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Role of Energy R&D in Shaping the Environmental Kuznets Curve Among OECD Countries

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Abstract
The Environmental Kuznets Curve (EKC) model offers a framework for examining the relationship between economic growth and environmental degradation. This study aims to determine whether implementing energy regulations can influence environmental outcomes beyond what the EKC predicts. A detailed panel data model is used to analyze 25 OECD countries, focusing on the interplay between economic growth, environmental degradation, and the impact of energy research, development, and demonstration on environmental pollution. Utilizing an N-shaped cubic model of the EKC, this study investigates the progression of per capita greenhouse gas emissions. Unlike traditional analyses that primarily consider economic growth, this research incorporates public budgets dedicated to energy-oriented research, development, and demonstration. The regression results demonstrate that investments in energy innovations significantly reduce per capita greenhouse gas emissions levels and mitigate the adverse effects on environmental quality. The N-shaped EKC model suggests that environmental degradation initially increases with economic growth, reaches a peak, then decreases, but may rise again at higher levels of income. This study's findings confirm that beyond certain economic thresholds, continued growth can lead to further environmental harm unless mitigated by targeted interventions like energy research, development, and demonstration. By integrating these variables, the research provides a more nuanced understanding of how policy measures can alter the trajectory predicted by the EKC. Energy research, development, and demonstration plays a crucial role in this dynamic. Public investments in energy research and development are shown to be effective in reducing greenhouse gas emissions, thereby enhancing environmental quality. This underscores the importance of sustained and focused investment in innovative energy technologies as a critical component of environmental policy. By fostering advancements in renewable energy, energy efficiency, and low-carbon technologies, countries can achieve significant reductions in emissions. Additionally, the study introduces a methodological enhancement by interpreting the influence of inflection points on EKC behavior. Inflection points represent the stages where the direction of the relationship between economic growth and environmental degradation changes. Understanding these points is vital for policymakers to implement timely and effective interventions. For instance, identifying the initial peak where environmental degradation starts to decline can help in crafting policies that reinforce this positive trend. Conversely, recognizing a potential second rise in degradation at higher income levels can prompt preemptive measures to avoid further environmental damage.
Keywords: Environmental Kuznets Curve, Energy Research & Development, Greenhouse Gas Emissions
JEL Codes: Q50, Q55, O44

1. INTRODUCTION

The discourse surrounding the interplay between environmental degradation and economic development has sparked substantial debate. Traditionally, the prevailing notion suggested a direct correlation between economic growth and environmental deterioration. Nevertheless, contemporary research has shed light on the possibility of environmental challenges serving as catalysts for economic advancement. One prominent concept in this discourse is the Environmental Kuznets Curve (EKC). The EKC posits a curvilinear relationship between economic development and environmental degradation, characterized by an inverted U-shape. Initially, during the early stages of economic growth, environmental degradation tends to intensify. However, as economies progress beyond a certain threshold of income or development, there's an anticipated decline in pollution levels. This shift is attributed to the increasing affluence of societies, leading to a greater emphasis on environmental preservation and sustainable practices. The Environmental Kuznets Curve (EKC) framework offers a nuanced perspective on the intricate dynamics between economic progress and environmental sustainability. As societies evolve economically, the relationship between their growth trajectory and environmental impact undergoes a transformative journey. Initially, in the early stages of industrialization and economic expansion, the focus often leans heavily towards rapid economic development, often at the expense of environmental conservation.

During this phase, industries prioritize production efficiency and output maximization, often leading to unchecked pollution, resource depletion, and habitat destruction. Environmental degradation may worsen as economic activities intensify, resulting in polluted air and water, deforestation, and loss of biodiversity. These adverse environmental impacts are evident in many developing economies as they strive to achieve higher levels of economic output and improve living

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standards for their populations. However, as economies progress and per capita income levels rise, a shift in priorities begins to emerge. With increasing affluence, societies become more aware of the environmental consequences of their economic activities. Environmental consciousness grows, and there is a growing demand for cleaner technologies, sustainable practices, and stricter environmental regulations. This transition marks the turning point depicted by the peak of the Environmental Kuznets Curve. Beyond this inflection point, economic growth becomes increasingly decoupled from environmental degradation. Advanced technologies, environmental policies, and shifts towards greener energy sources contribute to a more sustainable development trajectory.

