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Deciphering the Nexus Between Renewable Energy Consumption and Environmental Pollution: A GMM Model Analysis Across Diverse Economies

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ABSTRACT

Addressing green economic issues is crucial for reducing environmental pollution and fostering sustainable development. Green economics promotes sustainable practices, including renewable energy. While renewable energy reduces emissions and reliance on fossil fuels, its full environmental impact is not entirely understood. More academic research is needed to investigate these interactions and develop strategies to mitigate any adverse effects. This study examines the impact of renewable energy consumption on environmental pollution across 53 countries from 2009 to 2021. Utilizing the Generalized Method of Moments approach by Arellano and Bond (1991) with instrumental variables, the findings show that renewable energy consumption significantly reduces CO_2 and GHG emissions. Furthermore, control variables including globalization, government spending, and COVID-19 reduce emissions, while economic growth increases them. The impacts also vary across different countries, highlighting the complexity of environmental issues. As a result, this study proposes policy recommendations to improve sustainable environmental development.

Keywords: CO_2 Emissions, Greenhouse Gas Emissions, Renewable Energy, Environmental Pollution
JEL Classifications: Q20; Q52; F62

1. INTRODUCTION

Environmental pollution is an increasingly serious global issue, causing numerous adverse effects on human health, particularly on the respiratory and renal systems due to toxin accumulation during filtration (Khan and Ghouri, 2011). This pollution also threatens the balance of the natural environment and the existence of species. One pressing concern is climate change driven by greenhouse gas emissions from vehicles, factories, and agriculture (Singh et al., 2023). This results in phenomena such as tropical flooding, sea level rise, and unpredictable climate change (IPCC, 2021), posing significant risks to both the environment and the economy (Ali and Oliveira, 2018). Recent studies indicate that the El Niño phenomenon in 2023-2024 could cause significant damage to the global economy (Chen et al., 2023), negatively affecting agricultural production and fostering conditions for disease spread. Additionally, increasing population density intensifies human activities, exerting great pressure on the environment. This impact extends beyond humans to aquatic and terrestrial organisms, including microorganisms in the ecosystem, posing a challenging problem for researchers worldwide in finding new energy sources to minimize environmental pollution (IPCC, 2018).

Environmental protection is a collective responsibility. Numerous scientific studies have identified effective measures to reduce environmental pollution, such as optimizing marine diesel engine performance to reduce CO_2 emissions (Tadros et al., 2020), altering nutrient sources for animals (Jongbloed and Lenis, 1992), struction (Karbassi et al., 2010). Recently, there has been growing researches focusing on the significant role of clean energy sources in improving environmental outcomes, especially in the economic development of businesses. Using clean energy enhances business image, brand reputation, and creates new business opportunities. Moreover, it ensures energy supply stability and encourages industry innovation and creativity. The interest in new clean energy sources has surged among researchers and businesses, leading to a new wave in research circles known as Renewable Energy.

Renewable energy, generated from natural sources that can be replenished quickly, includes solar, wind, water, biological growth, and geothermal heat. These energy sources do not deplete and produce harmful emissions or negatively impact the environment, unlike fossil fuels such as coal and oil. Renewable energy is crucial for reducing dependence on fossil fuels, lowering greenhouse gas emissions, and ensuring energy security (Holecheck et al., 2022). It also creates new opportunities for industries, enhances innovation, and promotes sustainable economic development. Renewable energy not only offers a solution to mitigate pollution but also aligns with the principles of sustainable development by promoting economic growth and environmental health (Sousa et al., 2022). In other words, renewable energy offers a viable solution to mitigate pollution, promote public health, and ensure economic stability. Comprehensive research in this area is essential for developing effective policies, guiding investments, and fostering a global transition towards a cleaner, more sustainable energy future. As a results, numerous studies have provided feasible solutions to promote renewable energy use to reduce environmental pollution (Aleixandre-Tudó et al., 2019; Islam et al., 2021; Bhattacharya et al., 2016; Saadat et al., 2020).

On the other hand, despite their benefits, renewable energy sources pose environmental risks. Wind turbines lead to high mortality rates among birds and bats, while photovoltaic substances can contaminate water and air, and manufacturing solar cells consumes significant water (Kiesecker et al., 2011). The study of Spellman (2014) found that hydropower could cause ecological disruptions, including flooding and habitat destruction, impacting species migration and reproduction. Due to the conflicting views on the relationship between renewable energy and environmental pollution, a comprehensive study on this relationship is necessary. Additionally, the previous studies often lack sufficient data and do not adequately consider control variables such as economic development, globalization, and economic scenarios like crises and epidemics, which are often overlooked in previous research. This limitation hinders their ability to comprehensively demonstrate the impact of renewable energy on environmental issues across global economies. Furthermore, statistical support for progressive policy measures remains vague and incomplete. Therefore, by studying the impact of renewable energy on environmental pollution across various economies, and considering economic development, globalization, and economic risks, we can achieve a balance between economic growth, environmental protection, and social well-being, ensuring a sustainable future for generations to come.

Given the escalating environmental challenges and the necessity for sustainable practices, it is essential to explore how renewable energy can mitigate pollution and foster a green economy. Drawing on spanning data from 53 countries spanning the years 2009-2021, this study investigates the impact of renewable energy on environmental pollution. The research utilizes the Generalized Method of Moments (GMM) approach developed by Arellano and Bond (1991), due to its ability to handle dynamic data address endogeneity, incorporate exogenous variables, and optimize estimation processes by using instrument variables. This enhances the reliability and efficiency of the data analysis, providing robust insights that can guide the transition to a green economy and sustainable future.

