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Appendix A

A1. Theoretical foundations of Environmental Kuznets Curve analysis: A synthetic literature review

A.1.1. Theoretical basis of the Environmental Kuznets Curve analyses

The economic process involves human activity that requires the consumption of resources. According to the classical view, any economic process must use resources such as labour, capital, and technology to produce goods and services (Krugman & Wells, 2018). During the emergence of classical economics, environmental protection was not a significant concern compared to issues such as industrial development, urbanisation, and technological advancement. However, basic economic theories played a crucial role in shaping the current discourse on the subject and laid the foundations for subsequent models.

Adam Smith (1776/2015) argues that natural resources are crucial for economic development as they provide raw materials for the production of goods and services and determine the possibilities for agricultural and other economic growth. He also notes that population growth and economic expansion lead to increased consumption, so it is important to use resources rationally based on the free market.

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David Ricardo did not address resource conservation and the environment directly. However, his work (1929) provides insight into his views on resource use, particularly in terms of land rent. The problems identified by Ricardo, such as the impact of excessive population growth on the depletion of natural resources, are important. These problems also serve as the foundation for later considerations in the field of environmental economics. Also, the environmental impact of natural resource use can be analysed using the land rent theory he formulated (Czyżewski & Matuszczak, 2016).

John Maynard Keynes, the founder of Keynesianism, did not directly address environmental issues and their relationship with the economy in his most important work (Keynes, 1936). However, his general conception of the government's role in the economy later found application in the ideas of Green Keynesianism, which argues that the state should intervene in the economy to stimulate economic growth while simultaneously limiting environmental degradation (Goldstein & Tyfield, 2018). Also, state interventionism itself in later years, in many countries will take environmental directions, and some authors such as Heyes (2000) and Sim (2006) will attempt to incorporate environmental constraints into a Keynesian macroeconomic framework.

Neoclassical economists have also highlighted the link between human economic activity and the depletion of natural resources. Arthur Pigou (2017) was one of the first economists to emphasise the importance of internalising external costs for the efficient allocation of resources. This concept suggests that economic actors should bear the full social costs of their actions, including environmental costs. Ronald Coase argues that pollution is an external cost problem, meaning that costs are borne by third parties who are not involved in the activity in question. To address this issue, Coase (1960) suggests negotiating between parties instead of relying on government intervention.

Kenneth Arrow (1969) introduced the concept of externalities into economic theory in 1969, demonstrating how they can lead to market inefficiencies. He suggests that government intervention may be necessary to solve these problems. Additionally, Arrow's research highlights the relationship between economic development and environmental effects, indicating that economic policy often overlooks the environment and assumes that economic growth is beneficial. Arrow et al. (1996) proposed that the limits of economic growth are due to the limited capacity of ecosystems to regenerate

Paul Davidson (1963), a post-Keynesian economist, is considered a pioneer of modern environmental economics. He integrated theoretical and empirical aspects of economic development and environmental concerns into economic science. Furthermore, he developed essential techniques for evaluating non-market goods, which are now commonly used in environmental economics (Holt et al., 1998). Another important economist, William Nordhaus (1993) proposes solutions to address climate change through global negotiations and CO_2 charges. However, he also criticises the high costs associated with combating global warming, which can negatively impact economic growth.

Nicholas Stern (2008) addressed the issue of the negative impact of CO_2 emissions on the economy in his work. He suggested that dedicating 1% of the world's GDP to preventing the negative effects of climate change is necessary, otherwise it could reduce global GDP by 20%. Stern argues that the market economy and countermeasures are most threatened by global warming and CO_2 emissions. To minimise the economic and social problems of pollution, he suggests implementing environmental taxes.

Robert Solow (1974) made a contribution to the field of the relationship between economy, resources, and environmental protection. He analysed the problem of natural resource depletion and proposed solutions in the form of substitution and conservation. Additionally, Solow contributed to research on the concept of sustainable development policy and its impact on the economic sphere (Solow, 1993). Based on Solow's model, Brock and Taylor (2010) developed the so-called Solow Green model, in which, taking into account environmental pollution, they examined the impact of technological progress on reducing CO_2 emissions.

