, USA, 2008.
67. Hausman, J.A. Specification tests in econometrics. *Econom. J. Econom. Soc.* **1978**, *46*, 1251–1271. [CrossRef]
68. Hausman, J.A.; Taylor, W.E. A generalized specification test. *Econ. Lett.* **1981**, *8*, 239–245. [CrossRef]
69. StataCorp. *Stata Release 16*; StataCorp: College Station, TX, USA, 2017.
70. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2020.
71. Davidson, R.; MacKinnon, J.G. *Estimation and Inference in Econometrics*; Oxford University Press: Oxford, UK, 1993.
72. Levin, A.; Lin, C.F.; Chu, C.S.J. Unit root tests in panel data: Asymptotic and finite-sample properties. *J. Econom.* **2002**, *108*, 1–24. [CrossRef]
73. Im, K.S.; Pesaran, M.H.; Shin, Y. Testing for unit roots in heterogeneous panels. *J. Econom.* **2003**, *115*, 53–74. [CrossRef]
74. Pesaran, M.H. A simple panel unit root test in the presence of cross-section dependence. *J. Appl. Econom.* **2007**, *22*, 265–312. [CrossRef]
75. Hlouskova, J.; Wagner, M. The Performance of Panel Unit Root and Stationarity Tests: Results from a Large Scale Simulation Study. *Econom. Rev.* **2006**, *25*, 85–116. [CrossRef]
76. Hong, S.H.; Wagner, M. *Nonlinear Cointegration Analysis and the Environmental Kuznets Curve*; Report; Institute for Advanced Studies (IHS): Vienna, Austria, 2008.
77. Pedroni, P. Critical values for cointegration tests in heterogeneous panels with multiple regressors. *Oxf. Bull. Econ. Stat.* **1999**, *61*, 653–670. [CrossRef]
78. Pedroni, P. Purchasing power parity tests in cointegrated panels. *Rev. Econ. Stat.* **2001**, *83*, 727–731. [CrossRef]
79. Westerlund, J. New simple tests for panel cointegration. *Econom. Rev.* **2005**, *24*, 297–316. [CrossRef]
80. Westerlund, J. Testing for error correction in panel data. *Oxf. Bull. Econ. Stat.* **2007**, *69*, 709–748. [CrossRef]
81. Wagner, M.; Hlouskova, J. The Performance of Panel Cointegration Methods: Results from a Large Scale Simulation Study. *Econom. Rev.* **2009**, *29*, 182–223. [CrossRef]
82. Acaravci, A.; Ozturk, I. On the relationship between energy consumption, CO_2 emissions and economic growth in Europe. *Energy* **2010**, *35*, 5412–5420. [CrossRef]
83. Al-Mulali, U.; Ozturk, I. The investigation of environmental Kuznets curve hypothesis in the advanced economies: The role of energy prices. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1622–1631. [CrossRef]
84. Stiglitz, J.E. Inequality and economic growth. In *Rethinking Capitalism*; Wiley-Blackwell: Hoboken, NJ, USA, 2016; pp. 134–155.
85. Castelló, A.; Doménech, R. Human capital inequality and economic growth: Some new evidence. *Econ. J.* **2002**, *112*, C187–C200. [CrossRef]

sustainability

MDPI

Article

Estimating Long-Run Relationship between Renewable Energy Use and CO_2 Emissions: A Radial Basis Function Neural Network (RBFNN) Approach

Pradyot Ranjan Jena [1,*], Babita Majhi [2] and Ritanjali Majhi [1]

[1] School of Management, National Institute of Technology Karnataka, Surathkal, Mangalore 575025, India; ritanjali@nitk.edu.in
[2] Department of CSIT, Guru Ghasidas Vishwavidyalaya (Central University), Bilaspur 495009, India; babita.majhi@gmail.com
* Correspondence: pradyotjena@nitk.edu.in; Tel.: +91-824-247-3237

Abstract: The long-run relationship between economic growth and environmental quality has been estimated within the framework of the environmental Kuznets Curve (EKC). Several studies have estimated this relationship by using statistical models such as panel regression and time series regression. The current study argues that there is a nonlinear relationship between environmental quality indicators and economic and non-economic predictors and hence an appropriate nonlinear model is required to predict it. An adaptive and nonlinear model, namely radial basis function neural network (RBFNN) has been developed in this study. CO_2 emission is used as the target output and renewable energy consumption share, real GDP, trade openness, urban population ratio, and democracy index are used as the predictors to estimate the EKC relationship for nineteen major CO_2 emitting countries that account for 78% of the global emissions. The model developed in this study could predict the CO_2 emissions of all the countries with more than 95% accuracy. This finding underlines the usefulness of the RBFNN model which can be used to predict emission levels of other pollution indicators at the global level. Further, comparing two models, one with all the predictors and the other excluding the renewable energy share, it was found that the model with renewable energy share predicts CO_2 emissions more accurately. This reinforces the already strengthening campaign to encourage industries and governments to increase the share of renewable energy in total energy use.

Keywords: EKC estimation; CO_2 emissions prediction; neural networks; radial basis function neural network; renewable energy consumption

Citation: Jena, P.R.; Majhi, B.; Majhi, R. Estimating Long-Run Relationship between Renewable Energy Use and CO_2 Emissions: A Radial Basis Function Neural Network (RBFNN) Approach. *Sustainability* **2022**, *14*, 5260. https://doi.org/10.3390/su14095260

Academic Editor: Bertrand Hamaide

Received: 19 March 2022
Accepted: 15 April 2022
Published: 27 April 2022

1. Introduction

The likely impacts of economic growth on environmental degradation have been analyzed and examined by economists for decades now but there is still no consensus on how different predictors such as trade openness and energy consumption affect environmental degradation [1]. Recent studies have highlighted the contribution of non-economic factors such as democracy in determining the environmental quality of a country [2,3]. A lack of consensus can be attributed to the countries studied, the period chosen, the choice of explanatory variables, and the methodologies used. The pioneering studies by the early researchers such as Grossman and Krueger [4,5], Shafik and Bandyopadhyay [6], and Selden and Song [7], have been continued with significant contributions by the later researchers over the years and produced a large number of empirical studies, which has popularly come to be known as "environmental Kuznets curve" (EKC). An inverted U-shaped EKC hypothesis states that as a country's economy develops, environmental pollution increases initially and then begins to decline until it reaches a certain income level threshold. Once a certain (threshold) income level is attained, this results in an environmental improvement [5,8,9]. Antweiler et al. [10] broke down the influence of international trade on the environment into three distinct effects: scale, composition, and technique, and then summed them together to calculate the overall impact of free trade on environmental quality. Later, Managi et al. [11], Tsurumi and Managi [12,13], Kagohashi et al. [14], and Abe et al. [15] produced more realistic results in the EKC relationship by treating income and trade openness as endogenous variables.

Although numerous studies produce different estimates of EKC, there is still a common shortcoming in these studies. The methods used are either time-series causality and cointegration tests or panel regressions and panel cointegration regressions. These methods typically estimate a single constant parameter for the relationship for the entire sample period. Even though some prominent research takes into account structural breaks in their estimated EKC relationship, they still produce constant estimates of the effect of economic growth on indicators of environmental quality over the entire predicted period [16]. We argue that there is a potential nonlinear relationship between air pollution and its economic predictors such as GDP per capita, renewable energy consumption, and trade openness over a period of time. If the apparent nonlinearities existing in this relationship are explicitly modeled, more accurate predictions can be made. This is the major contribution of this study to the EKC literature. We develop a nonlinear dynamic neural network model, namely the radial basis function neural network (RBFNN) model to predict the CO_2 emissions of 19 countries based on the economic factors such as real GDP (constant US$), renewable energy share in total energy use, and trade openness measured by export and import ratio to GDP and non-economic factors such as democracy status of a country and urban population ratio. In the RBFNN model, the predictors (inputs) are passed through a Gaussian function to receive information from each other through nodes (neurons) that enhance their prediction ability. The adjoining weights are continuously adjusted by the adaptive error learning process and the final output (CO_2 emission) is produced.

The other major contribution of this study is to highlight the effect of renewable energy consumption on the emission path of CO_2. Though several studies have used this variable in EKC estimation as detailed in Section 2, none of them have measured the accuracy of their estimations. These studies in the linear statistical framework estimated a single constant parameter for renewable energy's effect on environmental quality indicators. But whether these estimates could reliably predict the CO_2 emission path for the entire sample period they used is questionable. Unless, the studies compared the similarity between the predicted and actual level of emissions based on their estimated parameters and found a higher level of similarity, the validity of the estimates is doubtful. On this premise, we compared the predictive accuracy of our model by comparing the actual and predicted figures of CO_2 using the mean absolute percentage error (MAPE) values and found a very small error percentage. Furthermore, we used two specifications to predict CO_2 emissions for all countries. In the first specification, all the inputs except for renewable energy share are used as inputs and in the second, the latter is added to the list of inputs. Then, we compared the MAPE of the two specifications and found out that the MAPE of the specification in which renewable energy is used is much smaller for most countries compared to the one in which it is not used. This comparison of model predictions validates the contribution of renewable energy in reducing CO_2 emissions beyond a reasonable doubt.

We have used only one environmental indicator in this study i.e., CO_2 emission as this is considered the biggest contributor to climate change and has been given special attention in the reports of the Intergovernmental Panel on Climate Change (IPCC).

Finally, the democratic status of a country has been used as a non-economic factor in the non-linear neural network model. Only a very few studies have used this indicator to determine the shape of the EKC but they used it in the linear regression framework [2,3]. The nineteen countries selected for this study are the major emitters of CO_2. Eleven of these countries emit either 2% or more of the total global emissions and the rest eight countries emit 1%. They together account for 78% of the global CO_2 emissions. The details of the variables used and the source of the data are provided in Section 3. The RBFNN model is explained in Section 4. The simulation procedure is described in Section 5 and the results are interpreted in Section 6. Finally, Section 7 concludes with policy implications.

2. Literature Review

In recent years, the role of renewable energy consumption in the EKC relationship has been examined by various authors and the relationship between renewable energy and CO_2 emissions was found to be less clear-cut. While Sugiawan and Managi [17], Sinha and Shahbaz [18], Liu et al. [19], and Apergis et al. [20] claim that increasing renewable energy consumption will result in a long-run reduction in CO_2 emissions, other studies such as Adams and Nsiah [21], Saidi and Omri [22] found that renewable energy increases CO_2 emission in some countries while reducing in some others. A few other studies such as Menyah and Wolde-Rufael [23], Sinha et al. [24], and Tanti et al. [25] have found no significant long-term relationship between renewable energy consumption and CO_2 emission. Liu [26] while reviewing China's renewable energy law and policy observed several hindrances to higher use of renewable energy, such as problems with fragmentation, obsolescence, and lack of operability. Chen et al. [27] examined the possibility of an EKC relationship using provincial data in China spanning a period from 1995 to 2012. Their results show a heterogenous effect wherein there is no evidence of an inverted U-shaped relationship in the central and western regions but was observed in the eastern region.

Bilgili et al. [28] using a dataset for a period spanning 2003–2018 on a set of developed countries, discovered an EKC relationship only for higher CO_2 emitting countries. The N-shaped nexus, on the other hand, is more prevalent in countries with lower carbon emissions. They also discovered that research and development in energy efficiency is more effective at reducing carbon emissions than research and development in fossil fuels and renewable energy sources combined. Gyamfi et al. [29] by using data from 1995 to 2018, found no evidence of an N-shaped EKC in the countries under study; instead, they found an inverted U-shaped EKC relationship. They recommended that the usage of renewable energy be increased to reduce pollution emissions in these countries. Kirikkaleli and Adebayo [30] based on data for the period 1990–2015 and different time series econometric models found a long-run relationship between CO_2 emissions and their probable drivers. They discovered that long-term public-private partnership investment in energy has a favorable impact on CO_2 emissions. Yang et al. [31] using a dataset of manufacturing industries from 38 countries observed that increased consumption of renewable energy has resulted in modifications in the relationship between manufacturing growth and CO_2 emissions. Using data from the BRICS economies over a period from 1980 to 2016, Khattak et al. [32] examined the role of technological innovation and renewable energy use in the CO_2 emissions growth path. They discovered that except for Brazil, innovative efforts failed to reduce CO_2 emissions in China, India, Russia, and South Africa. They also demonstrated that except for South Africa, the increase in renewable energy use has helped reduce CO_2 emissions in the BRICS panel.

Using data from 31 provinces of China between 2007 and 2017, Zeraibi et al. [33] found that government expenditure has a positive effect on environmental quality in China. Chen et al. [34] using the panel data from China from 1980 to 2014, found a long-run relationship between per capita CO_2 emissions and the economic predictors. They discovered that economic growth, non-renewable energy generation, and international trade do not show an EKC relationship with CO_2 emissions but the inclusion of renewable energy production in the inputs confirmed the U-shaped EKC hypothesis. Khan et al. [35] using data from 34 high-income countries over the period 1995–2017 show a reciprocal relationship between GHG emissions and renewable energy in 22 countries. Yao et al. [36] using a dataset of 17 developing and developed countries spanning a period from 1990 to 2014, found the existence of both the EKC and renewable energy Kuznets Curve (RKC) hypotheses. They showed that a 10% increase in renewable energy consumption rate led to a reduction in carbon emissions by 1.6%.

Zeraibi et al. [37] used the levels of government expenditure as fiscal and broad money supply as monetary policy instruments to predict CO_2 emissions. Their findings reveal that expansionary fiscal policy led to an increase in CO_2 emissions whereas expansionary monetary policy decreased it in both the short- and long-run in China. They could not find evidence for the EKC hypothesis, rather the relationship between economic growth and carbon emissions was N-shaped. A carbon emission function was used by Balsalobre-Lorente et al. [38] to examine an EKC relationship between economic growth and CO_2 emissions in five European Union countries for the period 1985 to 2016. In the EU-5 countries, they discovered an N-shaped association between economic growth and CO_2 emissions. Furthermore, they discovered that the use of renewable electricity, the use of natural resources, and the use of innovative energy technologies all contribute to improved environmental quality. Using panel data from G20 countries, it has been shown by Paramati et al. [39] that FDI inflows reduce CO_2 emissions both in developed and developing economies, but stock market expansion slows in developed economies. They also discovered that the use of renewable energy significantly cuts CO_2 emissions while simultaneously increasing economic production across the countries represented in their panels. After conducting research on 30 nations over the period 2000 to 2013, Kim and Park [40] concluded that developing the financial sector in a country can aid in the deployment of more renewable energy, which in turn can assist reduce CO_2 emissions.

Apart from the economic factors, the environmental quality may also be affected by the non-economic factors such as the political institutions that are involved in the process of environmental policymaking in a country [41]. Several environmental problems, according to Romuald [42], can be attributed to institutional failure and ineffective government practices and policies. Goel et al. [43] claim that numerous measures have been enacted to compel economic agents to internalize environmental externalities (directly or indirectly). A critical aspect in the success of these initiatives is a country's institutional quality. Within this body of literature, some scholars have concentrated on the democracy–pollution nexus, while others have evaluated the effect of political freedom on pollution.

A few studies have taken into account political variables that are related to the income–pollution relationship [44,45]. The findings are mixed when examined empirically. According to the findings of the studies by Torras and Boyce [45], Barrett and Graddy [44], Li and Reuveny [46], and Farzin and Bond [47], democratization results in citizens being better informed and better equipped to demonstrate their dissatisfaction with government. Torras and Boyce [45] discovered that democracy had a favorable and statistically significant impact on environmental quality in general, and particularly in low-income nations. Farzin and Bond [47] discover evidence suggesting a country's level of democracy and the liberties that come with it are positively related to the condition of the environment. Several academics, on the other hand, believe that democracy may not improve or even deteriorate environmental quality [48–50]). Roberts and Parks [49], for example, conclude that democracy does not affect carbon emissions. In addition, Scruggs [50] finds that when wealth disparity is taken into account, there is no significant association between democracy level and three environmental indicators (dissolved oxygen demand, fecal coliform, and particle emissions). Midlarsky [48], on the other hand, indicates that a higher level of democracy is connected with a worse environmental performance in a country.

3. Materials

The International Energy Agency (IEA, Paris, France) has compiled data on carbon dioxide (CO_2) emissions from the combustion of natural gas, coal, oil, and other fuels, as well as emissions from industrial waste and nonrenewable municipal waste. This data has been used to select 19 countries based on their emission intensity as shown in Table 1. The website from which the emission shares are reproduced is "Each Country's Share of CO_2 Emissions | Union of Concerned Scientists (ucsusa.org)". The top emitting countries whose share is more than 2% of the global emission are China, U.S., India, Russia, Japan, Iran, South Korea, Saudi Arabia, Indonesia, Germany, and Canada. The rest eight countries considered in this study have a share of 1%.

Table 1. Fossil CO_2 emissions share and the absolute values of CO_2 emissions for selected countries.

Sl. No.	Emission Share of Selected Countries
1	China (28%)
2	U.S. (15%)
3	India (7%)
4	Russia (5%)
5	Japan (3%)
6	Iran (2%)
7	South Korea (2%)
8	Saudi Arabia (2%)
9	Indonesia (2%)
10	Germany (2%)
11	Canada (2%)
12	Brazil (1%)
13	South Africa (1%)
14	Mexico (1%)
15	Turkey (1%)
16	Australia (1%)
17	United Kingdom (1%)
18	Italy (1%)
19	France (1%)

The data on the predicted variable i.e., CO_2 emissions, and the predictors such as GDP in constant US$ measured in 2010, renewable energy share in total energy use, the urban population as a percentage of the total population, and trade openness for all 19 countries are drawn from the World Bank database for the period 1960 to 2019. The data for another predictor i.e., democracy is obtained from the database of Freedom House, which is an independent watchdog organization based in the USA. It collects and publishes data on the political rights (PR) and civil liberties (CL) of most countries of the world. The democracy index used in this study is constructed by adding the scores of PR and CL of the nineteen countries. The description of output and input variables and the data sources are provided in Table 2. The data files are available in the Supplementary Materials section of this article.

Table 2. Variable description and data source.

Variables	Data Source
Carbon dioxide emissions (mega ton)	World Development Indicators [51]
Renewable energy share in total energy use (%)	World Development Indicators [51]
GDP (constant 2005 US$)	World Development Indicators [51]
Urban Population Ratio	World Development Indicators [51]
Trade openness (ratio of imports plus exports to GDP	World Development Indicators [51]
Sum of the Freedom House Political Rights and Civil Liberties Indices	Freedom House [52]

Notes: All the data are annually from 1960 to 2019. Freedom in the World | Freedom House. http://data.worldbank.org/indicator. Accessed on 2 February 2022.

The compound annual growth rate (CAGR) of CO_2 emissions of the 19 countries between 1990 and 2019 is shown in Figure 1. The countries that experienced higher levels of CO_2 emissions during this period are China, India, Saudi Arabia, Iran, Turkey, and Brazil with 6.7%, 6.2%, 4.8%, 5.3%, 4.6%, and 3.2% respectively. On the other hand, the UK with −1.8%, Italy with −0.9%, France with −0.58%, the USA with 0.11%, Japan with 0.05%, and Canada with 1.3% are the countries that have managed a low emission growth path. The trends in Figure 1 indicate the existence of an EKC relationship as the CO_2 emissions have declined in developed countries and increased in highly developing countries.

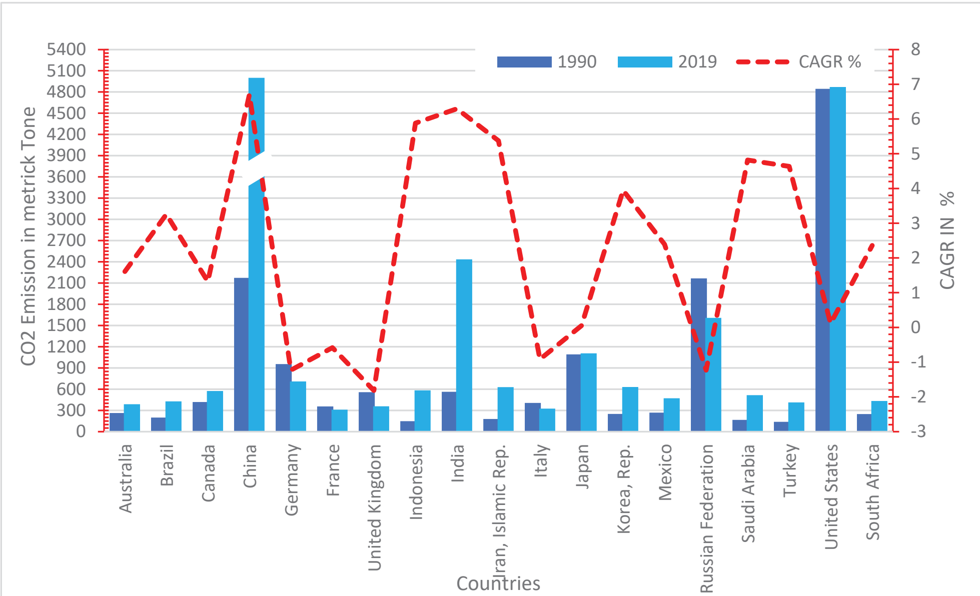


Figure 1. The growth rate of CO_2 emission (mt).

4. Development of Radial Basis Function Neural Network (RBFNN) Based CO_2 Prediction Model

Artificial neural networks (ANN) are nonlinear models having a lot of real-life applications. There are different types of architecture available under ANN such as feed-forward networks, and feedback networks which might be single layer or multilayer. Depending upon the nonlinearity associated with the problem the network is chosen judiciously. The RBFNN is a simple single hidden layer feed-forward network trained by a supervised learning algorithm [53]. The hidden layer nodes also known as centers use radial basis functions (RBF) or Gaussian functions. The nonlinear mapping of the data from the input to the output layer is done as it passes through the RBF or Gaussian functions. Mathematically, the RBF calculates the Euclidean distance between the input data and the nodes or centers present in the hidden layer. The weighted sum of the output of RBF nodes is considered the final output of the network.

