

**The Impact of Renewable Energy and Government Effectiveness on
CO₂ Emissions in the Top Ten Carbon-Emitting Countries**

by

Abdul Hayy Haziq bin Mohamad
(20010219)



Presented to the
FACULTY OF ECONOMICS AND BUSINESS
in Fulfillment of the Requirement for the Degree of

DOCTOR OF PHILOSOPHY
(Economics)

2025

UNIVERSITI MALAYSIA SARAWAK

DECLARATION

I hereby declare that the work presented in this thesis was conducted in full compliance with the regulations of Universiti Malaysia Sarawak (UNIMAS). Except where proper acknowledgment is given, this work is solely the effort of the author. This thesis has not been accepted for the award of any other degree and is not being **concurrently** submitted for any other academic qualification.

Signature



Student Name: Abdul Hayy Haziq bin Mohamad

Matric No: 20010219

Date: 10 October 2025

Faculty of Economics and Business

Universiti Malaysia Sarawak (UNIMAS)

ACKNOWLEDGMENT

As I reflect on the journey that has led me to the completion of this thesis, I am overwhelmed with gratitude for the many individuals who have played a pivotal role in my life and work. First and foremost, I wish to express my deepest appreciation to my family. To my beloved parents (Khatijah Binti Eddie and Mohamad bin Boll), your unwavering love, support, and sacrifices have been the foundation upon which I have built my dreams. Mom, your nurturing spirit and countless sacrifices have inspired me to push through challenges, while Dad, your wisdom and encouragement have guided me through difficult times. Thank you for instilling in me the values of hard work and perseverance. I am forever grateful for your presence in my life.

I would also like to extend my heartfelt thanks to my supervisor, Profesor Dr. Rossazana Bt Ab Rahim. Your profound knowledge, patience, and commitment to excellence have inspired me to strive for my best. You have challenged me to think critically and to approach my research with passion and curiosity. I am deeply appreciative of the time you invested in me and the confidence you have shown in my abilities. Additionally, I am thankful to Associate Professor Dr. Mohd Shahidan Shaari, whose encouragement and insightful feedback have significantly enriched my work. Your support has helped me navigate the complexities of my research, and I am grateful for your belief in my potential. I would also like to acknowledge my university for the generous sponsorship that allowed me to pursue my studies and for granting me study leave starting in March 2022. This opportunity has been invaluable, providing me with the time and resources to fully engage with my research and personal growth. I am proud to be part of such a supportive academic community. In closing, I want to express my gratitude to everyone who has been part of this journey.

The Impact of Renewable Energy and Government Effectiveness on CO₂ Emissions in the Top Ten Carbon-Emitting Countries

ABSTRACT

Over two-thirds of global carbon dioxide (CO₂) emissions come from just ten countries, making their emission trends critical for global mitigation. This study integrates the Environmental Kuznets Curve (EKC) with the STIRPAT framework to analyse the impact of renewable energy on CO₂ emissions in China, the United States, India, Russia, Japan, Indonesia, Iran, Germany, Saudi Arabia, and South Korea from 1996 to 2023. Using dynamic panel models, two interaction terms are introduced: Gross Domestic Product per capita with government effectiveness and renewable energy consumption with government effectiveness. These allow the study to capture how governance effectiveness shapes the effects of income growth and renewable energy use on CO₂ emissions. The results support EKC, confirming a non-linear link between income and emissions. Renewable energy significantly reduces CO₂ emissions, with a stronger effect in countries with an effective government. Governance plays a key moderating role, strengthening the emission-reducing impacts of both economic growth management and renewable energy adoption. This study provides robust evidence to guide CO₂ mitigation policies in high-emission economies. The findings emphasize that effective government and clean energy expansion must be pursued together rather than in isolation. For policymakers in the top ten emitters, this means that regulatory reforms should be integrated with large-scale renewable energy investment, while advanced economies must accelerate innovation and developing economies must enhance institutional quality to ensure that the environmental benefits of renewables are fully realised. This integrated approach is vital to achieving the Paris Agreement and Sustainable Development Goals.

Keywords: Carbon Dioxide Emissions, Renewable Energy, Government Effectiveness, Environmental Kuznets Curve (EKC), STIRPAT.

Kesan Tenaga Boleh Baharu dan Keberkesanan Tadbir Urus Kerajaan terhadap Pelepasan CO₂ dalam Kalangan Sepuluh Negara Penyumbang Karbon Tertinggi

ABSTRAK

Lebih dua pertiga pelepasan karbon dioksida (CO₂) global datang daripada hanya sepuluh buah negara, menjadikan tren pelepasan negara-negara ini kritikal untuk usaha mitigasi di peringkat global. Kajian ini menggabungkan Kerangka Keluk Alam Sekitar Kuznets (EKC) dengan rangka kerja STIRPAT bagi menganalisis kesan tenaga boleh baharu terhadap pelepasan CO₂ di China, Amerika Syarikat, India, Rusia, Jepun, Indonesia, Iran, Jerman, Arab Saudi dan Korea Selatan bagi tempoh 1996 hingga 2023. Menggunakan model panel dinamik, kajian ini memperkenalkan dua interaksi: Keluaran Dalam Negara Kasar per kapita dengan keberkesanan tadbir urus, serta penggunaan tenaga boleh baharu dengan keberkesanan tadbir urus. Kajian mengenal pasti bagaimana keberkesanan tadbir urus mempengaruhi kesan pertumbuhan pendapatan dan penggunaan tenaga boleh baharu terhadap pelepasan CO₂. Dapatan kajian menyokong EKC dengan mengesahkan hubungan bukan linear antara pendapatan dan pelepasan. Tenaga boleh baharu didapati mengurangkan pelepasan CO₂ secara signifikan, dengan kesan lebih kuat di negara yang memiliki tadbir urus berkesan. Tadbir urus sebagai faktor pengantara penting, yang mengukuhkan kesan pengurangan pelepasan melalui pengurusan pertumbuhan ekonomi dan penggunaan tenaga boleh baharu. Kajian ini menyediakan bukti kukuh bagi merangka dasar mitigasi CO₂ di negara berpelepasan tinggi. Dapatan menunjukkan bahawa tadbir urus berkesan dan pengembangan tenaga bersih perlu digerakkan serentak, bukan secara terpisah. Bagi pembuat dasar di 10 negara pemancar terbesar, gabungkan reformasi peraturan dengan pelaburan besar dalam tenaga boleh baharu. Ekonomi maju perlu mempercepat inovasi, ekonomi membangun perlu memperkukuh institusi supaya manfaat alam sekitar daripada tenaga boleh baharu tercapai sepenuhnya. Pendekatan bersepadu ini penting untuk memenuhi Perjanjian Paris dan Matlamat Pembangunan Mampan.

Kata Kunci: Pelepasan Karbon Dioksida, Tenaga Boleh Baharu, Keberkesanan Tadbir Urus, Keluk Kuznets Alam Sekitar (EKC), STIRPAT.

TABLE OF CONTENTS

DECLARATION	i
ACKNOWLEDGMENT	ii
ABSTRACT	iii
ABSTRAK	iv
TABLE OF CONTENTS	v
LIST OF TABLES.....	viii
LIST OF FIGURES.....	ix
LIST OF APPENDICES	x
LIST OF ABBREVIATIONS.....	xi
 CHAPTER 1: INTRODUCTION	1
1.1 Background of the Study	1
1.1.1 Background of Top 10 CO ₂ Emitting Countries	3
1.2 Problem Statements	8
1.3 Research Questions	10
1.4 Research Objectives	10
1.5 Significance of the Study.....	11
1.6 Scope of the Study.....	12
1.7 Organization of the Study	13
 CHAPTER 2: LITERATURE REVIEW	15
2.1 Introduction	15
2.2 Theoretical Studies	16
2.2.1 The Kuznets Hypothesis	17
2.3 Theoretical Studies: The STIRPAT Model	22
2.4 STIRPAT and Renewable Energy: Theoretical Extension	24
2.5 Linkage between Renewable Energy Consumption and National Output.....	27
2.6 Linkage between Economic Growth and Government Effectiveness	28
2.7 Empirical Studies: Environmental Kuznets Curve and Renewable Energy	31
2.8 Synthesis of the Empirical Studies.....	58
 CHAPTER 3: RESEARCH METHODOLOGY	62
3.1 Introduction	62
3.2 Methodology.....	63
3.2.1 Environmental Kuznets Curve (EKC).....	64

3.2.2	STIRPAT	65
3.3	Justification of Variables	67
3.3.1	CO ₂ Emissions Per Capita (LCO ₂)	67
3.3.2	Economic Growth (LGDP and LGDP ²)	68
3.3.3	Population (LPOPL)	69
3.3.4	Renewable Energy Consumption (LRE)	70
3.3.5	Government Effectiveness (LEIU)	70
3.3.6	Interaction Terms (LGDP*LEIU) and (LRE*LEIU).....	72
3.3.7	Concept Framework.....	74
3.4	Panel Data Analysis	77
3.4.1	Cross-Sectional Dependence Tests	77
3.4.2	Panel data and Pedroni Tests	78
3.4.3	Panel Unit Root Tests	79
3.4.4	Mean Group (MG) and Pooled Mean Group (PMG) Estimation.....	80
3.4.5	Autoregressive Distributed Lag Model (ARDL).....	82
3.4.6	Nonlinear Autoregressive Distributed Lag Model (NARDL).....	83
3.4.7	Justification for Using the NARDL Model.....	84
3.4.8	Error Correction Term (ECT)	86
3.5	Model Specification.....	87
3.5.1	Model 1: Baseline Model Using Aggregate Renewable Energy	87
3.5.2	Model 2: Asymmetric Impact of Renewable Energy on CO ₂ Emissions	88
3.5.3	Model 3: The Role of Government Effectiveness in the Renewable Energy	89
3.5.4	Model 4: Asymmetric of Renewable Energy and Government Effectiveness.....	91
3.5.5	Model 5: Interaction of Economic Growth and Government Effectiveness.....	92
3.5.6	Model 6: Interaction of Renewable Energy and Government Effectiveness.....	93
3.6	Conclusion.....	94

CHAPTER 4: FINDINGS AND DISCUSSIONS..... 96

4.1	Introduction	96
4.1.1	Descriptive Introduction	97
4.2	Panel Unit Root Test Results	99
4.3	Analysis ARDL Model 1 and NARDL Model 2	101
4.3.1	Cross-Sectional Dependence Tests Models 1 and 2	101
4.3.2	Pedroni Cointegration Test Models 1 and 2.....	102
4.3.3	Panel ARDL Estimation Results (Model 1).....	103
4.3.4	Nonlinear Adjustment and Coefficient Symmetry Test (Model 2).....	106
4.3.5	Panel Asymmetric ARDL Estimation Results (Model 2).....	107
4.4	Analysis ARDL Model 3 and NARDL Model 4	109

4.4.1	Cross-Section Dependence Test Results (Model 3 and Model 4)	109
4.4.2	Pedroni Residual Cointegration Test Results (Model 3 and Model 4).....	110
4.4.3	Panel ARDL Estimation Results (Model 3).....	111
4.4.4	Coefficient Symmetry Test Results (Model 4)	113
4.4.5	Panel Asymmetric ARDL Estimation Results (Model 4).....	114
4.5	Analysis ARDL Model 5	117
4.5.1	Cross-Section Dependence Test Results (Model 5).....	117
4.5.2	Pedroni Residual Cointegration Test Results (Model 5).....	118
4.5.3	Panel ARDL Estimation Results (Model 5).....	119
4.6	Analysis ARDL Model 6	122
4.6.1	Cross-Section Dependence Test Results (Model 6).....	122
4.6.2	Pedroni Residual Cointegration Test Results (Model 6).....	123
4.6.3	Panel ARDL Estimation Results (Model 6).....	124
4.7	Discussions and Findings	128
4.8	Conclusion.....	131
CHAPTER 5: CONCLUSIONS		133
5.1	Introduction	133
5.2	Summary Finding: Interpretation of STIRPAT and EKC Validity.....	134
5.2.1	In-Depth Evaluation of the STIRPAT Framework.....	134
5.2.2	In-Depth Evaluation of the EKC	137
5.3	Summary of Key Findings and Link to Research Objectives	142
5.4	Policy Implications.....	144
5.4.1	Policy Implication Related to Kyoto Protocol.....	145
5.4.2	Policy Implication related to Carbon Pollution Reduction Scheme	147
5.5	Limitations of the Study	149
5.6	Future Research Recommendations	151
5.7	Conclusion.....	153
REFERENCES		156
APPENDICES.....		176

LIST OF TABLES

Table 3.1: Description of Variables	73
Table 4.1: Descriptive Statistics	97
Table 4.2: Unit Root Results.....	99
Table 4.3: Cross-Section Dependence Results (Model 1 and 2)	132
Table 4.4: Pedroni Residual Cointegration Results (Model 1 and 2)	134
Table 4.5: Panel ARDL (Model 1).....	136
Table 4.6: Coefficient Symmetry (Model 2).....	140
Table 4.7: Panel NARDL (Model 2).....	141
Table 4.8: Cross-Section Dependence Results (Model 3 and 4)	144
Table 4.9: Pedroni Residual Cointegration Results (Model 3 and 4)	146
Table 4.10: Panel ARDL (Model 3).....	147
Table 4.11: Coefficient Symmetry (Model 4).....	151
Table 4.12: Panel NARDL (Model 4).....	152
Table 4.13: Cross-Section Dependence Results (Model 5)	156
Table 4.14: Pedroni Residual Cointegration Results (Model 5).....	157
Table 4.15: Panel ARDL (Model 5).....	159
Table 4.16: Cross-Section Dependence Results (Model 6)	163
Table 4.17: Pedroni Residual Cointegration Results (Model 6).....	164
Table 4.18: Panel ARDL (Model 6).....	166
Table 6.1: Summary of EKC	185