Paul Krugman (2016) advocates for a transition towards a green economy through market mechanisms, aiming to minimise the economic impact. He proposes market-based tools, such as *cap-and-trade* systems, which involve setting a limit on greenhouse gas emissions (cap) and allowing companies to trade emission rights (trade) within that limit. According to Krugman, *cap-and-trade* is an effective way to reduce emissions because it introduces market mechanisms that incentivize companies to reduce emissions at minimal costs.

Robert Pollin (2008) proposes an economic recovery programme that promotes job creation in the green sector, accelerates the transition towards a low-carbon economy, and maintains economic growth. In contrast, Mariana Mazzucato (2011) analyses the role of the state as an active participant in the innovation process. In the context of environmental protection, emphasises the significance of government investment in research and development of green technologies and regulations that encourage sustainable development.

Simon Kuznets (1955) had a significant influence on the study of the relationship between economic growth and income inequality. His research discovered that income inequality may initially increase with economic growth but will eventually decrease when economic growth reaches a certain level. This relationship is known as the Kuznets curve and has been adapted to broad economic research as the Environmental Kuznets Curve. The EKC demonstrates the relationship between economic growth and environmental pollution. This model, which is still the foundation of theoretical and empirical research in the field of environmental pollution and economic growth today, owes much to the pioneering work of (Grossman & Krueger, 1991).

The presented considerations lead to the conclusion that environmental aspects are present in all strands of economics. Classical and neoclassical economists emphasize that the free market and competition can lead to an efficient allocation of resources, including natural resources and energy. They also highlight externalities as a significant problem that can lead to the inefficient use of environmental resources. Therefore, they advocate for the costs of environmental destruction to be passed on to economic agents. However, it is crucial to construct these actions in a way that balances economic benefits and environmental costs. At the same time, classical economists see the reduction of CO_2 emissions because of technological progress and innovation, especially in the field of energy production. According to the principles of classical economics, taking care of the environment should not worsen economic growth or society's income. Technology provides the opportunity to protect the environment without negative impacts on the economy.

Proponents of the interventionist trend believe in the role of the State as an institution that formulates and implements environmental policy. They also emphasise the role of public investment in steering the economy towards sustainable development. Some economists who support this trend advocate radical solutions, even if they require an increase in debt and taxation. Importantly, the interventionist currents see an opportunity in these measures to stimulate the development of new sectors of the economy. This is expected to offer the possibility of circumventing the limits to economic growth imposed by environmental constraints in the long term. In accordance with these currents, global action is necessary to avoid the transfer of pollution.

The above concepts outline the problems of environmental economics as an interdisciplinary science that seeks to explain economic phenomena and processes while considering environmental issues. The field has a wide range of analytical, statistical, and econometric instruments to verify theories and hypotheses. The concept of sustainable growth remains central, ensuring that the needs of the current generation are met without jeopardising the ability of future generations to meet their own needs (Pearce et al., 1994). Summarising the main directions of economic thought on the relationship between environmental stewardship and the economy, we can identify four main research areas:

- Sustainable Development: Exploring how to combine economic growth with care for the environment and natural resources.
- Efficient Resource Allocation: Studying the optimal use of available resources, including energy, to preserve them for future generations.
- Technological Progress and Innovation: Enabling the creation of more efficient and eco-friendly production processes and developing alternative energy sources, such as renewable energy.

- Environmental Economic Modelling: Applying modern econometric models to analyse the impact of economic activity on the environment and seeking ways to achieve economic growth with minimal ecosystem impact.

A.1.2. Main directions of economics, economic growth and environmental pollution

The analysis of economic growth under constraints of limited resources highlights the complexities that policymakers and economists face in achieving sustainable development. This challenge becomes even more pronounced when considering the pressing issue of climate change, which, as demonstrated by numerous scientific studies, is inextricably linked to environmental degradation caused by excessive CO_2 emissions. Since the Industrial Revolution, the rapid rise in atmospheric CO_2—driven by fossil fuel consumption and deforestation—has led to significant environmental and economic consequences, underlining the need for integrating environmental concerns into economic policies.

According to most scientific studies, climate change is directly caused by environmental pollution resulting from excessive greenhouse gas emissions, particularly CO_2, since the Industrial Revolution. Atmospheric CO_2 levels have increased by an estimated 26% since that time, mainly due to the burning of fossil fuels and deforestation (Yoro & Daramola, 2020). Global warming is thus a consequence of economic development and increased production and income and cannot be considered separately from economic issues. However, awareness of this link was minimal until 1960, when Charles Keeling's work brought wider scientific attention to the problem (Franta, 2018).