The advantages of the RBFNN model in the prediction process are as follows:

(1) Training is faster in RBFNN as it involves a smaller number of computations. Hence it gives faster convergence.
(2) The function of each hidden node can be easily interpreted in RBFNN.
(3) There is no requirement to decide apriori the number of hidden layers in RBFNN, which is needed in some other models.

Taking into consideration the above advantages, the RBFNN model is used for the development of CO_2 emission prediction which is an optimization problem.

The block diagram of RBFNN based prediction model is shown in Figure 2. Each node in the hidden layer is an RBF or Gaussian function having a center and width. Let the centers and corresponding widths associated with h number of nodes in the hidden layer be represented as $c = c_1, c_2, c_3 \ldots c_h$ and $\sigma = \sigma_1, \sigma_2, \sigma_3 \ldots \sigma_h$ respectively. The same input $(x = x_1, x_2, x_3 \ldots x_n)$ is given to all the nodes of the hidden layer. The dimension of centers of every hidden node and the input data are the same, i.e., $c_i \in R^n, x \in R^n$. The output of each hidden node $(\phi_1, \phi_2, \phi_3 \ldots \phi_h)$ is multiplied by the weight values $(w_1, w_2, w_3 \ldots w_h)$ respectively to produce the final output of the network.

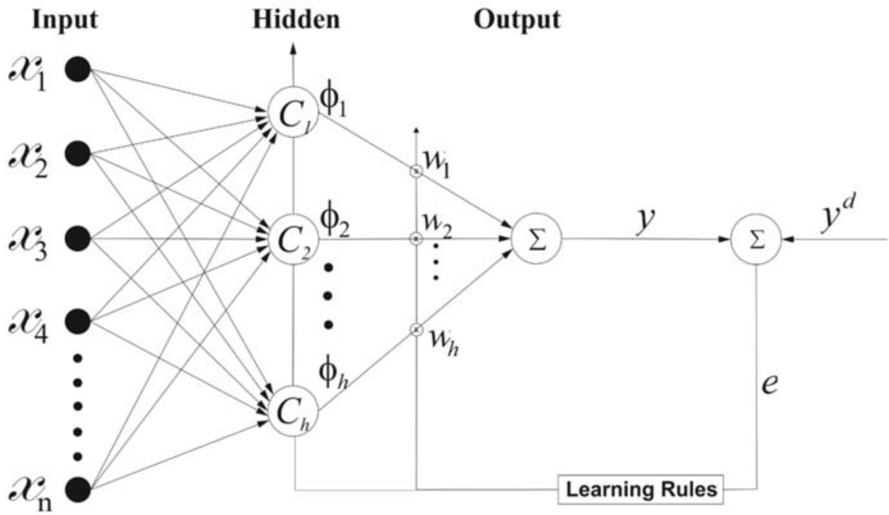


Figure 2. A schematic diagram of RBFNN based CO_2 prediction model with n number of inputs.

The output of *i*th hidden node ϕ_i is represented as

$$\phi_i(z) = e^{\frac{-z^2}{2\sigma_i^2}} \tag{1}$$

where, $z = ||x - c_i||$, denotes the Euclidean distance between input data and the corresponding centers and $\phi_i = \phi(||x - c_i||$. The final response of the RBFNN for a particular input is calculated as

$$y = \sum_{i=1}^{h} w_i \phi_i \tag{2}$$

Training of the RBFNN model is carried out iteratively for each training data, $\{x,\ y\}$. During this learning period the model parameters such as the weights, centers, and width values, $\{w_i,\ c_i,\ \sigma_i\}$ are updated until the error cost function is minimized. The error cost function e is given as

$$e = \frac{1}{2}\left(y^d - y\right)^2 \tag{3}$$

At any time instant t, the parameter update rules to change $\{w_i,\ c_i,\ \sigma_i\}$ are given below. The update rules are derived using the gradient descent algorithm.

$$w_i(t+1) = w_i(t) + \eta_1\left(y^d - y\right)\phi_i \tag{4}$$

$$c_{ij}(t+1) = c_{ij}(t) + \frac{\eta_2}{\sigma_i^2}\left(y^d - y\right)w_i\phi_i\left(x_j - c_{ij}\right) \tag{5}$$

$$\sigma_i(t+1) = \sigma_i(t) + \frac{\eta_3}{\sigma_i^3}\left(y^d - y\right)w_i\phi_i {z_i}^2 \tag{6}$$

where, y^d = desired or target value. In this case, it is the CO_2 emission value.

c_{ij} = *j*th element of *i*th center.

$\eta_1,\ \eta_2,\ \eta_3$ = learning rate for network parameters, $\{w_i,\ c_i,\ \sigma_i\}$ respectively.

5. Simulation Study

The simulation procedure explains the steps that are carried out during the development of the RBFNN based CO_2 emission prediction model. The three main steps involved in it are data preprocessing, training, and testing of the model.

5.1. Data Preprocessing

The data is collected from 19 different countries from 1960 to 2019. The EKC relationship is estimated using the CO_2 emissions as a parameter for environmental quality, renewable energy share in total energy used, the urban population as a percentage of the total population, real GDP, trade openness, and political freedom as the predictors of CO_2 emissions. The main objective of this study is to predict the CO_2 emission levels of major emitting countries based on the key predictors and to highlight the role of renewable energy in predicting CO_2 emission. For the second objective, we have used two specifications of the model. In the first specification, renewable energy share is excluded (partial model) and in the second all the predictors are used (full model). The purpose is to compare the predictive performance of the full model against the partial model. The hypothesis here is that the performance of the full model will be higher than the partial model, which would entail renewable energy as the major predictor of CO_2 emission. In the RBFNN model developed in the study, CO_2 emission is taken as the target output and the predictor variables as the inputs. The data for the target and input variables are normalized before they are used to develop the model. Normalization of the data is done by dividing each value of each column by the corresponding maximum value. Hence all the values lie between 0 to 1. Normalization is one of the important steps of data preprocessing as the RBFNN model is used for prediction purposes. The normalization of the data helps in faster convergence of the model. After normalization, the dataset is divided into two sets–training and testing sets. Randomly selected 80% of the data becomes the training set which is used to develop the RBFNN model and the remaining 20% of data becomes the testing set which is used for the evaluation of the model. As the sample size for each country contains 59 data tuples, randomly 47 data tuples (80%) are selected for the training of the model and 13tuples for the testing.

5.2. Training of the Model

During the training process, the neural network model learns from the past data iteratively and becomes adaptive. Referring to Figure 3, the RBFNN structure used for the simulation is 5:4:1. It has five inputs, four nodes or centers in the hidden layer, and one output. The four nodes of the hidden layer contain Gaussian functions. Each Gaussian function has a center and center-width. The number of centers at each Gaussian function is equal to the number of inputs. Since the number of inputs is five, in this case, each of the Gaussian functions at each neuron has five centers. Initially, the value of centers, center-width of Gaussian functions, and the connecting weights are initialized to remain between −0.5 to +0.5. Out of the training data set, a single data point containing five values is given as input to the model. It is then passed through the Gaussian functions of the hidden layer, multiplied with the corresponding weight values, and summed over to produce the estimated output. The error value is obtained by comparing the estimated output with the corresponding target value. The error value may be a positive or negative, hence squared error which is always positive is used as the cost function which needs to be minimized. Using the error value and the learning algorithm of RBFNN the weights, centers, and widths are updated. The detailed update equations are given in Equations (4)–(6). The process is repeated for all inputs and the corresponding error square values are calculated. This completes one experiment. This simulation process is repeated 2000 times until the mean squared error is minimized. The mean square error (MSE) value for each experiment or iteration is noted and plotted against the iteration to observe the convergence characteristics. The details of the parameters used for simulation are given in Table 3. Once the MSE is minimized the final value of weights, centers, and center-width are frozen. The model is then ready for testing purposes.

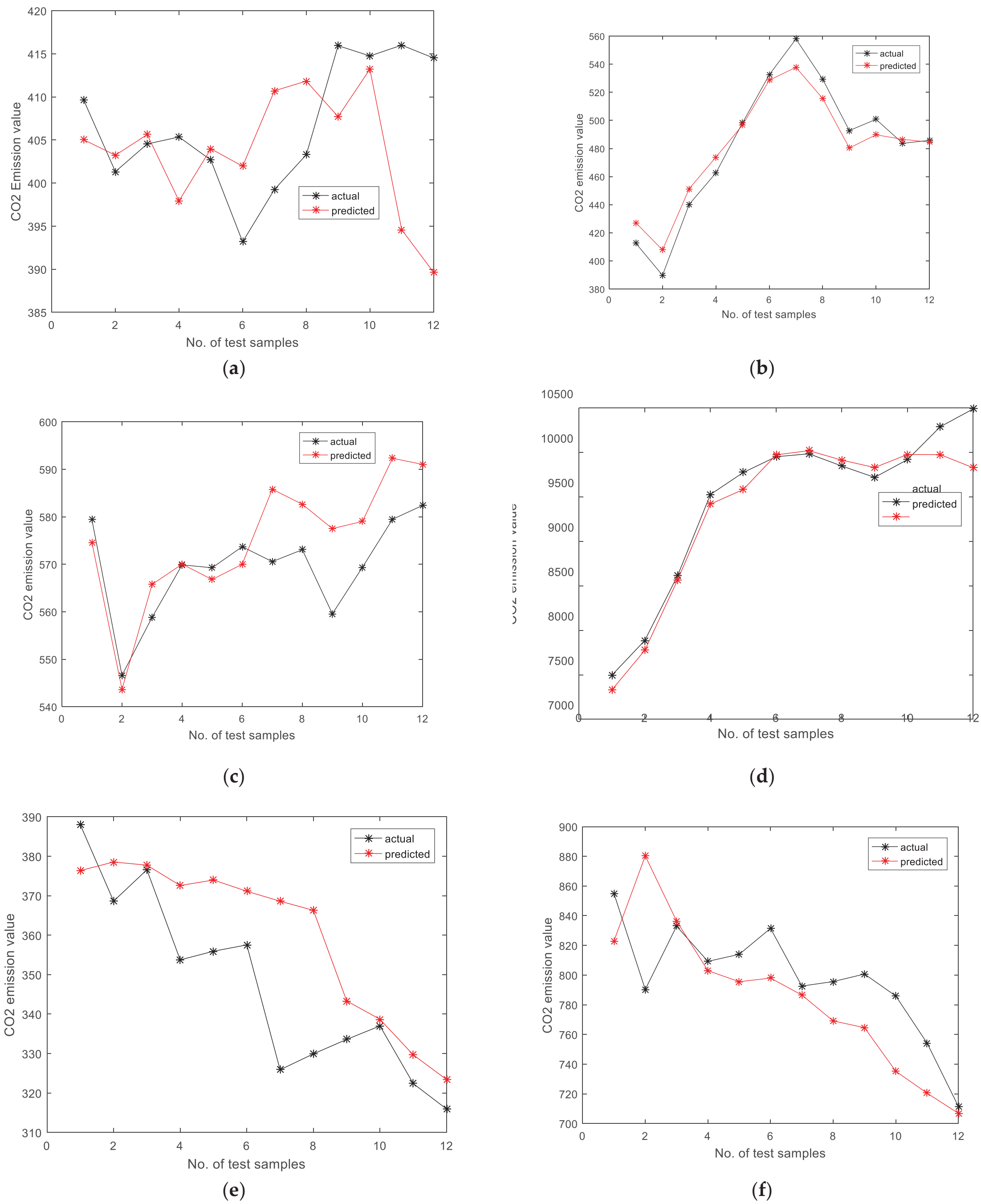


Figure 3. *Cont.*

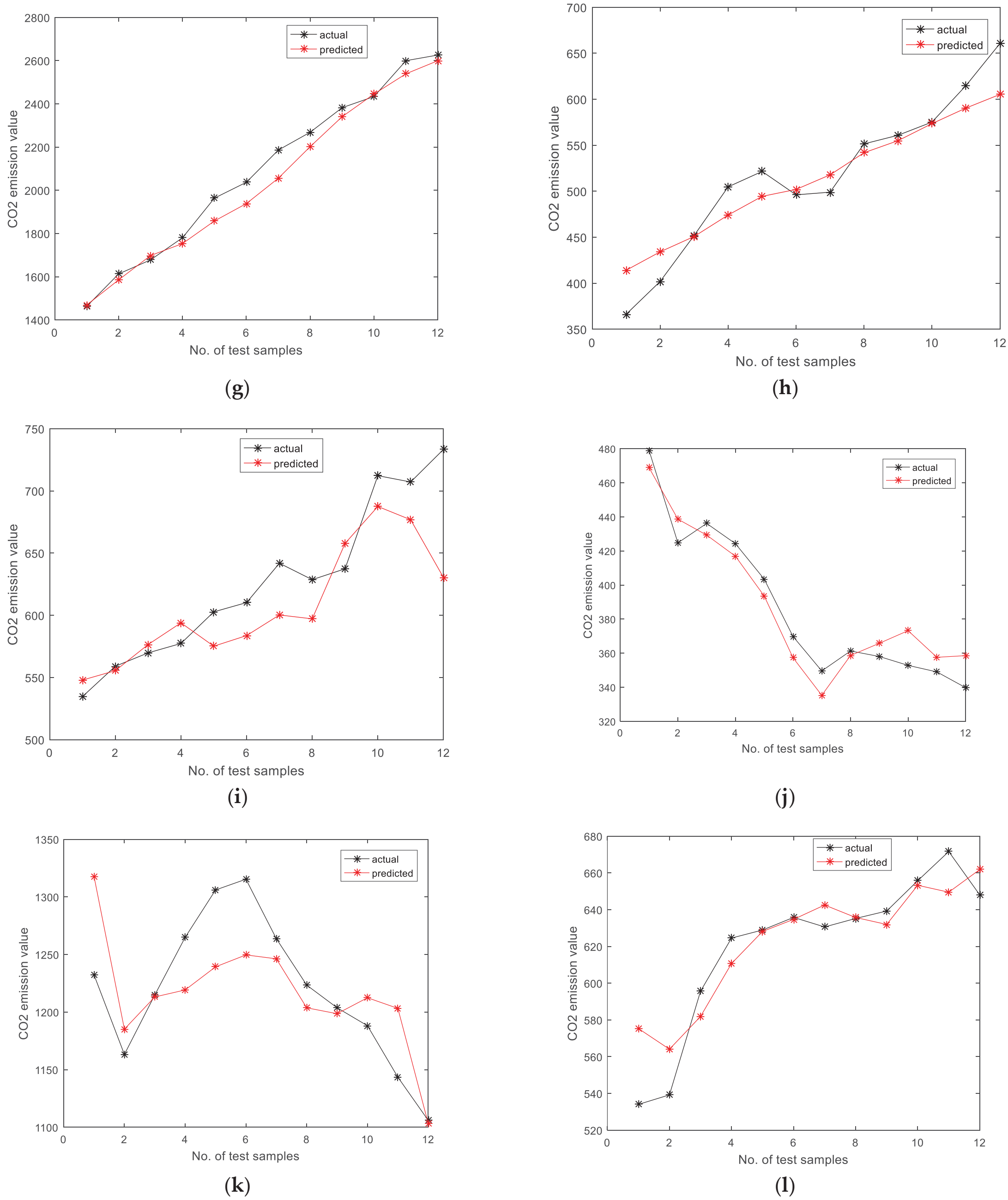
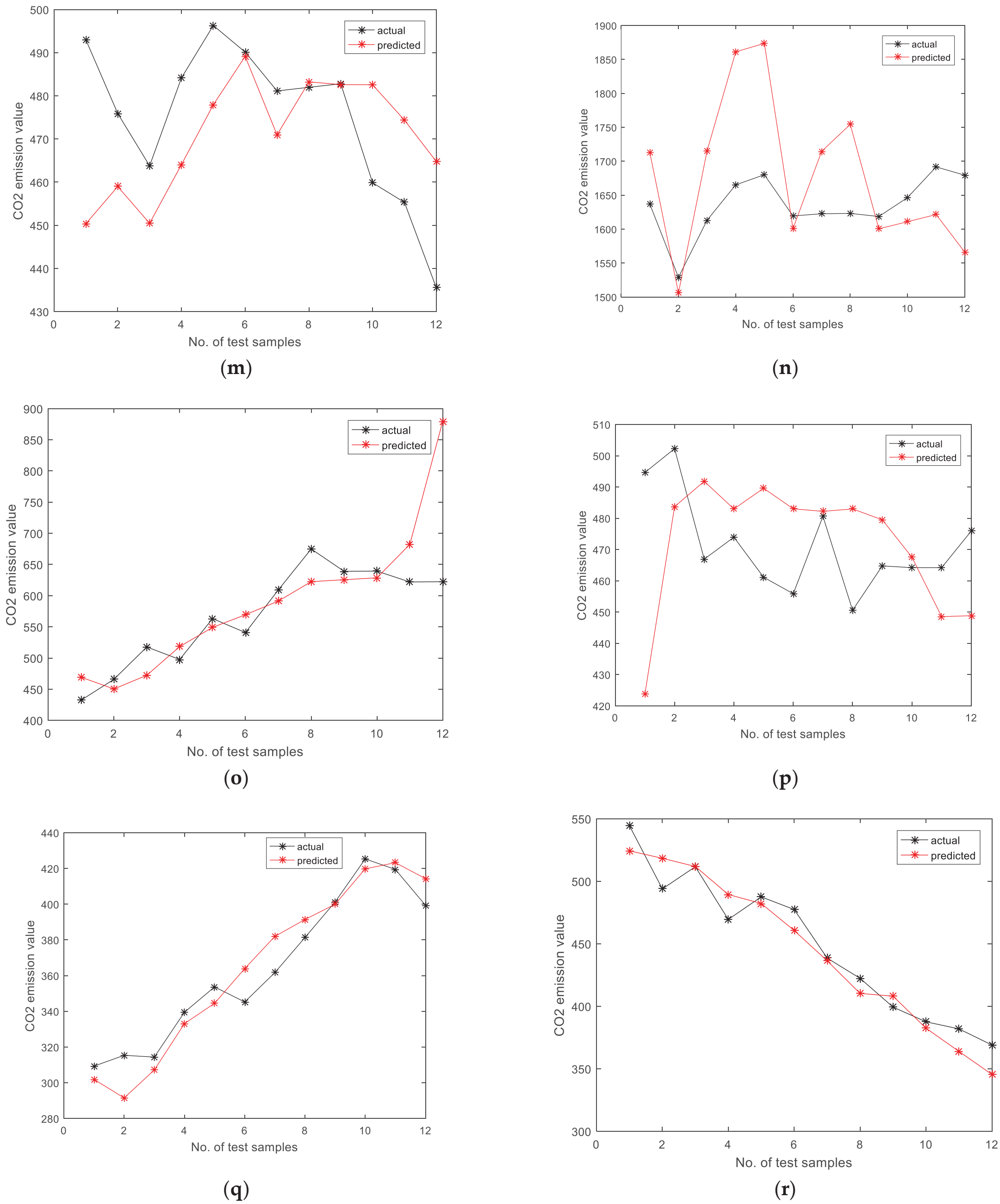


Figure 3. *Cont*.

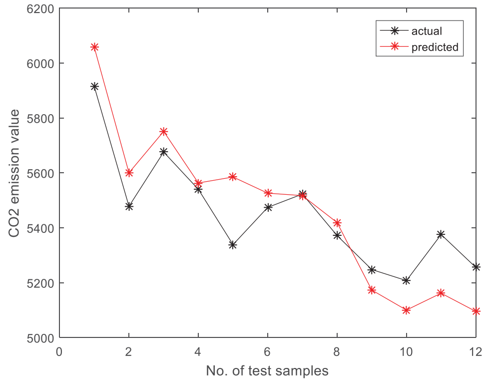


(m) **(n)**

(o) **(p)**

(q) **(r)**

Figure 3. *Cont*.



(s)

Figure 3. Actual and estimated CO_2 emission values during testing using the RBFNN model (**a**) for Australia; (**b**) for Brazil; (**c**) for Canada; (**d**) for China; (**e**) for France; (**f**) for Germany; (**g**) for India; (**h**) for Indonesia; (**i**) for Iran; (**j**) for Italy; (**k**) for Japan; (**l**) for the Korea Republic; (**m**) for Mexico; (**n**) for Russia; (**o**) for Saudi Arabia; (**p**) for South Africa; (**q**) for Turkey; (**r**) for the UK; (**s**) for the USA.

Table 3. Parameters used in the simulation.

Parameter	Value
Structure of RBF full model	5:4:1 (No. of inputs: 5, hidden neurons: 4, output: 1)
Structure of RBF partial model	4:4:1 (No. of inputs: 4, hidden neurons: 4, output: 1)
Number of Centres or nodes in the hidden layer	04
Number of experiments	2000
Number of training tuples (80%)	30
Number of testing tuples (20%)	07
Value of μ (learning parameter)	0.1

5.3. Testing of the Model

Once the model is trained, it is said to have been learned from the past data in an adaptive manner using an error correction method and well designed. After this, the model is being tested using the testing dataset to assess its prediction accuracy. Each data point of the testing set is used as an input to the model. These inputs are applied to the optimized RBFNN model, passed through the Gaussian function, weighted and then summed over to produce the estimated output of CO_2 emission value. Each of these estimated values is compared with the actual target value to evaluate the performance of the RBFNN based prediction model. The Mean absolute percentage error (MAPE) is calculated using Equation (7).

$$MAPE = \frac{1}{N}\sum_{l=1}^{N} abs((y^d(n) - y(n))/y^d(n) \times 100 \quad (7)$$

where N = no. of testing tuples.

$y^d(n)$ = desired value for the nth testing tuple.

$y(n)$ = the estimated value for the nth testing tuple.