LIST OF FIGURES

Figure 1.1:	Top 10 CO ₂ Emissions Worldwide in 2022	3
Figure 1.2.1:	CO ₂ China	4
Figure 1.2.2:	CO ₂ India	4
Figure 1.2.3:	CO ₂ USA.....	4
Figure 1.2.4:	CO ₂ Russia	4
Figure 1.2.5:	CO ₂ Japan.....	5
Figure 1.2.6:	CO ₂ Indonesia	5
Figure 1.2.7:	CO ₂ Iran	5
Figure 1.2.8:	CO ₂ Germany.....	5
Figure 1.2.9:	CO ₂ Saudi Arabia	6
Figure 1.2.10:	CO ₂ South Korea.....	6
Figure 2.1:	Kuznets Inverted U-Shape.....	19
Figure 2.2:	STIRPAT Model	23
Figure 3.1:	Model 1 Panel ARDL Approach.....	74
Figure 3.2:	Model 2 Panel NARDL Approach.....	74
Figure 3.3:	Model 3 Panel ARDL Approach.....	75
Figure 3.4:	Model 4 Panel NARDL Approach.....	75
Figure 3.5:	Model 5 Panel ARDL Approach (moderator LGDP*LEIU)	76
Figure 3.6:	Model 6 Panel ARDL Approach (moderator LGDP*LRE).....	76

LIST OF APPENDICES

Appendix 1: Summarise of EKC and Renewable energy.....	176
--	-----

LIST OF ABBREVIATIONS

ARDL	Autoregressive Distributed Lag Model
CH ₄	Methane
DFE	Dynamic Fixed Effects
EKC	Environmental Kuznets Curve
EU	European Union
GCC	Gulf Cooperation Council
GHG	Greenhouse gases
IPAT	Impact (I) $\times$ population (P) $\times$ affluence (A) $\times$ technology (T)
LCO ₂	Carbon dioxide emissions per capita (log)
LEIU	Government effectiveness (Economist Intelligence Unit Riskwire and Democracy Index in log)
LGDP	Gross Domestic Product Per Capita (log)
LGDP ²	Gross Domestic Product Per Capita Square (log)
LGDP*LEIU	Interaction: GDP per capita $\times$ government effectiveness
LPOPL	Total Population (log)
LRE	Renewable energy consumption (log)
LRE*LEIU	Interaction: Renewable energy $\times$ government effectiveness
MG	Mean Group
MtCO ₂	Million tons carbon dioxide emissions
N ₂ O	Nitrous oxide
NARDL	Nonlinear Autoregressive Distributed Lag Model
PMG	Pooled Mean Group
SDGs	Sustainable Development Goals
STIRPAT	Stochastic Impacts by Regression on Population, Affluence, and Technology

CHAPTER 1:

INTRODUCTION

1.1 Background of the Study

Carbon dioxide (CO₂) emissions have become one of the most critical environmental concerns of the modern era due to their dominant role in amplifying the greenhouse effect and disrupting the Earth's energy balance. Unlike other greenhouse gases, CO₂ is the most abundant human-induced emission, accounting for the largest share of global emissions associated with energy use, industrial processes, and land use changes (El-Hawwary et al., 2022; Yasmin et al., 2022; Filonchyk et al., 2024). According to Kuldasheva et al. (2023), CO₂ emissions remain the principal by-product of human activities such as fossil fuel combustion for electricity and transport, deforestation, and industrial expansion.

There are studies shows that since the onset of the industrial age, the concentration of CO₂ in the atmosphere has more than doubled compared to pre-industrial levels (Ali & Anufriev, 2023; Matemilola & Alabi, 2023). This sharp increase reflects the rapid pace of economic development, urbanisation, and population growth worldwide. The Intergovernmental Panel on Climate Change (IPCC) and recent studies emphasise that the energy sector, particularly fossil fuel burning, continues to be the single largest source of CO₂ emissions globally (Matemilola & Alabi, 2023). Deforestation also contributes significantly by reducing the natural capacity of forests to absorb CO₂ while releasing stored carbon back into the atmosphere (Omran & Schwarz-Herion, 2020; Reis & Guzman, 2023; Adam et al., 2024).

The direct link between economic growth, energy demand, and rising CO₂ emissions has been extensively documented. Borsha et al. (2024) highlight that higher gross domestic product per capita is usually associated with increased industrial production and energy use, resulting in greater CO₂ emissions. Otim et al. (2022) confirm that as energy consumption grows to support economic activities, CO₂ emissions rise accordingly, presenting ongoing challenges to environmental sustainability. Understanding this link remains vital for

policymakers who aim to maintain economic development without causing further CO₂ escalation (Teklie & Yağmur, 2024).

Reliable evidence shows that CO₂ emissions continue to grow rapidly. Wang et al. (2021) report that global CO₂ emissions have risen steadily alongside energy consumption, especially in emerging economies experiencing rapid industrialisation. This persistent rise in CO₂ alters the atmosphere's chemical balance, which affects temperature trends, weather patterns, and ecological conditions (Romm, 2022; Piccolroaz et al., 2020). Melting glaciers, retreating ice sheets, and changing precipitation levels are direct results of this continuous increase in CO₂ (Golledge, 2020; Allison et al., 2021; Shahgedanova, 2021).

In addition, the expansion and intensification of industrial activities in the highest CO₂-emitting countries such as China, the United States, India, Russia, Japan, Indonesia, Iran, Germany, Saudi Arabia and South Korea explain why these nations contribute more than two-thirds of total global CO₂ emissions. Their emission profiles reflect varied energy mixes, continued reliance on fossil fuels, and differences in technological capacity and policy implementation. This concentration of CO₂ emissions underscores the importance of examining country-specific drivers and the role of institutional contexts.

The consequences of increasing CO₂ emissions are not limited to the atmosphere. High CO₂ levels contribute to ocean acidification and disrupt global carbon cycles, which affects biodiversity, fisheries, and food production. Agricultural systems are exposed to yield instability and economic losses linked to CO₂-driven environmental changes. Human health is also indirectly threatened as environmental quality declines and the frequency of heat-related stress incidents rises in areas with high CO₂ output.

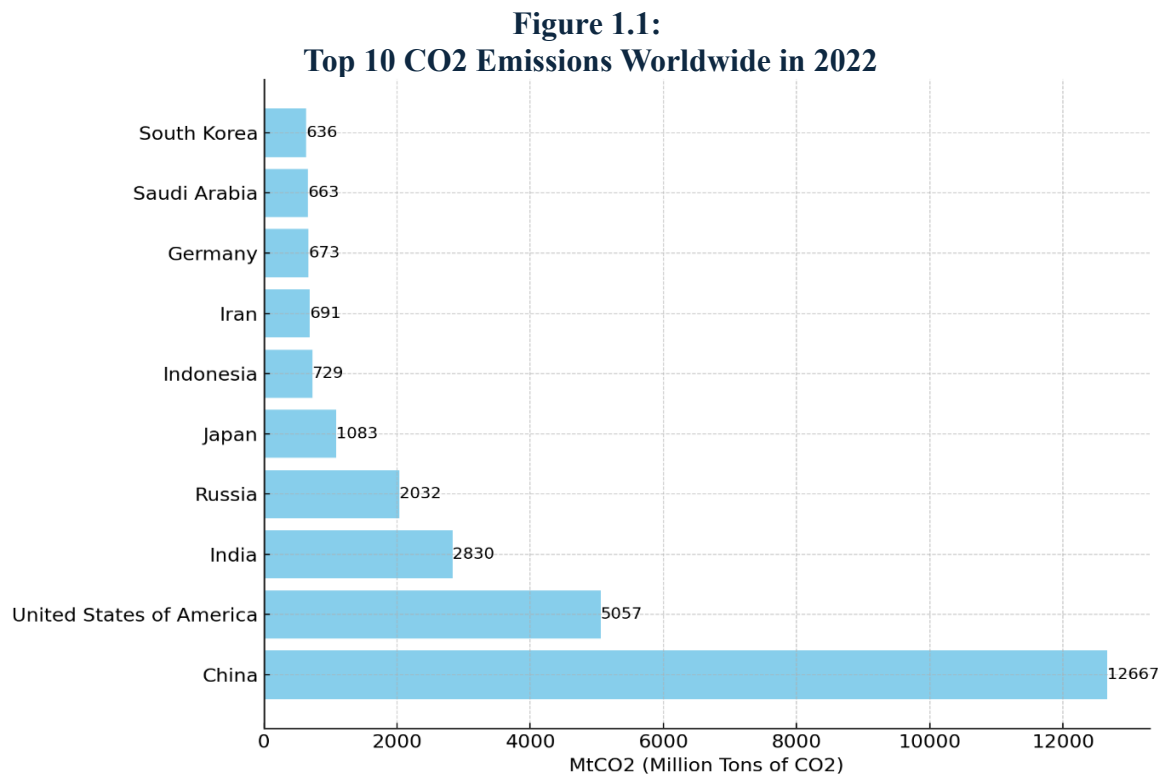
Given these facts, the urgent research and policy priority is to understand how CO₂ emissions respond to structural factors such as economic growth, energy consumption, and the governance effectiveness. Renewable energy deployment has emerged as a crucial strategy to reduce CO₂ emissions by replacing carbon-intensive energy sources. However, the speed and effectiveness of renewable energy adoption vary significantly between countries, often influenced by the strength of governance and institutional capacity.

Recent studies highlight those countries with stronger government and higher government effectiveness are better able to design and enforce policies that limit CO₂ emissions while supporting economic development (Omri & Jabeur, 2024; Salvador &

Sancho, 2021). Effective governance can determine the success of environmental regulations, investment in clean technology, and stable long-term support for renewable energy. In contrast, weak government can limit the benefits of renewable energy expansion and hinder progress in reducing CO₂ emissions.

1.1.1 Background of Top 10 CO₂ Emitting Countries

Figures 1.1 present the trends in carbon dioxide (CO₂) emissions per capita for the ten countries with the highest total CO₂ emissions, namely China, India, the United States, Russia, Japan, Indonesia, Iran, Germany, Saudi Arabia and South Korea, over the period from 1990 to 2022. Each graph shows the annual CO₂ emissions per person alongside a linear trend line, providing a clear visual representation of the long-term direction and pattern of emissions for each country.



Source: Global Carbon Project (2022)

The top 10 highest CO₂ emitting contributed more than two-thirds of global emissions, with China, the United States, and India alone accounting for nearly half of the total. China, the world's largest emitter, has long been recognized as a key player in global climate negotiations (Mohamad et al., 2023).

Its emissions are largely driven by its massive industrial base and reliance on coal for electricity generation. Similarly, the United States, the second-largest emitter, has a CO₂ emissions profile dominated by emissions from electricity generation, transportation, and industrial activities. India, the third-largest emitter, faces a unique challenge as it seeks to balance rapid economic growth and urbanization with sustainable development.