Subsequent analyses of the relationship between global warming and the economy have led to a wealth of scientific publications. The development of the EKC and advancements in econometric modelling have provided valuable insights into the relationship between CO_2 emissions and economic growth. Currently, there are three main research streams utilising the EKC:

- General Relationship Between CO_2 Emissions and Economic Growth: This stream focuses on the broad links between CO_2 emissions and economic growth, aligning with issues of sustainable development (Lazăr et al., 2019).
- Energy Consumption and Economic Growth: Researchers concentrate on how energy consumption during economic growth contributes to greenhouse gas emissions, fitting into concepts of resource allocation and the depletion of natural resources like fossil fuels (Khan et al., 2019).
- Impact of Renewable Energy and Innovations: This area examines how renewable energy sources and technological innovations affect environ-

mental pollution and economic growth, relating to the use of technological progress to improve environmental quality while stimulating the economy (Abid et al., 2022).

The EKC was introduced by Panayotou (1993), who hypothesised an inverted U-shaped relationship between economic growth and environmental pollution. This concept led to the abandonment of earlier linear theories suggesting that halting economic growth was necessary to protect the environment (Malenbaum, 1978). The EKC has significantly influenced economic research and environmental policy. Initially, it posited that pollution increases during early economic growth but decreases after surpassing a certain income threshold—the turning point—where further growth leads to environmental improvement (Dinda, 2004). While the hypothesis is logical and scientifically appealing, numerous studies have shown that these relationships do not always follow the theoretical pattern.

In 1993, empirical data for NAFTA countries first confirmed the inverted U-shaped relationship between economic growth and environmental pollution (Grossman & Krueger, 1991). Since then, the number of studies on this topic has grown rapidly, supported by advancements in statistical and econometric methods. Leal and Marques (2022) identified over 200 scientific articles from 1998 to 2022 addressing this research area. The EKC has evolved to include several variants influenced mainly by the elasticity of GDP concerning environmental pollution, leading some researchers to identify U-shaped, N-shaped, and inverted N-shaped curves.

Global studies using panel data have indicated mixed EKC patterns. Halkos (2011) found both U-shaped and N-shaped curves on a global scale. X. Li and Lin (2013), analysing data from 110 countries between 1971 and 2008, observed that per capita CO_2 emissions in high-income countries remain stable as incomes rise. They also noted convergent relationships between per capita CO_2 emissions and GDP per capita in countries with similar income levels. This finding contradicts the EKC hypothesis, which suggests that CO_2 emissions decrease after income exceeds the turning point. Additionally, they found that a 1% increase in per capita GDP leads to a global increase of 0.02% in per capita CO_2 emissions.

Al-Mulali, Weng-Wai et al. (2015) examined 93 countries using the Generalised Method of Moments (GMM) and confirmed the inverted U-shaped relationship between environmental pollution and GDP growth in high-income countries. However, this relationship was not evident in low-income countries. The turning point appears only at a stage of economic development where technologies that improve energy efficiency and generate renewable energy are accessible. Due to high costs, these technologies are often unavailable to low-income countries, resulting in continued increases in CO_2 emissions. Shahbaz et al. (2015) reported similar findings in a global study of 99 countries from 1975 to 2015. According to Sarkodie and Strezov (2019a), the EKC takes an inverted U shape, with the turning point at an average GDP per capita of USD 8,910. Low- and middle-income countries fall below this income threshold, while high-income countries are above it. A recent panel study by Fávero et al. (2022) covering 187 countries from 1800 to 2016 confirms significant inequality in per capita CO_2 emissions among countries, linked to unequal GDP per capita distribution. The authors indicate that, in the long term, the EKC takes an N shape.