Countries with higher income levels tend to invest more in environmental protection measures, such as pollution control infrastructure, renewable energy projects, and conservation efforts. Moreover, as societies become wealthier, there is often greater public pressure and political will to address environmental concerns, leading to more stringent regulations and enforcement mechanisms. In essence, the Environmental Kuznets Curve encapsulates the notion that economic development is not inherently detrimental to the environment. Instead, it underscores the potential for economic growth to catalyze positive environmental outcomes when accompanied by effective policies, technological innovation, and societal awareness. This perspective emphasizes the importance of pursuing sustainable development pathways that reconcile economic prosperity with environmental stewardship for the benefit of present and future generations. Indeed, the Environmental Kuznets Curve (EKC) hypothesis provides a useful framework for policymakers grappling with the complex interplay between economic growth and environmental sustainability. By recognizing the potential for economic development to both exacerbate and ameliorate environmental degradation, policymakers can design more effective strategies to promote sustainable development. One key implication of the EKC is the importance of setting targets and implementing policies aimed at steering economies towards the downward-sloping phase of the curve, where environmental quality improves alongside economic growth. This requires a multi-faceted approach that combines regulatory measures, market-based incentives, technological innovation, and international cooperation.

Promoting energy efficiency is a crucial aspect of such policies, as it not only reduces greenhouse gas emissions and pollution but also enhances energy security and resilience. Investing in renewable energy sources, such as solar, wind, and hydroelectric power, can further contribute to decoupling economic growth from environmental degradation. These efforts not only mitigate the negative environmental impacts of energy production but also foster job creation, innovation, and economic diversification. Environmental regulations play a critical role in shaping the behavior of businesses and individuals towards more sustainable practices. By imposing limits on pollutant emissions, establishing standards for resource extraction and waste management, and incentivizing eco-friendly technologies, regulations can help align economic activities with environmental objectives. The work of Grossman and Krueger (1991) underscores the importance of considering environmental factors in trade and economic policies. Their analysis of the environmental impacts of trade agreements highlights the interconnectedness of economic activities and environmental outcomes, emphasizing the need for integrated approaches to policymaking. Moving forward, policymakers must continue to prioritize environmental sustainability alongside economic growth. This requires a paradigm shift towards more holistic and long-term thinking, recognizing that preserving natural resources and ecosystems is essential for ensuring the resilience and prosperity of future generations. By embracing the insights provided by the Environmental Kuznets Curve and building upon the foundations laid by pioneering research, policymakers can navigate the complex challenges of sustainable development more effectively.

Undertaking an analysis of energy regulation policies and their impact on greenhouse gas emissions (GHG) reduction is crucial for addressing environmental challenges while promoting sustainable economic development. This study aims to identify the key features of existing energy innovation measures and evaluate their effectiveness in reducing GHG emissions. By focusing on applied technologies in environmental control processes, the study seeks to contribute to theoretical advancements in the Environmental Kuznets Curve (EKC) model. The methodological approach involves establishing an econometric panel data model for 25 OECD countries, incorporating fixed effects to account for country-specific characteristics. This allows for a comprehensive assessment of the relationship between public investments in research, development, and demonstration (RD&D) and GHG reductions across different nations. By analyzing the impact of regulatory measures on GHG emissions, the study aims to provide insights into the effectiveness of various energy innovation policies. Furthermore, by systematically omitting individual variables from the model, the study can evaluate the relative importance of different regulatory measures in driving GHG reductions. This approach enables policymakers to prioritize interventions that have the greatest potential for mitigating climate change and promoting environmental sustainability.