**Figure 1.2.1:
China CO₂**

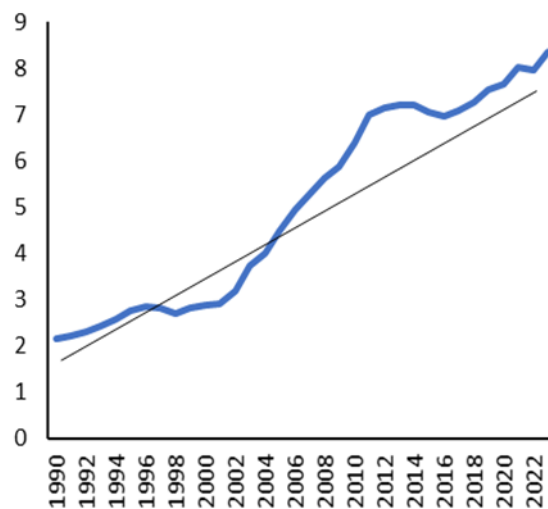


**Figure 1.2.2:
India CO₂**

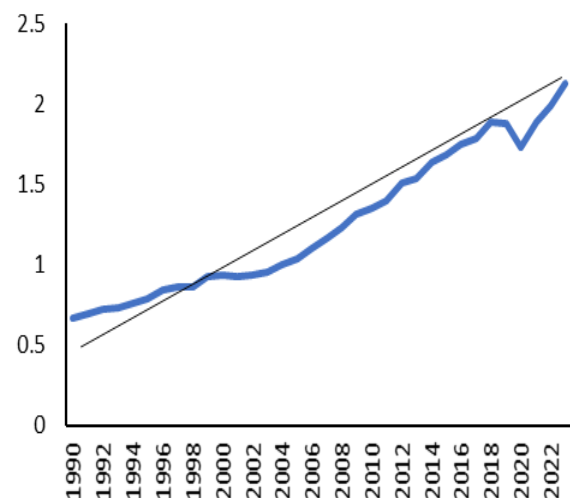


**Figure 1.2.3:
USA CO₂**

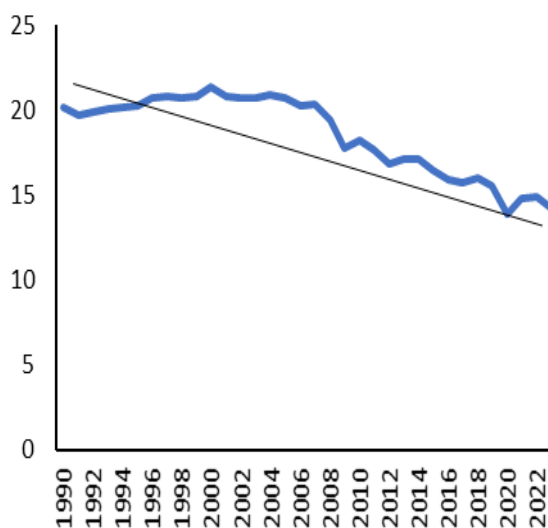


**Figure 1.2.4:
Russia CO₂**

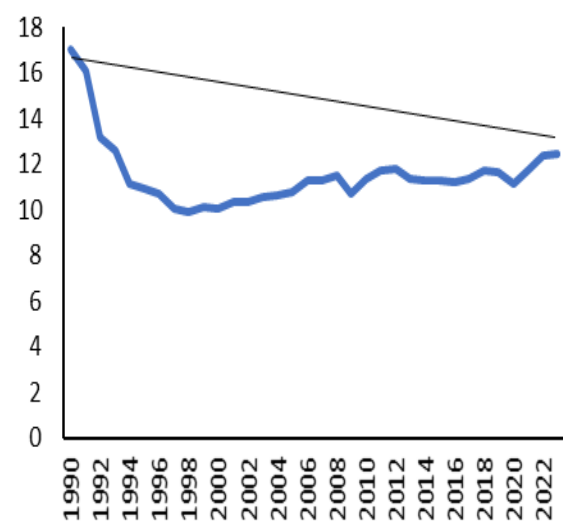


**Figure 1.2.5:
Japan CO₂**

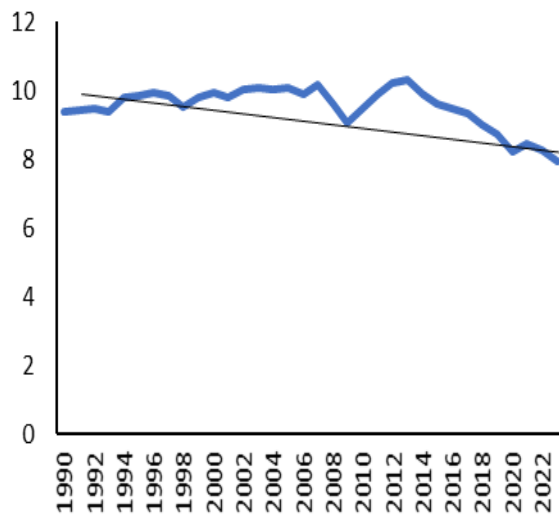


**Figure 1.2.6:
Indonesia CO₂**

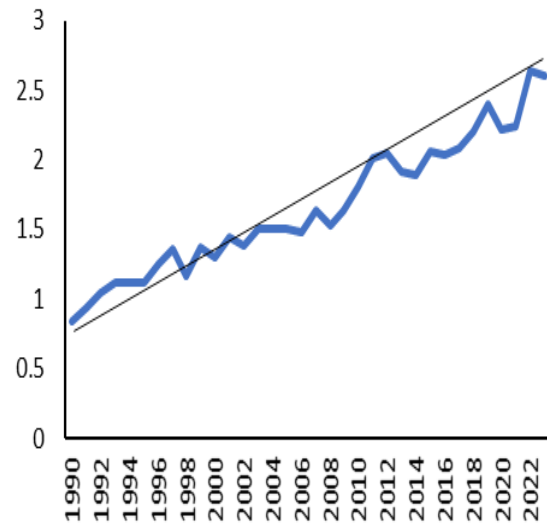


**Figure 1.2.7:
Iran CO₂**

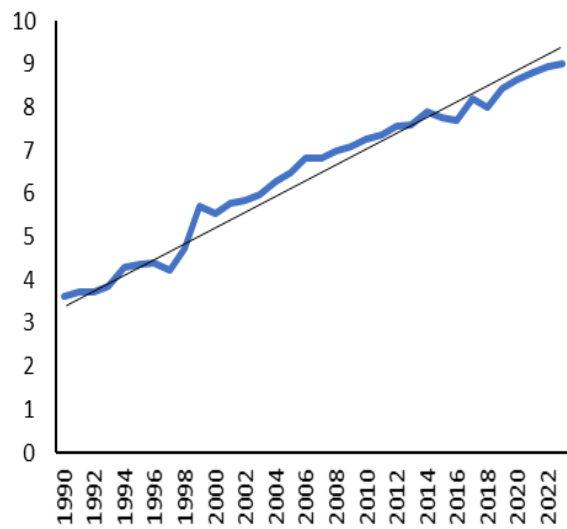


**Figure 1.2.8:
Germany CO₂**

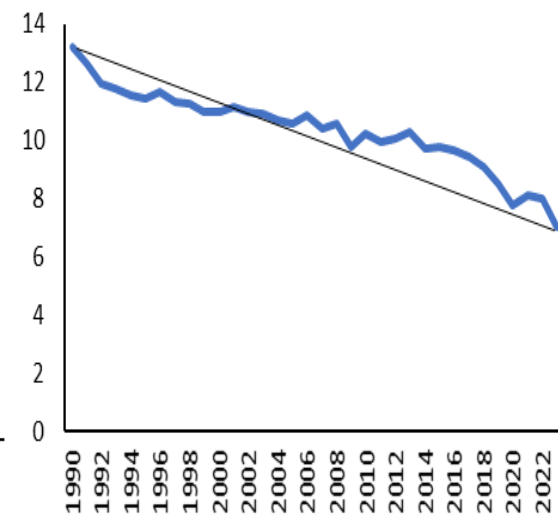


**Figure 1.2.9:
Saudi Arabia CO₂**

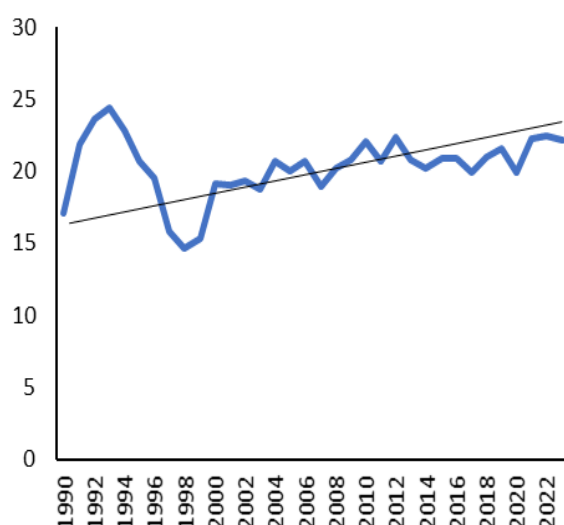
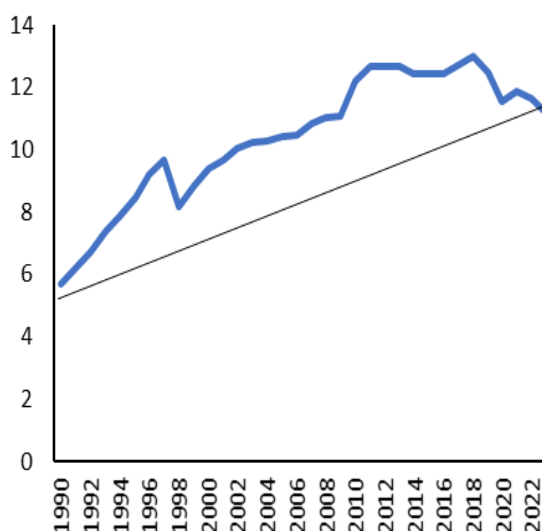


**Figure 1.2.10:
South Korea CO₂**



These Figures 1.2.1 to 1.2.10 reveal considerable differences in the evolution of CO₂ emissions per capita among the world's major emitters, reflecting variations in their stages of economic development, energy mix, industrial structure and policy responses. In Figure 1.2.1, China demonstrates a pronounced and consistent increase in per capita CO₂ emissions across the entire period, rising from below 2 metric tons in the early 1990s to over 8 metric tons by 2022. This rapid growth mirrors China's transformation into the world's largest industrial economy, with sustained reliance on coal-fired power generation and heavy industry to support urbanisation and export-oriented manufacturing.

In Figure 1.2.2 shows the CO₂ for India, while starting from a lower baseline, also shows a steady upward trajectory in per capita CO₂ emissions, indicating that the country's robust economic expansion and rising energy demand continue to depend significantly on fossil fuels. Although India's per capita emissions remain lower than those of other top emitters, the consistent increase highlights the policy challenge of decoupling economic growth from carbon intensity. In contrast, the Figure 1.2.3 shows the United States exhibits a clear downward trend in per capita CO₂ emissions over the same period. From values consistently above 20 metric tons per capita in the early 1990s, the United States has managed to reduce this figure to below 16 metric tons by 2022. This decline reflects multiple factors, including improvements in energy efficiency, shifts from coal to natural gas and renewables in electricity generation, and the impact of environmental regulations and technological innovation.

Russia's trend in Figure 1.2.4, shows an initial sharp decline in per capita CO₂ emissions following the economic restructuring of the early post-Soviet period, followed by relative stabilisation with moderate fluctuations. Despite this initial drop, Russia's per capita emissions remain high compared to global averages, largely due to its fossil fuel export sector and energy-intensive domestic industries. In Figure 1.2.5, Japan's CO₂ emissions per capita have gradually declined over time, with occasional fluctuations linked to energy policy shifts. Notably, the closure of nuclear plants after the Fukushima disaster led to increased fossil fuel imports, temporarily affecting emissions levels. Overall, the trend line indicates progress towards lower per capita emissions as Japan continues to implement energy efficiency measures and expand its renewable energy capacity.

Indonesia's graph illustrates (Figure 1.2.6) a gradual but steady rise in per capita CO₂ emissions, consistent with its status as a fast-growing emerging economy. The country's energy system remains heavily reliant on coal and oil, and land use changes also contribute significantly to its emissions profile. The sustained upward trend underscores the importance of diversifying the energy mix and strengthening governance to manage emissions more effectively. Iran displays a similar pattern (Figure 1.2.7), with per capita CO₂ emissions increasing steadily from the early 1990s to 2022.

This pattern reflects Iran's heavy dependence on oil and gas for domestic energy consumption and the challenges posed by limited diversification of the energy sector. Germany in Figure 1.2.8, presents a contrasting example among industrialised economies. Its per capita CO₂ emissions have shown a clear downward trend, declining from about 13 metric tons to below 8 metric tons per capita. This achievement highlights the effectiveness of Germany's proactive environmental policies, investments in renewable energy, and measures to enhance energy efficiency in industry and households.

Saudi Arabia stands out for its high and relatively volatile per capita CO₂ emissions. The Figure 1.2.9 shows considerable fluctuations but maintains a generally high average level, which is a direct consequence of the country's economic dependence on oil production and high domestic energy consumption supported by substantial fossil fuel subsidies. Figure 1.2.10 shows, South Korea's per capita CO₂ emissions increased steadily until around 2012 and then began to show a slight decline in recent years. This recent moderation may reflect the country's efforts to adopt cleaner technologies, promote renewable energy and

implement stronger environmental standards in response to international climate commitments.

These graphical trends form an essential empirical foundation for this study. They clearly demonstrate that while some countries have managed to slow or reduce their CO₂ emissions per capita, others continue to experience steady or even accelerating increases in line with industrial expansion and rising energy demands. This divergence underscores the reality that there is no universal pathway for managing CO₂ emissions and that national economic contexts, energy policies, and the strength of governance effectiveness fundamentally shape each country's emission trajectory. Therefore, it is crucial to conduct research that explains how renewable energy use and government effectiveness interact with economic growth to influence CO₂ emissions in these major emitting countries. This is especially important because these nations collectively account for more than two-thirds of global CO₂ emissions and their energy transition strategies will determine the feasibility of achieving global carbon neutrality targets.

By examining both the direct effects and the conditional role of governance, this study aims to fill significant gaps in the existing literature and provide robust evidence that supports more effective and context-sensitive policy solutions. The insights gained will help policymakers understand the conditions under which renewable energy and institutional improvements can work together to break the historical link between economic growth and high CO₂ emissions, contributing to more sustainable development paths for the world's largest emitters.

1.2 Problem Statements

Anthropogenic climate change remains the defining environmental challenge of the 21st century, with carbon dioxide (CO₂) emissions as its most significant driver. The persistent rise in CO₂ emissions, largely attributed to the combustion of fossil fuels, industrial activity, and unsustainable energy use, poses serious risks to global ecological balance, public health, and economic stability. A disproportionate share of this problem originates from a small group of countries. Ten economies, namely China, the United States, India, Russia, Japan, Indonesia, Iran, Germany, Saudi Arabia, and South Korea, collectively account for more than two-thirds of global CO₂ emissions. Their central role in shaping global emission trajectories, combined with their diverse development stages, energy

structures, and institutional settings, makes them a critical focus for examining the drivers of emissions.

Economic growth, often proxied by Gross Domestic Product (GDP) per capita, has long been recognised as a fundamental driver of environmental degradation. As economies expand, industrial production, energy consumption, and transportation demand typically rise, leading to higher CO₂ emissions. However, this relationship is not strictly linear. The Environmental Kuznets Curve (EKC) hypothesis suggests that emissions increase in the early stages of growth but eventually decline after a certain income threshold once countries adopt cleaner technologies and implement stronger environmental regulations. Although widely applied, empirical support for the EKC has been mixed, with results varying across countries, time periods, and methodological approaches.

Alongside EKC, the STIRPAT framework (Stochastic Impacts by Regression on Population, Affluence, and Technology) provides a more flexible approach to modelling human environmental impact. This framework extends the traditional IPAT identity into an econometric form, enabling the estimation of how population growth, affluence, and technology influence environmental outcomes. Population growth is commonly associated with rising energy demand, while affluence increases consumption and emissions. Technology, however, can act as either a driver or mitigator of emissions depending on its nature and application.