6. Results

In this study, two models such as the full model (with renewable energy) and the partial model (without renewable energy) are used to compare the performance of prediction accuracy (Table 4, columns 3 and 4). The MAPE values in Table 4, Col. 3 exhibit that the RBFNN based prediction model can predict the CO_2 emission figures accurately as the MAPE is less than 5% for all the countries except for Russia and Saudi Arabia, which have 5.4% and 8.2% respectively.

Table 4. MAPE value for CO_2 emission prediction.

Emission Intensity	Countries	Full Model (with Renewable Energy)	Partial Model (without Renewable Energy)
High-emission countries	China	1.63	100.00
	The USA	1.95	6.44
	India	2.46	3.06
	Russia	5.40	100.00
	Japan	2.80	4.19
	Iran	4.38	4.76
	South Korea	2.17	2.78
	Saudi Arabia	8.17	4.98
	Indonesia	4.41	4.57
	Germany	3.56	5.56
	Canada	1.4	1.01
Low-emission countries	Brazil	2.16	4.65
	South Africa	4.82	6.47
	Mexico	3.45	5.32
	Turkey	3.05	6.73
	Australia	2.06	1.82
	UK	2.96	4.88
	Italy	2.94	11.38
	France	4.37	8.26

The linear regression models produce a single parameter estimate for the entire sample period. Hence, there is no adaptive process using the error to update the coefficients of the linear model. These linear models, therefore, produce a large error that makes the parameter estimates less precise. In contrast, the RBFNN model has an adaptive process that makes the model learn from the error iteratively and thus, helps in reducing the error with each iteration. This process of error learning through the feed-forward procedure makes the model adaptive. When the error is minimized completely, the final parameters are frozen. The weights can be interpreted as impact coefficients of the inputs with respect to the output variable, i.e., CO_2 emissions. Unlike the linear regression models, these coefficient values are not a single estimate, but rather produced through an adaptive error learning procedure and hence, yield highly precise parameter estimates. Along with the weights, the RBFNN model also produces optimal center values and the values of width.

From the 19 countries considered in this study, 11 are categorized as high emitting countries, each having a share of 2% or more. The rest 8 countries have a share of 1% each and are categorized as low emitting countries. We compared the MAPE values in the full model (Col. 3) with that of the partial model (Col. 4). The purpose is to show the relative contribution of renewable energy share in total energy used in the prediction of CO_2 emissions. Although some of the past studies have shown rather a strong effect of renewable energy in the EKC shape [34], given that they have used linear statistical models, the magnitude of the effect that they show may not be reliable. In this study, the RBFNN model provides a reliable prediction of CO_2 emissions, and hence, the difference in prediction accuracy between the full and partial models can be directly attributed to the renewable energy share. The full model has yielded less MAPE value for 17 countries out of the total 19, thus confirming the significant contribution of renewable energy share in total energy in predicting the CO_2 emission value. The prediction accuracy of these country cases is nearly 98%.

The actual and estimated values of CO_2 obtained from the RBFNN model during testing are plotted in Figure 3a–s. The Figures show that there is a higher degree of convergence between the actual and estimated values of CO_2 during the testing.

China is the biggest emitter of CO_2 accounting for 28% of the global emissions. In the last decade, China has transformed its manufacturing sector to integrate the circular economy model that focuses on the reuse and recycling of materials. The country has set up industrial parks in which the principles of the circular economy have been integrated into the entire supply chain of the companies [54]. Despite these efforts, China is expected to remain the biggest emitter of CO_2 with a rising share of the emissions. The heavy reliance on coal-burning for energy generation in the country is a big challenge in the process of decarbonizing the manufacturing sector. Although India still relies heavily on coal to meet the energy demand, the country's focus on renewable energy generation may set it on the low carbon emission path. The country has a goal of generating 175 GW of power through renewable sources by 2022 which comprises 100 GW from solar, 60 GW from wind, 10 GW from bioenergy, and 5 GW from small hydropower sources. Certain technological innovations in the field of renewable energy such as canal-top solar plants are boosting India's efforts to reduce CO_2 emissions in near future.

In the case of the USA, both the real GDP and renewable energy consumption variables bear a negative association with CO_2 emissions as reflected in Figure 1, where a downward movement in CO_2 emissions in the country can be observed. This finding supports the EKC hypothesis that beyond a threshold level of economic growth, any further increase in real GDP improves the environmental quality as more resources can be committed to innovating cleaner technologies and upgrading the infrastructure in manufacturing.

Earlier statistical models have estimated the elasticity values for the scale, income, and substitution effects of economic growth and trade liberalization [55–57]. These models have assumed a log-linear relationship between air pollution and income per capita and trade to GDP ratios. After estimating the elasticity values, they have added them to arrive at a net impact of growth and trade on pollution. However, as we argued in earlier sections, these models suffer from the non-adaptive behavior of the statistical relationship. The RBFNN model developed in this study helps estimate the nonlinear relationship adaptively. However, the RBFNN model does not produce equivalent elasticity values which can be added to provide a net impact.

7. Conclusions

The Intergovernmental Panel on Climate Change (IPCC) has warned about the catastrophic effects of global warming if the global mean temperature is not pegged at 1.5 °C above the pre-industrial level of warming by the end of the 21st century [58]. The current level of atmospheric temperature has already reached 1.2 °C above the pre-industrial level. At the Paris climate summit of 2015, about 200 countries pledged to reduce CO_2 emissions. In this context, the current study estimates the CO_2 emissions of 11 high emitting and 8 low emitting countries. The prediction of CO_2 emissions is done following the EKC framework, however, the study contributes to this literature by developing and using an artificial neural network model known as RBFNN.

Based on a dataset spanning 1960 to 2019, the RBFNN model can predict the CO_2 values of two sets of high emitting and low emitting countries with nearly 98% accuracy. The models predict based on both the traditional economic predictors as well as a novel non-economic predictor such as the political freedom index. By comparing the prediction error values of the full model with a partial model wherein renewable energy share is excluded, the simulation results show that the full model achieves higher prediction accuracy. This finding establishes with higher certainty compared to the earlier statistical models that renewable energy indeed holds the key for future CO_2 emission reduction, thus curbing the climate change effects.

The policy implication of this finding is that the rapidly industrializing countries such as China, India, Brazil, Iran, and Indonesia have to rethink their industrial policy and growth model. First, there is a need to innovate on cleaner technologies that would require less energy per output, and secondly, fossil fuel-based energy generation needs to be substituted with renewable energy generation. Though, both China and India have taken big strides in this direction in terms of China's push for the adoption of a circular economy model in industry and India's focus on ambitious renewable energy generation targets, they still need to allocate large investments for rapid reformation of their emission reduction plans.

This study makes two main contributions to the literature on EKC and the current climate crisis. First, the nonlinear adaptive models such as RBFNN provide accurate prediction for CO_2 levels of major emitting countries in the world and hence can be used in a more generalized way. Since this is an adaptive model with low complexity, it is easier to predict the future CO_2 emission levels accurately with less computational time. However, to implement this research idea for real policymaking, there is a need to build an emission simulation software package integrating this simulation model. This software can simulate the future emission levels of CO_2 and other environmental quality indicators as well such as SO_2, PM_{10}, and NO_2 by inputting the key predictor values to the model in real-time. Given its low computational requirement and high level of accuracy, it can equip policymakers with information for future emission paths of the countries and global emission levels. Second, as our findings show that higher renewable energy consumption can reduce CO_2 emissions, there should be more investments in this energy generation to replace non-renewable energy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14095260/s1, The Excel files D1–D6.

Author Contributions: Conceptualization, P.R.J. and R.M.; methodology, B.M., P.R.J. and R.M.; software, B.M.; validation, B.M., P.R.J. and R.M.; formal analysis, P.R.J. and B.M.; investigation, P.R.J. and R.M.; data curation, B.M.; writing—original draft preparation, P.R.J., B.M. and R.M.; writing—review and editing, P.R.J. and B.M.; supervision, P.R.J.; project administration, P.R.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from the National Institute of Technology Karnataka, Surathkal and the Scheme for Promotion of Academic and Research Collaboration (SPARC), Ministry of Education, Government of India [Proposal ID–302].: P-302.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this study are available in the Supplementary Materials.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Shahbaz, M.; Sinha, A. Environmental Kuznets curve for CO_2 emissions: A literature survey. *J. Econ. Stud.* **2019**, *46*, 106–168. [CrossRef]
2. Joshi, P.; Beck, K. Democracy and carbon dioxide emissions: Assessing the interactions of political and economic freedom and the environmental Kuznets curve. *Energy Res. Soc. Sci.* **2018**, *1*, 46–54. [CrossRef]
3. You, W.H.; Zhu, H.M.; Yu, K.; Peng, C. Democracy, financial openness, and global carbon dioxide emissions: Heterogeneity across existing emission levels. *World Dev.* **2015**, *1*, 189–207. [CrossRef]
4. Grossman, G.M.; Krueger, A.B. *Environmental Impacts of a North American Free Trade Agreement*; National Bureau of Economic Research: Cambridge, MA, USA, 1991. [CrossRef]
5. Grossman, G.M.; Krueger, A.B. Economic growth and the environment. *Q. J. Econ.* **1995**, *110*, 353–377. [CrossRef]
6. Shafik, N.; Bandyopadhyay, S. *Economic Growth and Environmental Quality: Time-Series and Cross-Country Evidence*; World Bank Publications; The World Bank: Washington, DC, USA, 1992; Volume 904.
7. Selden, T.M.; Song, D. Environmental quality and development: Is there a Kuznets curve for air pollution emissions? *J. Environ. Econ. Manag.* **1994**, *27*, 147–162. [CrossRef]

8. Solarin, S.A.; Al-Mulali, U.; Musah, I.; Ozturk, I. Investigating the pollution haven hypothesis in Ghana: An empirical investigation. *Energy* **2017**, *124*, 706–719. [CrossRef]
9. Stern, D.I. The rise and fall of the environmental Kuznets curve. *World Dev.* **2004**, *32*, 1419–1439. [CrossRef]
10. Antweiler, W.; Copeland, B.R.; Taylor, M.S. Is free trade good for the environment? *Am. Econ. Rev.* **2001**, *91*, 877–908. [CrossRef]
11. Managi, S.; Hibiki, A.; Tsurumi, T. Does trade openness improve environmental quality? *J. Environ. Econ. Manag.* **2009**, *58*, 346–363. [CrossRef]
12. Tsurumi, T.; Managi, S. Decomposition of the environmental Kuznets curve: Scale, technique, and composition effects. *Environ. Econ. Pol. Stud.* **2010**, *11*, 19–36. [CrossRef]
13. Tsurumi, T.; Managi, S. The effect of trade openness on deforestation: Empirical analysis for 142 countries. *Environ. Econ. Pol. Stud.* **2014**, *16*, 305–324. [CrossRef]
14. Kagohashi, K.; Tsurumi, T.; Managi, S. The effects of international trade on water use. *PLoS ONE* **2015**, *10*, e0132133. [CrossRef] [PubMed]
15. Abe, K.; Ishimura, G.; Tsurumi, T.; Managi, S.; Sumaila, U.R. Does trade openness reduce a domestic fisheries catch? *Fish. Sci.* **2017**, *83*, 897–906. [CrossRef]
16. Shahbaz, M.; Khan, S.; Tahir, M.I. The dynamic links between energy consumption, economic growth, financial development and trade in China: Fresh evidence from multivariate framework analysis. *Energy Econ.* **2013**, *40*, 8–21. [CrossRef]
17. Sugiawan, Y.; Managi, S. The environmental Kuznets curve in Indonesia: Exploring the potential of renewable energy. *Energy Pol.* **2016**, *98*, 187–198. [CrossRef]
18. Sinha, A.; Shahbaz, M. Estimation of environmental Kuznets curve for CO_2 emission: Role of renewable energy generation in India. *Renew. Energy* **2018**, *119*, 703–711. [CrossRef]
19. Liu, X.; Zhang, S.; Bae, J. The impact of renewable energy and agriculture on carbon dioxide emissions: Investigating the environmental Kuznets curve in four selected ASEAN countries. *J. Clean. Prod.* **2017**, *164*, 1239–1247. [CrossRef]
20. Apergis, N.; Jebli, M.B.; Youssef, S.B. Does renewable energy consumption and health expenditures decrease carbon dioxide emissions? Evidence for sub-Saharan Africa countries. *Renew. Energy* **2018**, *127*, 1011–1016. [CrossRef]
21. Adams, S.; Nsiah, C. Reducing carbon dioxide emissions; Does renewable energy matter? *Sci. Total Environ.* **2019**, *693*, 133288. [CrossRef]
22. Saidi, K.; Omri, A. Reducing CO_2 emissions in OECD countries: Do renewable and nuclear energy matter? *Prog. Nucl. Energy* **2020**, *126*, 103425. [CrossRef]
23. Menyah, K.; Wolde-Rufael, Y. Energy consumption, pollutant emissions and economic growth in South Africa. *Energy Econ.* **2010**, *32*, 1374–1382. [CrossRef]
24. Sinha, A.; Shahbaz, M.; Sengupta, T. Renewable energy policies and contradictions in causality: A case of next 11 countries. *J. Clean. Prod.* **2018**, *197*, 73–84. [CrossRef]
25. Tanti, P.C.; Srujana, I.S.; Jena, P.R. Can increase in the share of renewable energy in economic growth shift turning point of EKC? Evidence from time-series analysis in India. *J. Environ. Account. Manag.* **2020**, *8*, 257–266. [CrossRef]
26. Liu, J. China's renewable energy law and policy: A critical review. *Renew. Sustain. Energy Rev.* **2019**, *99*, 212–219. [CrossRef]
27. Chen, Y.; Zhao, J.; Lai, Z.; Wang, Z.; Xia, H. Exploring the effects of economic growth, and renewable and non-renewable energy consumption on China's CO_2 emissions: Evidence from a regional panel analysis. *Renew. Energy* **2019**, *1*, 341–353. [CrossRef]
28. Bilgili, F.; Kuşkaya, S.; Khan, M.; Awan, A.; Türker, O. The roles of economic growth and health expenditure on CO_2 emissions in selected Asian countries: A quantile regression model approach. *Environ. Sci. Pollut. Res.* **2021**, *28*, 44949–44972. [CrossRef]
29. Gyamfi, B.A.; Adedoyin, F.F.; Bein, M.A.; Bekun, F.V. Environmental implications of N-shaped environmental Kuznets curve for E7 countries. *Environ. Sci. Pollut. Res.* **2021**, *28*, 33072–33082. [CrossRef]
30. Kirikkaleli, D.; Adebayo, T.S. Do public-private partnerships in energy and renewable energy consumption matter for consumption-based carbon dioxide emissions in India? *Environ. Sci. Pollut. Res.* **2021**, *28*, 30139–30152. [CrossRef]
31. Yang, M.; Wang, E.Z.; Hou, Y. The relationship between manufacturing growth and CO_2 emissions: Does renewable energy consumption matter? *Energy* **2021**, *232*, 121032. [CrossRef]
32. Khattak, S.I.; Ahmad, M.; Khan, Z.U.; Khan, A. Exploring the impact of innovation, renewable energy consumption, and income on CO_2 emissions: New evidence from the BRICS economies. *Environ. Sci. Pollut. Res.* **2020**, *27*, 13866–13881. [CrossRef]
33. Zeraibi, A.; Balsalobre-Lorente, D.; Shehzad, K. Testing the environmental Kuznets curve hypotheses in Chinese provinces: A nexus between regional government expenditures and environmental quality. *Int. J. Environ. Res. Public Health* **2021**, *18*, 9667. [CrossRef] [PubMed]
34. Chen, Y.; Wang, Z.; Zhong, Z. CO_2 emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. *Renew. Energy* **2019**, *131*, 208–216. [CrossRef]
35. Khan, M.T.I.; Yaseen, M.R.; Ali, Q. Nexus between financial development, tourism, renewable energy, and greenhouse gas emission in high-income countries: A continent-wise analysis. *Energy Econ.* **2019**, *83*, 293–310. [CrossRef]
36. Yao, S.; Zhang, S.; Zhang, X. Renewable energy, carbon emission and economic growth: A revised environmental Kuznets Curve perspective. *J. Clean. Prod.* **2019**, *235*, 1338–1352. [CrossRef]
37. Zeraibi, A.; Ahmed, Z.; Shehzad, K.; Murshed, M.; Nathaniel, S.P.; Mahmood, H. Revisiting the EKC hypothesis by assessing the complementarities between fiscal, monetary, and environmental development policies in China. *Environ. Sci. Pollut. Res.* **2021**, *29*, 23545–23560. [CrossRef] [PubMed]

38. Balsalobre-Lorente, D.; Shahbaz, M.; Roubaud, D.; Farhani, S. How economic growth, renewable electricity and natural resources contribute to CO_2 emissions? *Energy Policy* **2018**, *113*, 356–367. [CrossRef]
39. Paramati, S.R.; Mo, D.; Gupta, R. The effects of stock market growth and renewable energy use on CO_2 emissions: Evidence from G20 countries. *Energy Econ.* **2017**, *66*, 360–371. [CrossRef]
40. Kim, J.; Park, K. Financial development and deployment of renewable energy technologies. *Energy Econ.* **2016**, *59*, 238–250. [CrossRef]
41. Dasgupta, P.; Maler, K.G. Poverty, institutions, and the environmental resource-base. In *Handbook of Development Economics*; Behrman, J., Srinivaan, T.N., Eds.; Elsevier Science: Amsterdam, The Netherlands, 1995; Volume 3A.
42. Romuald, K.S. Democratic Institutions and Environmental Quality: Effects and Transmission Channels. No. 120396. In Proceedings of the 2011 European Association of Agricultural Economists International Congress, Zurich, Switzerland, 30 August–2 September 2011.
43. Goel, R.K.; Herrala, R.; Mazhar, U. Institutional quality and environmental pollution: MENA countries versus the rest of the world. *Econ. Syst.* **2013**, *37*, 508–521. [CrossRef]
44. Barrett, S.; Graddy, K. Freedom, growth, and the environment. *Environ. Dev. Econ.* **2000**, *5*, 433–456. [CrossRef]
45. Torras, M.; Boyce, J.K. Income, inequality, and pollution: A reassessment of the environmental Kuznets curve. *Ecol. Econ.* **1998**, *25*, 147–160. [CrossRef]
46. Li, Q.; Reuveny, R. Democracy and environmental degradation. *Int. Stud. Q.* **2006**, *50*, 935–956. [CrossRef]
47. Farzin, Y.H.; Bond, C.A. Democracy and environmental quality. *J. Dev. Econ.* **2006**, *81*, 213–235. [CrossRef]
48. Midlarsky, M.I. Democracy and the environment: An empirical assessment. *J. Peace Res.* **1998**, *35*, 341–361. [CrossRef]
49. Roberts, J.T.; Parks, B.C. *A Climate of Injustice: Global Inequality, North-South Politics, and Climate Policy*; MIT Press: Cambridge, MA, USA, 2007.
50. Scruggs, L.A. Political and economic inequality and the environment. *Ecol. Econ.* **1998**, *26*, 259–275. [CrossRef]
51. World Bank. *World Development Indicators*; World Bank: Washington, DC, USA, 2021.
52. Freedom House. Freedom in the World. 2021. Available online: www.freedomhouse.org/ratings/index.htm (accessed on 2 February 2022).
53. Haykin, S. *Neural Networks and Learning Machines*; Prentice Hall: New York, NY, USA, 2009.
54. Geng, Y.; Sarkis, J.; Bleischwitz, R. How to Globalize the Circular Economy. *Nature* **2019**, 153–155. [CrossRef]
55. Shahbaz, M.; Shahzad, S.J.H.; Mahalik, M.K. Is globalization detrimental to CO_2 emissions in Japan? New threshold analysis. *Environ. Model. Assess.* **2018**, *23*, 557–568. [CrossRef]
56. Jena, P.R. Does trade liberalization create more pollution? Evidence from a panel regression analysis across the states of India. *Environ. Econ. Pol. Stud.* **2018**, *20*, 861–877. [CrossRef]
57. Shahbaz, M.; Nasir, M.A.; Roubaud, D. Environmental degradation in France: The effects of FDI, financial development, and energy innovations. *Energy Econ.* **2018**, *74*, 843–857. [CrossRef]
58. Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M.I.; et al. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. In *Climate Change 2021: The Physical Science Basis*; Cambridge University Press: Cambridge, UK, *in Press*. Available online: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf (accessed on 2 February 2022).

sustainability

MDPI

Article

How Does the Carbon Tax Influence the Energy and Carbon Performance of China's Mining Industry?

Runqing Zhu and Boqiang Lin *

Collaborative Innovation Center for Energy Economics and Energy Policy, China Institute for Studies in Energy Policy, School of Management, Xiamen University, Xiamen 361005, China; 35720180155017@stu.xmu.edu.cn
* Correspondence: bqlin@xmu.edu.cn or bqlin2004@vip.sina.com

Abstract: As the world's largest energy consumer, China's CO_2 emissions have significantly risen, owing to its rapid economic growth. Hence, levying a carbon tax has become essential in accelerating China's carbon neutralization process. This paper employs the two-stage translog cost function to calculate the price elasticity of the mining industry's energy and input factors. Based on the price elasticity, the carbon tax's influence on the mining industry's energy and carbon performance is estimated. In the calculation of energy efficiency, the non-radial directional distance function is adopted. The results express that the carbon tax significantly decreases the mining industry's CO_2 emissions and promotes its energy and carbon performance. In addition to levying a carbon tax, the government should also strengthen the market-oriented reform of the oil and power infrastructure to optimize the mining industry's energy structure.