However, the limitations of the EKC framework and the continued environmental degradation observed in many economies have led some scholars to question whether economic growth can truly be decoupled from environmental harm. Alternative approaches, such as degrowth and post-growth, argue that continuous GDP expansion is neither necessary nor desirable to achieve societal well-being (Hickel & Kallis, 2020; Kallis et al., 2018). These perspectives propose reducing resource consumption, restructuring economies towards social and ecological sustainability, and prioritising well-being over economic output. Proponents of degrowth emphasise that instead of relying on technological progress to mitigate environmental damage, economies should transition towards lower production and consumption levels while ensuring equity and high quality of life through redistribution and public services (Latouche, 2009).

A.1.3. Factors influencing the course of the EKC curve

There is no consensus in the literature regarding the factors influencing the shape of the EKC. Researchers employ various methods, variables, and polynomial forms, and the associated theory is continually evolving. Kaika and Zervas (2013) suggest that income distribution and democratic standards affect the EKC's shape. As civil society develops and wealth and living standards improve, citizens exert more pressure to reduce environmental pollution (Joshi & Beck, 2018). However, Usman et al., (2019) find that while democracy's impact on limiting environmental degradation is statistically significant in the short term, it is weak and insignificant in the long run. This may be due to shifts in political priorities affecting economic and environmental policies.

Technological progress is another key factor determining the EKC's shape. The *scale effect* refers to how economic growth increases CO_2 emissions, particularly in less developed countries where rapid growth takes precedence over environmental protection (Udeagha & Ngepah, 2024). This is accompanied by the 'composition effect', where developing economies focus on intensive industrial development based on fossil fuels and heavy exploitation of energy resources (Beyene & Youssef, 2023). Weaker environmental policies in these countries often attract high-energy, high-emission industries (Sarkodie & Strezov, 2018). As incomes rise and citizens demand lower levels of environmental pollution, this necessitates the implementation of increasingly stringent regulations. To adapt to these new regulations, companies must employ more advanced technology, accelerating technological progress. In the literature, this phenomenon is called the "technology effect" and is the final element that determines the U-shaped EKC (Htike et al., 2022). Mitigating the composition effect and reducing pollution alongside economic growth can be achieved through energy transformation driven by technological advances. Policies that increase the supply of renewable energy and promote energy-efficient solutions enable countries to combat global warming while boosting GDP (Bilgili et al., 2016).

International trade and globalisation significantly influence the EKC. Uneven environmental regulations can lead companies to relocate polluting industries to countries with laxer standards—typically lower-income nations prioritising economic growth and investment over environmental concerns. This phenomenon is known as the Pollution Haven Hypothesis (Bashir, 2022; Sarkodie & Strezov, 2019b). Studies indicate that the EKC often exhibits an inverted U shape. Wealthier countries tend to outsource energy-intensive and polluting industries to developing nations. While this shift contributes to GDP growth in the recipient countries, it also leads to increased environmental pollution as their economies expand (Mustafa et al., 2024).

Some researchers explain the N-shaped EKC by noting that environmental degradation intensifies during early development stages but improves rapidly after reaching a certain wealth level. However, as economies attain very high income levels, degradation may rise again due to factors like increased consumption, industrialisation, urbanisation, and resource extraction (Numan et al., 2022). Balsalobre-Lorente et al. (2017) attribute the N shape to a lack of innovation and outdated technologies that fail to overcome the scale effect. Including cubic functions of GDP in models has led some researchers to identify an inverted N-shaped EKC. This suggests that after initial high pollution levels decrease with GDP growth, CO_2 emissions may rise again beyond a certain income threshold. This pattern has been observed in former Eastern Bloc countries transitioning to market economies (Özokcu & Özdemir, 2017). Generally, the EKC takes an inverted U shape in the short term and an N shape in the long term (Zhang, 2021). Wang, Yang, et al. (2023) argue that income inequality influences the EKC's N shape: economic growth increases CO_2 emissions when income inequality is low but reduces emissions as inequality rises.

Energy consumption and the energy mix also significantly impact EKC models. Utilising renewable and nuclear energy can reduce long-term pollution Voumik et al. (2023). However, merely increasing income and the share of renewables may not suffice to lower CO_2 emissions. Energy policies are necessary to correct environmental externalities and reduce dependence on non-renewable resources (Balsalobre-Lorente et al., 2017). Additionally, EKC models often unrealistically assume that pollution externalities are optimally internalised during economic development, implying a socially efficient price for pollution (D. I. Stern, 2017). Policy intervention is crucial. Arrow et al. (1996) argue that without climate policies, taxation, and support for energy innovation, economic growth will not automatically reduce air pollution problems. Without environmental regulations, any correction of pollution via the income–environmental quality relationship may only occur at unnecessarily high-income levels.