Within this context, renewable energy use represents a key technological pathway for reducing emissions. Renewable sources such as solar, wind, hydro, and biomass have been promoted globally as sustainable alternatives to fossil fuels. Yet, progress has been uneven. Many high-emission countries face institutional, financial, and infrastructural constraints that slow their energy transitions. This raises the unresolved question of whether renewable energy consumption has produced substantial emission reductions in the world's largest emitters.

In addition, institutional quality has become increasingly recognised as a decisive factor in environmental outcomes. Government effectiveness, defined as the quality of public services, the credibility of policy implementation, and the enforcement of regulations, can support the enforcement of environmental standards, foster investment in clean technologies, and ensure coherent transition strategies. Despite its importance, government effectiveness remains largely absent from empirical analyses of the growth–energy–

emissions nexus. Its interaction with economic growth and renewable energy, in particular, is underexplored in the context of the ten highest CO₂-emitting countries, where institutional capacity may determine the effectiveness of government policies.

1.3 Research Questions

- i. What is the effect of renewable energy on CO₂ emissions in the top ten CO₂-emitting countries?
- ii. Does the Environmental Kuznets Curve (EKC) hypothesis hold in the top ten carbon-emitting countries, reflecting a non-linear relationship between economic growth and CO₂ emissions?
- iii. How does population size influence CO₂ emissions in the top ten carbon-emitting countries within the STIRPAT framework?
- iv. How does government effectiveness moderate the relationship between renewable energy and CO₂ emissions per capita?

1.4 Research Objectives

The general objective of this study is to investigate the determinants of CO₂ emissions per capita in the ten highest carbon-emitting countries from 1996 to 2023 by applying a dual theoretical framework that integrates the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT model, using dynamic panel estimation techniques. The specific objectives are:

- i. To investigate the effect of renewable energy on CO₂ emissions in the top 10 CO₂-emitting countries.
- ii. To test the Environmental Kuznets Curve (EKC) hypothesis by examining the non-linear relationship between economic growth and CO₂ emissions in the top 10 CO₂-emitting countries.
- iii. To assess the effect of population size on CO₂ emissions in the top 10 CO₂-emitting countries within the STIRPAT framework.

- iv. To examine the moderating role of government effectiveness in the relationship between renewable energy and CO₂ emissions.

1.5 Significance of the Study

This study makes several important contributions to the literature on environmental economics, renewable energy policy, and institutional governance, particularly in the context of high-emitting countries. At its core, it addresses the policy dilemma of balancing economic growth with environmental sustainability in governance-diverse contexts. By combining robust econometric analysis with the Environmental Kuznets Curve (EKC) and STIRPAT frameworks, the study enhances both empirical scope and methodological depth.

First, this study provides one of the most comprehensive and updated empirical assessments of the EKC in the top ten CO₂-emitting countries, which together account for more than two-thirds of global emissions. Unlike most EKC studies confined to single-country or regional blocs, this study analyses both developed and developing economies using a consistent panel dataset, thereby offering stronger comparative benchmarks and more generalisable insights into whether economic growth can align with environmental sustainability in the world's most consequential emitters.

Second, this study advances the STIRPAT framework by explicitly modelling renewable energy as a key technological factor. This approach captures its role in decarbonisation strategies more directly than prior studies that often-treated technology as residual. The use of dynamic and non-linear models allows for testing asymmetric effects, recognising that increases and decreases in renewable energy adoption may produce different environmental outcomes. This methodological innovation addresses a major limitation of symmetric treatments in earlier study.

Third, this study is among the first to systematically examine the moderating role of government effectiveness in the growth–energy–emissions nexus. By incorporating interaction terms between income, renewable energy, and governance, the analysis demonstrates how institutional capacity conditions the environmental effectiveness of both economic growth and renewable energy deployment. This contribution highlights the conditional pathways through which governance can either strengthen or constrain climate mitigation.

Fourth, this study makes a methodological contribution by employing dynamic panel estimation techniques that capture both short-run and long-run effects while addressing concerns of endogeneity and temporal adjustment. This improves the robustness of results and provides clearer distinctions between transitory and persistent drivers of emissions, thereby advancing empirical methods in environmental economics.

Finally, this study contributes to policy debates by clarifying the conditions under which renewable energy transitions and effective governance can lead to meaningful emission reductions. By highlighting the synergistic potential between clean technology and government effectiveness, the study supports a more integrated approach to sustainable development, consistent with international frameworks such as the Paris Agreement, SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action). While the main focus remains on the top ten emitters, Malaysia is discussed as an applied extension, providing context-specific lessons for its National Energy Transition Roadmap (NETR) and net-zero 2050 agenda without overshadowing the multi-country analysis.

1.6 Scope of the Study

This study investigates the dynamic determinants of carbon dioxide (CO₂) emissions per capita in the ten highest CO₂-emitting countries: China, the United States, India, Russia, Japan, Indonesia, Iran, Germany, Saudi Arabia, and South Korea. These countries are selected based on their cumulative contribution to global CO₂ emissions, which collectively exceeds two-thirds of the world total. Their inclusion is highly relevant to the scope of this study for several reasons. First, these countries represent a mix of developed and developing economies with diverse energy structures, industrial profiles, and institutional capacities. This diversity provides a valuable empirical basis to assess how economic growth, renewable energy consumption, and government effectiveness interact to influence CO₂ emissions under varying national contexts.

Second, these countries are central players in global climate governance, accounting for the majority of emissions-related negotiations and commitments under international frameworks such as the Paris Agreement. Their policy choices, energy transitions, and institutional reforms will significantly shape the trajectory of global climate change mitigation. Therefore, understanding the emission dynamics within these countries has both

academic and policy relevance, offering insights that can inform global strategies for achieving net-zero targets.

This study period from 1996 to 2023 is chosen for three key reasons. First, it marks a critical era in global environmental policy and climate diplomacy, beginning shortly before the Kyoto Protocol (1997) and extending through the Paris Agreement (2015) and beyond. This allows for the examination of CO₂ emissions trends and mitigation responses during a period of increasing international climate commitments. Second, many high-emitting countries began adopting renewable energy policies and institutional reforms in the late 1990s and early 2000s, making this period ideal for assessing the long-term effects of clean energy transitions and governance improvements.

Third, the availability of consistent and comparable panel data across countries becomes significantly more robust starting from 1996, especially for institutional indicators such as government effectiveness, and energy and emissions variables. The inclusion of data through 2023 ensures that the analysis remains current, capturing the most recent developments in global energy markets, post-COVID-19 recovery patterns, and institutional shifts. Overall, this 28-year window provides both historical depth and policy relevance for understanding the dynamic drivers of emissions in the world's largest polluting economies.

1.7 Organization of the Study

This study is structured into five chapters, each designed to build upon the previous to provide a coherent and in-depth analysis of the dynamic determinants of carbon dioxide (CO₂) emissions per capita in the ten highest-emitting countries between 1996 and 2023. Chapter 1 introduces the study by establishing the background and context of the rising trend in CO₂ emissions. It outlines the research problem, states the research questions and objectives, explains the significance of the study, and defines its scope. This chapter lays the conceptual groundwork for the analysis that follows. It outlines the research problems, formulates the key research questions and objectives, and explains the significance and scope of the study. This chapter establishes the foundational context that guides the rest of the thesis.

Chapter 2 presents a thorough review of the theoretical foundations and empirical literature. It discusses key frameworks such as the Environmental Kuznets Curve (EKC) and the STIRPAT model, as well as studies that examine the relationships among economic

growth, renewable energy consumption, and government effectiveness in driving environmental outcomes. This chapter identifies existing research gaps and justifies the inclusion of asymmetric effects and interaction terms in the study's empirical modelling.

Chapter 3 outlines the research methodology adopted for the analysis. It describes the data sources, variables, and model specifications, including the use of dynamic panel estimation techniques such as the ARDL and NARDL models. This chapter also explains the construction of interaction terms to evaluate the moderating role of government effectiveness in the link between economic and technological variables and CO₂ emissions.

Chapter 4 presents and interprets the empirical findings. It discusses the short-run and long-run dynamics of the relationships among GDP per capita, renewable energy consumption, government effectiveness, and CO₂ emissions. Special attention is given to the asymmetric effects of renewable energy and the influence of government effectiveness through interaction terms. The analysis is contextualised with reference to the unique political and economic profiles of the ten selected countries.

Chapter 5 concludes the thesis by summarising the major findings, discussing their policy implications, and highlighting the relevance of institutional reform alongside clean energy transition strategies. The chapter also reflects on the study's limitations and offers recommendations for future research, including the need for sector-specific and governance-disaggregated analyses. Together, these chapters provide a structured and integrated investigation of the multifaceted drivers of CO₂ emissions in the world's most carbon-intensive economies, contributing valuable insights to the formulation of more effective climate policies and sustainable development strategies.

CHAPTER 2:

LITERATURE REVIEW

2.1 Introduction

This chapter presents an in-depth review of the theoretical and empirical literature examining the interrelationships among energy consumption, economic growth, and environmental sustainability. The review is structured to establish a coherent framework for understanding how different energy sources, particularly renewable energy, interact with macroeconomic variables to influence environmental outcomes across diverse national contexts.

The first section (2.2) lays the theoretical foundation by introducing two central frameworks: the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT model. These models provide conceptual lenses for analysing the non-linear dynamics of economic development and environmental degradation, and for identifying the socio-economic and technological drivers of emissions. Subsequent sections elaborate on the theoretical origins and extensions of the EKC (Section 2.3) and the STIRPAT model (Section 2.4), highlighting their relevance in contemporary sustainability research.

Section 2.5 explores the nexus between renewable energy consumption and national output, emphasising the mechanisms through which clean energy can stimulate economic activity while mitigating environmental harm. Section 2.6 examines the critical role of government effectiveness in aligning economic expansion with environmental objectives and facilitating the renewable energy transition. Finally, Section 2.7 synthesises a large body of recent empirical studies (2024–2025) that apply the EKC and STIRPAT frameworks across multiple regional and national settings. These studies not only reaffirm the EKC hypothesis but also underscore the conditional role of renewable energy, governance, innovation, trade, and financial development in shaping emissions trajectories. This comprehensive review provides the necessary empirical grounding to guide the research design and model specification in the subsequent chapters of this study.

2.2 Theoretical Studies

The empirical theory adopted in this study is grounded in the STIRPAT model, which extends the classic IPAT identity by introducing stochastic terms and allowing for empirical flexibility. According to Khan and Cui (2022) and Amin et al. (2023), the theoretical lens postulates that environmental impact (I) is influenced by population (P), affluence (A), and technology (T), each of which can vary across countries and over time. In this study, population growth is captured directly, while affluence is proxied by GDP per capita and its squared term to allow for non-linearities, in line with the Environmental Kuznets Curve (EKC) hypothesis. Technology, often operationalised through energy use and efficiency, is represented here by renewable energy consumption, which reflects a cleaner technological pathway (Wu et al., 2021; Usman & Hammar, 2021). To deepen the analysis, the study incorporates interaction terms between government effectiveness and both affluence (GDP per capita $\times$ government effectiveness) and technology (renewable energy $\times$ government effectiveness).

These interaction terms extend the STIRPAT framework by embedding institutional capacity into the environmental impact equation, thereby acknowledging that the effects of economic and technological variables are not uniform across governance contexts. This integration offers a more nuanced theoretical basis for examining CO₂ emissions across diverse high-emitting countries. Achieving sustainable economic growth while maintaining environmental integrity has become a central challenge for policymakers and scholars. Several theoretical frameworks have been developed to explain the interdependencies between economic development and environmental outcomes.

The EKC hypothesis posits a non-linear relationship between per capita income and environmental degradation. At the early stages of development, pollution and resource depletion intensify due to industrialisation and weak environmental oversight. However, beyond a certain income threshold, economic growth leads to structural transformations, technological innovations, and environmental awareness that reduce ecological pressures. This inverted-U relationship suggests that economic progress, under the right institutional conditions, can eventually lead to environmental improvement.

The application of EKC and STIRPAT in this study is especially relevant given the focus on the world's ten highest carbon dioxide (CO₂) emitting countries. These countries not only contribute a substantial share of global emissions but also exhibit diverse economic

structures, energy consumption patterns, and policy regimes. The EKC provides a foundational hypothesis to examine whether rising income levels in these countries are associated with reduced environmental degradation at higher development stages. Meanwhile, STIRPAT offers analytical flexibility to assess the role of socio-economic and technological variables-especially the share of renewable energy-in shaping emissions trajectories.

Using EKC helps test whether these top CO₂ emitters exhibit the hypothesised turning point beyond which environmental quality improves. At the same time, STIRPAT enables a deeper examination of the underlying forces such as energy mix, demographic pressure, and affluence, which may condition or even delay the realisation of the EKC path. This combined framework supports a nuanced understanding of whether and how renewable energy can offset the environmental costs of rapid industrialisation and economic expansion in high-emitting countries. In the context of the present study, the EKC and STIRPAT frameworks serve as essential tools to investigate whether the expansion of renewable energy can mitigate the environmental costs of economic growth. These theories guide empirical strategy and help identify the mechanisms through which energy systems interact with broader socio-economic forces.

2.2.1 The Kuznets Hypothesis

The relationship between economic growth and income inequality remains one of the most enduring themes in development economics. One of the most influential explanations of this dynamic is the Kuznets Hypothesis, introduced in 1955 by economist Simon Kuznets (Kuznets, 1955; Leal & Marques, 2022; Ritu & Kaur, 2024). Kuznets proposed that as a nation undergoes economic development, inequality tends to rise in the early stages, peaks, and then gradually declines, resulting in an inverted-U-shaped curve when inequality is plotted against income per capita. This hypothesis has since become foundational for scholars analysing the distributive consequences of development.