Keywords: carbon tax; price elasticity; translog cost function; energy and carbon performance

Citation: Zhu, R.; Lin, B. How Does the Carbon Tax Influence the Energy and Carbon Performance of China's Mining Industry? *Sustainability* **2022**, *14*, 3866. https://doi.org/10.3390/su14073866

Academic Editor: Bertrand Hamaide

Received: 31 January 2022
Accepted: 21 March 2022
Published: 24 March 2022

1. Introduction, Literature Review, and Motivation of the Paper

1.1. Introduction

With the goal of carbon neutralization proposed by China's government, the low-carbon transformation of the energy economy has become an inevitable trend [1]. As the world's largest energy consumer, China's CO_2 emissions have risen as a result of its rapid economic growth. According to the 2021 BP World Energy Statistical Yearbook [2], China's carbon dioxide emissions were 9.90 billion tons in 2020, about 30.66% of the global carbon dioxide emission. Even though China's CO_2 emission growth rate has slowed down in recent years, achieving the carbon peak goal in 2030 is a difficult challenge especially when industrialization and urbanization are advancing rapidly. According to the Environmental Kuznets Curve (EKC), when the economy grows to a certain extent, the environmental quality will be improved with the continuous growth of per capita income [3]. The EKC has been confirmed in many developed countries. To reduce CO_2 emissions and ensure China's sustainable development, the energy reform of traditional industries is imperative.

As China's traditional heavy industry, the mining industry (MI) is vital to the national economy and infrastructure construction. Although the central government has put forward the control for the total energy consumption and intensity and implemented strict control over all kinds of coal power projects, optimizing the energy structure and reducing coal consumption has been a gradual process. At present, coal is still China's primary energy source. According to the 2021 BP World Energy Statistical Yearbook [2], China's coal energy consumption accounted for 56.56% of its national energy consumption in 2020. Therefore, ensuring China's coal supply at this stage is essential for energy security. On the other hand, the MI provides an important material guarantee for China's industrial development and various infrastructure construction, which makes it a pillar industry for China's modernization. However, the MI's CO_2 emission cannot be ignored as a high energy-consuming industry. Based on the China Energy Statistical Yearbook [4], China's

MI's CO_2 emission in 2019 was about 747 million tons, which exceeded the total CO_2 emission of many countries in 2019. Reducing the MI's CO_2 emissions and improving its energy efficiency are essential for carbon neutralization.

A variety of policy means must be employed to decrease CO_2 emissions. The carbon trade market and carbon tax have attracted extensive attention in recent years. The carbon trade market means that the government department formulates the total carbon emission and allocates carbon emission quotas to each enterprise participating in the carbon market. If the enterprise's CO_2 emission is below the quota, the enterprise sells the remaining quota to obtain income. If the enterprise's CO_2 emission exceeds the quota, it must purchase quotas from other enterprises. Since 2011, China has carried out the pilot work of the carbon market construction in seven provinces and cities, which has taken an essential step towards the national carbon emission reduction and carbon peak goal in 2030 [5–8]. In 2021, the national carbon emission trading market launched online trading, and more than 2000 key emission units were included in the market. China's carbon market will become the largest market in the world, covering about 4.5 billion tons of CO_2 emission [9]. However, the carbon market mainly covers the power generation industry and key emission units. Even when the carbon market is mature in the future, it is still difficult to cover the whole industry.

Conversely, allocating carbon emission quotas can also be very complex as the carbon tax is a price policy. The government department stipulates the tax rate, and the market determines the carbon dioxide emission reduction. Although the carbon tax policy cannot control the total amount of carbon dioxide emission, it has a lower administrative cost, broader coverage, and is easier to coordinate with other policies [10]. On the other hand, the carbon tax policy can also increase government revenue to enable the government to continue its investments in emission reduction projects to form a sustainable emission reduction path. As a carbon tax is a valuable way to control carbon emission, Japan, Australia, the Netherlands, Norway, Sweden, and Colombia have successively implemented carbon tax policies [11]. To sum up, the carbon tax is essential for rationalizing the policy system and accelerating China's carbon neutralization process.

1.2. Literature Review and Motivation of the Paper

In recent years, the carbon tax has been a hot issue in economics. Although China's government has begun to levy resource taxes on fossil fuels, it has not yet set up a tax aimed explicitly at carbon dioxide emission. The carbon tax is a type of environmental tax, and environmental tax is the general name of a series of tax systems aimed at protecting the ecological environment. The research on environmental tax can be traced back to Arthur Cecil Pigou [12]. Pigou first proposed to make up the gap between the private cost and social cost of polluters' production through levying a tax, which is the "Pigouvian tax". Tullock [13] pointed out that the Pigouvian tax can achieve a "double benefit" effect through the internalization of external costs. Pearce [14] proposed the concept of "double dividend" when studying the influence of the carbon tax on global warming. The research pointed out that levying carbon tax can reduce carbon dioxide emission and support environmental protection services or economic development. There has been long-standing research on carbon tax in academia, as most economists believe that carbon tax policy can bring multiple benefits. Newell and Pizer [15] believe that the carbon tax is generally higher than the carbon market under uncertain terms of net social welfare. The research of Wittneben [10] and Goulder and Schein [16] showed that the total administrative cost of carbon tax policy is low, and it is easy to coordinate with other carbon emission reduction policies. However, some scholars question the carbon tax. The enterprises' profits will reduce because the carbon tax policy raises carbon dioxide emission costs. A relatively higher carbon tax rate may inhibit the development of enterprises, while a relatively lower tax rate cannot reduce carbon dioxide emission [17]. Newell and Pizer [18] believed that a carbon tax will encounter excellent resistance in practice, and levying a carbon tax can be difficult. Chen and Chen [19] think that carbon tax raises the financial burden of enterprises.

He et al. [20] showed that a carbon tax will reduce the savings and investment of enterprises and squeeze the living space of small and medium-sized enterprises. In conclusion, the formulation of the carbon tax policy is a very complex problem.

In recent years, as the world pays more and more attention to carbon dioxide emissions reduction, carbon tax policies have begun to attract scholars' attention. Ghaith and Epplin [21] studied how the carbon tax influences the household electricity cost in the U.S and estimated whether it is sufficient to encourage households to install grid-connected solar or wind energy systems. Chen and Hu [22] explored the behavior strategies of producers under different carbon taxes and subsidies. They found that levying carbon tax can provide more incentives for the manufacturing industry than low-carbon technology subsidies. The research of Zhou, An, Zha, Wu, and Wang [11] showed that adopting the block carbon tax can visibly reduce the tax burden of enterprises and encourage enterprises to produce low-carbon products. Brown et al. [23] showed that the carbon tax policy can increase employment opportunities in the United States. Denstadli and Veisten [24] believed that Norwegian tourists are willing to accept the higher air costs to pay the carbon tax. Cheng et al. [25] studied how the carbon tax influences energy innovation in the Swedish economy. They found that when the rate exceeds a certain point, increasing the carbon tax rate will not promote energy innovation. Gokhale [26] believed that Japan's carbon tax rate is too low to achieve carbon emission reduction targets in 2030. Hammerle, et al. [27] investigated the citizens' acceptance of carbon tax. They found that supporting low-income families is conducive to the promotion of the carbon tax policy.

Due to the proposal of China's carbon peak and carbon neutralization goal, the academic heat on carbon tax policy is gradually increasing. Although China has not officially launched the carbon tax policy, its research has attracted more and more attention from scholars. The research directions mainly focus on the influence of the carbon tax on economic growth and the actual effect of CO_2 emission reduction. Zhou et al. [28] discussed the influence of the carbon tax on China's transportation industry with the CGE model. They found that the carbon tax can bring the most negligible negative impact on the transportation industry. Shi et al. [29] discussed how different carbon tax rates influence China's construction industry's energy consumption. The results showed that when the carbon tax is 60 yuan/ton, it can achieve the emission reduction target and minimize the negative impact. Li et al. [30] took Shanxi Province of China as an example to prove that carbon tax is instrumental in relieving the employment pressure in coal-rich regions. Hu et al. [31] contrasted the resource tax and carbon tax from different aspects. They found that the carbon tax's comprehensive performance is much better than the resource taxes.

The effect of the carbon tax on CO_2 emission reduction is associated with energy substitution [32]. Levying a carbon tax will cause energy price changes, as the energy cost increases based on its carbon dioxide emission coefficient. Manufacturers will prefer clean energy to replace high-carbon energy. Furthermore, the carbon tax can raise the total energy cost and reduce the relative cost of other input factors, making producers more inclined to use other input factors to replace energy input. Many scholars have studied energy price elasticity and input factors price elasticity in China, but these studies do not consider the relevance between them [33–35]. Cho et al. [36] believed that the price change of a single energy type can lead to the substitution among energy and lead to the substitution among input factors. Therefore, the two kinds of price elasticity should be considered. Pindyck [37] proposed a two-stage translog cost function to include the correlation of energy price elasticity and input factors price elasticity. In recent years, many pieces of literature have used this method to calculate price elasticity [38–43]. Based on these studies, this paper uses the two-stage translog cost function to estimate the price elasticity of the energy and input factors in the MI. Furthermore, based on the price elasticity, the influence of the carbon tax on the energy and carbon performance (ECP) of China's MI is also explored. The contributions are as follows. Firstly, different from the previous studies [44–46], based on estimating the carbon tax's influence on carbon dioxide emission reduction, a non-radial directional distance function (NDDF) is adopted to calculate the

ECP of the MI and the influence of the carbon tax on ECP is explored. Secondly, the translog cost function is employed to measure the price elasticity of energy and input factors in China's MI, which supplements the existing literature. Finally, according to the empirical results, corresponding policy recommendations are proposed which are vital to achieving China's carbon peak and carbon neutralization goals.

The second part describes the methodologies and data while the third part calculates the price elasticity of energy and input factors in China's MI. The fourth part estimates the MI's carbon dioxide emission reduction potential and the influence of carbon tax on the MI's ECP. In the fifth part, the corresponding policy suggestions are put forward according to the empirical results of this paper.

2. Methodologies and Data

2.1. Calculation of the Price Elasticity

Based on Cho, Nam and Pagán [36] and Ma et al. [47], this paper assumes that the MI in each province has a quadratic differentiable total output function, which links the total output (Y) with the capital (K), labor (L) and energy (E). According to Yang, Fan, Yang, and Hu [44] and Li and Sun [48], energy can be combined into three types: coal, oil, and electricity. Assuming that the production function is weakly separable among the main energy, capital, and labor components, a total energy price index is constructed including coal price, oil price, and electricity price. In addition, presuming that all input factors are homogeneous, a homogeneous translog energy cost share equation is specified [36], and the total production function is described as:

$$Y = F[K, L, E(CO, OI, EL)] \tag{1}$$

where CO, OI, and EL represent the MI's coal, oil, and electricity consumption respectively. If the input factors' price and the output are exogenous, Equation (1) can also be described by a unique cost function. According to the duality theory, the cost function is also weakly separable.

$$C = G[P_K, P_L, P_E(P_{CO}, P_{OI}, P_{EL}); Y] \tag{2}$$

where C represents the total cost. P_K and P_L mean the prices of capital and labor. P_E is the total energy price index. Since the translog function is considered as the second-order approximation of any quadratic differentiable cost function. To facilitate estimation, Equation (2) is converted into a non-homogeneous translog cost function [42,49]:

$$\begin{aligned} lnC = \beta_0 + & \sum_i \beta_i lnP_i + \sum_i \varnothing_i lnYlnP_i + \tfrac{1}{2}\sum_i \sum_j \beta_{ij} lnP_i lnP_j + \beta_Y lnY \\ & + \tfrac{1}{2}\beta_{YY}(lnY)^2 + \beta_t t + \tfrac{1}{2}\beta_{tt} t^2 + \sum_i \beta_{it} t lnP_i + \beta_{Yt} t lnY \ (i, j = K, L, E) \end{aligned} \tag{3}$$

In Equation (3), Y, C, and P represent the output, total cost, and inputs price of the MI, respectively. T represents the time trend. The first year is equal to 1, the second year is equal to 2, and so on. To minimize the cost function, according to Shephard lemma, the demand of input factors is defined as the partial derivative of the total cost function to the corresponding prices, that is:

$$x_i = \frac{\partial C}{\partial P_i} \ (i = K, L, E) \tag{4}$$

In Equation (4), x_i is the i-th input demand. C represents the total cost. P_i represents the i-th input price. To sum up, the cost-share function can be expressed as:

$$S_i = \frac{x_i \cdot P_i}{C} = \frac{P_i}{C} \cdot \frac{\partial C}{\partial P_i} = \frac{\partial lnC}{\partial lnP_i} \tag{5}$$

S_i means the i-th input factor's share. Bring Equation (3) into Equation (5) and take the partial derivative of the lnC to lnP_i, then S_i can be expressed as:

$$S_i = \frac{\partial lnC}{\partial lnP_i} = \beta_i + \varnothing_i lnY + \sum_{j=1}^{3} \beta_{ij} lnP_j + \beta_{it} t \ (i, j = K, L, E) \quad (6)$$

According to Zha, et al. [50], the following regularization conditions need to be set for Equation (6):

$$\beta_{ij} = \beta_{ji} \ for \ all \ i \neq j \quad (7)$$

$$\sum_i \beta_i = 1; \sum_i \beta_{ij} = \sum_j \beta_{ij} = 0; \ \sum_i \varnothing_i = \sum_i \beta_{it} = 0 \ (i, j = K, L, E) \quad (8)$$

By estimating the coefficient in Equation (6), the input factors' own-price elasticity η_{ii} and cross-price elasticity η_{ij} can be calculated as:

$$\eta_{ii} = \frac{\beta_{ii}}{S_i} + S_i - 1, \ (i = j) \ and \ \eta_{ij} = \frac{\beta_{ij}}{S_i} + S_j, (i \neq j) \ (i, j = K, L, E) \quad (9)$$

To measure the MI's input factors price elasticity, the total energy price is needed. Based on Pindyck [37], the total cost function and the energy price function are both assumed to follow the translog form. The energy price function can be described as:

$$lnP_E = \gamma_0 + \sum_m \gamma_m lnP_m + \frac{1}{2} \sum_m \sum_n \gamma_{mn} lnP_m lnP_n + \sum_m \gamma_{mt} t lnP_m \ (m, n = CO, OI, EL) \quad (10)$$

In Equation (10), m and n represent the energy types. P_m and P_n represent the energy price. P_E represents the total energy price index. By differentiating Equation (10) with various energy prices, the energy share equation can be derived as follows:

$$S_m^{fuel} = \frac{\partial lnP_E}{\partial lnP_m} = \gamma_m + \sum_n \gamma_{mn} lnP_n + \gamma_{mt} t \ (m, n = CO, OI, EL) \quad (11)$$

Like Equation (6), Equation (11) requires the following constraints:

$$\gamma_{mn} = \gamma_{nm} \ for \ all \ m \neq n \quad (12)$$

$$\sum_m \gamma_m = 1; \sum_m \gamma_{mn} = \sum_n \gamma_{mn} = 0; \ \sum_m \gamma_{mt} = 0 \ (m, n = CO, OI, EL) \quad (13)$$

Based on Equation (11), the own-price elasticity of the three energy types ε_{mm} and cross-price elasticity ε_{mn} can be calculated as:

$$\varepsilon_{mm} = \frac{\gamma_{mm}}{S_m^{fuel}} + S_m^{fuel} - 1, \ (m = n) \ and \ \varepsilon_{mn} = \frac{\gamma_{mn}}{S_m^{fuel}} + S_n^{fuel}, (m \neq n) \ (m, n = CO, OI, EL) \quad (14)$$

Nevertheless, the energy price elasticity is considered with the condition that the total energy consumption is maintained [37]. According to Cho, Nam and Pagán [36] and Floros and Vlachou [51], this paper further considers the feedback effect due to the price change of a single energy type, the energy's own-price elasticity and cross-price elasticity as specified:

$$\varepsilon_{mm}^* = \varepsilon_{mm} + \eta_{EE} \cdot S_m^{fuel}, \ (m = n) \ and \ \varepsilon_{mn}^* = \varepsilon_{mn} + \eta_{EE} \cdot S_n^{fuel}, (m \neq n) \ (m, n = CO, OI, EL) \quad (15)$$

In Equation (15), η_{EE} is the energy's own-price elasticity of the MI, according to Equation (9).

2.2. Calculation of ECP

To measure the impact of CO_2 emissions on the MI's energy efficiency, the NDDF is employed to benchmark the ECP of the MI. The input factors include capital stock (K), labor (L), and energy (E). The total industrial output value (Y) of the MI is the desirable output, and the carbon dioxide emission (C) is the undesirable output. The production technology set is described as:

$$T = \{(K, L, E, Y, C) : (K, L, E) \ can \ produce \ (Y, C)\} \quad (16)$$

According to Zhou, et al. [52], the production technology set can be represented by the following linear constraints:

$$T = \{(K,L,E,Y,C) : (K,L,E) \; can \; produce \; (Y,C)\}$$
$$\begin{array}{c} \sum_{t=1}^{T}\sum_{n=1}^{N} \lambda_{nt} K_{nt} \leq K \\ \sum_{t=1}^{T}\sum_{n=1}^{N} \lambda_{nt} L_{nt} \leq L \\ \sum_{t=1}^{T}\sum_{n=1}^{N} \lambda_{nt} E_{nt} \leq E \\ \sum_{t=1}^{T}\sum_{n=1}^{N} \lambda_{nt} Y_{nt} \geq Y \\ \sum_{t=1}^{T}\sum_{n=1}^{N} \lambda_{nt} C_{nt} = C \\ \lambda_{nt} \geq 0 \\ t = 1,2,3,\ldots,T \\ n = 1,2,3,\ldots,N \end{array} \tag{17}$$

λ_{nt} can be considered as the intensity variable by using convex combinations. Zhou, Ang and Wang [52] proposed a formal definition of the NDDF:

$$\overrightarrow{ND}(K,L,E,Y,C;g) = \sup\left\{w^T\beta : ((K,L,E,Y,C) + diag(\beta)\cdot g)\epsilon T\right\} \tag{18}$$

where $w = (w_K, w_L, w_E, w_Y, w_C)^T$ represents the weight given to each factor, and $g = (g_K, g_E, g_L, g_Y, g_C)^T$ represents the change direction of each factor. $\beta = (\beta_K, \beta_E, \beta_L, \beta_Y, \beta_C)^T \geq 0$ is the slack vector, representing the rate of increase or decrease of each factor. $diag(\beta)$ means the diagonalization of β. To measure the ECP of the MI, this paper sets the weight vector as $w = \left(0,0,\frac{1}{3},\frac{1}{3},\frac{1}{3}\right)^T$, the direction vector as $g = (0,0,-E,Y,-C)$, and the slack vector as $\beta = (0,0,\beta_E,\beta_Y,\beta_C)^T \geq 0$. The NDDF's linear optimization problem can be described as follows:

$$\begin{array}{c} \overrightarrow{ND}(K,\ E,\ L,\ Y,\ C;g) = max\ w_E\beta_E + w_Y\beta_Y + w_C\beta_C \\ \sum_{t=1}^{T}\sum_{n=1}^{N} \lambda_{nt} K_{nt} \leq K \\ \sum_{t=1}^{T}\sum_{n=1}^{N} \lambda_{nt} L_{nt} \leq L \\ \sum_{t=1}^{T}\sum_{n=1}^{N} \lambda_{nt} E_{nt} \leq E - \beta_E g_E, \\ \sum_{t=1}^{T}\sum_{n=1}^{N} \lambda_{nt} Y_{nt} \geq Y + \beta_Y g_Y, \\ \sum_{t=1}^{T}\sum_{n=1}^{N} \lambda_{nt} C_{nt} = C - \beta_C g_C, \\ \beta_E,\beta_Y,\beta_C \geq 0,\ \lambda_{nt} \geq 0 \\ n = 1,2,3,\ldots,N\ t = 1,2,\ldots,T \end{array} \tag{19}$$

According to Equation (19), the optimization result is $\beta^* = \left(0,0,\ \beta_E^*,\beta_Y^*,\beta_C^*\right)^T$. According to Zhou, Ang, and Wang [52], the energy and carbon performance index (ECPI) can be expressed as:

$$ECPI = \frac{\frac{1}{2}\left[\left(1-\beta_E^*\right) + \left(1-\beta_C^*\right)\right]}{1 + \beta_Y^*} \tag{20}$$

The value of *ECPI* is between 0 and 1. The higher the value, the better the ECP.

2.3. Impact of the Carbon Tax on MI's ECP

The carbon tax can cause changes in energy prices. According to Agostini et al. [53], the energy price rise because of the carbon tax is described as follows:

$$\Delta p_i = \frac{t \times e_i}{p_i} \times 100\% \; (i = CO, OI, EL) \tag{21}$$

where ΔP_i is the increasing rate of the i-th energy's price. t means the carbon tax rate. e_i represents the CO_2 emission coefficient of the i-th energy. p_i is the initial price of the i-th energy source. Based on similar research [32,44], this paper assumes that the carbon tax price is 50 yuan/ton. According to Chen [54], the calculation of CO_2 emissions can be described as follows:

$$C_t = \sum E_i \times NCV_i \times CEF_i \times COF_i \times (\frac{44}{12}) \tag{22}$$

where C_t is CO_2 emission. E_i is the consumption of each energy. NCV_i represents the average low calorific value; CEF_i is the carbon coefficient in the 2006 IPCC report; COF_i is carbon oxidation factor. According to Equation (22), the CO_2 emission coefficient of each energy can be expressed with the following equation:

$$e_i = NCV_i \times CEF_i \times COF_i \times (\frac{44}{12}) \tag{23}$$

Therefore, levying a carbon tax will change the energy prices as follows:

$$np_i = (1 + \Delta p_i) \times p_i \; (i = CO, OI, EL) \tag{24}$$

where np_i is the i-th energy price after levying the tax. The change in energy price will cause the change in energy demand, which can be described as follows:

$$\Delta E_i = \sum_j \Delta p_j \times \varepsilon_{ij}^* \times E_i \; (i, j = CO, OI, EL) \tag{25}$$

Among them, ε_{ij}^* is the own-price elasticity and cross-price elasticity of each energy type in Equation (15). Changing the consumption of different energy types will lead to changes in the energy structure of the MI, resulting in changing the total energy price index. Therefore, the total energy price index of the MI must be re-estimated with Equations (10) and (13) so that the changes in the labor and capital stock of the MI can be further calculated. The changes of capital and labor are as follows:

$$\Delta D_i = \left(\frac{\Delta P_E}{P_E}\right) \cdot \eta_{iE} \cdot D_i \; (i = K, L) \tag{26}$$

ΔPE represents the change in the MI's total energy price index. D_i is the original demand of the i-th input factor and η_{iE} is the cross-price elasticity between energy and the i-th input factor. Finally, due to the change of energy structure caused by the carbon tax, the change of carbon dioxide emission of the MI can be described as follows:

$$\Delta CO_2 = \sum_i \sum_j \Delta p_j \times \varepsilon_{ij}^* \times E_i \times e_i \; (i, j = CO, OI, EL) \tag{27}$$

The changes in ECP of the MI due to the carbon tax can be calculated by Equations (26) and (27).