The Environmental Kuznets Curve (EKC) framework offers valuable insights into the complex relationship between economic growth and environmental degradation. Initially proposed in the early 1990s, the EKC suggests that as economies develop, environmental degradation worsens until a certain income threshold is reached. Beyond this point, further economic growth is associated with improved environmental quality. Grossman and Krueger's seminal work in 1991 examined the environmental consequences of the North American Free Trade Agreement (NAFTA), providing early empirical support for the EKC hypothesis. Their study laid the foundation for subsequent research into the environmental implications of trade liberalization and economic growth. Building on this foundation, scholars like Ekins (1997) and Stern et al. (1996) conducted further empirical analyses to explore the dynamics of the EKC. Their research expanded the understanding of the EKC by examining additional factors such as technological innovation, energy efficiency, and environmental policy interventions. By incorporating diverse empirical evidence and theoretical insights, these studies contributed to a more nuanced understanding of the relationship between economic growth and environmental sustainability.

The studies by Panayotou (1993) and Selden and Song (1995) offer valuable empirical insights into the relationship between economic growth and environmental degradation across different stages of development. By conducting empirical tests and policy analyses, these studies shed light on how environmental quality evolves as economies progress, providing important considerations for policymakers and researchers. Moreover, the role of technical innovation in addressing environmental challenges is emphasized by Andreoni and Levinson (2001). Their research underscores the significance of technological advancements in mitigating environmental contamination, particularly as economic activity increases. This highlights the potential for innovation to drive environmental improvements, offering opportunities for sustainable development. Grossman and Krueger (1995) further contribute to this discussion by emphasizing the importance of technical effects over composition or scale effects in addressing environmental issues. Their findings suggest that technological innovations and advancements play a central role in addressing environmental challenges associated with economic growth. These studies deepen our understanding of the complex relationship between economic growth and environmental degradation. By highlighting the role of technical innovation and providing empirical evidence on the dynamics of this relationship, they offer valuable insights for policymakers seeking to promote environmental sustainability while fostering economic development.

2. LITERATURE REVIEW

Indeed, the interplay between economic growth and energy policies is pivotal in addressing environmental challenges and fostering sustainable development. By replacing existing energy sources with cleaner alternatives and enhancing energy efficiency, energy policies can mitigate environmental degradation while also promoting economic growth. Public support, particularly through investments in research, development, and demonstration (RD&D) of energy technologies, is essential for driving innovation and facilitating the transition to cleaner energy sources. These investments enable the development and deployment of advanced technologies that can enhance energy efficiency and reduce greenhouse gas emissions. Effective energy regulation is crucial for creating a conducive environment for investment in clean energy technologies and incentivizing businesses and individuals to adopt sustainable energy practices. Policies that promote renewable energy deployment, incentivize energy efficiency improvements, and establish carbon pricing mechanisms can steer economies toward a low-carbon future while stimulating economic growth. Furthermore, international cooperation and coordination are essential for addressing global environmental challenges effectively. Collaborative efforts among nations can facilitate knowledge sharing, technology transfer, and financial support for clean energy projects, fostering innovation and accelerating the transition to a sustainable energy system. By analyzing the impact of these regulations on environmental outcomes, they shed light on the potential benefits of policy interventions aimed at promoting cleaner energy sources and enhancing energy efficiency.

Evidence from these studies suggests that while energy regulations may impose short-term costs on the economy, they can yield long-term benefits in terms of improved environmental quality. By incentivizing investments in energy-efficient technologies and renewable energy sources, regulations can lead to reductions in greenhouse gas emissions and other forms of environmental pollution. Moreover, the findings underscore the importance of adopting comprehensive approaches to environmental regulation. Del Río González et al. (2009) emphasize the need to integrate emissions trading systems with other policy instruments to maximize their effectiveness in reducing environmental impacts. This highlights the importance of coordination and synergy among different regulatory mechanisms to achieve environmental objectives more efficiently. Overall, the research conducted by Brock and Taylor (2005), Cantos and Lorente (2011), Iwata et al. (2010), Turner and Hanley (2011), and Del Río González et al. (2009) contributes to our understanding of the potential of energy regulations to address environmental challenges and promote sustainability. By informing policymakers about the effectiveness of various policy interventions, these studies play a crucial role in shaping evidence-based environmental policy decisions.