2.2.1.1 Historical of Kuznets Theory

Kuznets formed his hypothesis based on a combination of empirical observation and historical analysis of industrialising nations, particularly the United States, United Kingdom, and Germany (Kuznets, 1971). These countries, during their transition from agrarian to industrial economies in the 19th and early 20th centuries, witnessed sharp rises in income

inequality. Kuznets noticed that the shift from a predominantly rural, agriculture-based society to an urban, industrialised one introduced significant disparities in earnings. Agricultural workers tended to have lower and more uniform incomes, while industrial workers and capital owners in urban areas experienced greater income variability and substantially higher returns.

Kuznets presented his theory during a period of heightened interest in economic development following World War II (Kuznets, 1964). At the time, policymakers and economists were searching for models to explain how structural transformation could impact social equity. In the American Economic Review paper, "Economic Growth and Income Inequality," was based on limited historical data, including U.S. income tax records and national accounts, but its implications were profound (Kuznets, 2019). Furthermore, according to Stern (2017), Kuznets linked inequality patterns to demographic changes, particularly urban migration, and to the accumulation and reinvestment of capital. His insights laid the groundwork for future empirical testing and inspired decades of debate on whether inequality is an inevitable phase of growth or the result of policy and institutional choices. Even though his model was descriptive rather than prescriptive, it helped to shape global development discourse in both academic and policy-making spheres.

2.2.1.2 The Environmental Kuznets Curve (EKC): Theoretical Extension

Inspired by the original Kuznets Hypothesis, the Environmental Kuznets Curve (EKC) extends this analytical framework to the domain of environmental quality (Stern, 2017; Martínez-Navarro et al., 2020). The EKC posits that environmental degradation first increases with economic growth but eventually declines after a country surpasses a certain income level. This pattern, also shaped like an inverted U, reflects a transition from industrialisation-driven pollution to an era of cleaner technologies and heightened environmental consciousness (Dinda, 2004; Chowdhury & Moran, 2012; Stern, 2017).

At its core, the Kuznets Hypothesis is built around the idea of a dual-sector economy. Initially, most people are employed in agriculture with similar low incomes. Industrialisation brings higher, but more unevenly distributed wages. Urban sectors offer new opportunities, but the transition also widens inequality temporarily (Andersson, 2024; Okoth & Omar, 2025). Capital owners and skilled labour in cities benefit early on, while the rural majority lags behind. Over time, structural transformations emerge. As more people shift to the industrial sector, income opportunities broaden. Governments also introduce redistributive

policies in response to socio-political pressure. The spread of education and social infrastructure plays a vital role in reducing disparities. As a result, inequality declines, and creating the characteristic inverted-U curve (Stern, 2017; Leal & Marques, 2022).

Figure 2.1:
Kuznets Inverted U-Shape

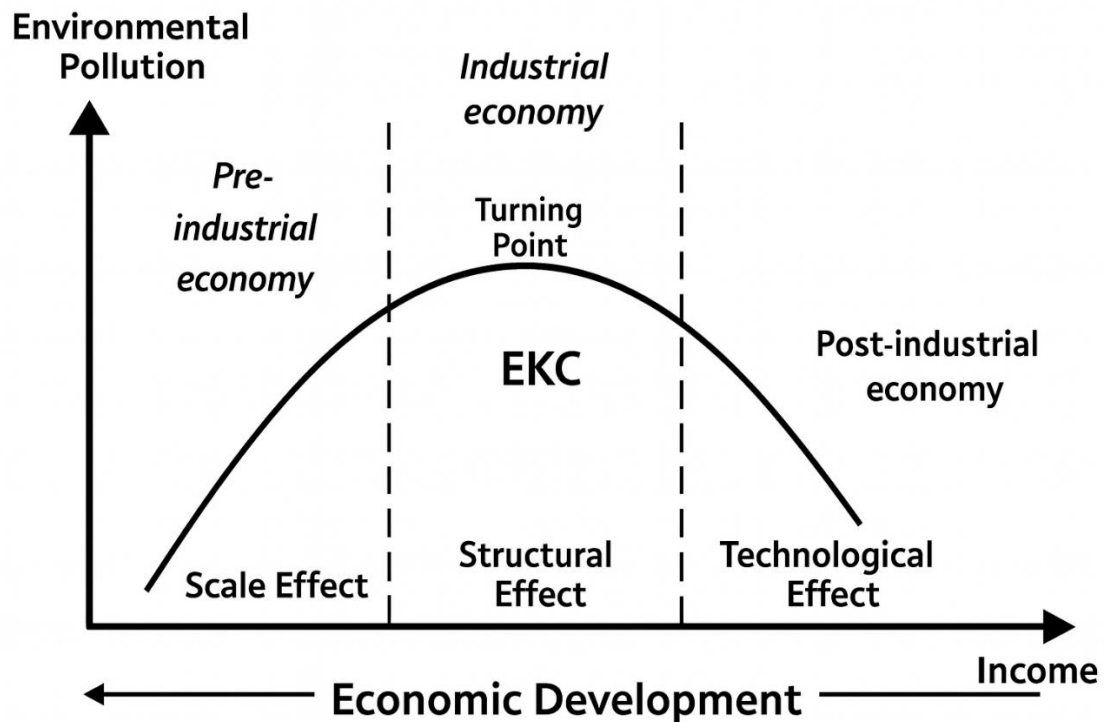


Figure 2.1 shows the inverted U-shape represents the central hypothesis of the Environmental Kuznets Curve (EKC). According to Zaman (2018) and Bisset (2023), the curve suggests that as an economy grows and income per capita increases, the impact on the environment follows a three-stage process; the initial, middle and final stage. Economic growth with increasing environmental degradation is classified as the initial stage. At the early stages of economic development, when a country has a low income per capita, the priority is often economic growth. During this phase, industries are typically developing, and there is a high reliance on natural resources and energy-intensive activities (e.g., agriculture, manufacturing, fossil fuel consumption). This led to the environmental degradation (e.g., pollution, deforestation, CO₂ emissions) tends to increase because environmental regulations may be lax, and there is often less public awareness or concern about environmental issues. The focus is on economic survival and growth, often at the cost of the environment.

The middle stage is the turning point of the EKC, the economy continues to grow and income per capita increases, the negative environmental impact reaches a peak. At this stage, economic growth might still lead to increased environmental degradation, but the rate of this increase starts to slow down. This is the critical juncture where further increases in income per capita no longer lead to further environmental degradation. Instead, the relationship begins to reverse, and environmental degradation starts to decrease. The turning point signifies the income level at which economic growth starts to coincide with improvements in environmental quality.

Various factors contribute to this turning point, each playing a crucial role in altering the trajectory of environmental impact as economies develop. One of the most significant factors contributing to the turning point in the EKC hypothesis is technological advancement. As countries become wealthier, they have more resources to invest in research and development, leading to the creation and adoption of cleaner and more efficient technologies. These technological improvements often reduce the environmental impact of production processes (Ebhotu & Jen, 2020). For example, advancements in renewable energy technologies, such as solar and wind power, have provided alternatives to fossil fuels, reducing greenhouse gas emissions.

Additionally, innovations in waste management and recycling technologies have enabled economies to handle waste more sustainably, further mitigating environmental degradation (Rena et al., 2022). As these technologies become more widespread, they contribute to a reduction in environmental damage, helping economies to move past the turning point and towards a path of sustainable development. Another crucial factor influencing the turning point is the implementation of environmental regulations (Heggelund, 2021; Kulmer et al., 2022).

As economies grow, governments often respond to the increasing environmental challenges by enacting stricter environmental laws and regulations. These regulations are designed to limit pollution, manage natural resources more sustainably, and protect ecosystems. For instance, governments may impose emissions standards on industries, mandate the use of pollution control technologies, or implement carbon pricing mechanisms to reduce greenhouse gas emissions. International agreements and standards, such as the Paris Agreement, also play a role in shaping domestic environmental policies (Delbeke et al., 2019). These regulatory frameworks not only curb environmental degradation but also

create incentives for businesses to innovate and adopt greener practices, contributing to the overall improvement in environmental quality as income levels rise.

According to Michaelowa et al. (2019), the structural transformation of an economy from an industrial base to a service-oriented one is another factor that can contribute to the turning point. In the early stages of economic development, countries typically rely heavily on manufacturing and extractive industries, which tend to have a significant environmental footprint. However, as economies develop, there is often a shift towards the service sector, which generally has a lower environmental impact. Services sector such as finance, education, healthcare, and information technology are less resource-intensive and produce fewer emissions compared to heavy industries like mining, manufacturing, and construction. This shift not only reduces the overall environmental burden but also aligns with the growing consumer and business demand for sustainability, thereby contributing to the transition beyond the turning point.

Finally, increased public awareness and concern about environmental issues play a pivotal role in reaching the turning point. As societies become more affluent, citizens often become more educated and aware of the negative impacts of environmental degradation. This heightened awareness leads to greater demand for environmental protection and sustainable practices (Yuan & Cao, 2022). Public pressure can drive policy changes, encourage businesses to adopt corporate social responsibility (CSR) practices, and promote consumer preferences for environmentally friendly products (Le, 2022). Moreover, non-governmental organizations (NGOs) and advocacy groups often emerge as powerful voices in pushing for stronger environmental regulations and holding governments and corporations accountable for their environmental impact. The collective action driven by increased public awareness helps to shift the balance towards environmental sustainability, marking a key moment in the transition past the turning point.

Lastly the final stage, where the economic growth with decreasing environmental degradation. At higher income levels, the economy continues to grow, but environmental degradation decreases. This stage reflects a more sustainable development model where economic growth is decoupled from environmental harm. Then, the economy may benefit from improved environmental technologies, higher standards of living that allow for better waste management, energy efficiency, and more robust environmental policies. Public and

private sectors may invest more in renewable energy, sustainable practices, and conservation efforts, further driving down environmental degradation.

Empirical support for the Kuznets Hypothesis has been mixed. Early studies found evidence for the inverted-U shape in many developed countries. However, later cross-country analyses challenged its universality. In several low- and middle-income countries, inequality has persisted or even worsened alongside income growth (Ali, 2023; Duong & Flaherty, 2023). The expected downturn is often absent. Much of the critique stems from the changing global landscape. Unlike the relatively closed economies of Kuznets' time, modern nations operate within globalised trade and capital flows. According to Roy-Mukherjee & Udeogu (2021), Du et al. (2023), Ullah et al. (2024), modern Kuznets curve have the elements of technological change, labour mobility, and financial liberalisation, which significantly shape income distribution. Moreover, government with inclusive institutions and strong governance tend to experience more equitable development. In contrast, extractive systems can allow elite capture, allowing inequality to persist regardless of growth. Acemoglu and Robinson (2016) argue that these political factors are central to understanding long-term inequality trends.

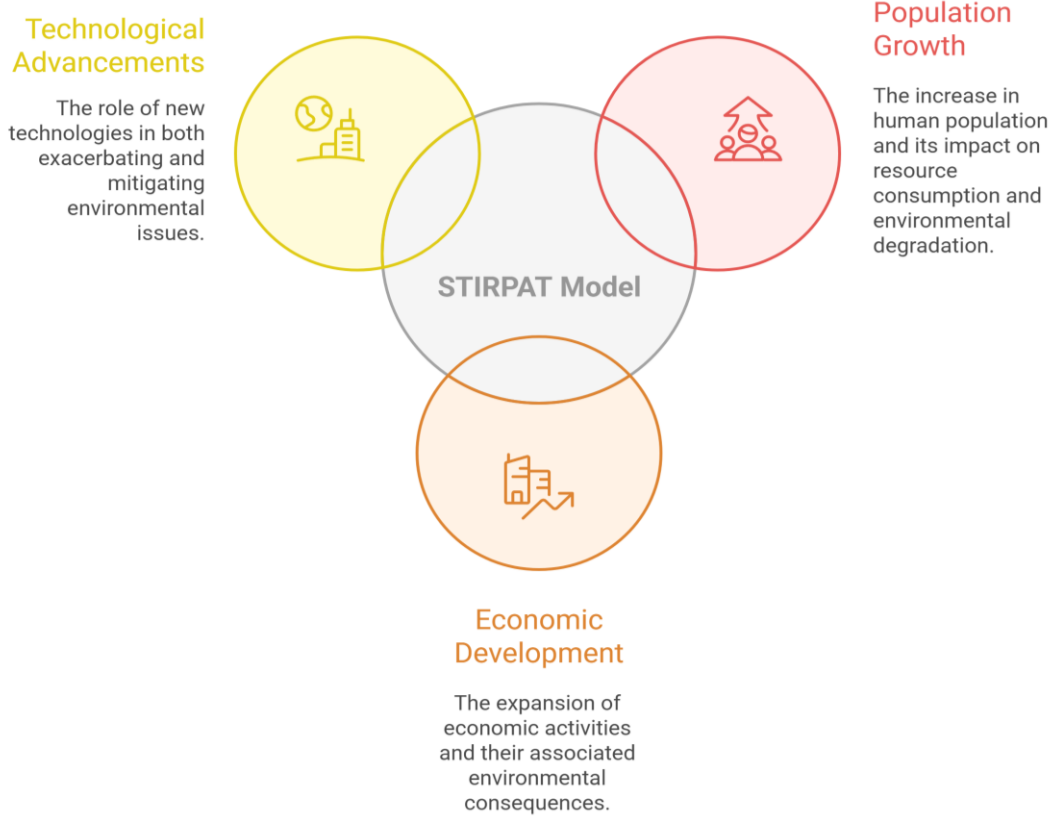
The theoretical underpinning of the EKC is grounded in structural economic change and shifting public priorities. In the initial stages of development, nations prioritise industrial growth and job creation over environmental protection. Natural resources are exploited to fuel growth, and weak environmental regulations fail to mitigate the consequences. As economies mature, however, the population's awareness and concern for environmental quality increase, prompting governments to enact stricter environmental policies and businesses to adopt cleaner production technologies. As such, environmental indicators such as CO₂ emissions, air pollution, and deforestation begin to show improvement beyond a certain income threshold.