2.4. Data Processing

The panel data of China's MI spans from 2004 to 2019. Based on similar research [32,38,42–44,46], this paper chooses the main variables which are necessary for calculating the price elasticities with a two-stage translog function, including capital stock (K) and its price (P_K), the labor (L) and its price (P_L), energy consumption (E) and its classified price (P_{CO}, P_{OI}, P_{EL}), the gross industrial output value (Y), and carbon dioxide emission (C). Considering that some provinces have a small proportion of the MI or lack the data, this paper excludes the observation data from Beijing, Shanghai, Zhejiang, Jiangsu, Hainan, and Tibet to ensure estimation accuracy. All nominal variables in this paper are deflated to the fixed price in 2004.

The gross industrial output value data is taken from China Industry Statistical Yearbook [55]. Since the China Industry Statistics Yearbook from 2012 to 2016 only counts the industrial sales output value of the MI, the average ratio between the gross industrial output value and the industrial sales output value from 2004 to 2011 is adopted to estimate the gross industrial output value from 2012 to 2016. From 2018 to 2019, the statistical subjects of the China Industry Statistical Yearbook have changed. Therefore, this paper uses the operating income of the MI to replace the gross industrial output value. The data in 2017 are measured by the linear interpolation method since they are not counted.

The perpetual inventory method is employed to measure the MI's capital stock, which is described as follows:

$$K_{it} = K_{it-1}(1 - \delta_{it}) + I_{it} \tag{28}$$

K_{it} represents the capital stock. δ_{it} stands for depreciation rate. I_{it} is fixed asset investment. The depreciation rate is weighted according to the classification of the investment, and the fixed asset investment data of the MI is extracted from China Statistical Yearbook. The price of capital stock is measured as follows [44]:

$$P_K(it) = r(t) + \delta(t) - \pi(it) \quad (29)$$

where, $P_K(it)$ is the price of capital stock in each province. $r(t)$ means the loan interest rate of the fixed asset. $\delta(t)$ is the depreciation rate in Equation (28). $\pi(it)$ means the actual inflation rate calculated according to the consumer price index (CPI) of each province. The loan interest rate and the CPI of each province are extracted from the CEIC database [56].

The labor data is extracted from China Industry Statistical Yearbook [55]. Due to the lack of data on labor in 2011, the linear interpolation method is adopted to supplement the data. The average annual wage of the MI represents the labor price, which is extracted from the China Labor Statistical Yearbook [57].

The energy consumed by the MI includes raw coal, coke, washed coal, other washed coal, crude oil, gasoline, diesel, kerosene, fuel oil, liquefied petroleum gas, natural gas, and electricity. For ease of calculation, this paper combines raw coal, coke, washed coal, and other washed coal into coal consumption; and combines crude oil, gasoline, diesel, kerosene, fuel oil, and liquefied petroleum gas into oil consumption. Because the natural gas consumption of the MI is small and the unit is not easy to be unified with other energy varieties, this paper ignores the natural gas consumption. Electricity consumption in the MI is a separate category. The energy prices are extracted from the CEIC database [56]. Due to the lack of provincial industrial energy price data, this paper takes the energy prices of coal, oil, and natural gas in provincial capitals in 2004 as the benchmark price and uses the provincial energy purchase price index to calculate the energy prices. The power price of each provincial capital city is used as the proxy variable of the power price of the MI. The calculation method of CO_2 emission is the same as that in Zhu and Lin [58], which will not be repeated in this paper. The descriptive statistics of all data are shown in Table 1.

Table 1. Descriptive statistics of data.

Variables	Unit	N	Mean	Sd	Min	Max
C	10^4 tons	400	4430.00	5890.00	34.44	32,419.00
Y	10^8 CNY	400	953.50	971.70	43.69	5249.00
L	10^4 persons	400	25.95	23.62	1.24	108.40
K	10^8 CNY	400	1541.00	1344.00	21.07	6441.00
E	10^4 tons of standard coal	400	1624.00	2140.00	28.62	11,680.00
P_K	/	400	0.16	0.02	0.10	0.25
P_L	CNY/person	400	49,821.00	26,875.00	10,838.00	144,803.00
P_{EL}	CNY/10^4 KW·h	400	6981.00	1243.00	3640.00	9300.00
P_{OI}	CNY/ton	400	6841.00	1512.00	4095.00	12,895.00
P_{CO}	CNY/ton	400	679.20	207.10	242.20	1361.00

3. Empirical Results

In other similar studies, few scholars paid attention to the control variables when estimating the price elasticity with the two-stage translog cost function. Yang, Fan, Yang and Hu [44] took the industrial structure and economic development level as control variables because they believed those factors can influence the price elasticities. Moreover, based on Lin and Zhu [59], the ownership structure can influence the rebound effect of MI, which may affect its energy price elasticity. Therefore, to eliminate the influence of other endogenous factors, this paper chooses economic development level, industrial structure, and ownership structure as control variables. Industrial structure refers to the proportion of MI in the whole industry in each province. The economic development level refers to the per capita GDP in each province. The ownership structure refers to the proportion of MI's state-owned capital in each province. This paper employs the step-by-step method to calculate the required parameters to calculate the price elasticity of energy and input factors. First, Equation (11) is estimated by the seemingly uncorrelated regression (SUR) method. The total energy price index is calculated by Equation (10). Finally, the parameters in Equation (6) are estimated using the SUR method. After getting the corresponding parameters, the price elasticity can be calculated through Equations (9), (14), and (15). It should be noted that the energy price used in Equation (6) is the total energy price index calculated by Equation (10). On the other hand, there are two reasons that the constant term in Equation (10) is ignored. Firstly, because Equation (11) is derived from Equation (10), the constant term is eliminated in Equation (11). Secondly, when estimating Equation (6), the logarithm of the total energy price index of the MI is used. Therefore, ignoring the constant term in Equation (10) will not affect the estimation result of Equation (6).

3.1. Estimation Results of Energy Cost Share Equation and Input Cost Share Equation

Equation (11) is estimated by the SUR method. Due to the constraints of Equation (13), when assessing the simultaneous equations, a singular matrix will be generated. Therefore, one of the equations must be deleted. The estimation results are expressed in Table 2. In the coal cost share equation, except for the coefficient of oil price which is not significant, the coefficient of other energy prices is significant at 1%, and the constant term's coefficient is significant at 5%. In the electricity cost share equation, the coefficients of all energy prices and constant term are significant at 1%.

Table 2. Estimation results of energy cost share equation.

Variables	S_{CO}^{fuel}	S_{EL}^{fuel}
lnP_{EL}	0.114 ***	0.245 ***
	(3.394)	(7.117)
lnP_{OI}	0.0261	−0.359 ***
	(0.718)	(−11.08)
lnP_{CO}	−0.140 ***	0.114 ***
	(−2.681)	(3.394)
t	0.0259 ***	−0.000751
	(6.577)	(−0.273)
Constant	0.274 **	0.470 ***
	(2.112)	(5.531)
Control variables	Yes	Yes
Observations	400	400
R-squared	0.166	0.217

z-statistics in parentheses. *** $p < 0.01$, ** $p < 0.05$.

According to the estimation results of Equation (11), the total energy price index of the MI can be measured by Equation (10). As for estimating the factor cost share equation, similar to the energy cost share equation, to avoid generating a singular matrix in the estimation process, the energy cost equation is deleted, as the estimation results of capital and labor cost equations are shown in Table 3. In the capital cost share equation, the coefficients of all input factor prices and constant term are significant at 1%. In the labor cost share equation, except that the coefficient of total energy price is significant at 5%, the coefficients of other input factor prices and the constant term are significant at 1%. According to the estimation results of the energy cost share equation and input factor cost share equation, most of the coefficients are significant at 1%, indicating that the translog function has an excellent explanatory ability for the energy cost and input factor cost of the MI.

3.2. The Price Elasticity of Energy and Input Factors

According to the coefficients estimated by the energy cost share equation and the input factor cost share equation, the price elasticity of energy and input factors of the MI can be obtained. For the own-price elasticity, if it is positive, the demand for energy or input factors will increase with the price rise. If it is negative, the demand for energy or input factors will decrease with the price increase. For the cross-price elasticity, if it is positive, it means that the two kinds of energy sources or input factors are substitutes. If it is negative, it means that the two kinds of energy sources or input factors are complements.

The improved energy price elasticity of the MI can be measured based on Equation (15). In Table 4, except for the oil price elasticity which is positive, the coal and electricity price elasticities are negative for the own-price elasticity. It indicates that the demand for coal and electricity in the MI gradually decreases with the rise of price, while the oil demand gradually increases. The coal own-price elasticity's absolute value is greater than 1, indicating that China's MI's coal demand is very sensitive to price. Coal accounts for the most significant share in the total energy consumption of the MI due to China's special resource endowment. During the 13th Five Year Plan, the government requires to control the total energy consumption and energy intensity, which means that by 2020, the unit energy consumption will decrease by 15% compared with that in 2015, and the total energy consumption will be limited in 5 billion tons of standard coal. According to the "double control" policy, coal consumption must be limited to reduce energy intensity. For China's MI, rising coal prices can control coal consumption effectively.

Table 3. Estimation results of input factor cost share equation.

Variables	S_K	S_L
lnP_K	0.151 ***	−0.0744 ***
	(5.619)	(−5.313)
lnP_E	−0.0765 ***	0.0329 **
	(−2.957)	(2.213)
lnP_L	−0.0744 ***	0.0414 ***
	(−5.313)	(2.740)
lnY	−0.0537 ***	0.0201 ***
	(−6.833)	(4.769)
t	0.0182 ***	−0.00749 ***
	(6.632)	(−3.584)
Constant	2.038 ***	−0.648 ***
	(7.561)	(−4.341)
Control variables	Yes	Yes
Observations	400	400
R-squared	0.457	0.224

z-statistics in parentheses. *** $p < 0.01$, ** $p < 0.05$.

Table 4. Own-price and cross-price elasticity of energy.

Own-Price Elasticity		Cross-Price Elasticity	
ε^*_{CO-CO}	−1.058	ε^*_{CO-EL}	0.385
ε^*_{EL-EL}	−0.093	ε^*_{CO-OI}	0.140
ε^*_{OI-OI}	0.879	ε^*_{EL-CO}	0.580
		ε^*_{EL-OI}	−1.019
		ε^*_{OI-CO}	0.369
		ε^*_{OI-EL}	−1.781

On the other hand, the electricity's own-price elasticity's absolute value is the lowest among the three energy sources, implying that the MI's electricity demand is not sensitive to price changes, which is consistent with the conclusions in Li and Lin [32] and Tan and Lin [42]. Due to the proposal of the goal of carbon neutralization, China is accelerating the process of electrification and expanding the proportion of power in the use of terminal energy in various industries. Therefore, the electricity demand is more rigid than that of coal. As for oil, its own-price elasticity is positive, which indicates that the oil price is distorted. The results are similar to Yang, Fan, Yang, and Hu [44].

There is a substitution relationship between energy types in the MI for the cross-price elasticity between electricity and coal, oil and coal. The cross-elasticity coefficient is less than 1, indicating that these energy sources lack elasticity with each other, and the actual effect of adjusting the mining energy structure by changing the energy prices may be limited. On the other hand, electricity and oil are complementary, indicating that oil and electricity are difficult to replace each other. Since the operation of the MI requires much mechanical equipment, oil and electricity represent the core energy of production and operation. Thus, when the increase of mining equipment causes the rise in oil consumption, the scale of the logistics department also needs to be expanded, so the electricity consumption will also rise.

The price elasticity between input factors can be measured according to Equation (9). In Table 5, the own-price elasticity of capital stock, energy, and labor is negative, indicating that the demand for all input factors will decline with the price rising. All input factors' own-price elasticity's absolute values are less than 1, meaning that the demands of all input factors are not sensitive to the change of prices. The capital stock has the smallest absolute value, and the labor has the largest. Tan and Lin [42] and Du, Lin, and Li [46] have reached similar conclusions. As the MI is an energy-intensive industry, its fixed assets' proportion is high such as plants and mining facilities, which is hard to adjust in the short term. Therefore, mining enterprises are more dependent on capital stock. On the other hand, the rigidity of the labor in the MI is the smallest, meaning that the change of labor demand is more sensitive than other input factors.

Table 5. Own-price and cross-price elasticity of input factors.

Own-Price Elasticity		Cross-Price Elasticity	
η_{K-K}	−0.216	η_{K-E}	0.168
η_{E-E}	−0.532	η_{K-L}	0.048
η_{L-L}	−0.592	η_{E-K}	0.221
		η_{E-L}	0.312
		η_{L-K}	0.100
		η_{L-E}	0.493

The cross-price elasticities between all input factors are positive, meaning that there are substitution relationships between all input factors. However, the absolute values of all cross-price elasticity are less than 1, indicating that both labor and capital stock can only finitely replace energy. Similar to the research results of Li and Lin [32] and Du, Lin, and Li [46], among the cross-price elasticities of input factors, the cross-price elasticity between energy and labor is the largest. China has a large population base and rich labor resources. Using labor to substitute for energy consumption can not only reduce CO_2 emission but also alleviate the pressure of social employment. There is a substitution relationship between energy and capital in the MI, which is similar to the research results of Pindyck [37], Ma, Oxley, Gibson, and Kim [39], and Wang and Lin [41]. According to Li and Lin [32], if enterprises update their production equipment, their production efficiency will be improved, as less energy will be consumed under the same output. Therefore, increasing the investment in energy-saving equipment and R&D funds is instrumental in reducing energy investment.

4. Results and Discussion

This part explores the influence of carbon tax on the MI's ECP. Since the government has not imposed the carbon tax at this stage, this paper follows similar research to set the carbon tax price at 50 yuan/ton. According to Zhu and Lin [58], China's provinces can be divided into three regions. Table 6 shows the regional classification.

Table 6. The area classification.

Region	Provinces
Eastern	Tianjin, Hebei, Liaoning, Fujian, Shandong, Guangdong
Central	Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan
Western	Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang

Due to the different CO_2 emission coefficients, the carbon tax levied per unit consumption of the various energy sources is different under the fixed carbon tax rate. Levying carbon tax will cause changes in energy prices, which will cause changes in various energy consumption in the MI, resulting in changes in CO_2 emission and the total energy price index. The changes in input factors can be calculated according to the own-price elasticity and cross-price elasticity of input factors. Assuming that the desired output of the MI remains unchanged, the change of the MI's CO_2 emission and ECP can be measured according to the new input factors.

According to Equation (27), the MI's CO_2 emission reduction potential is calculated in each region. Based on Figure 1, assuming that the carbon tax rates are 50 yuan/ton, in 2019, the MI's CO_2 emission reduction potential in China is 121.13 million tons. Yang, Fan, Yang, and Hu [44] explored the influence of the carbon tax on China's CO_2 mitigation. The results show that 197 million tons of CO_2 can be eliminated in 2010 under the 50 yuan/ton tax rate. Li and Lin [32] explored that the carbon tax can cause 311.2 million tons of CO_2 mitigation in 2012 under the 50 yuan/ton tax rate. Liu and Lin [45] explored that China's building construction industry can mitigate 3.83 million tons of CO_2 in 2012 under the 50 yuan/ton tax rate. Du, Lin, and Li [46] found that levying a carbon tax of 50 yuan/ton can eliminate 62.67 million tons of China's metallurgical industry's CO_2 emissions. According to the previous studies, levying a carbon tax can indeed reduce carbon dioxide emission at the national level and the industrial level. Due to the huge amount of CO_2 emission, the MI's CO_2 emission reduction potential is greater than that of the traditional manufacturing industries. Moreover, the carbon dioxide emission reduction potential in the eastern area is the smallest, while that of the western area is the largest. The carbon tax will increase energy costs and make the mining enterprises use capital and labor instead of energy. The reduction of energy consumption will decrease CO_2 emissions. As the western region is rich in coal, oil, and gas resources and the mining enterprises are mostly concentrated in the western region, the carbon tax takes more conspicuous emission reduction effects in the western area.

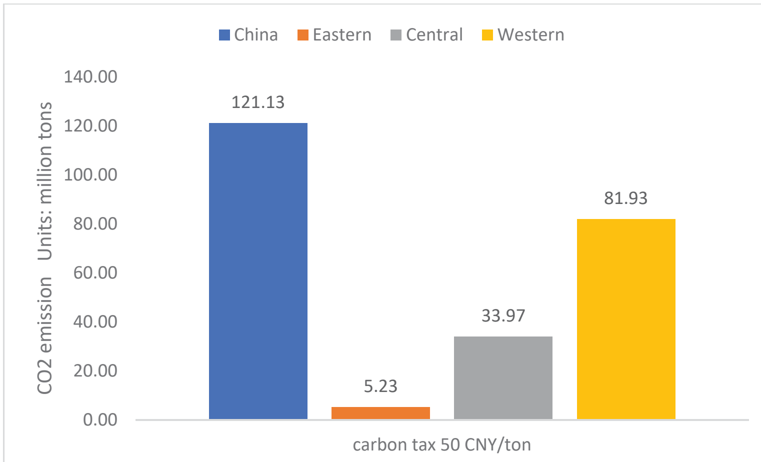


Figure 1. CO_2 emission reduction potential of the MI in 2019.

The samples under different carbon tax rates are put into one technology set to calculate the ECP. As shown in Figure 2, without the carbon tax, the average value of the ECP is 0.211. When the carbon tax rate is 50 yuan/ton, the average ECP of China's MI is 0.218, which is 2.86% higher than that without the carbon tax. Among the regions, the ECP of the MI in the eastern region does not increase, while that of the central and western regions significantly improved. Under the carbon tax rate of 50 yuan/ton, the ECP of the MI in the western region increases by 7.24% compared with that without a carbon tax, and the growth rate is the largest among all regions.

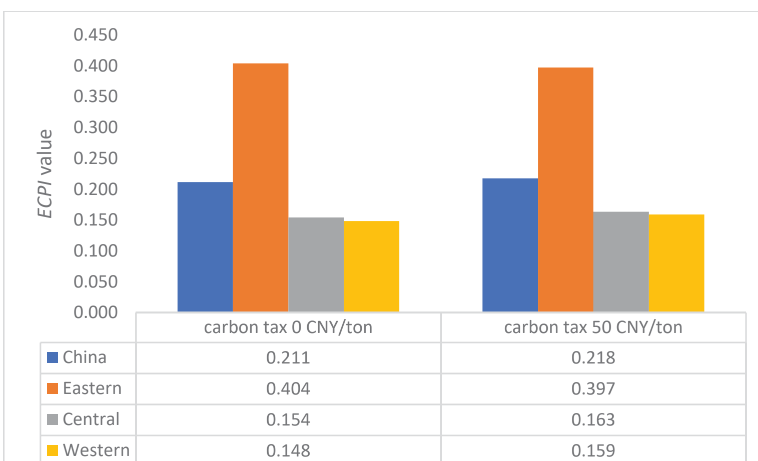


Figure 2. Changes in ECP of the MI in regions from 2004 to 2019.

Due to the carbon tax, the mining enterprises will prefer capital and labor to energy in the production process. Further, the carbon tax can also optimize the energy consumption structure of mining enterprises and promote enterprises to choose cleaner energy. Without a carbon tax, the ECP of the MI in the eastern region is much higher than that in the central and western regions because the eastern region has a higher level of economic development, a stricter environmental management system, and advanced production technology. Therefore, the carbon tax's impact on the ECP in the eastern region is not significant. On the other hand, the technological level of the central and western areas is comparatively backward, as they lack talents and capital compared with the eastern region. Therefore, most mining enterprises in the central and western areas use energy to replace capital and labor, resulting in low ECP. Higher energy prices will force the MI in central and western regions to use capital and labor to replace energy consumption. Therefore, the carbon tax policy significantly promotes the MI's ECP in the central and western regions.

5. Conclusions and Policy Recommendations

5.1. Conclusions

Based on the price elasticity of energy and input factors, this paper estimates the carbon tax's influence on the ECP of China's MI. Firstly, the price elasticity of energy and input factors in the MI is estimated with the two-stage translog cost function. Secondly, the changes in MI's ECP in each region are calculated with NDDF. The conclusions are as follows:

For the energy price elasticity of the MI, except for the oil's own-price elasticity, which is positive, the own-price elasticities of coal and electricity are negative, meaning that the demand for coal and electricity in the MI decreases with the increase of price. Moreover, except for the cross-price elasticities between oil and electricity, which are negative, the other cross-price elasticities are positive, indicating that oil and electricity are complimentary, while the other types of energy are substitutes. For the price elasticity of input factors in the MI, the own-price elasticity of all input factors is positive, meaning that the demand for capital, labor, and energy decreases with the price increase. The cross-price elasticities of all input factors are positive, meaning that the MI's capital, labor, and energy are substitutes. It is shown that the carbon tax can significantly decrease the CO_2 emission of the MI and promote its ECP. Under the carbon tax rate of 50 yuan/ton, the ECP of the MI in the eastern area does not raise, while that of the central and western areas significantly improved.