The study is organized into five primary sections: Section 1 introduces the research. Section 2 provides a comprehensive literature review of the renewable energy sources, the environmental pollution and the relationship between the use of renewable energy sources and the environmental pollution issues. Section 3 details and elucidates the research methodology and data. Section 4 presents and discusses the research findings and checks the robustness test. Section 5 offers the main conclusions and policy recommendations.

2. LITERATURE REVIEW

2.1. Environmental Pollution

In recent decades, the relentless pursuit of economic development has often been synonymous with industrialization, urbanization, and increased energy consumption, primarily reliant on fossil fuels. This trajectory has undeniably propelled economies forward, elevated living standards, and spurred technological innovation. However, it has also inflicted immeasurable environmental damage, manifesting in alarming levels of pollution, habitat degradation, and climate change (Karasoy and Akçay, 2019; Haapanen and Tapio, 2016). The Multifaceted Nature of Environmental Pollution Environmental pollution remains an escalating concern with profound implications for ecosystems, human health, and planetary health. The most significant impact of environmental emissions is climate change. Greenhouse gases, such as CO_2, CH_4, and N_2O, trap heat in the Earth's atmosphere, leading to global warming. The Intergovernmental Panel on Climate Change (IPCC, 2018) reports that human-induced emissions have increased global temperatures, resulting in severe weather patterns, rising sea levels, and the loss of biodiversity. Environmental emissions adversely affect human health. Fine particulate matter PM2.5 and other air pollutants are linked to respiratory and cardiovascular diseases. A study by Lelieveld et al. (2019) estimates that outdoor air pollution causes millions of premature deaths annually. The health impacts are particularly severe in urban areas with high emission levels.

The primary metrics for assessing environmental pollution are the CO_2 index and the greenhouse gas index, which serve as indicators of the extent and impact of pollution (Cherni and Jouini, 2017; Cao et al., 2022). Pollution manifests through various lenses, influenced by factors such as economic development, globalization, and renewable energy consumption while research results on emissions and the determinants are mixed. Firstly the relationship between economic development and CO_2 emissions has been extensively studied, with most findings indicating a positive correlation. Using time-domain techniques such as Bounds testing, Bayer, and Hanck co-alignment, ARDL, FMOLS, and DOLS, Adebayo (2021) found that increases in GDP correlate with rising CO_2 emissions in Japan. Similar results were reported by Sahu and Kumar (2020) in their study on India, reinforcing the notion that economic growth leads to higher CO_2 emissions. Secondly, research findings on the relationship between globalization and CO_2 emissions are mixed. On one hand, some studies suggest that globalization can reduce CO_2 emissions. For instance, Zaidi et al. (2019) and Saint et al. (2019) found that globalization has contributed to lower CO_2 emissions in Turkey. Similarly, Islam et al. (2021) argue that while economic development initially increases CO_2 emissions, the long-term effects are less pronounced. Conversely, other studies highlight the adverse effects of globalization on environmental pollution. Chienwattanasook et al. (2021) posit that economic growth, fueled by financial development, can exacerbate CO_2 emissions by enabling the acquisition of industrial equipment at lower costs, thus increasing energy consumption. Furthermore, Sheraz et al. (2022) using FMOLS, DMOLS, and CS-ARDL models, suggest that the development of stock and financial markets can increase CO_2 emissions, even as globalization lowers borrowing costs and stimulates economic growth through fossil fuel use. Thirdly, renewable energy consumption (REC) presents a viable solution for reducing environmental pollution. Karasoy and Akcay (2019) demonstrated that REC significantly reduces CO_2 and GHG emissions. This finding is consistent with research emphasizing the role of renewable energy in mitigating adverse environmental impacts (Akram et al., 2020; Halkos and Paizanos, 2013). However, the impact of REC varies between developed and developing countries. In developed nations, REC has a statistically significant negative impact on CO_2 and GHG emissions, while in developing countries, this impact is not statistically significant (Iqbal et al., 2023).

2.2. Renewable Energy

Renewable energy has gained substantial attention in recent decades as a crucial component for addressing the dual challenges of energy security and environmental sustainability. Renewable energy, derived from perpetually replenished natural sources such as sunlight, wind, water, geothermal heat, and biomass, offers a sustainable alternative to finite fossil fuels like coal, oil, and natural gas. This form of energy, being generated from natural processes, is inherently clean and non-depleting (Hien, 2022). The primary types of renewable energy include solar power, wind energy, hydropower, geothermal energy, and biomass energy.

Renewable energy offers numerous benefits that contribute to its growing adoption and integration into global energy systems. Renewable energy sources produce little to no greenhouse gas emissions compared to fossil fuels. This significantly reduces air pollution and mitigates climate change. For instance, wind and solar power produce negligible emissions during operation (Lund, 2014). Furthermore, renewable energy reduces dependence on imported fuels and enhances energy security by diversifying the energy supply. This is particularly important for countries that rely heavily on fossil fuel imports (Hossain et al., 2016). Renewable energy supports sustainable development by providing access to clean and affordable energy. This is crucial for improving living standards and fostering economic development in developing regions (World Bank, 2017). The renewable energy sector has stimulated economic growth. Chienwattanasook et al. (2021), in their study of ASEAN countries utilizing the GMM methodology, argue that renewable energy sources facilitate the economic development. Similarly, Majeed et al. (2022) in their study on BRICS economies, agree that financial growth, environmental innovations, energy productivity, and energy prices are critical factors that enhance the use of renewable energy sources.