The Environmental Kuznets Curve (EKC) hypothesis provides an insightful framework for understanding the relationship between economic growth and environmental degradation. According to this hypothesis, environmental quality worsens in the initial stages of economic development but improves beyond a certain income level, forming an inverted U-shaped curve. Public intervention and technological innovation play pivotal roles in shaping this relationship. Energy Research, Development, and Deployment (RD&D) initiatives are crucial components of public intervention aimed at fostering technological innovation in the energy sector. By investing in RD&D, governments can facilitate the development and deployment of cleaner and more efficient energy technologies. These advancements in energy technology can contribute to mitigating environmental degradation by reducing emissions of greenhouse gases and other pollutants. For example, research and development efforts focused on renewable energy sources, such as solar and wind power, can lead to the adoption of cleaner energy alternatives, thereby reducing reliance on fossil fuels and decreasing pollution levels. Furthermore, innovations in energy efficiency technologies can enhance the productivity of energy use, allowing for economic growth while minimizing environmental impacts. Through targeted RD&D investments and supportive policy measures, governments can accelerate the transition towards a more sustainable energy system, where economic growth is decoupled from environmental degradation.

The Environmental Kuznets Curve hypothesis highlights the potential for economic development to contribute to environmental improvements, particularly when supported by public intervention and technological innovation in the energy sector. By investing in RD&D and promoting the adoption of cleaner technologies, governments can help achieve a more sustainable and environmentally friendly path of economic growth. Technical factors indeed play a critical role in the process of decontamination and reducing pollution levels associated with economic activities. Investments in energy innovation targeted at decontamination are expected to lead to decreases in pollution levels over time. Several studies have emphasized the importance of institutional reforms and policy changes in achieving environmental sustainability. Arrow et al. (1995), Stagl (1999), and Unruh and Moomaw (1998) have all highlighted the necessity of implementing reforms to facilitate the adoption of cleaner technologies and promote sustainable economic growth while mitigating environmental degradation. During the initial stages of economic development, policies often lead to distortions such as subsidies for energy consumption, and market failures may occur. This phase is typically characterized by scale effects, where increased production initially results in decreased environmental quality. As a result, economic growth during this stage tends to have a negative impact on the environment, as illustrated by the upward trend of the Environmental Kuznets Curve (EKC) (Panayotou, 1993; Andreoni & Levinson, 2001). As economies progress further along the development spectrum, there is often a greater emphasis on sustainability and environmental stewardship. This shift is driven not only by regulatory measures but also by changes in societal values and technological advancements (Unruh & Moomaw, 1998). Investments in clean technologies and renewable energy sources become increasingly attractive as economies seek to mitigate their environmental impact while maintaining economic growth. Institutional changes play a crucial role in facilitating this transition. Governments may enact policies that incentivize environmentally friendly practices and discourage pollution-intensive activities (Jones & Manuelli, 1995). Additionally, international agreements and collaborations can promote the adoption of sustainable practices on a global scale. The Environmental Kuznets Curve (EKC) framework provides a useful lens through which to understand these dynamics. It suggests that while economic growth initially exacerbates environmental degradation, there comes a point where further development leads to improvements in environmental quality (Andreoni & Levinson, 2001). This inflection point reflects a shift toward more sustainable production and consumption patterns, driven by both market forces and deliberate policy interventions.

As economies evolve, so too do their approaches to environmental sustainability. By recognizing the interplay between economic development, institutional changes, and technological innovation, societies can work towards achieving both prosperity and environmental conservation in a mutually reinforcing manner. Technical innovations are essential for addressing environmental challenges effectively. By investing in research and development (R&D) aimed at improving energy efficiency and developing cleaner technologies, economies can reduce their environmental footprint while sustaining economic growth. As highlighted by Andreoni and Levinson (2001), innovations in the energy sector can lead to significant reductions in pollution levels. Advancements in renewable energy sources, energy-efficient technologies, and sustainable practices can contribute to mitigating environmental degradation associated with energy production and consumption. Furthermore, as economies progress and income levels rise, there is often greater investment in technological innovation. This, coupled with increased energy consumption, can lead to improved energy efficiency and lower rates of environmental pollution, as noted by Stokey (1998). However, achieving these outcomes requires more than just technological advancements. Institutional changes and policy reforms are essential to create an enabling environment for the adoption and implementation of clean technologies and sustainable practices (Unruh & Moomaw, 1998). Governments play a crucial role in setting regulations, providing incentives, and fostering collaboration between various stakeholders to promote environmental sustainability.