Despite extensive research on the EKC, significant uncertainty remains about its trajectory and the relationship between economic growth and environmental pollution. Different variables and factors included in models lead to varying results, even for the same countries. Outcomes are influenced by the dependent variables used, estimation methods, and the length of time series analysed. Excessive aggregation of countries without accounting for their specific characteristics can result in misleading data patterns.

A.1.4. Gaps and controversies in the application of the EKC

The EKC has been widely debated, with many researchers criticising its assumptions. A primary objection is the presumption that environmental damage can be reversed, potentially promoting growth-focused policies that neglect environmental consequences. Rashid Gill et al (2018) argue that the ‘grow now, clean up later’ approach is too resource-intensive and may lead to unsustainable environmental costs. The EKC theory does not consider whether environmental damage incurred before reaching the turning point negatively impacts future GDP, such as costs for disease treatment or reforestation. Some resources may be irreversibly lost even after surpassing economic thresholds. For instance, Zeng et al. (2020) found that climate warming is causing insect migration harmful to agriculture, and it’s uncertain if reducing CO_2 emissions can reverse this. Some researchers propose the Green Solow Model as a better alternative, addressing EKC’s shortcomings (Leal & Marques, 2022).

The convergence hypothesis posits that pollution declines faster in high-pollution countries or that it decreases in developed nations while increasing in developing ones. The EKC suggests wealthy countries initially have high pollution levels, but data from Central and Eastern Europe contradict this (D. I. Stern, 2017). Additionally, the convergence hypothesis implies that pollution changes are not necessarily tied to economic growth, conflicting with the EKC. Munasinghe (1999) recommends that developing countries bypass growth stages causing significant environmental harm. The EKC also assumes a normal distribution of global income and uniform development patterns, ignoring the effects of different pollution types, consumption habits, and cultural factors (Kaika & Zervas, 2013). Ansuategi & Perrings (2000) argue that EKC models often overlook transboundary and intergenerational externalities. Empirical studies lack evidence of an inverted U-shaped relationship for pollutants with delayed effects. Additionally, countries exporting pollution-intensive activities are less likely to decouple growth from environmental degradation.

Previous research has largely neglected green finance topics like green taxes, bonds, and their impact on financial markets (Long et al., 2022). It's uncertain whether financial institutions will fund the green transition or if wealthy nations will support poorer ones. Kotchen (2020) argues that conventional approaches to climate finance are ineffective, suggesting that focusing on net benefits holds greater potential. Another issue the EKC overlooks is geopolitical risk and armed conflict. Countries may reduce CO_2 reduction efforts to fund military budgets amid war risks, as seen with increased defence spending in Europe due to the Ukraine conflict. Public willingness to finance climate policies may also wane. Li et al. (2024) find that geopolitical risk and energy-intensive arms production correlate with higher carbon emissions over time. Syrian data show that while CO_2 emissions drop in the short term during conflict due to economic damage and population loss, they increase later because of arms production (Wang, Li et al., 2023).

Unexpected global events like the COVID-19 pandemic also impact CO_2 emissions. Andreoni (2021) found that EU restrictions led to a short-term reduction of 195 million tonnes of CO_2 but caused a significant GDP decline. Conversely, Baky Haskuee and Asgary (2023) suggest that economic recovery leads to long-term CO_2 increases, especially in developing countries. Such changes may result from economic fluctuations not considered in the long-term EKC. York (2012) notes that recessions and booms affect CO_2 emissions. Burke et al. (2015) found no strong evidence that emissions' elasticity to growth is greater during expansions than recessions but observed that emissions rise faster after booms and slow down after recessions over longer periods.

In summary, factors influencing CO_2 emissions are more complex than just economic income, necessitating further investigation into the EKC. The model may omit relevant variables, suggesting that dynamic stochastic general equilibrium (DSGE) models could be a solution. Lei et al. (2023) applied such a model to China's economy to study multiple factors affecting growth and CO_2 emissions. Non-parametric and non-linear methods also offer new insights.