Despite its benefits, renewable energy faces several challenges and potential environmental risks that need to be addressed. Solar and wind energy are intermittent, depending on weather conditions and time of day. This variability poses challenges for grid stability and requires the development of energy storage solutions and smart grid technologies (Fthenakis et al., 2009). Moreover, while renewable energy is generally more environmentally friendly than fossil fuels, it is not without impacts. Wind turbines can harm bird and bat populations, and large-scale hydropower projects can disrupt aquatic ecosystems and displace communities (Kiesecker et al., 2011). The availability of renewable energy resources also varies geographically. For instance, solar power is more effective in regions with high solar insolation, while hydropower depends on the availability of water resources (REN21, 2020). Lastly, initial investments in renewable energy infrastructure can be high, although costs are decreasing. Government incentives and supportive policies are often necessary to make renewable energy financially viable (IRENA, 2020).

Renewable energy is a key solution for addressing the global challenges of energy security, environmental sustainability, and climate change. While there are challenges to its widespread adoption, the benefits of renewable energy far outweigh the drawbacks.

2.3. Impact of Renewable Energy on Environmental Issues

In recent years, there have been many studies confirming that renewable energy is the key to balancing economic development goals and environmental issues, a promising solution to sustainable development. Naseem and Guang (2021), using fixed effects (FE) and generalized method of moments (GMM) methods, investigated the South Asian Association for Regional Cooperation (SAARC) from 2000 to 2017 and found an inverse relationship between the development of renewable energy sources and environmental pollution. Similarly, Cao et al. (2022) utilized the Cointegration method to study OECD countries from 1985 to 2018, concluding that renewable energy significantly reduces CO_2 emissions in both the short and long term. Vasylieva et al. (2019) affirmed that increasing renewable energy use could help Ukraine and EU countries reduce greenhouse gas emissions by 25% by 2050. Research by Sheraz et al. (2022) on belt and road initiative (BRI) countries for the period 2003-2019, using FMOLS, DMOLS, and CS-ARDL methods, found that a 1% increase in renewable energy consumption leads to a reduction in CO_2 emissions by 0.0332% in the long run and 0.2510% in the short run. These findings suggest that shifting from fossil fuels to renewable energy can significantly mitigate CO_2 emissions. Jiang and Khan (2023) also employed GMM models for the same period and reached similar conclusions, highlighting the environmental benefits of renewable energy in BRI countries. Furthermore, a study by Onuoha et al. (2023) on sub-Saharan Africa from 1990 to 2020 echoed these results. However, despite these positive aspects, renewable energy also poses potential environmental risks. Spellman (2014) raised concerns about habitat degradation from photovoltaic substances contaminating water and air. Additionally, solar cells, while not requiring water for electricity generation, still involve water use in manufacturing processes. Centralized solar thermal power plants and biomass power plants, like all thermal power plants, require water for cooling, which can negatively impact groundwater resources and land use. Hydropower, while not emitting air pollutants, can cause significant ecological disruptions, including large-scale flooding and habitat destruction, affecting species migration and reproduction.

The relationship between renewable energy and environmental pollution is complex and governed, influenced by many factors. The initial factor linking renewable energy and the environment is globalization. Globalization facilitates access to advanced technologies and foreign direct investment, potentially promoting industrialization and modernization. However, this often depends on fossil fuels, leading to severe environmental degradation (Appannagari, 2017). Studies by Chienwattanasook et al. (2021) and Sheraz et al. (2022) indicate that globalization can increase CO_2 emissions when countries prioritize economic growth over environmental protection. Onuoha et al. (2023) also argue that globalization and financial market development can hinder the adoption of renewable energy sources, thereby harming the environment. Conversely, globalization can also provide opportunities for cooperation and technology transfer, enhancing the adoption of renewable energy and contributing to sustainable development. Research by Sahu and Kumar (2020) and Cao et al. (2022), supports the view that globalization can reduce CO_2 emissions through these mechanisms.

Economic development significantly impacts the relationship between renewable energy and environmental pollution. Fossil fuel-based energy consumption, driven by economic growth, often exacerbates environmental degradation. Adebayo (2021) and Chienwattanasook et al. (2021) found that increases in GDP correlate with higher CO_2 emissions. In contrast, coupling economic development with renewable energy adoption can yield long-term environmental benefits, as demonstrated by Onuoha et al. (2023). Studies by Onuoha et al. (2023), Vasylieva et al. (2019), and Kalayci and Hayaloglu (2018) confirm that this approach can reduce CO_2 and GHG emissions.

Government spending is another crucial factor influencing the relationship between renewable energy and environmental pollution. Government expenditures on public goods and services, including renewable energy investments, can significantly reduce environmental pollution. Halkos and Paizanos (2013) argue that increased government spending on environmentally friendly initiatives can lower CO_2 emissions. This view is supported by Ozyilmaz et al. (2023), who studied G7 countries from 1997 to 2020, and Ifa and Guetat (2021), who examined eight South Mediterranean countries from 1980 to 2020 using ARDL and VECM methods.

Economic crises can have profound effects on the renewable energy sector and its relationship with environmental pollution. During economic downturns, investments in renewable energy projects often decline due to reduced financial resources and shifting government priorities. For instance, the 2008 global financial crisis led to a slowdown in renewable energy investments, as countries prioritized economic recovery over environmental initiatives (Kim and Lee, 2019). This reduction in renewable energy investments can increase reliance on fossil fuels, exacerbating environmental pollution. However, some studies suggest that economic crises can also create opportunities for a green transition. For example, the European Union’s post-crisis recovery plan included significant investments in renewable energy and energy efficiency, aiming to stimulate economic growth while reducing carbon emissions (European Commission, 2010). This indicates that strategic policy responses to economic crises can potentially strengthen the renewable energy sector and mitigate environmental pollution.