2.3 The STIRPAT Model

The STIRPAT model (Figure 2.2), short for Stochastic Impacts by Regression on Population, Affluence, and Technology, is a conceptual and empirical framework designed to examine the anthropogenic drivers of environmental degradation. Developed in the early 1990s by Thomas Dietz and Eugene A. Rosa, STIRPAT emerged as a response to the limitations of the earlier IPAT identity introduced by Ehrlich and Holdren in 1971 (York et

al., 2003; Xiong et al., 2024). While the IPAT equation, $I = P \times A \times T$, served as a powerful heuristic in drawing attention to environmental stress caused by human activity, it was deterministic and lacked empirical flexibility. STIRPAT evolved to address these limitations, offering a more dynamic and statistically estimable approach (York et al., 2022).

**Figure 2.2:
STIRPAT Model**



According to Pal and Mahalik (2025) and Al-Mulali et al. (2024) STIRPAT's primary theoretical contribution lies in its ability to transform a deterministic identity into a stochastic model, thereby enabling hypothesis testing and empirical refinement. Unlike IPAT, which treats each component as exerting a fixed, proportional influence on impact, STIRPAT accommodates variable elasticities and interaction effects. This makes it better suited for understanding how changes in income distribution, demographic composition, or technological structure condition environmental outcomes (Zhu et al., 2025).

A seminal contribution to the development of the STIRPAT model was made by York et al. (2003), who applied it to test the relationships among population, affluence, and technology with carbon emissions across multiple nations. Their work provided robust empirical support for the model and demonstrated that population and affluence exert statistically significant and positive impacts on environmental degradation. Notably, their

findings underscored that population growth alone could not account for rising emissions without considering the influence of affluence and technological structure. This study marked a pivotal moment in legitimising STIRPAT as a tool for environmental sociology and policy modelling. It also opened the door for numerous empirical applications across various environmental outcomes including deforestation, water use, biodiversity loss, and energy consumption.

2.4 STIRPAT and Renewable Energy

The STIRPAT model has been widely used in empirical research to assess the determinants of environmental impact across different countries and time periods. For instance, studies have employed the model to examine the relationship between population growth and carbon emissions, revealing that population size has a significant impact on emissions, even when controlling for affluence and technology (Aziz et al., 2023). Other research has focused on the role of economic development in environmental degradation, exploring how affluence influences the consumption patterns that drive environmental change (Xing et al., 2023; Yu et al., 2023).

As global economies increasingly pursue decarbonisation, the STIRPAT model has gained renewed relevance in analysing the environmental implications of renewable energy. Traditional interpretations of the technology term (T) in the STIRPAT model often included metrics such as energy intensity or emissions per unit of GDP (Wu et al., 2021). However, in recent applications, researchers have explicitly incorporated renewable energy variables into the model to test whether shifts in energy sources can reduce ecological impacts (Amer et al., 2024; Sun et al., 2024; Borsha et al., 2024). By estimating the elasticity of technology, researchers can assess whether technological advancements are sufficient to offset the environmental pressures associated with population growth and increased affluence (Wang & Taghvae, 2023).

The global shift toward renewable energy is one of the most critical responses to the climate crisis, as it directly addresses the primary source of carbon dioxide (CO₂) emissions: fossil fuel combustion. Renewable energy sources such as solar, wind, hydro, and biomass offer cleaner alternatives that can meet rising energy demand while minimising environmental harm. As energy production and consumption account for over 70 percent of

global greenhouse gas emissions, transforming energy systems is essential to achieving long-term emission reductions (International Energy Agency, 2020).

In recent years, significant progress has been made in scaling up renewable energy capacity worldwide. Technological advances, decreasing costs, and growing policy support have accelerated the adoption of renewables across both developed and developing economies. Many governments have introduced mechanisms such as feed-in tariffs, renewable portfolio standards, tax incentives, and public investment strategies to incentivise clean energy transitions. Empirical studies confirm that increasing the share of renewable energy in the national energy mix is associated with measurable reductions in CO₂ emissions, particularly in countries with strong regulatory frameworks and energy infrastructure (Saidi and Omri, 2020).

However, the impact of renewable energy on emissions varies considerably across countries. Among the ten highest CO₂-emitting nations (China, the United States, India, Russia, Japan, Indonesia, Iran, Germany, Saudi Arabia, and South Korea), progress in renewable energy adoption has been uneven. While some countries have made notable strides in expanding solar and wind capacity, others remain heavily reliant on coal, oil, or natural gas to support their economic growth. High energy demand from industrialisation, urbanisation, and transportation continues to outpace renewable energy deployment in several of these countries, reducing the overall decarbonisation effect.

Another key concern is the potential asymmetry in the effects of renewable energy consumption on CO₂ emissions. Increases in renewable energy use tend to result in more substantial emission reductions compared to the potential rise in emissions caused by a decline or slowdown in renewable energy growth. This means that any policy or investment uncertainty that disrupts the growth of renewables can have a disproportionately negative environmental impact. Therefore, consistency and continuity in policy support are crucial to maintaining downward pressure on national emission levels.

For the world's highest-emitting countries, renewable energy is more than a domestic issue. It is a matter of global importance. These countries collectively account for more than two-thirds of global CO₂ emissions, and their energy transitions will shape the future of climate action. Whether through large-scale solar farms in China and India, offshore wind developments in the United States and Germany, or biomass and hydro projects in Indonesia and Russia, the scope and effectiveness of renewable energy policies in these countries will

have far-reaching consequences. Success in expanding renewable energy use not only helps reduce emissions but also improves air quality, reduces reliance on imported fossil fuels, and enhances energy security.

Nevertheless, technical challenges such as storage capacity, and intermittency remain, particularly in countries with underdeveloped energy infrastructure. Moreover, the speed and effectiveness of renewable energy expansion are closely tied to political will, institutional coordination, and the availability of long-term financing. Countries that fail to address these barriers risk locking themselves into carbon-intensive pathways that are incompatible with international climate goals. Therefore, the renewable energy plays a vital role in reducing CO₂ emissions, especially in the top ten emitting countries where its adoption can make a significant global difference.

In this context, renewable energy consumption is treated as an exogenous or endogenous component of the technology variable, allowing scholars to test whether countries with higher shares of renewables experience a dampening effect on the environmental pressures associated with population and economic growth. A growing body of empirical literature supports the inclusion of renewable energy as a mitigating factor. Studies have shown that greater reliance on solar, wind, and hydroelectric energy can significantly lower CO₂ emissions, particularly when accompanied by strong regulatory and institutional support (Usman and Hammar, 2021; Sun et al., 2024; Amer et al., 2024).

Furthermore, STIRPAT's flexible structure enables the exploration of interactions between renewable energy deployment and other socio-economic drivers. For instance, some studies have included interaction terms between affluence and renewables to assess whether wealthier nations are more likely to benefit from clean energy transitions (Liao et al., 2021; Eyuboglu and Uzar, 2025). Others have examined the role of renewable energy in moderating the environmental effects of urbanisation, industrialisation, and international trade (Aquilas et al., 2024).

This evolution in the application of STIRPAT reflects a broader shift in environmental research and recognises technological substitution, particularly toward clean energy, as a critical factor in shaping sustainable development pathways. In sum, STIRPAT continues to serve as a foundational tool for understanding how structural changes in energy systems can influence ecological outcomes.

2.5 Linkage between Renewable Energy Consumption and National Output

Energy consumption and national output are fundamentally interconnected through production, industrial activities, and technological progress (Wu & Chen, 2017). As a key input in economic activities, energy is indispensable for powering industries, transportation, digital infrastructure, and household consumption. Hence, changes in energy use can significantly influence the level of a country's output, commonly measured by gross domestic product (GDP) (Tudor & Sova, 2021; Mohsin et al., 2022).

According to Kongkuah et al. (2022), the relationship between energy consumption and economic growth has been conceptualised through four main hypotheses. The growth hypothesis suggests that energy consumption leads to economic growth, while the conservation hypothesis argues that economic growth drives energy demand. The neutrality hypothesis posits no causality between the two. In this particular interest is the bi-directional relationship, also known as the feedback hypothesis, which asserts that energy consumption and economic growth mutually influence each other.

In a bi-directional relationship, not only does higher energy consumption support increased production, improved industrial performance, and greater national income, but at the same time, as the economy grows, energy demand rises due to expanded industrial output, greater transportation needs, and higher household consumption (Rafindadi et al., 2022). From a theoretical standpoint, renewable energy contributes to economic growth through several key mechanisms. It enhances energy security by reducing reliance on imported fossil fuels, which improves trade balances and lessens exposure to global price volatility.

Ehigiamusoe and Dogan (2024) provide evidence from low-income countries showing that while renewable energy (RE) on its own reduces carbon emissions, the RE*GDP interaction has a positive effect on emissions. Thus, there is a clear linkage between renewable energy consumption, economic growth, and environmental outcomes. The interaction term (RE*GDP) illustrates that the environmental impact of renewable energy is not uniform but depends on income levels. As national output increases, the effectiveness of renewable energy in reducing emissions may weaken, especially in low-income countries. This reinforces the need to understand how energy is integrated into the economy and to adopt targeted policies that promote both clean energy and sustainable growth.

2.6 Linkage between Economic Growth and Government Effectiveness

In this study, government effectiveness is conceptualised as the capacity of public institutions to design, formulate, and implement sound policies, deliver essential public services efficiently, and maintain policy credibility over time. The indicator reflects perceptions of the quality of bureaucracy, independence of the civil service from political pressures, the quality of policy formulation and implementation, and the government's commitment to such policies.

Although the Economist Intelligence Unit's (EIU) Democracy Index primarily assesses the state of democracy, it provides valuable complementary insights into government effectiveness. The Democracy Index evaluates countries on a 0 to 10 scale based on five key dimensions: electoral processes and pluralism, the functioning of government, political participation, political culture, and civil liberties (World bank Data, 2025).

While it does not measure government effectiveness directly, the index's subcomponents, particularly those related to government functioning and institutional accountability, can reflect broader perceptions of how well a government operates and engages with its citizens. Therefore, it offers a contextual lens on the governance environment, including aspects of transparency, responsiveness, and policy coherence.

By integrating government effectiveness into this study, the analysis captures not only the technical capacity of the state but also the broader institutional environment that supports or constrains environmental governance. This is particularly relevant when assessing how countries implement climate policies, promote renewable energy, and enforce environmental regulations. In this study, government effectiveness is examined both as a direct explanatory variable and as a moderating factor through the interaction terms with GDP per capita ($LGDP*LEIU$) and renewable energy consumption ($LRE*LEIU$) to determine whether government effectiveness influences the impact of economic and technological drivers on CO₂ emissions.

While the scientific understanding of global warming has advanced considerably, the success of mitigation strategies increasingly depends not only on technological innovation but also on the institutional capacity of governments to implement them effectively. In this context, government effectiveness has emerged as a critical yet often underexplored determinant of environmental performance. It refers to the ability of public institutions to

design, coordinate, and enforce policies, thereby enabling or constraining a nation's capacity to reduce carbon emissions (Salvador and Sancho, 2021; Huang et al., 2025).

Governments with high institutional effectiveness are better equipped to formulate long-term climate policies, mobilise resources for clean energy investments, enforce environmental regulations, and promote behavioural change through education and incentives (Omri and Jabeur, 2024). These functions are essential for the successful execution of carbon pricing mechanisms, renewable energy deployment, energy efficiency standards, and conservation strategies. In contrast, countries with weak government effectiveness often face fragmented policymaking, regulatory capture, bureaucratic inefficiencies, and limited enforcement capabilities, all of which undermine decarbonisation efforts.

Recent empirical studies increasingly support the idea that institutional strength moderates the relationship between economic growth, renewable energy adoption, and CO₂ emissions. For instance, in countries with strong governance, economic growth is more likely to be decoupled from environmental degradation due to effective pollution controls, cleaner industrial processes, and accelerated adoption of green technologies (Zhang et al., 2022; Naseem et al., 2021).

Similarly, the impact of renewable energy on emissions reduction tends to be more pronounced where governments ensure effective implementation and integration through coherent policies, regulatory stability, and supportive infrastructure. Without these institutional supports, even large-scale investments in renewables may fail to deliver the desired environmental benefits due to inefficiencies in execution and lack of accountability.

The Intergovernmental Panel on Climate Change (IPCC) recognises government effectiveness as a key enabler of climate action, underscoring that technical solutions alone are insufficient without strong governance mechanisms to guide, support, and sustain them (IPCC, 2022). This is particularly relevant in the context of the world's ten highest CO₂-emitting countries: China, the United States, India, Russia, Japan, Indonesia, Iran, Germany, Saudi Arabia, and South Korea.

These countries account for over two-thirds of global emissions and differ significantly in terms of political systems, regulatory capacity, and institutional development. Such diversity provides a unique opportunity to examine how government

effectiveness interacts with economic and technological factors to shape national emissions trajectories. Therefore, while global warming is driven by physical processes rooted in greenhouse gas accumulation, the capacity to reduce these emissions is deeply institutional.