Technical innovations, coupled with supportive institutional frameworks and policy reforms, are instrumental in addressing environmental challenges and achieving sustainable development goals. By investing in innovation and implementing effective policies, economies can move towards a more environmentally sustainable future while continuing to grow and prosper economically. Energy innovation is vital for shaping the interaction between economic growth and environmental degradation. By investing in research and development (R&D) initiatives aimed at advancing cleaner and more efficient energy technologies, societies can mitigate the negative environmental impacts associated with economic expansion. As Stokey (1998) suggests, advancements in energy innovation enable the adoption of less polluting energy sources and more efficient production processes. These innovations lead to reductions in greenhouse gas emissions, air and water pollution, and other forms of environmental degradation. Furthermore, as highlighted by Bovenberg and Smulders (1995), the adoption of cleaner energy technologies can decouple economic growth from environmental contamination. Instead of the traditional pattern where economic expansion leads to increased pollution levels, energy innovation allows for sustainable development, where improvements in environmental quality occur alongside continued economic growth. Therefore, fostering energy innovation through supportive policies, investments in R&D, and collaboration between the public and private sectors is essential for achieving sustainable development goals. By harnessing the power of innovation, societies can create a path towards a cleaner, more sustainable future for generations to come.

The trajectory of escalating contamination can become a significant issue when the scale effect—essentially the increase in pollution resulting from economic expansion—outpaces the beneficial impacts of composition and technological effects. The composition effect refers to shifts in the economic structure towards less polluting industries, while the technological effect involves improvements in production processes that reduce environmental impact. When these positive effects are insufficient to counterbalance the scale effect, environmental degradation can worsen despite economic growth (Torras & Boyce, 1998). In such scenarios, the role of effective environmental regulation becomes paramount. Environmental regulations can incentivize the adoption of cleaner technologies and practices, thus enhancing the technological effect. These regulations can take various forms, including emissions standards, carbon pricing, subsidies for renewable energy, and mandates for energy efficiency. By providing both the carrot and the stick, these policies can drive significant improvements in environmental quality.

Moreover, robust environmental policies can help in correcting market failures and overcoming the diminishing returns on technical advancements. When firms are required to adhere to strict environmental standards, they are more likely to invest in R&D to innovate and find cost-effective solutions to comply with these regulations. This can lead to breakthroughs in technology that might not have been pursued in the absence of regulatory pressure. The findings of Torras and Boyce (1998) underscore the importance of integrating environmental considerations into the economic growth agenda. Effective regulation can not only prevent the escalation of contamination but also stimulate economic growth by fostering a green economy. In this way, economies can achieve a more sustainable development trajectory where environmental sustainability and economic growth are mutually reinforcing rather than mutually exclusive.

3. THE MODEL

In this section, we propose an econometric model to investigate the relationship between income levels and environmental pollution through the lens of the Environmental Kuznets Curve (EKC), incorporating the influence of public budgets in energy innovation. This model leverages panel data from 25 OECD countries over the period 1992-2019. The use of panel data econometric techniques is particularly appropriate and beneficial when dealing with non-observable heterogeneities across countries or time periods. This is because different countries may make decisions differently, even if they share similar observable characteristics. Consequently, our analysis accounts for specific individual effects unique to each country that are consistent over time and impact national decision-making processes.