Health pandemics, such as the COVID-19 pandemic, have complex impacts on renewable energy and environmental pollution. The pandemic initially caused a decline in energy demand and disruptions in supply chains, affecting renewable energy projects worldwide (IEA, 2020). However, the subsequent economic recovery packages in many countries included substantial investments in renewable energy as a means to stimulate economic growth and create jobs (REN21, 2020). The COVID-19 pandemic also led to temporary reductions in air pollution due to lockdown measures and reduced industrial activity. This highlighted the potential environmental benefits of decreased fossil fuel consumption and the importance of renewable energy in maintaining these gains in the long term (Le Quéré et al., 2020). The pandemic underscored the need for resilient and sustainable energy systems that can withstand global crises and contribute to environmental sustainability.

Numerous studies have examined the relationship between renewable energy consumption and environmental factors, yet they often yield conflicting results regarding the factors affecting renewable energy and environmental pollution. These studies typically focus on specific countries or regions, lacking comprehensive data sets to assess these relationships globally. This study aims to address these gaps by using a broad dataset from 53 countries between 2009 and 2021 to produce more generalizable results. Additionally, this study considers control variables such as economic development, globalization, and economic scenarios like crises and epidemics, which are often overlooked in previous research. These are all possibilities that can accurately and comprehensively represent the impact of the use of renewable energy on environmental pollution in various economies around the world. Moreover, statistical support for progressive policy measures is ambiguous and incomplete. Therefore, in this study, we conduct a review of factors affecting the development and use of renewable energy sources and environmental pollution, thereby providing policy implications to promote the development of renewable energy sources, and achieve sustainable development by using GMM estimation method. To carry out the study, the authors reviewed and studied the results of the previous studies in Table 1.

Table 1: An overview of the previous studies on the environment pollution issues

Author	Country of study	Time	Research methodology	Result
Islam et al. (2021)	Bangladesh	1972-2016	ARDL	1. Globalization affects CO_2 emissions (−) 2. Economic growth negligibly affects CO_2 (+) emissions in the long run 3. Economic growth significantly affects CO_2 (+) emissions in the short term
Adebayo (2021)	Japan	1970-2015	ARDL, DOLS, FMOLS	CO_2 to GDP (+)
Kalayci and Hayaloglu (2018)	North American Free Trade Agreement countries (NAFTA)	1990-2015	FE, Wald Chi2, Durbin Watson Accreditation	1. Economic globalization affects CO_2 (+) 2. GDP affects CO_2 emissions (−)
Sahu and Kumar (2020)	India	1971-2014	ARDL	1. Globalization affects CO_2 emissions (−) 2. GDP affects CO_2 emissions (+)
Chienwattanasook et al. (2021)	ASEAN countries	2004-2018	FE	1. Globalization affects CO_2 emissions (−) 2. GDP affects CO_2 emissions (+)
Saint et al. (2019)	Turkey	1970-2014	ARDL	1. GDP affects CO_2 emissions (+)
Naseem and Guang (2021)	Sub-Saharan countries (SAARC)	2000-2017	FE and GMM	1. Renewable energy to CO_2 emissions (−) 2. Economic growth to CO_2 emissions (+)
Cao et al. (2022)	OECD countries	1985-2018	FE	1. Globalization affects CO_2 emissions (−) 2. Renewable energy to CO_2 emissions (−) 3. Economic growth to CO_2 emissions (+)
Vasylieva et al. (2019)	Ukraine and EU countries	2000-2016	EKC environmental curve FMOLS, DMOLS	1. Renewable energy to greenhouse gas emissions (−) 2. GDP to greenhouse gas emissions (−)
Sheraz et al. (2022)	BRI countries	2003-2019	FMOLS, DMOLS, CS-ARDL	1. Renewable energy to CO_2 emissions (−) 2. Globalization affects CO_2 emissions (+)
Jiang and Khan (2023)	Brazil, Russia, India, China	1995-2019	GMM	1. Renewable energy to greenhouse gas emissions (−)
Iqbal et al. (2023)	BRICS countries	1990-2018	CUP-BC, CUP-FM	1. Financial globalization affects the consumption of renewable energy (+) 2. Environmental dynamics affecting renewable energy consumption (+) 3. Energy output affects renewable energy consumption (+) 4. Energy prices affect renewable energy consumption (+) 5. Economic growth affects the consumption of renewable energy (−)
Onuoha et al. (2023)	29 SSA countries	1990-2020	IV-GMM	1. Public debt affects renewable energy consumption (−) 2. Carbon emission index affects renewable energy consumption (−) 3. Financial developments affect the consumption of renewable energy (−) 4. Economic development affects the consumption of renewable energy (−) 5. Economic urbanization affects the consumption of renewable energy (+)
Ozyilmaz et al. (2023)	G7 countries	1997-2020	GMM	1. Public expenditure affects CO_2 emissions (−)
Halkos and Paizanos (2013)	77 countries	1980-2000	GMM	1. Government spending affects CO_2 emissions (−)
Ifa and Guetat (2022)	8 southern Mediterranean countries	1980-2020	ARDL and VECM	1. GDP affects the consumption of renewable energy REC (+) 2. Renewable energy consumption affects GDP (+) in the long term 3. Renewable energy consumption affects government spending (+) 4. Public expenditure affects the consumption of renewable energy (+)

Source: Compiled by the author group

3. METHODOLOGY AND DATA

3.1. Model

The regression model used in the project to assess the impact of renewable energy consumption on environmental pollution is shown through the following equation:

$$ENV_{i,t} = \beta_0 + \beta_1 REC_i + \beta_2 CONTROL_{i,t} + \theta_t + u_{i,t} \quad (*)$$

Where:

ENV is a dependent variable evaluated the environment polution based on carbon dioxide emissions (CO_2) and greenhouse gas emissions (GHG) of country i in year t.