Government effectiveness, through its influence on policymaking, resource allocation, regulatory enforcement, and public engagement, acts as a catalyst for successful climate mitigation. Recognising and incorporating this institutional dimension is essential for designing integrated, effective, and sustainable pathways to carbon neutrality, especially in the most emission-intensive economies where policy impact is globally consequential.

Government effectiveness plays a central role in aligning economic growth with environmental sustainability (Zhang et al., 2024; Wang et al., 2024). As economies seek to transition towards low-carbon and resource-efficient models, the role of the public sector in steering this transformation becomes increasingly important. Effective governance ensures that the necessary institutional frameworks, regulatory mechanisms, and fiscal tools are in place to promote a green economy and support the expansion of renewable energy (Dzwigol et al., 2023).

According to Salvador and Sancho (2021), in the context of environmental governance, government effectiveness reflects the ability of institutions to design and implement coherent policies that address climate change, pollution control, natural resource management, and sustainable development. A well-functioning government can integrate environmental priorities into national development planning, enforce environmental regulations, and coordinate cross-sectoral actions to mitigate ecological degradation. These functions are vital for supporting the shift toward a greener economic model, where economic progress is decoupled from environmental harm.

One of the key areas where government effectiveness intersects with green growth is in the promotion of renewable energy. The development of clean energy infrastructure often requires long-term planning, public-private collaboration, and consistent policy signals (Chou et al., 2023). Governments that demonstrate high levels of administrative competence are more likely to design supportive policies such as feed-in tariffs, renewable portfolio standards, green procurement guidelines, and carbon pricing mechanisms. These instruments reduce investor uncertainty and attract private capital into the renewable energy sector, which contributes both to economic growth and environmental objectives.

Moreover, effective governments are better positioned to allocate public funds efficiently, including the use of green fiscal stimulus and climate finance to support renewable energy deployment and energy efficiency programmes (Abdmouleh et al., 2015; Bhandary et al., 2021). Transparent and accountable governance enhances trust among stakeholders, encourages citizen participation in environmental initiatives, and ensures that subsidies and incentives reach their intended targets. In contrast, weak governance structures often lead to policy fragmentation, regulatory capture, or corruption, which can hinder the scale-up of clean technologies and undermine climate resilience efforts (Okesiji, 2025; Kus and Jackson, 2025).

Empirical research supports the notion that government effectiveness amplifies the positive impact of renewable energy on economic growth (Shrimali and Kniefel, 2011; Yang and Park, 2020). Countries with higher government effectiveness tend to experience stronger returns on green investments, greater innovation in clean technologies, and more efficient transitions toward sustainable energy systems. Additionally, government effectiveness contributes to the broader green economy by promoting sustainable transport, circular economy practices, ecological taxation, and green skills development, all of which support inclusive and resilient growth.

Thus, government effectiveness is not only vital for maintaining macroeconomic stability but also for ensuring that economic growth occurs within environmentally responsible boundaries. As countries pursue climate commitments under frameworks such as the Paris Agreement and the Sustainable Development Goals (SDGs), enhancing the effectiveness of public institutions becomes essential for delivering green economic outcomes and accelerating the transition to renewable energy.

2.7 Empirical Studies: Environmental Kuznets Curve and Renewable Energy

Recent empirical studies have reaffirmed the Environmental Kuznets Curve (EKC) hypothesis while placing increasing emphasis on the role of renewable energy in achieving environmental sustainability. A notable contribution by Sun and Qamruzzaman (2024) conducted a comprehensive analysis of BRICS+T countries, assessing the simultaneous influence of technological innovation, clean energy, trade openness, and natural resource rents on four environmental indicators: CO₂ emissions, ecological footprint, load capacity

factor, and its inverse. Their findings validated the EKC hypothesis and demonstrated that clean energy adoption plays a critical role in mitigating environmental degradation. Technological innovation was also found to consistently reduce emissions, highlighting the importance of eco-friendly industrial transformation. Interestingly, trade openness and resource rents had mixed effects, underscoring the importance of regulatory frameworks in ensuring that economic openness does not exacerbate ecological harm.

Study by Odei, Dunyo, and Anderson (2025) focused on the moderating effect of research and development (R&D) on the EKC dynamics in 25 emerging markets from 2000 to 2020. Using fixed effects and system GMM estimation, the study confirmed the EKC hypothesis, with evidence showing that R&D investments initially strengthen the positive relationship between economic growth and emissions but later weaken it, indicating an earlier turning point in pollution trajectory. Renewable energy consumption was also found to significantly reduce emissions, supporting its role as a crucial driver in decoupling growth from environmental harm.

In a related study, Pan et al. (2024) examined the effect of forestry trade on CO₂ emissions over the period 1996 to 2022. Using the dynamic common correlated effects (DCCE) and augmented mean group (AMG) approaches, the results confirmed the presence of the EKC in the context of the forest sector. Although trade in forest products increased emissions, renewable energy and political stability were found to mitigate CO₂ levels, indicating the potential of green energy and governance to offset sectoral pressures.

Gyamfi et al. (2024) analysed the differentiated impacts of government effectiveness and globalization on emissions in open and closed economies from 1990 to 2020. The findings validated the EKC hypothesis across both groups. For open economies, renewable energy had a significant negative effect on emissions, while non-renewable energy worsened environmental outcomes. In contrast, closed economies exhibited positive emission effects from most variables except renewable energy, which still helped reduce pollution. These results suggest that openness to trade and institutions can amplify the environmental benefits of clean energy.

Bakry et al. (2024) assessed the role of digital finance in shaping CO₂ emissions within 52 developing economies from 2010 to 2019. Using IV-GMM estimation, the study found an inverted U-shaped relationship between digital finance and emissions, consistent

with the EKC framework. The results also showed that renewable energy consumption had a strong mitigating effect on emissions, reinforcing the idea that digital and environmental reforms must work hand-in-hand to deliver sustainable results.

Research by Warsame, Daror, and Abdullahi (2025) extended the EKC hypothesis to the ecological footprint in IGAD countries. Applying PMG and various panel cointegration methods, the study confirmed that economic growth initially increases ecological degradation but eventually reduces it in line with the EKC. Renewable energy, despite its statistically insignificant coefficient, was negatively associated with ecological footprint, highlighting its potential in long-run sustainability strategies.

While Mamkhezri and Khezri (2024) explored the global spillover effects of renewable energy and R&D on CO₂ emissions using spatial and time-fixed effects models across 54 countries from 2003 to 2017. The results supported the EKC hypothesis and demonstrated that global R&D not only reduces emissions directly but also exerts positive spillover effects via renewable energy deployment and clean economic growth pathways. These findings highlight the importance of cross-border collaboration in advancing the global climate agenda.

Suyanto et al. (2024) investigated the EKC hypothesis in G20 countries with a focus on institutional quality and government expenditure. Although renewable energy played a positive role in reducing emissions, the findings showed that government expenditure often increased CO₂ levels due to insufficient alignment with environmental goals. Nevertheless, strong institutions contributed to lower emissions by enabling the implementation of cleaner technologies and stricter regulations.

Said (2024) examined the relationship between financial inclusion and environmental pollution in sub-Saharan Africa using DOLS, FMOLS, and IV-GMM approaches. The results supported the EKC hypothesis, showing that financial inclusion increases emissions but moderates the environmental effect of renewable energy by enhancing its emission-reducing capacity. This dual role implies that financial inclusion policies must be carefully integrated with green energy strategies to ensure their environmental efficacy.

Lu et al. (2024) explored the long-run and short-run determinants of environmental pollution in BRICS-T countries using CS-ARDL and robust estimation techniques such as

FE-DK and AMG. Their analysis spanned from 1990 to 2022 and confirmed the Environmental Kuznets Curve (EKC) hypothesis. The results indicated that economic growth, urbanization, and energy use were positively associated with environmental degradation. However, renewable energy consumption, good governance, and financial globalization significantly reduced pollution levels, suggesting that structural reforms and cleaner energy transitions are essential for sustainable development in emerging economies.

Leitão (2024) examined the relationship between human development, trade, foreign direct investment (FDI), and renewable energy consumption in the G7 countries from 1990 to 2019. Employing a variety of panel econometric techniques, including FMOLS, DOLS, ARDL, and quantile regressions, the study found strong support for the inverted U-shaped EKC hypothesis. The findings revealed that renewable energy improves air quality and mitigates CO₂ emissions, while human development also plays a role in reducing environmental degradation. These results underscore the importance of integrating socio-economic development with environmental policy in advanced economies.

Haciimamoglu (2025) contributed to the EKC literature by evaluating both the EKC and Load Capacity Curve (LCC) hypotheses in BRICS nations. Using the Method of Moments Quantile Regression (MMQR), the study assessed how economic complexity and renewable energy consumption influence environmental degradation over the 1992–2017 period. Results validated both the EKC and LCC hypotheses across all quantiles, with renewable energy consistently improving environmental quality. Economic complexity contributed positively to environmental outcomes only in the higher quantiles, suggesting that sophisticated economies are better equipped to manage ecological sustainability.

Doğan and Dalkılıç (2024) conducted a country-specific study on the United States to investigate how media coverage affects CO₂ emissions. Using co-integration methods such as CCR, FMOLS, and DOLS within the EKC framework, the results highlighted a significant role in raising awareness and shaping public discourse on environmental issues. The Climate Policy Uncertainty (CPU) index was negatively associated with emissions, indicating that heightened public attention through media can contribute to cleaner environmental outcomes. Additionally, renewable energy and FDI were found to reduce emissions, further supporting the EKC hypothesis.

Ratnadewati et al. (2024) investigated the EKC hypothesis in ten ASEAN developing countries between 1999 and 2020 using panel regression and spatial data analysis. Contrary to many other findings, the EKC hypothesis was not validated. However, renewable energy was highlighted as a crucial factor in reducing greenhouse gas emissions, while population growth, economic activity, and fossil fuel electricity generation were identified as key contributors to environmental degradation. The authors emphasized the need for stricter regulations and a transition toward low-carbon exports and energy-efficient consumption.

Su et al. (2025) expanded the EKC discussion by introducing the concept of economic fitness in a sample of 121 countries from 1995 to 2019. Their analysis demonstrated that countries with higher economic fitness experienced reduced CO₂ emissions, and the EKC turning point occurred at a lower income level compared to those with low economic fitness. Renewable energy use was negatively associated with emissions, suggesting that investments in renewable energy and innovation accelerate environmental improvements, particularly in developing nations.

Bekun et al. (2024) examined the FDI–CO₂ relationship in South Asian countries using an augmented mean group (AMG) estimator. Unlike the traditional EKC, this study proposed a cubic or N-shaped EKC, revealing that while CO₂ emissions initially increase with GDP and FDI, they decline after a certain threshold before rising again. Renewable energy was identified as a substitute to fossil-based growth, contributing to emissions reduction. The results point toward the necessity of directing FDI into environmentally sustainable sectors.

Mahmood (2024) focused on the MENA region to investigate how military expenditures and conflicts interact with environmental degradation. Using spatial econometrics over the 1997–2020 period, the study confirmed the EKC hypothesis but also found that military spending and wars intensified CO₂ emissions, both locally and regionally through spillover effects. Conversely, renewable energy reduced emissions within individual countries, although it had mixed effects at the regional level. These findings highlight the trade-off between national security investments and environmental sustainability.

Çatık et al. (2024) investigated the effects of energy consumption, globalization, and income inequality on ecological footprints in 49 countries from 1995 to 2018. Although a long-run relationship was found among the variables, the results did not support the EKC

hypothesis. However, renewable energy was consistently linked to environmental improvements, especially in countries with higher economic growth. The threshold model revealed that the environmental benefits of renewable energy were more significant in higher-growth regimes.

Menyari (2024) studied the impact of tourism, FDI, trade openness, economic growth, and renewable energy on CO₂ emissions in 17 Mediterranean countries. Using heterogeneous panel estimators and the Dumitrescu-Hurlin causality test, the results confirmed the EKC hypothesis and showed that renewable energy, trade, and FDI contribute to lowering emissions. Furthermore, renewable energy and trade openness were found to be Granger-cause economic growth, suggesting a virtuous cycle between clean energy, international economic integration, and sustainability.

Study by Mata et al. (2024) examined the Environmental Kuznets Curve (EKC) hypothesis by analysing the short- and long-run effects of renewable energy, trade openness, and urban density on CO₂ emissions across 30 high-income countries between 2000 and 2020. Using the Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) model with Augmented Mean Group (AMG) estimation for robustness, the study confirmed the EKC hypothesis and found that renewable energy consumption reduces emissions in both the short and long term. However, trade openness was associated with increased emissions, while urban density had an insignificant impact on environmental outcomes.

Zahra et al. (2025) conducted a comparative assessment of the role of green growth, technological innovation, agricultural eco-efficiency, and trade openness on carbon neutrality in China, the United States, and India using quarterly data from 2010 to 2022. Panel quantile regression revealed a U-shaped relationship between emissions and both green growth and green technology, while agricultural eco-efficiency followed an inverted U-shaped curve. Trade openness was found to increase emissions. These findings indicate that green growth policies must consider threshold effects and the complexity of environmental responses across development stages.

Balsalobre-Lorente et al. (2024) investigated the long-run effects of economic complexity, human development, energy innovation, and renewable energy on ecological footprint in the G7 countries between 1991 and 2018. Using CUP-FMOLS, panel VAR, and bootstrap causality analysis, the results indicated that renewable energy significantly reduced

ecological footprints. Although the EKC hypothesis was not the primary focus, the analysis suggested that human development and innovation moderate environmental degradation positively, especially when coupled with renewable energy policies.