5.2. Policy Recommendations

Based on the calculation results of this paper, the carbon tax cannot only reduce the carbon dioxide emission of the MI but also promote its ECP. Although the carbon trading market has been launched in China, it still needs a long process to cover enough industries. While promoting China's carbon trading market, the government should join fiscal and tax means to promote carbon emission reduction, such as levying carbon tax on industries not included in the carbon trading market. At present, China only collects resource tax on fossil energy. In 2016, the Chinese government began to implement the resource tax reform, changing the resource tax from quantity-based tax to ad valorem tax [60], which can better reflect the scarcity of mineral resources. However, resource tax is a tax levied on producers, which can only increase the energy cost in the upstream link. If the energy price is distorted, it cannot transfer the negative externalities of energy use to consumers, which has a limited influence on CO_2 emission reduction. Moreover, the resource tax is not designed for CO_2 emission reduction, and its tax rate cannot effectively reflect the CO_2 emission coefficients of different energy types. According to Hu, Dong, and Zhou [31], compared with resource tax, the carbon tax has greater advantages in energy utilization and environmental protection. Therefore, the government should accelerate the process of carbon tax policy.

According to the energy cross-price elasticity of MI, the effect of using electricity to replace coal and oil is limited. Moreover, the absolute value of the input factors cross-price elasticity is small, which indicates that the effect of using labor and capital stock to replace energy is limited. Since the MI is a high energy-consuming industry and the energy demand is rigid, the government should promote the upgrading of the MI's energy structure. At present, the National Development and Reform Commission encourages electrolytic aluminum enterprises to improve the utilization level of non-aqueous renewable energy such as wind power and photovoltaic power, which should occupy more than 15% of the total power consumption [61]. Therefore, the government should encourage mining enterprises to increase the proportion of renewable energy. Li and Lin [32] believe that government departments should also take a variety of measures to limit the use of fossil energy, such as restricting enterprises from installing and using high-carbon facilities. Further, the government can introduce new fiscal and tax policies to support the development of low-carbon projects in the MI. For example, preferential tax rates can be given to low-carbon projects.

5.3. Limitations and Future Research

This paper has limitations. This paper uses the price elasticity between energy and input factors in the MI to predict the changes in energy structure and input factors caused by the carbon tax. However, the carbon tax may influence the price elasticity and lead to a deviation of the results. The future study will build a CGE model to estimate the influence of exogenous policies on the MI's energy efficiency.

Author Contributions: Conceptualization, R.Z. and B.L.; methodology, R.Z.; software, R.Z.; validation, R.Z. and B.L.; formal analysis, B.L.; investigation, B.L.; resources, B.L.; data curation, R.Z.; writing—original draft preparation, R.Z.; writing—review and editing, R.Z.; visualization, R.Z.; supervision, B.L.; project administration, B.L.; funding acquisition, B.L. All authors have read and agreed to the published version of the manuscript.

Funding: This paper is supported by the National Natural Science Foundation of China (Key Program, No. 72133003).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: [https://data.cnki.net/Yearbook/Navi?type=type&code=A] (accessed on 10 September 2021).

Acknowledgments: We are very grateful to the anonymous reviewers for their careful review work and their constructive comments.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chen, B.; Zhang, H.; Li, W.; Du, H.; Huang, H.; Wu, Y.; Liu, S. Research on provincial carbon quota allocation under the background of carbon neutralization. *Energy Rep.* **2022**, *8*, 903–915.
2. Looney, B. *Statistical Review of World Energy*; BP p.l.c.: London, UK, 2021.
3. Grossman, G.M.; Krueger, A.B. *Environmental Impacts of a North American Free Trade Agreement*; National Bureau of Economic Research: Cambridge, MA, USA, 1991.
4. China Energy Statistical Yearbook. Available online: https://data.cnki.net/yearbook/Single/N2021050066 (accessed on 10 September 2021).
5. Ouyang, X.; Fang, X.; Cao, Y.; Sun, C. Factors behind CO_2 emission reduction in Chinese heavy industries: Do environmental regulations matter? *Energy Policy* **2020**, *145*, 111765.
6. Zhou, C.; Zhou, S. China's Carbon Emission Trading Pilot Policy and China's Export Technical Sophistication: Based on DID Analysis. *Sustainability* **2021**, *13*, 14035.
7. Xia, Q.; Li, L.; Dong, J.; Zhang, B. Reduction Effect and Mechanism Analysis of Carbon Trading Policy on Carbon Emissions from Land Use. *Sustainability* **2021**, *13*, 9558.
8. Wu, Q.; Tambunlertchai, K.; Pornchaiwiseskul, P. Examining the Impact and Influencing Channels of Carbon Emission Trading Pilot Markets in China. *Sustainability* **2021**, *13*, 5664.
9. Available online: http://www.hb.xinhuanet.com/2021--07/17/c_1127665800.htm (accessed on 10 September 2021).
10. Wittneben, B.B.F. Exxon is right: Let us re-examine our choice for a cap-and-trade system over a carbon tax. *Energy Policy* **2009**, *37*, 2462–2464.
11. Zhou, D.; An, Y.; Zha, D.; Wu, F.; Wang, Q. Would an increasing block carbon tax be better? A comparative study within the Stackelberg Game framework. *J. Environ. Manag.* **2019**, *235*, 328–341.
12. Arthur, P. *The Economics of Welfare*; (3rd edition 1928); McMillan and Co.: London, UK, 1920.
13. Tullock, G. Excess benefit. *Water Resour. Res.* **1967**, *3*, 643–644.
14. Pearce, D. The role of carbon taxes in adjusting to global warming. *Econ. J.* **1991**, *101*, 938–948.
15. Newell, R.G.; Pizer, W.A. Regulating stock externalities under uncertainty. *J. Environ. Econ. Manag.* **2003**, *45*, 416–432.
16. Goulder, L.H.; Schein, A.R. Carbon taxes versus cap and trade: A critical review. *Clim. Chang. Econ.* **2013**, *4*, 1350010.
17. Zhang, Z.; Baranzini, A. What do we know about carbon taxes? An inquiry into their impacts on competitiveness and distribution of income. *Energy Policy* **2004**, *32*, 507–518.
18. Newell, R.G.; Pizer, W.A. Indexed regulation. *J. Environ. Econ. Manag.* **2008**, *56*, 221–233.
19. Chen, J.-X.; Chen, J. Supply chain carbon footprinting and responsibility allocation under emission regulations. *J. Environ. Manag.* **2017**, *188*, 255–267.
20. He, S.; Yin, J.; Zhang, B.; Wang, Z. How to upgrade an enterprise's low-carbon technologies under a carbon tax: The trade-off between tax and upgrade fee. *Appl. Energy* **2018**, *227*, 564–573.

21. Ghaith, A.F.; Epplin, F.M. Consequences of a carbon tax on household electricity use and cost, carbon emissions, and economics of household solar and wind. *Energy Econ.* **2017**, *67*, 159–168.
22. Chen, W.; Hu, Z.-H. Using evolutionary game theory to study governments and manufacturers' behavioral strategies under various carbon taxes and subsidies. *J. Clean. Prod.* **2018**, *201*, 123–141.
23. Brown, M.A.; Li, Y.; Soni, A. Are all jobs created equal? Regional employment impacts of a U.S. carbon tax. *Appl. Energy* **2020**, *262*, 114354.
24. Denstadli, J.M.; Veisten, K. The flight is valuable regardless of the carbon tax scheme: A case study of Norwegian leisure air travelers. *Tour. Manag.* **2020**, *81*, 104150.
25. Cheng, Y.; Sinha, A.; Ghosh, V.; Sengupta, T.; Luo, H. Carbon tax and energy innovation at crossroads of carbon neutrality: Designing a sustainable decarbonization policy. *J. Environ. Manag.* **2021**, *294*, 112957.
26. Gokhale, H. Japan's carbon tax policy: Limitations and policy suggestions. *Curr. Res. Environ. Sustain.* **2021**, *3*, 100082.
27. Hammerle, M.; Best, R.; Crosby, P. Public acceptance of carbon taxes in Australia. *Energy Econ.* **2021**, *101*, 105420.
28. Zhou, Y.; Fang, W.; Li, M.; Liu, W. Exploring the impacts of a low-carbon policy instrument: A case of carbon tax on transportation in China. *Resour. Conserv. Recycl.* **2018**, *139*, 307–314.
29. Shi, Q.; Ren, H.; Cai, W.; Gao, J. How to set the proper level of carbon tax in the context of Chinese construction sector? A CGE analysis. *J. Clean. Prod.* **2019**, *240*, 117955.
30. Li, X.; Yao, X.; Guo, Z.; Li, J. Employing the CGE model to analyze the impact of carbon tax revenue recycling schemes on employment in coal resource-based areas: Evidence from Shanxi. *Sci. Total Environ.* **2020**, *720*, 137192.
31. Hu, H.; Dong, W.; Zhou, Q. A comparative study on the environmental and economic effects of a resource tax and carbon tax in China: Analysis based on the computable general equilibrium model. *Energy Policy* **2021**, *156*, 112460.
32. Li, J.; Lin, B. Inter-factor/inter-fuel substitution, carbon intensity, and energy-related CO_2 reduction: Empirical evidence from China. *Energy Econ.* **2016**, *56*, 483–494.
33. Smyth, R.; Kumar Narayan, P.; Shi, H. Inter-fuel substitution in the Chinese iron and steel sector. *Int. J. Prod. Econ.* **2012**, *139*, 525–532.
34. Lin, B.; Wesseh, P.K. Estimates of inter-fuel substitution possibilities in Chinese chemical industry. *Energy Econ.* **2013**, *40*, 560–568.
35. Bloch, H.; Rafiq, S.; Salim, R. Economic growth with coal, oil and renewable energy consumption in China: Prospects for fuel substitution. *Econ. Model.* **2015**, *44*, 104–115.
36. Cho, W.G.; Nam, K.; Pagán, J.A. Economic growth and interfactor/interfuel substitution in Korea. *Energy Econ.* **2004**, *26*, 31–50.
37. Pindyck, R.S. Interfuel substitution and the industrial demand for energy: An international comparison. *Rev. Econ. Stat.* **1979**, *61*, 169–179.
38. Liu, K.; Bai, H.; Yin, S.; Lin, B. Factor substitution and decomposition of carbon intensity in China's heavy industry. *Energy* **2018**, *145*, 582–591.
39. Ma, H.; Oxley, L.; Gibson, J.; Kim, B. China's energy economy: Technical change, factor demand and interfactor/interfuel substitution. *Energy Econ.* **2008**, *30*, 2167–2183.
40. Lin, B.; Tian, P. Energy conservation in China's light industry sector: Evidence from inter-factor and inter-fuel substitution. *J. Clean. Prod.* **2017**, *152*, 125–133.
41. Wang, X.; Lin, B. Factor and fuel substitution in China's iron & steel industry: Evidence and policy implications. *J. Clean. Prod.* **2017**, *141*, 751–759.
42. Tan, R.; Lin, B. The influence of carbon tax on the ecological efficiency of China's energy intensive industries—A inter-fuel and inter-factor substitution perspective. *J. Environ. Manag.* **2020**, *261*, 110252.
43. Lin, B.; Xu, M. Exploring the green total factor productivity of China's metallurgical industry under carbon tax: A perspective on factor substitution. *J. Clean. Prod.* **2019**, *233*, 1322–1333.
44. Yang, M.; Fan, Y.; Yang, F.; Hu, H. Regional disparities in carbon dioxide reduction from China's uniform carbon tax: A perspective on interfactor/interfuel substitution. *Energy* **2014**, *74*, 131–139.
45. Liu, H.; Lin, B. Energy substitution, efficiency, and the effects of carbon taxation: Evidence from China's building construction industry. *J. Clean. Prod.* **2017**, *141*, 1134–1144.
46. Du, Z.; Lin, B.; Li, M. Is factor substitution an effective way to save energy and reduce emissions? Evidence from China's metallurgical industry. *J. Clean. Prod.* **2021**, *287*, 125531.
47. Ma, H.; Oxley, L.; Gibson, J. Substitution possibilities and determinants of energy intensity for China. *Energy Policy* **2009**, *37*, 1793–1804.
48. Li, J.; Sun, C. Towards a low carbon economy by removing fossil fuel subsidies? *China Econ. Rev.* **2018**, *50*, 17–33.
49. Berndt, E.R.; Wood, D.O. Technology, Prices, and the Derived Demand for Energy. *Rev. Econ. Stat.* **1975**, *57*, 259–268.
50. Zha, D.; Zhou, D.; Ding, N. The determinants of aggregated electricity intensity in China. *Appl. Energy* **2012**, *97*, 150–156.
51. Floros, N.; Vlachou, A. Energy demand and energy-related CO_2 emissions in Greek manufacturing: Assessing the impact of a carbon tax. *Energy Econ.* **2005**, *27*, 387–413.
52. Zhou, P.; Ang, B.W.; Wang, H. Energy and CO2 emission performance in electricity generation: A non-radial directional distance function approach. *Eur. J. Oper. Res.* **2012**, *221*, 625–635.
53. Agostini, P.; Botteon, M.; Carraro, C. A carbon tax to reduce CO_2 emissions in Europe. *Energy Econ.* **1992**, *14*, 279–290.
54. Chen, S. Estimation of China's Industrial Sub-industry Statistics: 1980–2008. *China Econ. Q.* **2011**, *10*, 735–776. (In Chinese)

55. China Industry Statistical Yearbook. Available online: https://data.cnki.net/yearbook/Single/N2022010304 (accessed on 10 September 2021).
56. CEIC Data Base. Available online: https://insights.ceicdata.com/ (accessed on 10 September 2021).
57. China Labor Statistical Yearbook. Available online: https://data.cnki.net/yearbook/Single/N2021020042 (accessed on 10 September 2021).
58. Zhu, R.; Lin, B. Energy and carbon performance improvement in China's mining Industry: Evidence from the 11th and 12th five-year plan. *Energy Policy* **2021**, *154*, 112312.
59. Lin, B.; Zhu, R. How does market-oriented reform influence the rebound effect of China's mining industry? *Econ. Anal. Policy* **2022**, *74*, 34–44.
60. China State Taxation Administration. Notice on Comprehensively Promoting the Reform of Resource Tax. Available online: http://www.chinatax.gov.cn/n810341/n810755/c2132534/content.html (accessed on 10 September 2021).
61. China National Development and Reform Commission. Notice on Improving the Step Price Policy of Electrolytic Aluminum Industry. Available online: https://www.ndrc.gov.cn/xwdt/tzgg/202108/t20210827_1294890.html?code=&state=123 (accessed on 10 September 2021).

sustainability

MDPI

Article

Analysing the Pattern of Productivity Change in the European Energy Industry

Djula Borozan * and Dubravka Pekanov Starcevic

Faculty of Economics, University of Osijek, 31000 Osijek, Croatia; dubravka.pekanov@efos.hr
* Correspondence: borozan@efos.hr

Abstract: For an industry to succeed in a competitive market, it should continuously take care of not only its stakeholders but also its technical efficiency and productivity. In this paper, data envelopment analysis was combined with Malmquist productivity analysis to investigate the pattern of multifactor productivity changes in the European energy industry over the period from 2005–2016. The results showed that the whole industry was technically inefficient and had large potential for improvement. A slight average increase in productivity that was observed over the studied period proved to be sensitive to the financial and economic situation and equally sensitive to technological and efficiency advances. As for efficiency gains, they reflected the nature of the energy industry, implying that they were due to scale efficiencies rather than human resource improvements. Although technological innovation and the optimal scale of production increased productivity, the slow pace at which this occurred and the negative outlook highlighted by the observed trends call for more serious consideration of the future productivity deployment of the European energy industry, particularly in the context of its decarbonisation, diversification, and modernisation.

Keywords: productivity changes; technical efficiency; energy industry; DEA-based Malmquist productivity index; European Union

Citation: Borozan, D.; Pekanov Starcevic, D. Analysing the Pattern of Productivity Change in the European Energy Industry. *Sustainability* **2021**, *13*, 11742. https://doi.org/10.3390/su132111742

Academic Editor: Bertrand Hamaide

Received: 5 September 2021
Accepted: 22 October 2021
Published: 24 October 2021

1. Introduction

The increasing need for renewables and energy supply diversification as well as for continuous technological progress poses major challenges to the energy sector, which plays an important role in the European economy, directly employing around 1.61 million people and generating around EUR 250 billion in value added, equivalent to the around 4% of value added of the non-financial European Union (EU) business economy [1].

The EU is committed to ensuring energy security, sustainability, and affordability in the context of sustainable development. However, recent studies have shown that the European energy industry faces efficiency problems. Barros and Peypoch [2] and Borozan and Pekanov Starcevic [3] found evidence that energy companies in the EU do not operate at the efficiency frontier, which requires efficiency improvements and necessitates significant changes and structural transformations of the energy system. Transformation is critical to achieving the Paris Agreement targets [4] and the 2050 climate neutrality target set out in the European Green Deal [5], which aims to promote economic growth through the use of green technologies and to support the transition to a low-carbon economy. It also proposes a reduction in greenhouse gas (GHG) emissions to at least 55% by 2030 compared to 1990 levels, which is a significant increase from the 40% target set in the 2030 Climate and Energy Framework [6], as well as achieving the 7th and 3th United Nations Sustainable Development Goals (SDGs) [7]. At the same time, the EU's "Fit for 55 package" will enable the adaptation of current EU legislation to the 2030 and 2050 targets [8]. This will bring remarkable changes in the energy industry.

Increasing the efficiency of the energy industry is extremely important, as it leads to reducing energy costs, maintaining industry competitiveness, and generating revenue to finance investments [9]. Additionally, it leads to an increase in multifactor productivity (hereafter referred to as productivity), which is commonly defined as the ratio between aggregate outputs and aggregate inputs used in the production process. In the last decade, there have been few studies on the efficiency and productivity of the energy industry worldwide [10–12]. However, to the best of our knowledge, there have been no studies analysing productivity changes in the European energy industry. Only its subsectors have been the subject of such analyses [13–15]. This is surprising, especially from a policy point of view, considering that the EU wants to take further steps towards an integrated energy market and a common energy policy.

This paper aims to provide evidence of changes in terms of the multifactor productivity of the European energy industry during the period from 2005–2016, i.e., the period before the powerful institutional changes in the energy industry took place, particularly the Paris Agreement [4], which came into force in 2016, and the Energy Union Strategy [16], which was published in 2015. Following the production function approach and global environmental requirements, productivity changes are considered in a multivariate framework that consists of both desirable and undesirable outputs—revenues and GHG emissions, respectively, and three inputs—labour, investment, and assets. By applying this approach, the paper separates the effects of changes in efficiency from those related to technological changes. It also examines the causes of changes in efficiency, both those related to pure technical efficiency and those resulting from changes in the scale of efficiency.

Data were retrieved from the annual financial reports of the main energy companies in each EU country. Since these companies had an average market share of more than 50% in their countries in 2016 [17] and since many of them have been on the list of the largest European energy companies based on total market capitalization [18,19], these companies are used as a proxy for the European energy industry. The paper first employs data envelopment analysis (DEA) and then Malmquist productivity index (MPI) analysis. The former is a linear programming-based technique that aims to estimate the relative efficiency of the decision-making units (DMUs) operating in the same industry by using multiple inputs to produce multiple outputs [20]. The latter uses mixed-period distance functions to calculate efficiency and productivity changes. The MPI allows researchers to distinguish between technical efficiency changes and technological changes [21]. A decomposition of these components, which relate to both efficiency and productivity changes, can provide insight into the trends and sources of productivity changes in the European energy industry.

The DEA method, originally proposed by Charnes et al. [20], has recently been applied to assess the performance of energy companies (Wu et al. [22] for China; Tavana et al. [23] for Iran; and Borozan and Pekanov Starcevic [3] for the European energy industry). However, these studies failed to consider productivity changes, which seem to be under the influence of turbulent economic times. Understanding the causes of these changes can help energy policy authorities and regulators at EU and national levels to initiate policy measures aimed at ensuring energy availability, increasing energy efficiency, and mitigating climate change.

This paper makes a threefold novel contribution to the literature. First, it considers the changes in productivity in the European energy industry, focusing on their sources–technological innovations and technical efficiency. Second, the paper shows that turbulent economic times have a negative impact on the productivity development path of European energy companies, indicating its procyclical pattern. The changes in efficiency and productivity are manifested along a mild downward trend that is caused by the delayed and inadequate responses of the energy industry to structural changes. Third, this paper provides strong support for the transformation of the European energy industry towards decarbonisation, diversification, and modernisation.

The remainder of this paper is organised as follows: The next section presents the conceptual background explaining multifactor productivity and the main findings from the literature. The second section describes the sample and data as well as the methodology used to calculate the changes in productivity. Section 3 discusses the main findings of the paper, and the last section provides conclusions.

2. Conceptual Background with a Literature Review

Multifactor productivity represents the portion of output that cannot be explained by the totality of inputs used in production and thus indicates the efficiency and intensity of the inputs used [24]. Productivity changes can be divided into two components: change in technical efficiency and technological change, resulting from catching up with best practices and promoting innovation in the technological process, respectively. In addition, the (in)efficiency of companies can result from technical and scale (in)efficiency [25]. Technical efficiency refers to the achievement of maximum output from a given input, while scale efficiency implies the use of an optimal set of inputs. Consequently, technical efficiency refers to achieving best practice in the industry given the technology, while scale efficiency refers to adjusting the scale of operations. Therefore, for a company to increase its total factor productivity, it should increase its efficiency, invest in new technological innovations, or do both.

Productivity in the energy industry has mostly been studied at the country level. For example, Abbot [26] studied multifactor productivity in the Australian electric utility industry, Ramos-Real et al. [27] analysed productivity changes in Brazilian electric utilities, and Liu et al. [11] studied technical efficiency and productivity in Taiwanese energy companies. Specifically, country-level studies tend to be conducted in China (e.g., Song et al. [28], who measured productivity in the Chinese thermal power industry, Lu et al. [12], who analysed and predicted total factor productivity for Chinese petroleum companies, and Zhang et al. [29], who studied multifactor productivity in the Chinese coal industry).