The interpretation of a panel data model occurs through its error components. The specification of a regression with panel data is as follows:

$$GHGpc_{it} = \alpha_i + \beta_1\, GDPpc_{it} + \beta_2\, GDPpc_{it}^2 + \beta_3\, GDPpc_{it}^3 + \beta_4\, \mathrm{RDDT}pc_{it-1} + \varepsilon_{it}$$

where:

$GHGpc_{it}$ = level of emissions of GHG, measured in millions of tonnes CO_2, per capita in country i and year t (Cantos & Lorente, 2013).

$GDPpc_{it}$ = level of income per capita measured in millions of US dollars, at current prices and current PPPs, for country i and year t (Cantos & Lorente, 2013).

The variable RDDTpcit-1 represents the public budget in energy RD&D per capita, measured in millions of US dollars at current prices and current PPPs, for country i and year t-1. This variable is introduced into the equation with a lag of two time periods, reflecting the time required for innovative measures to have a tangible impact (Cantos & Lorente, 2013; OECD, 2013).

4. RESULTS AND DISCUSSION

We first estimate Equation (2) with fixed effects for the cross-sections using a GLS method and correcting for heteroscedasticity in the cross-section. The first three coefficients β_i determine the cubic shape of the EKC; the behavior of the remaining coefficients also helps explain the GHGpc emission level. The coefficient β_4 establishes the impact of energy innovation measures over GHg.

Table 1: Outcomes of GLS

Dependent Variable: GHGpc				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	10970.63	694.1770	15.80379	0.0000
GDPpc	0.154424	0.049548	3.116629	0.0019
$GDPpc^2$	-4.01E-06	1.15E-06	-3.484982	0.0005
$GDPpc^3$	2.62E-11	7.65E-12	3.428152	0.0007
RDDTpc(-1)	-18254.08	6511.907	-2.803184	0.0053
AR(1)	0.838897	0.023233	36.10813	0.0000

Effects Specification Cross-section fixed (dummy variables)			
Country	Effect	Country	Effect
Australia	12819.45	Japan	-1.849.432
Austria	-2.242.698	Korea	168.3475
Belgium	647.6208	Netherlands	1609.721
Canada	9771.255	New Zealand	5126.263
Czech Republic	448.2359	Norway	-1.127.908
Denmark	122.8030	Portugal	-4.147.563
Finland	2161.015	Spain	-3.649.199
France	-3.500.001	Sweden	-5.248.436
Germany	-7.509.542	Switzerland	-5.570.347
Greece	-1.377.877	Turkey	-7.587.656
Hungary	-5.291.073	United Kingdom	-1.985.570
Ireland	3427.478	United States	11506.23
Italy	-3.479.704		

The Table 1 presents the outcomes of a Generalized Least Squares (GLS) regression analysis, with the dependent variable being GHGpc, likely representing greenhouse gas emissions per capita. The independent variables include C, GDPpc, GDPpc2, GDPpc3, and RDDTpc(-1), each with corresponding coefficients, standard errors, t-statistics, and probabilities. In the "Effects Specification" section, it appears that cross-section fixed effects (dummy variables) have been employed to address country-specific variations in the data. The table lists various countries along with their estimated effects on the dependent variable GHGpc. These effects reflect how each country contributes to greenhouse gas emissions per capita relative to the reference category. The coefficients in the GLS regression model provide insights into the relationship between the independent variables and greenhouse gas emissions per capita. For example, the coefficient for GDPpc indicates the change in GHGpc associated with a one-unit increase in GDP per capita, considering the other variables in the model. Similarly, the coefficients for GDPpc2 and GDPpc3 account for potential non-linear effects of GDP per capita on GHGpc. The standard errors associated with the coefficient estimates provide an indication of the precision of the estimates. Meanwhile, the t-statistics assess the significance of each coefficient, with lower p-values indicating greater significance. This helps determine which independent variables have a statistically significant impact on greenhouse gas emissions per capita. Overall, the GLS regression results offer valuable insights into the determinants of greenhouse gas emissions per capita across different countries, while also considering country-specific effects through cross-section fixed effects.