The increasing availability of data allows for more complex models without losing degrees of freedom. However, it's essential to explore multiple areas to better understand the intricate relationship between environmental pollution and the economy. Due to inconsistencies in many studies, the EKC hypotheses cannot be fully and unequivocally evaluated, and the supporting theory has methodological and statistical gaps.

A.1.5. The Environmental Kuznets Curve in European Union countries

The European Union has been intensifying its efforts to reduce CO_2 emissions globally for many years, with the Green Deal serving as its strategy for transforming towards a sustainable and zero-emission economy. Although there is a relatively large body of research on growth and CO_2 emissions concerning individual countries or regions, studies focusing specifically on EU countries are relatively modest (Mardani et al., 2019; Sovacool et al., 2021). This is particularly important because such research should underpin political and economic decision-making.

One of the first attempts to analyse the EKC for EU countries was by Bengochea-Morancho et al. (2001), who studied member states from 1981 to 1995 using a fixed-effects model. They found that a 1% increase in GDP led to a 0.18% rise in emissions in middle-income countries and a 0.97% increase in low-income countries. The study also revealed significant disparities between the most industrialised countries and others, leading the authors to recommend that climate policy should consider the economic specifics of each member state. Later, Martínez-Zarzoso et al. (2007) added a population variable to the model, finding that population growth affects emissions more than proportionally in countries that recently joined the EU, while in older member states, the elasticity is less than one and insignificant.

Acaravci and Ozturk (2010) examined data from 19 EU countries between 1960 and 2005 using the Autoregressive Distributed Lag (ARDL) model. They concluded that the EKC hypothesis holds in the long term only for Denmark, Germany, Greece, Iceland, Italy, Portugal, and Switzerland. They also found that increased energy consumption impacts CO_2 emissions in certain countries. López-Menéndez et al. (2014) studied 27 EU countries from 1996 to 2010 and obtained an inverted N-shaped EKC. They suggested that due to the nonlinear estimation results, countries should be grouped based on their level of development in models. Renewable energy was identified as significantly reducing CO_2 emissions.

Dogan and Seker (2016) analysed data for 15 EU countries from 1980 to 2012 using the Dynamic Ordinary Least Squares Estimator (DOLS) and included squared income. They identified a U-shaped EKC for these countries and found that real income significantly impacts CO_2 emissions in low-income countries, with elasticity decreasing as GDP per capita rises. Renewable energy consumption and trade openness were found to reduce CO_2 emissions, while non-renewable energy consumption increases them. Al-Mulali, Ozturk, et al. (2015) used data from twenty three EU countries between 1990 and 2013 with the Fully Modified Ordinary Least Squares (FMOLS) method. They found that a 1% GDP increase raises CO_2 emissions by 0.41%. Urbanisation and financial development contribute to long-term emissions growth, whereas trade openness and renewable energy reduce emissions.

Kasman and Duman (2015) also employed the FMOLS method for 15 EU countries from 1992 to 2010, confirming the standard inverted U-shaped EKC. Their model included energy consumption, trade openness, and urbanisation, all significantly impacting CO_2 emissions. Pejović et al. (2021) investigated 28 EU countries from 2008 to 2018 using a Vector Autoregression (VAR) model. They found that, in the short term, a 1% increase in GDP leads to a 0.47% decrease in CO_2 emissions. Increased use of renewable energy sources was shown to directly reduce CO_2 emissions.

Gardiner and Hajek (2020) conducted a study on 23 EU countries from 1990 to 2015 using VAR, Vector Error Correction Model (VECM), and FMOLS methods. They observed a small positive long-term impact of GDP growth on reducing CO_2 emissions. For new member countries, energy consumption and employment negatively impacted emissions, while in older members, energy consumption, employment, and exports had this effect. Onofrei et al. (2022) analysed 27 EU countries from 2000 to 2017 using fixed-effects regression. They found that, on average, a 1% change in GDP leads to a 0.072% change in CO_2 emissions. Their results suggest that economic growth does not automatically reduce EU countries' vulnerability to climate change but only slows the rate of CO_2 emissions growth. Loures and Ferreira (2019) applied a qualitative comparative fuzzy set analysis on data from 2010, 2012, and 2014 for 28 EU countries. They identified a direct relationship between CO_2 emissions and economic growth, noting that the main factors influencing emission reduction were economic crises and energy consumption.