REC is renewable energy consumption measured in Joule units.

CONTROL are control variables that are included in the model to exclude the influence of other factors on the relationship between REC and ENV. The control factors include *KOFGl, lnGovern, lnGDP, Covid, Crisis*, and *INF.* The descriptions and data sources for all variables used in this study are presented in Table 2

Based on the baseline model in equation (*), the study regresses the following equations:

$$CO_{2i,t} = \beta_0 + \beta_1 REC_{i,t} + \beta_{2a} KOFGl_{i,t} + \beta_{2b} lnGovern_{i,t} + \beta_{2c} lnGDP_{i,t} + \beta_{2d} Covid_{i,t} + \beta_{2e} Crisis_{i,t} + \beta_{2f} INF_{i,t} + t + u_{i,t} \quad (1)$$

$$GHG_{i,t} = \beta_0 + \beta_1 REC_{i,t} + \beta_{2a} KOFGl_{i,t} + \beta_{2b} lnGovern_{i,t} + \beta_{2c} lnGDP_{i,t} + \beta_{2d} Covid_{i,t} + \beta_{2e} Crisis_{i,t} + \beta_{2f} INF_{i,t} + t + u_{i,t} \quad (2)$$

3.2. Research Data

This study utilized an unbalanced panel dataset comprising data from 53 countries over the period 2009-2021. The research aimed to investigate the impact of renewable energy adoption in both developing and developed countries, with a particular focus on assessing the level of renewable energy utilization across different country groups. The primary data sources included the World Bank, the KOF Swiss Economic Institute (2023), the BP Statistical Review of World Energy, and the International Energy Agency Report (2023). To enhance the accuracy and reliability of the dataset, a three-step data filtering process was implemented. First, data on renewable energy consumption were collected for the period 2009-2021. Second, the relevant variables were aggregated based on their explanatory relationship with REC. Finally, observations with excessive missing data or defects that could significantly affect the analysis were excluded. After this filtering process, the final dataset consisted of 689 observations, structured as a balanced panel dataset.

3.3. Research Methodology

The research employs balanced panel data to align with the objective of assessing the impact of renewable energy on environmental pollution across various countries worldwide. Typically, with panel data, methods such as Pooled Ordinary Least Squares, Random Effects Model, and Fixed Effects Model are commonly used in research studies. The aforementioned models were unable to fully address endogenous issues, thus the primary model selected and utilized in this study was the generalized method of moments (GMM) model, as developed by Arellano and Bond (1991). The reason is that GMM allows the study to take into account fluctuations over time which is essential in environmental and economic studies where data patterns can change significantly (Arellano and Bond, 1991). This allows for a more accurate analysis of how renewable energy adoption impacts environmental pollution over different periods. Moreover, one of the key strengths of the GMM model is its ability to handle endogeneity issues. Endogeneity arises when explanatory variables are correlated with the error term, leading to biased and inconsistent estimates. The GMM approach uses instrumental variables to address this problem, enhancing the reliability of the results (Blundell and Bond, 1998). Additionally, the GMM model efficiently manages exogenous variables, which are crucial in understanding the multifaceted impacts of renewable energy. Variables such as economic development, globalization, and macroeconomic factors changes can significantly influence the relationship between renewable energy and environmental pollution. The GMM model helps incorporate these variables, providing a more comprehensive analysis. Furthermore, the GMM model optimizes the estimation process, improving the efficiency and accuracy of the analysis. This is particularly important in studies with complex datasets and multiple variables, where traditional models might fall short (Roodman, 2009). Lastly, by addressing issues like heteroskedasticity and autocorrelation, the GMM model enhances the reliability and robustness of the data analysis. This is crucial for producing credible and actionable research findings that can inform policy and investment decisions in the renewable energy sector.

The regression analysis in this study was conducted in three sequential steps. First, the robustness of the model was assessed by performing the Wooldridge test for autocorrelation and the White test for heteroskedasticity. The results, presented in Table 3, indicate that the Wooldridge test confirms the presence of autocorrelation, as evidenced by the P-value. Furthermore, the Modified-Wald test results demonstrate the presence of heteroskedasticity within the model. In the second step, regression analysis of equations (1) and (2) was conducted using the generalized method of moments (GMM) to address these model deficiencies. This analysis was performed both from an overall perspective and separately for different groups of countries. Finally, in the third step, the study verified the consistency of the model's results by re-estimating equations (1) and (2) using three alternative estimation models: Ordinary least squares (OLS), random effects model (REM), and fixed effects model (FEM).