As far as the European energy industry is concerned, there is an obvious lack of studies on productivity. On the one hand, this is surprising given the role of the energy industry in a country. Indeed, the energy industry plays a strategic role in European countries, but it operates below the efficiency frontier [3]. Its high capital intensity should be an important factor contributing to its productivity. However, due to recent changes in energy markets caused by the slow introduction of new, more efficient technologies and practices as well as the shift from manufacturing to service-based industries (i.e., from more energy-intensive to less energy-intensive industries) the profitability of the energy industry has decreased significantly, calling into question its ability to innovate in line with recent increasing economic, social, and environmental demands. On the other hand, energy generation is the largest contributor to anthropogenic GHG emissions. We would therefore expect numerous studies to address this issue.

Few researchers have investigated productivity changes in European energy companies. Barros [30] used DEA and MPI analysis to investigate changes in total productivity on a sample of hydroelectric plants of Portugal Electricity Company and decomposed them into technical efficiency and technological change. He concluded that the firms experienced an average improvement in technical efficiency and technological change, with the latter being higher. Moreover, an increase in scale efficiency was higher than an increase in pure technical efficiency. Lo Storto and Capano [13] analysed productivity changes in the renewable electricity generation sector in Europe over the period from 2002–2011 using DEA and MPI analysis for a sample consisting of companies in the electricity industry in 31 European countries. They found that total productivity was unstable over that period, while technological change contributed to productivity improvements and that efficiency remained stable. Corsatea and Giaccaria [14], while focusing on the electricity and gas sectors of 13 European countries, also found that technological change is the main driver of environmental productivity growth. This was calculated using MPI. They also documented the beneficial effects of market reforms on technical environmental efficiency over the period from 1995–2013. Lu and Lu [31] used DEA to investigate intertemporal efficiency and executive efficiency based on carbon dioxide (CO_2) emissions from fossil fuels in 28 EU countries. They used CO_2 as an undesirable output to analyse its impact on energy efficiency over the period from 2009–2013. Their research mainly reports on intertemporal efficiency. Sanchez-Ortiz et al. [15] studied the efficiency and productivity of five Spanish electricity distribution companies, also using DEA and MPI analysis. They found overall positive efficiency and concluded that overcapacity and tariff deficits have a negative impact on firm efficiency.

One should observe that DEA and the MPI are commonly used approaches to assess efficiency and productivity changes in the energy industry (e.g., [10,27,32]). Certainly, some researchers have used alternative DEA models. For example, Zhang et al. [29] used the super-slack-based measure (Super-SBM) with the MPI to evaluate the total factor productivity of 25 Chinese coal companies. Lu et al. [12] combined three-stage DEA with time series neural networks to evaluate and predict the total factor productivity of 50 Chinese petroleum companies. Finally, Song et al. [28] used DEA and the Malmquist–Luenberger index to evaluate the productivity of the Chinese thermal industry.

To sum up, this paper has pointed out the apparent lack of research regarding efficiency and productivity changes in the energy industry. Although some researchers have studied productivity changes in the European context, to our knowledge, no one has analysed efficiency and productivity changes in the European energy industry. This paper fills this research gap by exploring productivity changes by considering desirable and undesirable outputs. Accordingly, the hypothesis is that the European energy industry experienced only a mild increase in productivity during the period under consideration. We assume that this is primarily a consequence of insufficient technological innovation and a lack of substantial changes in efficiency.

2.1. Sample and Data

The sample consists of 28 EU energy companies that had the largest market share in each member state and that published their financial statements online during the period from 2005–2016. Only three companies were excluded from the initial sample: Ignalinos atomine elektrine (financial statements not publicly available), Twinerg SA (a subsidiary of Electrabel SA, which, in turn, is a subsidiary of GDF SUEZ), and the British Energy Group (acquired by EDF France in 2008). The companies included are part of the electricity industry and are mostly wholly or partially state-owned.

Following the production function approach, three inputs were selected: total assets (representing resources used to generate revenue), the number of employees (representing the total employed workforce), and gross investments (representing investment in new technologies important to the company's future growth), and two outputs: revenue (income generated from the normal operation of the company) and GHG emissions (undesirable output). Total assets, the number of employees, and gross investments have been commonly used as inputs to evaluate the efficiency of energy companies (for the number of employees, see [33,34]; for total assets, see [2]; and for gross investments, see [30]). Regarding GHG emissions, Korhonen and Luptacik [35] found that identifying environmental factors as inputs or outputs does not affect the efficiency frontier. Therefore, we treated GHG emissions as an undesirable output of energy production.

Eurostat was used a data source for the GHG emissions [17], as data thereon were not available in all of the annual financial reports of the included European energy companies. All other data used in DEA analysis were taken from their annual reports.

2.2. Methods

A DEA-based Malmquist productivity index was used to calculate the rates of productivity change. It represents a standard approach to measure and evaluate productivity growth. The calculation process was conducted in two steps; DEA was used in the first step, and Malmquist productivity indices were calculated in the second.

DEA model: Considering the advantages of using DEA, specifically its non-parametric characteristic and its possibility of working with multiple inputs and outputs, the present paper has considered it to be a suitable technique for calculating the technical efficiency scores. Assuming that managers can control inputs more easily than outputs, where a proportional increase in inputs could lead to a disproportionate change in outputs, this paper uses the input-oriented DEA model with constant and variable returns to scale

(CRS and VRS, respectively). This type of the DEA model, presented by Model (1), was introduced by Banker et al. [36]. It refers to a situation with K number of inputs, M number of outputs, and n number of DMUs. In this case, for the i-th energy company, x_i stands for a $K \times 1$ vector of inputs and y_i denotes an $M \times 1$ vector of outputs. Moreover, the $(K \times n)$ input matrix X and the $(M \times n)$ output matrix Y represent the data of all n energy companies. The described model is as follows:

$$\begin{gathered}\text{Min}_{\theta,\lambda}\ \theta, \text{subject to} - y + Y\lambda \geq 0, \\ \theta x_i - X\lambda \geq 0, \lambda \geq 0,\end{gathered} \tag{1}$$

where θ refers to the efficiency score of the i-th DMU, and λ is an $n \times 1$ vector of constants.

Banker et al. [36] extended the model developed by Charnes et al. [20] by adding a convexity constraint, $e\lambda = 1$ (e is a $1 \times n$ vector of ones) to account for variable returns to scale. They proposed decomposing the overall technical efficiency into pure technical efficiency and scale efficiency. While the former refers to the ability of management to use given resources efficiently, the latter refers to the ability to exploit economies of scale by operating on the efficiency frontier. The efficiency frontier is constructed as a discrete piecewise linear combination of the most efficient units. Scale efficiency (SE) is presented as the ratio of technical efficiency (TE) to pure technical efficiency (PTE). A DMU is only considered efficient if both $\Theta = 1$ and all associated slack variables in the model equal zero. For more details, see [37].

The Malmquist productivity index (MPI): The MPI, which was empirically implemented by Färe et al. [21] using the DEA method, was used to assess the energy companies' productivity changes over time. It has been extensively applied to measure productivity changes. More specifically, MPI calculates the ratio of the distances the data that are associated with a common technology. The model with constant returns to scale can be stated as follows [21]:

$$MPI_0\left(x^{t+1}, y^{t+1}, x^t, y^t\right) = \left(\frac{D_0^{t+1}(x^{t+1}, y^{t+1})}{D_0^t(x^t, y^t)}\right)\left[\left(\frac{D_0^t(x^{t+1}, y^{t+1})}{D_0^{t+1}(x^{t+1}, y^{t+1})}\right)\left(\frac{D_0^t(x^t, y^t)}{D_0^{t+1}(x^t, y^t)}\right)\right]^{1/2}, \tag{2}$$

where MPI_0 measures the productivity of production points (x^{t+1}, y^{t+1}) relative to the production point (x^t, y^t). The index is calculated by using mixed period technical efficiency scores denoted by $d_0^t(x_0^t, y_0^t)$ and $d_0^{t+1}\left(x_0^{t+1}, y_0^{t+1}\right)$ in periods t and $t + 1$, respectively, thus using the technology of the period t and the technology of the subsequent period $t + 1$. Since productivity changes can be measured relative to the period t or relative to the period $t + 1$, the MPI is defined as the geometric mean of these two indices. If the value of the MPI exceeds 1, then this indicates a productivity improvement between the periods t and $t + 1$. The inverse case holds for an index value that is less than 1.

The first component (in round brackets) of Expression (2) measures the technical efficiency (TEC) changes over two periods, and the second component (in square brackets) measures the technology (TC) changes over two periods. More precisely, the first component measures whether or not a DMU is approaching its efficiency frontier, while the second component measures whether the frontier is shifting out over time. If the values of any of these components are greater than 1, they indicate improvement. The reverse case holds. If the index is equal to 1, then there are no changes in productivity.

Under the VRS assumption, there is a difference between the CRS distance function and the VRS distance function. Therefore, the changes in technical efficiency are the product of the changes in the pure technical efficiency (PTE), which can be calculated under the assumption of VRS, and the change in scale efficiency (SE), which is a mixture of the CRS and VRS efficiencies. The SE change measures the degree to which a DMU approaches its most productive scale over the period of interest.

Coelli et al. [38] suggest using the Malmquist productivity index based on CRS distance functions, even if the underlying technology exhibits VRS. The reason for this is that productivity change estimates based on VRS distance functions are biased. It is recommended that the VRS distance function only be used to estimate pure technical efficiency and scale efficiency. Therefore, in the first step, we calculated MPI (i.e., the indices TEC and EC) based on CRS; then, in the second step, we further decomposed TEC into PTE change and SE change based on VRS.

3. Empirical Results with Discussion

3.1. Preliminary Analysis

Using the Tukey box plot method, outliers were removed from further analysis because they could have affected the shape of an efficiency frontier, leading to unreliable DEA efficiency results. Two companies were found to be outliers, EDF France and the British Energy Group, possibly because of the size of their businesses. In addition to these two companies, Enel SpA was also found to be an outlier in 2014–2016 due to significant changes in monetary figures. Considering that a calculation of the MPI requires a balanced panel data set and the fact that data were not available from certain energy companies for the period of interest, the final sample was reduced to 19 European companies (Table A1 in the Appendix A).

The process of mean normalisation was performed to eliminate potentially conflicting situations arising from the data, such as different units, scales, and magnitudes (see, [39]). Wang et al. [40] emphasised that this procedure does not affect the efficiency scores obtained by using DEA analysis. Table 1 shows the descriptive statistics of selected outputs (total revenue and GHG emissions) and inputs (total asset, number of employees, and investment) that reveal the heterogeneity within energy companies.

Table 1. Descriptive statistics.

Output/Input	Obs	Mean	Std. Dev.	Minimum	Maximum
Total revenue (in millions of euros at 2015 constant prices)	228	8028.89	12,122.40	67.98	54,422.75
GHG emissions from the energy sector (in millions of tonnes)	228	97.57	175.89	5.79	841.33
Total asset (in millions of euros at 2015 constant prices)	228	20,927.41	28,154.89	1022.45	125,869.62
Number of employees	228	14,017.41	15,987.69	188.00	85,928.00
Investment (in millions of euros at 2015 constant prices)	228	1497.51	2739.71	5.08	16,978.30

The correlation matrix (Table A2 in the Appendix A) shows that there is a significant and positive correlation between the output and input variables. Therefore, the isotonicity property is satisfied, and DEA can be used to estimate the efficiency scores.

3.2. Results with Discussion

Following Coelli et al. [38], both the CRS and VRS scores were calculated, and their results are presented in Figure 1. During the observed period, the technical efficiency score was the highest under CRS in 2007 (0.648), under VRS in 2006 (0.859), and showed scale efficiency in 2007 (0.807). Significant deterioration in technical efficiency scores was observed in the crisis and post-crisis periods. Consistent with this finding, Lo Storto and Capano [13] observed a downward trend in the efficiency of aggregate renewable electricity generation capacity during the period 2002–2011, but they realised that countries with a higher share of installed renewable electricity generation capacity nevertheless experienced an increase in efficiency during the period from 2009–2011. Moutinho et al. [41] also found that technical efficiency scores were lower in most of the 26 European countries observed during the 2009–2012 period, including the financial crisis. Wang and Le [42] provided evidence of the loss of technical efficiency for 17 European countries during 2013–2017. Moreover, their calculated average efficiency score of 0.835 indicates that the EU energy industry was in a worse position than the EU economy as a whole, which also makes technical efficiency a concern. Borozan [43] affirmed that the largest changes in EU-28 productivity over the period from 2000–2018 occurred during the economic crisis. It seems that a mild downward trend in energy efficiency is consistent with the downward trend observed in the European economy.

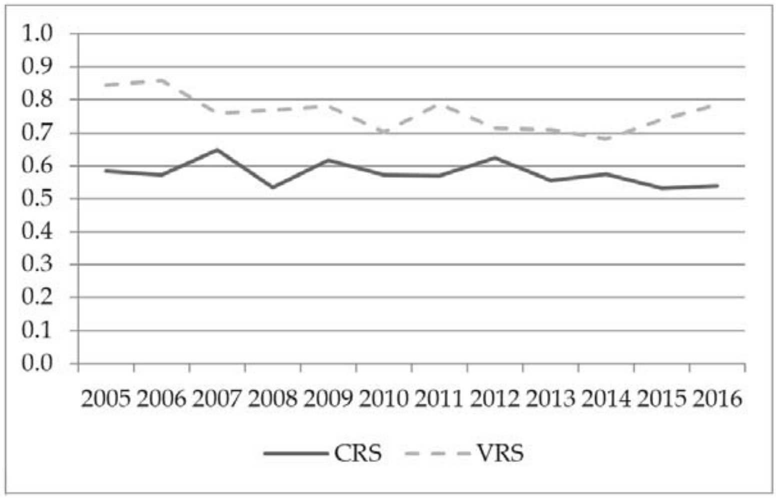


Figure 1. Development of CRS and VRS scores.

European energy industry efficiency decreased at an annual average rate of 0.73% under CRS and by 0.68% under VRS. Only two energy companies are on the efficiency frontier under the CRS assumption and five companies under the VRS assumption in the period considered. Average efficiency scores of 0.577 (under CRS) and 0.761 (under VRS) imply that energy companies could perform better and that scale inefficiency exists (mean scale efficiency score of 0.743). They should improve their performance significantly to reach the efficiency frontier. Although a direct comparison is not possible, as it was not possible in the growth trend case above, it seems that the European energy industry had more room for improvement than the European economy.

Table 2 shows the results of productivity changes decomposed into technical efficiency changes (i.e., pure technical efficiency and scale efficiency change) and technology changes. The MPI changes calculated for the European energy industry as a whole averaged 1.5%, with a low of − 8.4% in the 2008–2009 period and a high of 8.8% in 2006–2007. This average value suggests that the European energy industry only achieved modest productivity growth, while the MPI values indicate that the productivity development path followed a procyclical pattern in the period considered in the present study. Labour productivity procyclicality has already been observed in the EU [44–46] but not at the energy industry level. Looking at the trends, the European energy industry, which is represented by the 19 largest companies, shows a slight downward movement with a compound rate of change of 0.093%. Considering the possible consistency of productivity movements in the energy industry with multifactor or labour productivity of the whole economy, it is worth pointing out the results observed in the literature. Indeed, several authors have found a long-term downward trend in European labour productivity [44,47], suggesting declining competitiveness compared to other advanced economies and emerging markets. Timmer et al. [44] considered the reason for the productivity decline to be the decline of traditional manufacturing but also insufficient investment in technology. Thus, they estimated that labour productivity in the EU-15 fell by 0.7% over the period 2007–2009. From the perspective of the energy industry, whose deterioration in performance after the 2008 financial crisis is particularly striking [48], another reason could be that investments in renewables experienced a sharp decline after a significant increase until 2011. For example, in 2011, they amounted to USD 131.7 billion, and after that year, these investments were significantly reduced, stagnating at around USD 65 billion in 2012–2019 [49]. This is in line with the observations of Lo Storto and Capano [13], who found a growth trend of about 6% on average in renewable electricity generation capacity over the period from 2002–2011. They explained this growth with technological advances rather than efficiency changes.

Table 2. MPI and its components.

Period	Malmquist Productivity Change Index (MPI)	Efficiency Change Index (TE)	Technology Change Index (TEC)	Pure Technical Efficiency Change Index (PTE)	Scale Efficiency Change Index (SE)
2005–2006	1.011	1.086	0.933	1.025	1.058
2006–2007	1.088	0.943	1.156	0.957	0.984
2007–2008	1.079	0.945	1.142	0.943	1.003
2008–2009	0.916	1.131	0.815	1.077	1.050
2009–2010	1.039	1.030	1.013	0.990	1.042
2010–2011	1.045	1.009	1.029	0.982	1.027
2011–2012	1.063	0.972	1.093	0.976	0.995
2012–2013	0.991	1.027	0.969	1.014	1.013
2013–2014	0.944	0.934	1.016	0.954	0.976
2014–2015	0.991	0.975	1.019	0.992	0.983
2015–2016	1.001	1.081	0.931	1.061	1.018
mean	1.015	1.012	1.011	0.998	1.014

Clearly, further research is needed to investigate the relationship between productivity in the European energy industry and the European economy. Furthermore, the differences in productivity between renewables and non-renewables need to be investigated. Indeed, large energy companies differ in terms of their energy mix, which is likely to have an impact not only on their own productivity but also on the productivity of the industry as a whole. Previous research has confirmed that the energy mix, which includes different conventional sources (e.g., coal or gas) and renewables (e.g., hydro, wind, biomass or solar photovoltaic), matters for productivity and growth [50–52] and that creating an optimal energy mix that takes into account productivity and carbon emissions is a critical challenge for the modern world (see [53,54]). Midttun and Piccini [48] have documented that the good performance of the European energy industry only lasted through the first decade of the 21st century. They concluded that only those European energy companies that changed their energy mix to greener and smaller plants did better financially. The issue of energy mix is not addressed in this paper and requires further research.

On average, both components, i.e., technology changes and efficiency changes, contributed almost equally positively to the Malmquist index of the European energy industry. In this context, technical efficiency changes could be attributed to the average scale efficiency changes, with an increase rate of 1.4%, while the average pure technical efficiency changes had a negative impact, indicating moderate efficiency deteriorations in operational and management resources and activities. Given that the energy companies considered here are large companies, it is not surprising that they were able to reach the economies of scale. However, they faced a downward trend in scale efficiency during the period considered, which is also recognised in the literature as a possible cause of technical inefficiency [55]. This adverse trend in the European energy industry can be attributed, among other things, to a decline in final energy consumption from 1041 Mtoe in 2005 to 977 Mtoe in 2016 [56], increasing competition and thus decreasing utilisation capacities, and outdated technologies. The decarbonisation of the EU energy system is also expected to affect the future development and investment of energy companies and will further negatively impact scale efficiency. Indeed, the EU Taxonomy Report (Technical Annex) [57] defines sustainable investments as investments in those energy producers that emit less than 100 gCo2e/kWh. In comparison, highly efficient cogeneration plants emit around 300 g per hour. In this context, new investments in fossil fuel power plants will no longer be financially viable, and energy companies could therefore benefit from diversifying their portfolio from fossil fuels to renewables. Midttun and Piccini [48], who analysed the transformation of the European energy industry from the perspective of the core players in this industry, corroborated these observations.

Management inefficiency, reflected in pure technical efficiency, suggests that European energy companies have not sufficiently invested in the human resource potential of the companies. They face outdated business models and a shortage of human resources, especially, as it can be seen from the results, a shortage of researchers and engineers in the fields of R&D, environment, and quality management. However, they are important for the exploitation of new technologies and for the creation of innovations, know-how, and new green and low-carbon oriented business models (see [58]). Zhen et al. [59] emphasised that neglecting to improve R&D and human capital will have a negative impact on the competitiveness of renewable energy, which argues for investment in human capital development. Insufficient concern for human resources development seems to be related to the privileged position and soft budgeting that energy companies enjoy from being wholly or partially state-owned. Harmful effects of soft budget constraints on technical efficiency of energy companies have been noted by Borozan and Pekanov Starcevic [3], while Du et al. [60] have showed that electricity reforms have a positive impact on the technical efficiency of fossil-fuelled power plants in China. This would imply that state-owned companies could benefit from privatisation by operating in a more competitive market with higher quality management [14,61,62]. The implementation of a new green, digital, and low-carbon oriented business models and management strategies may be beneficial for energy companies (see, e.g, [48,58]).

One factor behind productivity changes in the European energy industry is technological innovation. The industry experienced a slight increase in technological progress and a shift in the best practice frontier, averaging 1.2% over the period considered. Technological innovation in the energy industry is crucial to the transformation of the energy system “to establish energy sustainability, competitiveness and security by 2020 and beyond” [63]. However, according to Sterlacchini [64], electricity companies in the EU reduced their R&D expenditures by 62% during the period from 1990–2004, which was mainly due to privatisation processes that exerted pressure to reduce costs. In addition, EU energy research and innovation budgets were cut by member states, with public sector spending on low-carbon technologies being lower in 2019 than it was in 2012, and member states continued to invest in fossil fuels rather than clean technologies after 2011 [65].

As already mentioned, productivity improvements did not follow a stationary growth rate but exhibited procyclical behaviour. Productivity improvements and losses can be observed in the development path of productivity change. The European energy industry experienced a productivity decline during the crisis period, especially during the financial crisis. A productivity decline during a crisis is not an unusual feature; other authors have already observed a procyclical nature of productivity [43,45,46]. The decline was also recorded in the post-crisis period (2012–2015), which was probably due to the prolonged slowdown and the dramatic decrease in new investments in the energy sector. Investments in Energy Union research and innovation priorities declined significantly after 2011 [65]. In contrast, European energy companies showed the highest productivity changes in the pre-crisis period, i.e., 2006–2007, which was due to technological progress rather than efficiency changes. However, the crises should not be seen as the only cause of the deterioration in the multifactor productivity of the European energy industry. Rather, the crisis periods are sources of short-term cyclical fluctuations that manifest themselves along a long-term downward trend caused by the delayed and inadequate responses of the energy industry and the whole European economy to structural changes.