These studies demonstrate that methodologies and results vary widely, often due to differences in data availability and the specific characteristics of the countries examined. Short time series may not provide significant insights for long-term relationships, and grouping countries without considering their developmental specifics can lead to heterogeneous results Brock & Taylor (2010). Therefore, dividing countries according to development level or other criteria yields more reliable findings (Leal & Marques, 2022).

Most studies incorporate additional variables beyond CO_2 emissions and economic growth, commonly including energy consumption. However, including numerous additional variables can lead to multicollinearity and errors in estimating the elasticity of CO_2 emissions relative to income, thus distorting the EKC's shape (Itkonen, 2012). The choice of methodology can significantly influence results, so comparing outcomes using different methods is advisable (Leal & Marques, 2022). Some studies include GDP squared to find a U-shaped EKC curve, while others suggest using GDP in cubic form. Husnain et al. (2021) note that different studies use linear, quadratic, and cubic forms without indicating which is more probable. Therefore, it seems reasonable to employ each specification and compare results.

In summary, the results of EKC studies for EU countries are inconclusive and often contradictory. Some confirm the existence of the EKC, while others refute it or highlight its nonlinear nature. The curve's shape varies between U-shaped and N-shaped depending on the study. Consequently, the Environmental Kuznets Curve cannot be considered a universal tool for forming the European Union's climate policy, as research findings are frequently ambiguous or inconsistent.

Appendix B

Table B1. List of keywords used during database analyses

First search keywords (naive search)	carbon dioxide, carbon emission, dioxide emission, ecological footprint, environmental degradation, environmental quality, environmental sustainability, gross domestic product, economic growth, financial development, foreign direct investment, natural resource, trade openness, energy consumption, non-renewable energy, renewable energy, technological innovation, Environmental Kuznets Curve, quantile regression, panel data, ARDL, EU, Europe, European Union
Second search keyword (litsearchr)	carbon dioxide, direct investment, ecological footprint, economic growth, empirical evidence, energy consumption, environmental degradation, environmental quality, environmental sustainability, financial development, gross domestic product, Kuznets curve, natural resources, non-renewable energy, renewable energy, technological innovation, trade openness, panel, European Union, carbon neutrality, sustainable development, model, regression, causality, ARDL, VAR, industrialization, nexus, quantile, urbanization, infrastructure, fossil fuels, CO_2

Source: own elaboration.

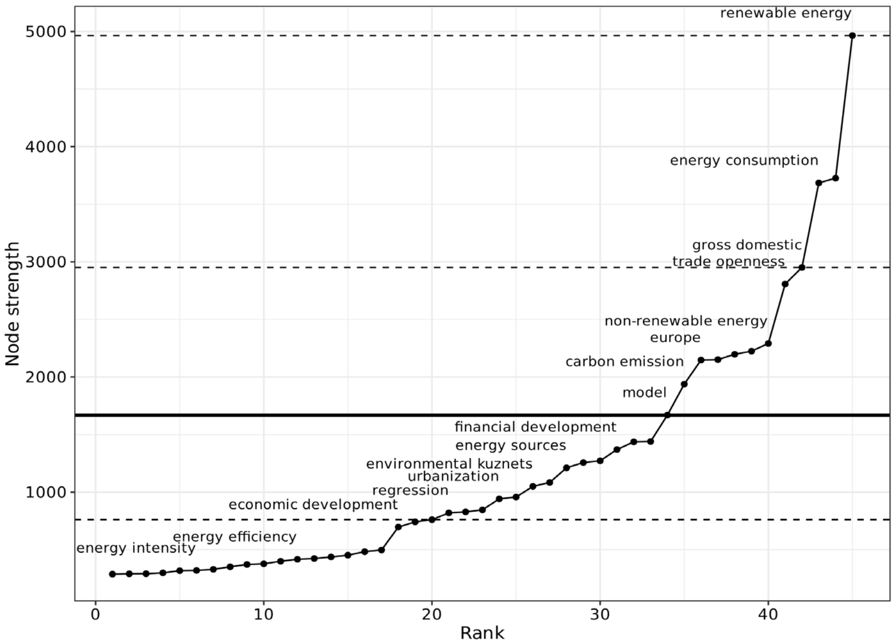

Figure B1. Plot of node strength for the terms under study

Source: own elaboration.