4. EMPIRICAL RESULTS

4.1. Descriptive Analysis

The descriptive statistical analysis results of the panel data variables are presented in Table 4. The findings indicate that the average CO_2 emissions per capita across countries are 6.613 metric tons/year, with maximum and minimum values of 23.001 and 0.357, respectively. Greenhouse gas emissions per capita range from 1.377 to 30.330, with a mean value of 9.181. The explanatory

Table 2: Variable's description and sources

Classification	Variable	Description	Measurement unit	Data source	Mark expectations	Previous studies
Dependent variables	CO_2_per_cap	Carbon dioxide emissions per capita by country	Metric tons per capita per year	The report of the International Energy Agency (2023)		Haapanen and Tapio (2016); John F. Clarke and Faoro (1966)
	GHG_per_cap	Greenhouse gas emissions per capita by country	Tons carbon dioxide equivalent per capita per year	The report of the International Energy Agency (2023)		Ramanathan and Feng (2009)
Explanatory variable	REC	Renewable energy consumption	Exajoules (input equivalent)	Bp Statistical Review of World Energy report	-	Karasoy and Akcay (2019)
Control variables	KOFGl	PCA index of social, economic, and political globalization index	Percentage of total	KOF Swiss Economic Institute (2023)	-	Rani et al. (2023); Vlahinić Lenz and Fajdetić (2021)
	lnGOVERN	Natural logarithm of general government final consumption expenditure	Current US$	World Bank (2023)	-	Halkos and Paizanos (2013); Adewuyi (2016)
	lnGDP	Natural logarithm of GDP	Current US$	World Bank (2023)	-	Jeon (2022)
	Covid19	Get value="1" for the year with Covid-19 Get value="0" for the year with no Covid-19			-	Saadat et al. (2020)
	Crisis	Get value="1" for the year with crisis Get value="0" for the year with no crisis			+	Yuan et al. (2019)
	INF	Inflation	Consumer prices (annual percentage)	World Bank (2023)	+	Ahmad et al. (2021)

Source: Synthesis by the author group

Table 3: Wooldridge test and white test

Wooldridge test			White test		
F test	Prob >F	The presence of autocorrelation	Chi2	Prob >chi2	The existence of heteroskedasticity
83.083	0.0000	√	62.79	0.0013	√

Source: Calculation by the author group

Table 4: Descriptive statistics

Variable	Obs	Mean	Standard deviation	Min	Max
CO_2_per_cap	689	6.613	4.543	0.357	23.001
GHG_per_cap	689	9.181	5.803	1.377	30.33
REC	689	0.446	1.077	0.01	11.32
KOFGl	689	74.066	11.118	47.06	90.93
lnGOVERN	689	25.203	1.293	22.375	28.844
lnGDP	689	27.024	1.192	24.462	30.78
Covid 19	689	0.153	0.361	0	1
Crisis	689	0.531	0.499	0	1
INF	689	3.633	4.857	−2.079	48.699

variable REC has an average value of approximately 0.446 and a standard deviation of 1.077, with a minimum value of 0.01 and a maximum value of 11.32.

4.2. Results and Discussion

Table 5 reveals the regression model results assessing the impact of renewable energy consumption on environmental pollution. Column (1) displays the outcomes for the CO_2 dependent variable, while column (2) presents results for the GHG dependent variable.

Table 5: Baseline results

Variable	(1)	(2)
	CO_2_per_cap	GHG_per_cap
REC	−0.974*** (0.037)	−0.943** (0.435)
CO_2_per_cap (−1)	−0.255** (0.124)	
GHG_per_cap (−1)		−0.205 (0.129)
KOFGl	−0.248*** (0.087)	−0.367*** (0.101)
lnGOVERN	−3.413* (1.961)	−2.763* (2.347)
lnGDP	3.389* (1.802)	2.897* (2.145)
Covid19	−0.458* (0.257)	−0.643* (0.303)
Crisis	0.185 (0.128)	0.213 (0.141)
INF	0.035 (0.023)	0.040 (0.026)
Obs	689	689
S test	0.028	0.033
AR (1)	0.008	0.026
AR (2)	0.002	0.002

Standard errors in parentheses
***P<0.01, **P<0.05, *P<0.1

The GMM results demonstrate an inverse relationship between REC and both CO_2_per_cap and GHG_per_cap, highlighting that increased renewable energy consumption leads to reductions in carbon dioxide and greenhouse gas emissions. Specifically, a 1% rise in renewable energy consumption reduces carbon emissions per capita by 0.97% and greenhouse gas emissions per capita by 0.94%. This finding is consistent with the research of Naseem and Guang (2021), who found a significant inverse relationship between REC and CO_2, indicating that renewable energy consumption decreases carbon emissions in SAARC countries.

The empirical findings can be explained as follows: Renewable energy sources used in electricity generation, heating, transportation, and industrial processes—such as solar, wind, hydroelectric, and biomass—serve as alternatives to fossil fuels like coal, oil, and natural gas. This displacement of fossil fuels, which emit greenhouse gases like CO_2, methane (CH_4), and nitrous oxide (N_2O), reduces GHG emissions. Consequently, renewable energy consumption directly lowers CO_2 and GHG emissions (Shahzad, 2012). Additionally, many renewable energy sources have low or zero carbon intensity. For example, solar and wind power generate electricity without emitting CO_2 during operation. Hydropower and biomass energy also produce significantly lower CO_2 levels compared to fossil fuel-based power plants. By using energy sources with lower carbon intensity, renewable energy consumption reduces overall GHG emissions, explaining the decrease in GHG and CO_2 emissions with increased renewable energy use (Petrović et al., 2020).