Although the data for several periods indicate that it is possible to achieve positive changes in efficiency and technology at the same time, it seems that the European energy industry has looked at the issue of technology changes rather than efficiency changes. The improvements in the energy industry, which have already shifted out of the frontier over time, have been initiated by the increased use of new Energy 4.0 technologies. Such technologies, such as smart grids, especially when combined with smart metering, will ultimately further enhance energy security and efficiency.

4. Conclusions

This paper investigated efficiency and productivity changes in the European energy industry. The initial sample comprised 28 EU energy companies over the period from 2005–2016, while the final sample was reduced to 19 companies. Three inputs were selected in the study: total assets, the number of employees, and gross investments. In addition, two outputs were included: revenues and GHG emissions. In the first step of the analysis, the DEA model was used to calculate the technical efficiency scores of the European energy companies, and in the second step, the Malmquist productivity indices were calculated to estimate productivity changes.

The results show an average productivity increase of 1.5% over the observed period, with the lowest value being 8.4% in 2008–2009 and the highest value being 8.8% in 2006–2007. As we hypothesized, the mild average increase in productivity is a consequence of insufficient technological innovation and lack of substantial changes in efficiency. Here, technical efficiency changes are related to the increasing rate of scale efficiency and the decreasing rate of pure technical efficiency. The deterioration of the latter is mainly due to factors related to operational and managerial capabilities, which are possibly caused by the privileged position of state-owned companies. Moreover, productivity changes that follow the changes in the European economy are procyclical. They can be observed in several periods: before, during, and after the crisis. As expected, the highest productivity changes were recorded in the pre-crisis period (2006–2007), which was mainly due to technological progress rather than efficiency changes. The largest decline was recorded at the very beginning of the crisis period. However, a decline was also recorded in the post-crisis period, which was likely due to the prolonged slowdown.

The results suggest that productivity changes reflect the nature and the role of the energy industry. The energy industry is a capital-intensive industry that consists of large companies that create their competitive advantage and added value by continuously investing in technology and by maintaining an optimal scale. However, the industry faces the challenge of a lack of quality management, researchers in R&D, and insufficient energy innovation, which would be the reason for slow progress in terms of future productivity changes and its further lagging behind the productivity of the overall economy. The threat to the future productivity of the European energy industry also comes from unfavourable trends in technological innovation and the maintenance of an optimal scale of production.

Several implications arise from the present results in relation to the decarbonisation, modernisation, and diversification of the European energy industry. Technological innovation should be intensified, particularly in view of the fact that in the post-2011 period countries have continued to invest large amounts of funding for research and innovation in the energy sector in fossil fuels rather than in clean technologies and energies. The fact that the energy sector invests little in research and innovation compared to other sectors will have a negative impact on the EU's efforts to become climate neutral. Therefore, the EU should do more to promote investment in clean technologies if it wants to achieve the SDGs of the UN and the EU's energy and climate policy goals. Moreover, technological innovation in the energy industry is considered an important factor in decoupling energy from the economy and thus minimising the impact of economic activity on environmental quality. Indeed, the decoupling effect of European greenhouse gas emissions is likely to be significantly influenced by technological innovation, especially in the context of greening and low-carbonising the energy industry. This is because green and low-carbon energy sources are seen as a crucial factor in maintaining environmental quality without compromising the achievement of economic goals and quality of life in general at the same time. This paper has not empirically tested the decoupling rate and decarbonisation of the European energy industry. Further research should address these issues. Technological innovation is also at the core of Energy 4.0, which aims to build smart grids, use big data and artificial intelligence, and manage renewable energy. Energy companies have the opportunity to leverage Energy 4.0 in their efforts to build sustainable business models and strategies.

Considering a decreasing trend in economies of scale and increasing competition in energy markets, portfolio diversification should be considered, providing opportunities to achieve the optimal scale of production and to consequently increase investment in clean energy technologies. In addition, the full or partial privatisation of state-owned energy companies could lead them to use more efficient management and to make better use of operational activities. Transformation into private energy producers is also a prerequisite for enabling the separation of energy production and transmission, which is one of the areas of the EU's third energy package that is aimed at improving the internal energy market. By increasing technical efficiency, the energy industry, as an energy producer and consumer, contributes to the decoupling of greenhouse gas emissions from gross domestic product, i.e., from economic activity. However, the need to increase the technical efficiency of the European energy industry is also crucial for the entire European economy, not only because industry should provide competitive energy, but also because this energy should be less carbon intensive. The reduction of harmful emissions, i.e., moving along the downward slope of the environmental Kuznets curve, requires significant changes in the energy industry. The paper suggests that two broad sets of action are needed in terms of technical efficiency. First, there should be a focus on the development of new green, digital, and low-carbon business models and management strategies to create a roadmap for the industry's operations. Second, the size and the scale of operations should be adapted to new green and low-carbon projects.

Future research should also provide a more detailed analysis of the factors influencing productivity trends in the European energy industry and over a broader time frame, with particular attention to the role of government and corporate ownership, distinguishing between renewable and non-renewable energy development paths. A deeper understanding of the determinants of productivity, including the impact of the energy mix, should ensure a solid background for concrete policy proposals aimed at accelerating the process of decarbonisation and modernisation of the European energy industry. The efficiency and effectiveness of individual technological innovations also need to be investigated in order to promote the most promising investments in these processes. Furthermore, the application of alternative methods, such as the Malmquist–Luberger index, could provide new insights in terms of the evaluation of the results obtained in this paper.

Author Contributions: Conceptualization, D.B.; methodology, D.B.; validation, D.B. and D.P.S.; formal analysis, D.B. and D.P.S.; investigation, D.B. and D.P.S.; data curation, D.P.S.; writing—original draft preparation, D.B. and D.P.S.; writing—review and editing, D.B. and D.P.S.; visualization, D.P.S.; supervision, D.B.; funding acquisition, D.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Croatian Science Foundation under the project IP-2020–02-1018.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The source of the data are the annual financial reports of the energy companies and the Eurostat database.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. EU energy companies included in the sample.

State	Energy Company	State	Energy Company
Austria	VERBUND Hydro Power GmbH	Latvia	Latvenergo
Belgium	GDF SUEZ	Lithuania	Ignalinos atomine elektrine
Bulgaria	Kozloduy NPP Plc	Luxembourg	Twinerg SA
Cyprus	Electricity Authority of Cyprus (EAC)	Malta	Enemalta Corp
Czech Republic	ČEZ Group	The Netherlands	Essent Nederland B.V.
Denmark	DONG Energy	Poland	PGE Polska Grupa energetyczna SA
Estonia	Eesti Energia	Portugal	EDP Producao
Finland	Fortum Power & Heat	Croatia	Hrvatska elektroprivreda d.d.
France	EDF France	Romania	Hidroelectrica
Germany	RWE Power AG	Slovakia	Vodohospodarska Vystavba, s.p.
Greece	PPC Public Power Corp SA	Slovenia	HSE Holding Slovenske elektrarne
Hungary	MVM Magyar Villamos Művek Zrt.	Spain	Iberdrola, SA
Ireland	ESB Electricity Supply Board	Sweden	Vattenfall
Italy	Enel SpA	United Kingdom	British Energy Group

Note: The time frame includes the years 2005–2016, except for the following companies: Enemalta (2005–2011; as of 2012, financial statements have not been available to the public), Essent Nederland B.V. (2005–2010; in 2010, RWE Power AG became the full owner of Essent), and PGE Polska Grupa Energetyczna SA (2007–2015; financial reports for 2005 and 2006 are not available to the public).

Table A2. Pearson correlation coefficients.

Variable.	Revenue	GHG	Asset	Employees	Investment
Revenue	1	-	-	-	-
GHG	0.8913 *	1	-	-	-
Asset	0.9529 *	0.7768 *	1	-	-
Employees	0.9059 *	0.8581 *	0.8380 *	1	-
Investment	0.5631 *	0.3664 *	0.5366 *	0.4831 *	1

Note: * statistically significant at the 0.05 significance level.

References

1. European Commission. Energy Sector Economic Analysis. Available online: https://ec.europa.eu/jrc/en/research-topic/energy-sector-economic-analysis (accessed on 14 April 2021).
2. Barros, C.P.; Peypoch, N. Technical efficiency of thermoelectric power plants. *Energy Econ.* **2008**, *30*, 3118–3127. [CrossRef]
3. Borozan, D.; Starcevic, D. P. European energy industry: Managing operations on the edge of efficiency. *Renew. Sust. Energy Rev.* **2019**, *116*, 109401. [CrossRef]
4. United Nations. Paris Agreement to the United Nations Framework Convention on Climate Change FCCC/CP/2015/10/Add.1. Available online: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed on 13 October 2021).
5. European Commission. *The European Green Deal, COM/2019/640 Final*; European Commission: Brussels, Belgium, 2019.
6. European Commission. *A Policy Framework for Climate and Energy in the Period from 2020 to 2030, COM/2014/015 Final*; European Commission: Brussels, Belgium, 2014.
7. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations: New York, NY, USA, 2015.
8. European Commission. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions "Fit. for 55": Delivering the EU's 2030 Climate Target. On the Way to Climate Neutrality, COM(2021) 550 Final*; European Commission: Brussels, Belgium, 2020.
9. European Commission. *Energy Prices and Costs in Europe, COM(2019) 1 Final*; European Commission: Brussels, Belgium, 2019.
10. Behera, S.K.; Farooquie, J.A.; Dash, A.P. Productivity change of coal-fired thermal power plants in India: A Malmquist index approach. *IMA J. Manag. Math.* **2011**, *22*, 387–400. [CrossRef]
11. Liu, W.B.; Wongchai, A.; Yotimart, D.; Peng, K.C. Productive Performance Analysis in Taiwan Energy Companies: Application of DEA Malmquist Index. *Adv. Mat. Res.* **2012**, *616–618*, 1354–1357. [CrossRef]
12. Lu, L.; Zhang, J.; Yang, F.; Zhang, Y. Evaluation and prediction on total factor productivity of Chinese petroleum companies via three-stage DEA model and time series neural network model. *Sustain. Comput.-Inf.* **2020**, *27*, 100397. [CrossRef]
13. Lo Storto, C.; Capano, B. Productivity changes of the renewable energy installed capacity: An empirical study relating to 31 European countries between 2002 and 2011. *Energy Educ. Sci. Tech. A* **2014**, *32*, 3061–3072.

14. Corsatea, T.D.; Giaccaria, S. Market regulation and environmental productivity changes in the electricity and gas sector of 13 observed European countries. *Energy* **2018**, *164*, 1286–1297. [CrossRef]
15. Sánchez-Ortiz, J.; Garcia-Valderrama, T.; Rodríguez-Cornejo, V.; Cabrera-Monroy, F. DEA window analysis and Malmquist index to assess efficiency and productivity in the Spanish electricity sector. *Int. J. Energy Sect. Manag.* **2020**, *15*, 765–788. [CrossRef]
16. European Commission. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank: A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy, COM(2015) 080 Final*; European Commission: Brussels, Belgium, 2015.
17. Eurostat. Database on Energy, Luxembourg. 2021. Available online: http://ec.europa.eu/eurostat/web/energy/data/main-tables (accessed on 15 January 2021).
18. Jardine, N. Meet the 20 Most Profitable Energy Companies in Europe. *Business Insider*. 11 November 2011. Available online: https://www.businessinsider.com/gazprom-profits-energy-europe-2011-11?op=1#20-gas-natural-fenosa-1 (accessed on 11 October 2021).
19. S&P Global Market Intelligence. Italy's Enel Tops List of 20 largest European Utilities by Market Cap. 20 June 2019. Available online: https://www.spglobal.com/marketintelligence/en/news-insights/trending/sgSxFo7P69ByGX1pBy4mvg2 (accessed on 11 October 2021).
20. Charnes, A.; Cooper, W.W.; Rhodes, E. Measuring the efficiency of decision making units. *Eur. J. Oper. Res.* **1978**, *2*, 429–444. [CrossRef]
21. Färe, R.; Grosskopf, S.; Norris, M.; Zhang, Z. Productivity growth, technical progress, and efficiency change in industrialized countries. *Am. Econ. Rev.* **1994**, *84*, 66–83.
22. Wu, J.; Zhu, Q.; Yin, P.; Song, M. Measuring energy and environmental performance for regions in China by using DEA-based Malmquist indices. *Oper. Res.* **2017**, *17*, 715–735. [CrossRef]
23. Tavana, M.; Khalili-Damghani, K.; Arteaga, F.J.S.; Hashemi, A. A Malmquist productivity index for network production systems in the energy sector. *Ann. Oper. Res.* **2020**, *284*, 415–445. [CrossRef]
24. Comin, D. Total factor productivity. In *Economic Growth*; Durlauf, S.N., Blume, L.E., Eds.; Palgrave Macmillan: London, UK, 2010; pp. 260–263.
25. Farrell, M.J. The measurement of productive efficiency. *J. R. Stat. Soc. Ser. A-G* **1957**, *120*, 253–281. [CrossRef]
26. Abbott, M. The productivity and efficiency of the Australian electricity supply industry. *Energy Econ.* **2006**, *28*, 444–454. [CrossRef]
27. Ramos-Real, F.J.; Tovar, B.; Iootty, M.; de Almeida, E.F.; Pinto, H.Q., Jr. The evolution and main determinants of productivity in Brazilian electricity distribution 1998–2005: An empirical analysis. *Energy Econ.* **2009**, *31*, 298–305. [CrossRef]
28. Song, Y.Y.; Liu, H.H.; Liu, X.X.; Yang, G.L. Measuring the productivity evolution of Chinese regional thermal power industries using global Malmquist-Luenberger productivity index. *Int. J. Energy Sect. Manag.* **2018**, *12*, 221–243. [CrossRef]
29. Zhang, W.; Meng, J.; Tian, X. Does de-capacity policy enhance the total factor productivity of China's coal companies? A Regression Discontinuity design. *Resour. Policy* **2020**, *68*, 101741. [CrossRef]
30. Barros, C.P. Efficiency analysis of hydroelectric generating plants: A case study for Portugal. *Energy Econ.* **2008**, *30*, 59–75. [CrossRef]
31. Lu, C.C.; Lu, L.C. Evaluating the energy efficiency of European Union countries: The dynamic data envelopment analysis. *Energy Environ.* **2019**, *30*, 27–43. [CrossRef]
32. Ahnagaran, A.A.; Nabavieh, S.A.; Taheri, S.D.M.; Gholamiangonabadi, D. Measurement of productivity changes by bootstrapping Malmquist in combined cycle power plants. In Proceedings of the 5th Conference on Thermal Power Plants (CTPP), Tehran, Iran, 10–11 June 2014; pp. 83–88.
33. Cullmann, A.; von Hirschhausen, C. Efficiency analysis of East European electricity distribution in transition: Legacy of the past? *J. Prod. Anal.* **2008**, *29*, 155–167. [CrossRef]
34. Jaunky, V.C. Divergence in technical efficiency of electric utilities: Evidence from the SAPP. *Energy Policy* **2013**, *62*, 419–430. [CrossRef]
35. Korhonen, P.J.; Luptacik, M. Eco-efficiency analysis of power plants: An extension of data envelopment analysis. *Eur. J. Oper. Res.* **2004**, *154*, 437–446. [CrossRef]
36. Banker, R.D.; Charnes, A.; Cooper, W.W. Some models for estimating technical and scale inefficiencies in data envelopment analysis. *Manag. Sci.* **1984**, *30*, 1078–1092. [CrossRef]
37. Cook, W.D.; Seiford, L.M. Data envelopment analysis (DEA)—Thirty years on. *Eur. J. Oper. Res.* **2009**, *192*, 1–17. [CrossRef]
38. Coelli, T.J.; Rao, D.S.P.; O'Donnell, C.J.; Battese, G.E. *An Introduction to Efficiency and Productivity Analysis*, 2nd ed.; Springer Science+Business Media: Berlin, Germany, 2005.
39. Sarkins, J. Preparing your data in DEA. In *Modelling Data Irregularities and Structural Complexities in DEA*; Zhu, J., Cook, W.D., Eds.; Springer: Boston, MA, USA, 2007; pp. 305–320.
40. Wang, Y.M.; Luo, Y.; Liang, L. Ranking decision making units by imposing a minimum weight restriction in the data envelopment analysis. *J. Comput. Appl. Math.* **2009**, *223*, 469–484. [CrossRef]
41. Moutinho, V.; Madaleno, M.; Robaina, M. The economic and environmental efficiency assessment in EU cross-country: Evidence from DEA and quantile regression approach. *Ecol. Indic.* **2017**, *78*, 85–97. [CrossRef]
42. Wang, L.W.; Le, K.D. Energy efficiency and improvement European countries: Data envelopment analysis approach. *Int. J. Sci. Res.* **2019**, *9*, 66–78. [CrossRef]

43. Borozan, D. Technical Efficiency and Productivity Change in the European Union with Undesirable Output Considered. *Energies* **2021**, *14*, 4937. [CrossRef]
44. Timmer, M.P.; Inklaar, R.; O'Mahony, M.; van Ark, B. Productivity and economic growth in Europe: A comparative industry perspective. *Int. Prod. Mon.* **2011**, *21*, 3–23.
45. Oberfield, E. Productivity and misallocation during a crisis: Evidence from the Chilean crisis of 1982. *Rev. Econ. Dynam.* **2013**, *16*, 100–119. [CrossRef]
46. Furceri, D.; Celik, S.K.; Jalles, J.T.; Koloskova, K. Recessions and total factor productivity: Evidence from sectoral data. *Econ. Model.* **2021**, *94*, 130–138. [CrossRef]
47. Draghi, M. The Productivity Challenge for Europe, Speeches, 30 November 2016. 2016. Available online: https://www.ecb.europa.eu/press/key/date/2016/html/sp161130_1.en.html (accessed on 10 October 2021).
48. Midttun, A.; Piccini, B.P. Facing the climate and digital challenge: European energy industry from boom to crisis and transformation. *Energy Policy* **2017**, *108*, 330–343. [CrossRef]
49. Statista. Renewable Energy in Europe, 2020. Available online: https://www-statista-com.ezproxy.nsk.hr/study/43575/renewable-energy-in-europe/ (accessed on 15 January 2021).
50. Li, K.; Lin, B. Impact of energy conservation policies on the green productivity in China's manufacturing sector: Evidence from a three-stage DEA model. *Appl. Energy* **2016**, *168*, 351–363. [CrossRef]
51. Kim, J.; Park, S. A contingent approach to energy mix policy. *Energy Policy* **2018**, *123*, 749–758. [CrossRef]
52. Díaz, A.; Marrero, G.A.; Puch, L.A.; Rodríguez, J. Economic growth, energy intensity and the energy mix. *Energy Econ.* **2019**, *81*, 1056–1077. [CrossRef]
53. Ritchie, H.; Roser, M. Energy, 2020. Available online: https://ourworldindata.org/energy (accessed on 12 October 2021).
54. Ahn, K.; Chu, Z.; Lee, D. Effects of renewable energy use in the energy mix on social welfare. *Energy Econ.* **2021**, *96*, 105174. [CrossRef]
55. Pacudan, R.; de Guzman, E. Impact of energy efficiency policy to productive efficiency of electricity distribution industry in the Philippines. *Energy Econ.* **2002**, *24*, 41–54. [CrossRef]
56. European Environment Agency (EEA). Primary and final energy consumption in Europe, 18 December 2020. Available online: https://www.eea.europa.eu/data-and-maps/indicators/final-energy-consumption-by-sector-11/assessment/ (accessed on 15 September 2021).
57. EU Technical Expert Group (TEG) on Sustainable Finance. Taxonomy Report: Technical Annex, March 2020. Available online: https://ec.europa.eu/info/sites/default/files/business_economy_euro/banking_and_finance/documents/200309-sustainable-finance-teg-final-report-taxonomy-annexes_en.pdf (accessed on 12 October 2021).
58. Latilla, V.M.; Urbinati, A.; Cavallo, A.; Franzo, S.; Ghezzi, A. Organizational re-design for business model innovation while exploiting digital technologies: A single case study of an energy company. *Int. J. Innov. Technol.* **2021**, *18*, 2040002. [CrossRef]
59. Zhen, W.; Xin-gang, Z.; Ying, Z. Biased technological progress and total factor productivity growth: From the perspective of China's renewable energy industry. *Renew. Sust. Energy Rev.* **2021**, *146*, 111136. [CrossRef]
60. Du, L.; He, Y.; Yan, J. The effects of electricity reforms on productivity and efficiency of China's fossil-fired power plants: An empirical analysis. *Energy Econ.* **2013**, *40*, 804–812. [CrossRef]
61. See, K.F.; Coelli, T. An analysis of factors that influence the technical efficiency of Malaysian thermal power plants. *Energy Econ.* **2012**, *34*, 677–685. [CrossRef]
62. Celen, A. Efficiency and productivity (TFP) of the Turkish electricity distribution companies: An application of two-stage (DEA&Tobit) analysis. *Energy Policy* **2013**, *63*, 300–310.
63. European Commission. Energy Technology & Innovation. Available online: https://ec.europa.eu/jrc/en/research-topic/energy-technology-innovation (accessed on 10 October 2021).
64. Sterlacchini, A. Energy R&D in private and state-owned utilities: An analysis of the major world electric companies. *Energy Policy* **2012**, *41*, 494–506.
65. European Commission. *Report from the Commission to the European Parliament and the Council on Progress of Clean Energy Competitiveness, COM(2020) 953 Final*; European Commission: Brussels, Belgium, 2020.

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland
Tel. +41 61 683 77 34
Fax +41 61 302 89 18
www.mdpi.com

Sustainability Editorial Office
E-mail: sustainability@mdpi.com
www.mdpi.com/journal/sustainability

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland

Tel: +41 61 683 77 34

www.mdpi.com

ISBN 978-3-0365-4670-4