Table B2. Classification of the concepts studied by subject matter

Group	Area	Terms
I	Emissions and environmental quality	carbon dioxide emissions, CO_2 emissions, environmental degradation, environmental pollution, environmental quality, climate change, ecological footprint, natural resources, fossil fuels
II	Energy and energy efficiency	clean energy, energy sources, energy consumption, energy efficiency, energy intensity, energy transition, renewable energy, non-renewable energy
III	Economic and social development	financial development, economic development, economic growth, urbanization, developing countries, gross domestic product, institutional quality, sustainable development, development goals.
IV	Trade policy and investment	trade openness, foreign direct investment, direct investment
V	Models and methods of analysis	autoregressive distributed lag, panel, empirical evidence, panel causality, regression, granger causality, quantile regression, causal analysis

Source: own elaboration.

Table B3. Log-linear model results

Effect	**Rating**	**Standard error**	***Z*–Statistics**	**Significance**	**95% confidence interval**	
					lower limit	**upper limit**
X1*X9	0.061	0.073	0.838	0.402	–0.082	0.205
X1*X3	0.149	0.073	2.032	0.042	0.005	0.292
X1*X6	–0.028	0.073	–0.389	0.697	–0.172	0.115
X1*X8	0.104	0.073	1.415	0.157	–0.040	0.247
X3*X6	0.005	0.073	0.072	0.943	–0.138	0.149
X3*X8	0.037	0.073	0.504	0.614	–0.107	0.180
X3*X9	–0.147	0.073	–2.010	0.044	–0.290	–0.004
X6*X8	0.062	0.073	0.845	0.398	–0.082	0.205
X6*X9	0.012	0.073	0.160	0.873	–0.132	0.155
X8*X9	–0.109	0.073	–1.492	0.136	–0.253	0.034
Y*X1	–0.145	0.073	–1.987	0.047	–0.289	–0.002
Y*X3	0.019	0.073	0.257	0.797	–0.125	0.162
Y*X6	–0.279	0.073	–3.808	0.000	–0.422	–0.135
Y*X8	0.163	0.073	2.233	0.026	0.020	0.307
Y*X9	0.148	0.073	2.022	0.043	0.005	0.291
Y	–0.774	0.073	–10.573	0.000	–0.917	–0.630
X1	–0.387	0.073	–5.283	0.000	–0.530	–0.243
X3	–0.302	0.073	–4.129	0.000	–0.445	–0.159
X6	0.812	0.073	11.092	0.000	0.668	0.955
X8	0.458	0.073	6.254	0.000	0.314	0.601
X9	–0.289	0.073	–3.956	0.000	–0.433	–0.146

Source: own elaboration.

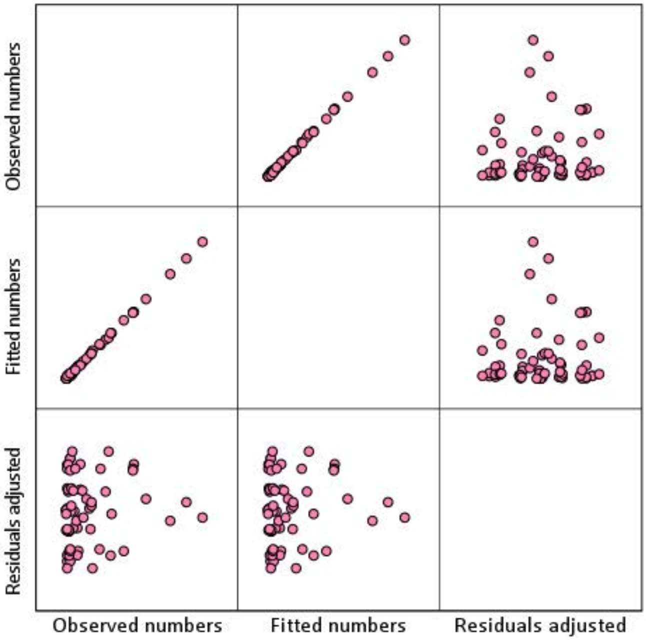

Figure B2. Log-linear model fitting plot

Source: own elaboration.

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