Regarding the control variables in the model, KOFGl and lnGOVERN show statistically significant negative relationships with GHG and CO_2 emissions. At a 1% significance level, KOFGl results indicate that globalization reduces GHG and CO_2 emissions. This is consistent with the reality that globalization fosters the development of efficient global supply chains, enabling production in locations with lower costs or comparative advantages, thus optimizing production processes to minimize energy consumption and emissions. This finding aligns with the study by Islam et al. (2021). Similarly, the significantly negative coefficient of lnGOVERN indicates an inverse relationship between government spending and GHG and CO_2 emissions. Increased government expenditure can reduce GHG and CO_2 emissions by promoting renewable energy deployment, supporting sustainable transportation, and implementing regulatory measures aimed at reducing GHG emissions. This result is similar to the findings of Halkos and Paizanos (2013) and Adewuyi (2016).

On the other hand, the model shows a positive correlation between economic growth and CO_2 emissions through the natural logarithm of GDP. Economic growth tends to increase CO_2 emissions due to higher energy demand, industrialization, transportation activities, infrastructure expansion, changing consumption patterns, and limited adoption of clean technologies. This presents a challenge for economic development without environmental pollution, consistent with studies by Cao et al. (2022).

Among the control variables, dummy variables COVID-19 and Crisis were used to represent the pandemic and crisis impacts on GHG and CO_2 emissions. The negative coefficient of COVID-19 indicates an adverse relationship with CO_2 and GHG emissions. Lockdowns during the pandemic led to widespread business and industrial facility closures, significantly reducing economic activity and industrial production. Consequently, fossil fuel consumption, a major GHG source, decreased. Industries like manufacturing, transportation, and construction, typically large GHG emitters, experienced operational slowdowns or disruptions, leading to lower emissions (Safarian, 2020). However, the impact of the Crisis and INF variables on emissions is not statistically significant.

In addition to the primary model, the study examined the varying impacts of each variable on GHG and CO_2 emissions between developed and developing countries. Table 6 presents the regression model results assessing the impact of renewable energy consumption on environmental pollution across these two groups. Columns (1) and (2) display the regression outcomes for equations (1) and (2) for developed countries, whereas columns (3) and (4) present the results for developing countries. Specifically, columns (1) and (3) contain the results with CO_2-dependent variables, while columns (2) and (4) show the results with GHG-dependent variables.

The findings in Table 6 indicate that the explanatory variable REC is statistically significant in the developed countries' columns, but

Table 6: GMM estimation results of developed countries and developing countries

Variable	Developed countries		Developing countries	
	(1)	(2)	(3)	(4)
	CO_2_per_cap	GHG_per_cap	CO_2_per_cap	GHG_per_cap
REC	−1.771*** (0.663)	−2.090*** (0.727)	−0.016 (0.148)	−0.071 (0.192)
CO_2_per_cap (−1)	−0.203** (0.099)		0.082 (0.082)	
GHG_per_cap (−1)		−0.125 (0.101)		−0.148 (0.175)
KOFGl	−0.115*** (0.133)	−0.191*** (0.143)	−0.051* (0.054)	−0.078* (0.071)
lnGOVERN	−2.263* (2.753)	−5.528* (3.118)	−2.918*** (1.037)	−4.064*** (1.529)
lnGDP	4.940* (2.799)	7.254** (3.108)	3.804*** (0.890)	4.808*** (1.274)
Covid19	−0.661* (0.338)	−1.142*** (0.374)	−0.074 (0.135)	−0.136 (0.184)
Crisis	0.227 (0.152)	0.132 (0.161)	0.065 (0.110)	0.047 (0.128)
INF	0.271 (0.053)	0.237*** (0.054)	−0.001 (0.007)	−0.007 (0.009)
Obs	366	366	323	323
S test	0.032	0.002	0.66	0.626
AR (1)	0.358	0.136	0.459	0.546
AR (2)	0.563	0.472	0.022	0.002

Standard errors in parentheses
***P<0.01, **P<0.05, *P<0.1

Table 7: OLS, FEM, REM estimation results

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	CO_2_per_cap	GHG_per_cap	CO_2_per_cap	GHG_per_cap	CO_2_per_cap	GHG_per_cap
	OLS	OLS	FEM	FEM	REM	REM
REC	−0.007*** (0.178)	−0.178*** (0.246)	−0.019** (0.043)	−0.001** (0.053)	−0.094*** (0.043)	−0.011*** (0.054)
KOFGl	−0.092** (0.019)	−0.157*** (0.026)	−0.057*** (0.022)	−0.097*** (0.027)	−0.167*** (0.020)	−0.065*** (0.026)
lnGOVERN	−1.060* (0.614)	−3.009* (0.848)	−1.173* (0.376)	−1.130* (0.470)	−1.205* (0.375)	−1.263* (0.467)
lnGDP	0.022* (0.639)	2.064* (0.883)	0.109* (0.429)	0.042* (0.537)	0.128* (0.425)	0.164** (0.530)
Covid19	−0.805* (0.404)	−0.792** (0.559)	−0.835* (0.071)	−0.930** (0.089)	−0.637* (0.071)	−0.957** (0.088)
Crisis	0.122 (0.303)	0.248 (0.419)	0.147 (0.054)	0.174 (0.068)	0.333 (0.055)	0.194 (0.068)
INF	0.009 (0.034)	0.059 (0.048)	0.009 (0.008)	0.007 (0.010)	0.058 (0.008)	0.006 (0.010)
Cons	−12.473 (4.784)	−23.318 (6.605)	−15.534 (5.103)	−10.826 (6.383)	−33.492 (4.858)	−13.128 (6.113)
Obs	689	689	689	689	689	689