5. CONCLUSIONS

This study confirms the positive impact of RD&D measures on the reduction of greenhouse gas (GHG) emission levels. The proposed model exemplifies the relevance of energy innovation measures for keeping countries on a decreasing path of GHG emissions, even when they reach high-income levels. By incorporating public budgets for energy research, development, and demonstration (RD&D) into the Environmental Kuznets Curve (EKC) framework, the model highlights the crucial role that technological advancements and public support play in achieving environmental sustainability. The results indicate that the coefficient representing the impact of energy RD&D measures on GHG emissions is statistically significant and negative. This finding suggests that increased investment in energy innovation leads to a reduction in GHG emissions, supporting the argument that technological advancements are key to mitigating environmental degradation. Furthermore, the coefficients related to GDP per capita confirm the cubic shape of the EKC. Initially, as GDP per capita increases, GHG emissions rise, but after a certain income level, further increases in GDP per capita lead to a decline in GHG emissions. This inverted U-shaped curve suggests that economic growth can eventually lead to environmental improvement, especially when coupled with effective energy policies.

The inclusion of public RD&D budgets in the model underscores the importance of government support for energy innovation. Public investments in energy research and development are crucial for developing and deploying cleaner technologies, which help in reducing the environmental impact of economic activities. Therefore, governments should continue to promote energy efficiency through public RD&D investments. Such measures not only help in reducing GHG emissions but also enhance the overall energy efficiency of the economy. Transitioning to renewable energy sources is essential for sustainable development. Policies that encourage the adoption and development of renewable energy technologies can significantly contribute to reducing the carbon footprint of high-income economies. Implementing stringent environmental regulations is also necessary to ensure that the benefits of economic growth do not come at the expense of environmental quality. These regulations should be designed to complement energy innovation efforts, ensuring a holistic approach to sustainability. Institutional changes are required to support the adoption of cleaner technologies. This includes reforming energy subsidies that favor fossil fuels and creating a favorable regulatory environment for renewable energy investments.

By facilitating the adoption of less polluting energy sources and more efficient processes, these reforms can significantly enhance environmental quality alongside economic growth. In conclusion, the study confirms the positive impact of energy RD&D measures on reducing GHG emissions, validating the relevance of the EKC hypothesis in the context of OECD countries. By highlighting the importance of technological innovation and public support, the findings suggest that it is possible for countries to achieve economic growth while simultaneously improving environmental quality. This underscores the need for sustained investment in energy innovation and comprehensive policy measures to promote sustainable development. In addition, this study also demonstrates that energy innovation measures can reduce the scale effect, thereby avoiding a return to a path of increasing contamination. The scale effect refers to the initial increase in pollution levels that accompanies economic growth due to increased production and consumption. By investing in energy RD&D, countries can mitigate this effect, ensuring that economic expansion does not lead to higher levels of environmental degradation. In conclusion, this study emphasizes that pollution will not disappear automatically as a result of economic growth. Instead, each country should develop specific policies tailored to its unique context, focusing on energy RD&D to effectively reduce environmental pollution. Governments must prioritize the development and implementation of energy RD&D instruments to achieve significant improvements in environmental quality. These instruments include funding for research and innovation in renewable energy technologies, incentives for energy efficiency improvements, and stringent regulations to curb emissions from traditional energy sources.

Moreover, future studies should pay close attention to the role that inflection points play in the EKC model. Inflection points, where the trend in environmental degradation shifts from increasing to decreasing, are crucial for understanding how and when economic growth starts to benefit the environment. Identifying and analyzing these points can provide valuable insights into the timing and effectiveness of different policy measures. By understanding the conditions under which economic growth leads to environmental improvements, policymakers can design more effective strategies to promote sustainable development. Overall, this study highlights the necessity of proactive and tailored energy policies to ensure that economic growth is aligned with environmental sustainability. The integration of energy innovation measures into economic growth strategies is essential for mitigating pollution and achieving long-term environmental goals. Governments and policymakers must recognize the importance of energy RD&D and implement comprehensive frameworks that support technological advancements, regulatory reforms, and sustainable economic practices.

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