Standard errors in parentheses
***P<0.01, **P<0.05, *P<0.1

the inverse is observed in the developing countries' columns. In developed countries, the data demonstrates that renewable energy consumption helps to reduce GHG and CO_2 emissions. Regarding the control variables, the Globalization Index (KOFGl) and Government Expenditure (lnGOVERN) are statistically significant and negatively correlated with CO_2 and GHG in both groups of countries while lnGDP shows a positive correlation with GHG and CO_2 emissions. Regarding crisis and epidemic variables, the COVID-19 variable has a negative impact on CO_2 and GHG, particularly evident in developed countries. The study did not identify any significant effect of the crisis variable (CRISIS) on CO_2 and GHG in either group consistent with main findings. Additionally, the inflation rate (INF) is not statistically significant in most models, except for model (2) in developed countries.

4.3. Robustness test

To evaluate the robustness of the model results, the study conducted additional regressions using various methods and compared these outcomes with the primary model. Specifically, the study performed regressions (1) and (2) using ordinary least squares (OLS), fixed effects model (FEM), and random effects model (REM), and compared these results with the primary model. The regression outcomes of the two primary models with OLS, FEM, and REM methods are presented in Table 7. The results indicate that the signs of the coefficients of all independent variables and the levels of statistical significance are consistent with those in the main GMM model.

5. CONCLUSION AND POLICY RECOMMENDATIONS

5.1. Conclusion

In the shift from a traditional economy to a knowledge-based economy, promoting the use of renewable energy has become essential for reducing environmental pollution and fostering sustainable development. Research findings indicate that renewable energy consumption (REC) negatively impacts carbon dioxide (CO_2) and greenhouse gas (GHG) emissions, underscoring the effectiveness of renewable energy in mitigating adverse environmental impacts. REC is not only a feasible solution for reducing environmental pollution but also a vital opportunity to advance sustainable development. The negative correlation between REC and both CO_2 and GHG highlights the critical importance of investing in and encouraging the use of renewable energy sources.

Additionally, control variables such as globalization (KOFGl), economic growth (lnGDP), environmentally friendly government spending (lnGOVERN), and the COVID-19 pandemic significantly influence environmental pollution levels. The variables globalization (KOFGl), environmentally friendly government spending (lnGOVERN), and COVID-19 show an inverse relationship with CO_2 and GHG, whereas economic growth (lnGDP) positively impacts both dependent variables. These results suggest that countries promoting globalization and government spending on environmental issues, along with effective pandemic management, will experience reduced environmental pollution. However, countries must carefully balance economic growth targets, as economic growth can exacerbate environmental pollution.

Furthermore, a clear distinction between developed and developing countries is evident. In developed countries, renewable energy significantly reduces CO_2 and GHG emissions, whereas this impact is not statistically significant in developing countries. Control variables also produce different outcomes between these groups. This highlights the complexity and multidimensionality of environmental issues. From these findings, the research underscores the importance of promoting renewable energy use and effectively managing control variables to reduce environmental pollution and achieve sustainable development goals. Consequently, it proposes appropriate strategies to foster sustainable environmental development in the future.

5.2. Policy Recommendations

Based on the model results, we propose the following policy recommendations to effectively address the complexities of greenhouse gas (GHG) and carbon dioxide (CO_2) emissions and promote sustainable development.

Firstly, the government should prioritize increased investment in technology transfer and emission reduction measures. This involves focusing on clean and energy-efficient technologies, such as solar power systems and reaction ovens, to significantly reduce CO_2 emissions and foster sustainable development. Additionally, increased spending should be coupled with incentivizing investors and businesses through mechanisms like tax reductions and financial assistance.

Secondly, investment in R&D and renewable energy infrastructure is crucial for addressing climate change and environmental pollution. Projects such as solar and wind power plants, along with energy storage systems, require sustained support through funding and collaboration between industry and academia. Developing countries can benefit from building infrastructure and enhancing research capacity, thereby creating high-quality jobs and transitioning to a knowledge-based economy.

Thirdly, the government and relevant agencies need to actively promote international cooperation and social investment in renewable energy. This can include knowledge-sharing and enhanced interactions between countries to achieve clean energy and environmental protection goals. Research from organizations like the World Health Organization and the Environmental Protection Agency highlights the benefits of transitioning to renewable energy, including reductions in pollution and respiratory disease risks. Key components of this effort include public-private partnerships, joint investment funds, and the protection of intellectual property rights. Moreover, investing in education and training can elevate workforce skills, facilitating the adoption of new technologies and responses to climate change.

Fourthly, it is essential for the government to invest in renewable energy projects, provide grants and tax incentives for clean technology investments, fund green technology R&D, and support environmental education and awareness projects. Implementing strict environmental policies and regulations is essential to ensure compliance and promote sustainable development.

Lastly, international cooperation is essential for achieving sustainable environmental outcomes. Governments should actively participate in global environmental agreements, support businesses in adopting international environmental standards, and promote the development of green supply chains. Facilitating the exchange of renewable energy technologies and expertise between nations can drive collective progress in emissions reduction. Moreover, engagement in international forums can provide opportunities for experience-sharing and the adoption of best practices from technologically advanced economies.

Overall, this set of policies proposes measures to reduce GHG and CO2 emissions by controlling and adjusting relevant macroeconomic factors. These policies play a crucial role in ensuring sustainable development and environmental protection, contributing to global efforts to mitigate climate change impacts. Successful implementation requires close cooperation from stakeholders, government determination, and international community support.

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