Kalim et al. (2024) explored the demand-based EKC hypothesis using data from 147 countries between 2008 and 2018. The study used Fully Modified Ordinary Least Squares (FMOLS) to evaluate the effects of aggregate demand, population density, financial development, and renewable energy. The results confirmed that aggregate demand increases emissions, while knowledge economy indicators and renewable energy consumption mitigate environmental damage. These findings highlight the relevance of demand-side policies and the knowledge economy in shaping sustainable consumption patterns.

Njie et al. (2024) analysed carbon emissions in Africa's top CO₂-emitting countries from 2000 to 2020, focusing on the potential for both an energy-based EKC and an FDI-based EKC. Using Feasible Generalized Least Squares (FGLS) and Panel Corrected Standard Errors (PCSE), the findings validated both types of EKC relationships. The study identified critical thresholds for energy use and FDI inflows and emphasised the importance of renewable energy in reducing environmental pressure. Policymakers are advised to prioritise clean energy investments and regulate environmentally harmful FDI flows.

Ketchoua et al. (2024) examined how technological innovation moderates the relationship between foreign direct investment and green growth in OECD countries. Using Ordinary Least Squares, System GMM, and Smoothed Instrumental Variables Quantile Regression (SIVQR), the results indicated that foreign direct investment hampers green growth unless complemented by strong innovation capacity. Renewable energy was shown to enhance production-based CO₂ productivity. The EKC hypothesis was confirmed in the context of production-based emissions, while demand-based productivity required further policy alignment.

Wahyudi et al. (2025) investigated the relationship between carbon emissions, GDP, transportation and warehousing sector growth, and renewable energy in Indonesia using time series data from 2011 to 2023. Applying the FMOLS approach, the study found that GDP and logistics sector expansion increased emissions, consistent with the EKC hypothesis. However, renewable energy consumption significantly reduced emissions, affirming its role

in sustainable transitions. The findings support investment in low-carbon transport infrastructure and the promotion of clean energy in logistics.

Alnour et al. (2024) evaluated the impact of financial commitments to renewable energy projects, public R&D spending, and energy patents on CO₂ emissions and economic growth in 34 countries from 2010 to 2019. Using the nonlinear panel ARDL model, the results indicated that financial commitments reduce emissions more effectively in the long-run than in the short term. Public R&D expenditure was also effective in reducing emissions, while energy patents had limited impact. The EKC hypothesis was not explicitly validated but the overall findings supported green innovation as a pathway to sustainability.

Hasanov et al. (2024) explored the effects of renewable energy consumption and total factor productivity on emissions across countries ranked in the Renewable Energy Country Attractiveness Index. Advanced panel methods confirmed that both renewable energy and productivity significantly reduce emissions. Conversely, higher income and imports were associated with increased emissions. Although not designed to test the EKC directly, the results supported the notion of non-linear environmental dynamics influenced by technological efficiency and clean energy.

Gazeloğlu and Erköliç (2025) assessed the influence of economic growth, international tourism, and renewable energy use on carbon emissions in Central American SICA countries between 2001 and 2020. Using FGLS and panel cointegration techniques, the study confirmed the EKC hypothesis and demonstrated that renewable energy significantly reduces emissions, while tourism and economic growth elevate them. These results suggest that low-carbon tourism and clean energy integration are key to achieving sustainable growth in the region.

Nugroho (2024) investigated the impact of agricultural technical efficiency on farm-gate emissions in 25 Asia developing countries from 1992 to 2021. Using frontier analysis and the generalized method of moments, the study confirmed the Environmental Kuznets Curve (EKC) hypothesis. It revealed that technical efficiency alone does not reduce emissions of CO₂, CH₄, and N₂O. Rather, emissions are driven by GDP growth and population expansion. Human development was the only factor found to effectively curb these emissions, while renewable energy and food prices showed varied effects. The study

highlights the need for improved human capital, selective use of clean energy, and a shift toward organic agricultural practices.

Cutcu et al. (2025) examined the influence of economic policy uncertainty and geopolitical risk on environmental quality across 17 countries over the period 1997 to 2022. Employing the Quantile Regression of Panel Data (QRPD) method and supporting it with OLS and panel causality tests, the analysis confirmed the EKC hypothesis. Economic policy uncertainty was found to enhance environmental quality across most quantiles, while geopolitical risks degraded it in the medium and high quantiles. The study identified bidirectional causality between environmental quality and most independent variables. The findings underscore the importance of maintaining political stability and energy transition efforts for environmental improvement.

Taher (2024) explored the effects of financial development and renewable energy consumption on CO₂ emissions in Lebanon from 1990 to 2021 using the ARDL model. The study confirmed the EKC hypothesis by identifying a positive relationship between income and emissions in the short-run, with a negative impact observed in the squared term. Renewable energy consistently contributed to emission reduction in both short and long-run. Financial development had mixed effects, showing a positive influence in the short term but turning negative in the long-run. The study suggests integrating green financial policies with renewable energy initiatives to strengthen Lebanon's environmental strategy.

Sobirov et al. (2024) conducted a comprehensive analysis of the factors influencing CO₂ emissions in 14 major Asian emitters between 1996 and 2020. Applying multiple econometric methods including MMQR, FMOLS, DOLS, and Driscoll–Kraay, the study confirmed the EKC hypothesis. The results showed that GDP, urbanisation, and foreign direct investment increase emissions, while renewable energy use and agricultural activity contribute to emission reductions. Notably, the impact of each variable varied across quantiles, indicating that environmental responses are non-uniform across income levels. These insights support differentiated policy approaches based on a country's stage of development.

Destiartono and Firmansyah (2024) tested the EKC hypothesis for methane emissions in Indonesia using ARDL bounds testing and annual data from 1990 to 2020. The results validated the EKC, revealing an inverted U-shaped relationship between GDP and

methane per capita. However, Indonesia's current income level remains below the turning point of 14,516 USD per capita, implying that emissions continue to rise. Renewable energy was found to significantly reduce methane emissions, suggesting that increasing the share of renewables in the energy mix can mitigate environmental degradation.

Rahman et al. (2024) examined the relationship between GDP, trade openness, renewable energy, and foreign direct investment (FDI) on CO₂ emissions in Bangladesh over the period 1972 to 2021. The ARDL model and Zivot–Andrews structural break test confirmed a long-run cointegration among the variables. The results supported the EKC hypothesis and showed that trade openness negatively affects environmental quality, whereas both renewable energy and FDI contribute to emission reductions. The study recommends promoting clean investment and green trade to ensure long-term environmental sustainability.

Liu et al. (2024) investigated the effect of Chinese outward foreign direct investment (CoFDI), renewable energy, and energy intensity on CO₂ emissions in 46 Belt and Road countries from 2005 to 2018. Using Driscoll–Kraay estimation, the results confirmed the EKC hypothesis and revealed heterogeneous outcomes across regions. In European countries, CoFDI reduced emissions, supporting the pollution halo hypothesis, while in Asian and MENA countries, CoFDI increased emissions, aligning with the pollution haven hypothesis. Renewable energy was consistently effective in lowering emissions, reinforcing its importance across diverse institutional contexts.

Georgescu et al. (2024) analysed the relationship between economic growth, renewable energy, urbanisation, and foreign direct investment on Norway's ecological footprint from 1990 to 2023. Using the ARDL model, the study identified a U-shaped EKC, where environmental benefits from growth decline after surpassing a certain income level. Renewable energy was found to significantly reduce the ecological footprint, while FDI had a detrimental effect. These results suggest that policy should aim to attract green investments and further expand renewable energy capacity to safeguard Norway's environmental sustainability.

Auteri et al. (2024) explored the interaction between government debt and renewable energy consumption in G7 countries from 1990 to 2021. Using FMOLS, DOLS, and quantile regression methods, the study found bidirectional causality between government debt and

renewable energy. Although not explicitly testing the EKC hypothesis, the findings implied that rising debt could limit renewable energy investment, while an increase in renewable energy helps stabilise public finances. This suggests a fiscal-environmental feedback loop, highlighting the need for coordinated macroeconomic and climate strategies.

Campos-Romero and Rodil-Marzábal (2024) examined the environmental impact of growth and participation in global value chains across 12 East and Southeast Asian economies. Incorporating measures of GDP, renewable energy, and value chain involvement, the study confirmed the EKC hypothesis but found significant heterogeneity depending on countries' roles in global production networks. Renewable energy contributed to emissions reduction, particularly in economies with downstream roles. The study highlights the importance of targeting technology adoption and green FDI to address environmental challenges linked to global trade integration.

Pata et al. (2025) introduced the Renewable Energy Kuznets Curve (RKC) hypothesis as a complement to the Environmental Kuznets Curve (EKC). Using Fourier-based time series analysis from 1973 to 2022 for the United States, the study examined whether rising income first stimulates renewable energy use or reduces carbon emissions. The results validated both the RKC and EKC hypotheses. Notably, the income threshold for increasing renewable energy consumption was lower than the turning point for reducing carbon emissions, implying that transitioning to renewables is a precursor to environmental improvement. This finding supports a policy direction where early economic growth should be leveraged to promote renewable energy uptake as a foundation for long-term emission reductions.

Celik et al. (2024) investigated material productivity, total factor productivity, and renewable energy in the Nordic countries over the period 1970 to 2019. The empirical analysis confirmed the EKC hypothesis and revealed that increases in both material productivity and renewable energy usage significantly reduced carbon emissions. The findings emphasised that green productivity improvements and renewables play a key role in achieving carbon neutrality in high-consumption economies, such as those in Scandinavia. These results provide critical policy insights into the efficient management of domestic material consumption while maintaining environmental goals.

Byaro et al. (2024) explored the impact of clean energy technologies on environmental sustainability in 29 sub-Saharan African countries using data from 2000 to 2018. Employing generalised quantile regression and Bayesian panel techniques, the study confirmed the EKC hypothesis and validated the Load Capacity Curve (LCC). The analysis demonstrated that renewable energy and clean cooking fuels significantly enhanced environmental sustainability across all quantiles. The findings also revealed a U-shaped relationship between income and environmental quality, indicating that low-income levels are initially associated with degradation, but improvements emerge at higher income brackets. The study suggests that reducing energy costs and increasing access to clean energy are central to sustainable development in the region.

Ozkan and Okay (2024) assessed the effects of economic policy uncertainty (EPU) and climate policy uncertainty (CPU) on CO₂ emissions in emerging and developed countries. Using the Pooled Mean Group estimator, the study confirmed the EKC hypothesis only in emerging economies under the EPU model. Renewable energy consumption was found to reduce emissions in both country groups. The study also highlighted that higher uncertainty could lead to lower emissions in emerging markets due to reduced energy-intensive consumption. These results suggest that targeted energy transition policies combined with efforts to stabilise economic expectations are essential for mitigating climate change.

Feng et al. (2024) evaluated the role of trade openness, human capital, and natural resources in carbon emissions for Central Asian countries from 1990 to 2020. Using the CS-ARDL model, the analysis validated the EKC hypothesis and revealed that energy use and natural resource exploitation increase emissions, while human capital and renewable energy mitigate them. The findings also noted that human capital moderates the environmental impact of natural resources, underscoring the value of education and skilled labour in environmental governance. The study calls for policies that invest in human capital and renewable technologies to support sustainable economic transitions.

Cao et al. (2024) examined the effect of technological innovation and energy structure on carbon emissions in China using FMOLS and data from 1990 to 2019. The results confirmed the EKC hypothesis and indicated that renewable energy, non-renewable energy, and technological advancement all contribute positively to emissions, suggesting that innovation without green direction can be environmentally detrimental. The study

identified a unidirectional causality from GDP to emissions and a bidirectional link between growth and energy use. These insights highlight the need for policies that align innovation systems with sustainability targets.

Horobet et al. (2024) provided a comparative EKC assessment for European countries, identifying a divergence in environmental outcomes. Using CS-ARDL and MMQR models, the study confirmed the EKC in Western Europe, while Eastern and Balkan countries exhibited a U-shaped relationship. Renewable energy had immediate emission-reducing effects in Western Europe, but its long-term effectiveness varied across regions. Trade openness was found to exacerbate emissions in the short-run. These findings suggest that regional policy differentiation is necessary to align economic growth with environmental targets within the European context.

Li et al. (2024) focused on energy security in the Yangtze River Delta region of China, applying entropy and coupling synergy degree methods. Although the study did not explicitly test the EKC hypothesis, it found a U-shaped relationship between renewable energy generation and energy security in some provinces. The results showed that renewable energy improved energy security in Zhejiang but had negligible effects in Shanghai. These findings indicate regional disparities in the benefits of renewable energy, which should inform the design of decentralised energy transition policies.

Muhammad et al. (2024) assessed the tri-dimensional nexus between energy consumption, economic growth, and environmental degradation in Pakistan by applying the ARDL model over the period 1972 to 2021. The study disaggregated energy sources into hydro, nuclear, and thermal energy to examine their individual and collective effects on economic performance and ecological footprint. The findings confirmed the Environmental Kuznets Curve (EKC) hypothesis in the Pakistani context. While energy consumption positively influenced economic growth in both the short and long-run, the environmental effects varied depending on the energy source. In the long-run, biocapacity from forest products contributed positively to environmental quality, whereas thermal and nuclear energy use exerted a negative influence. These results suggest that although energy is a driver of economic growth, Pakistan needs to prioritise the transition toward cleaner sources to address environmental concerns.

Bucak, Önder, and Çatık (2024) employed spatial econometric methods to evaluate the direct and spillover effects of renewable and fossil energy consumption on the ecological footprint of 26 EU countries from 1995 to 2020. The results supported the EKC hypothesis and revealed that renewable energy consumption in neighbouring countries had a negative impact on the local ecological footprint, indicating positive spillover benefits. In contrast, fossil energy consumption in both local and neighbouring countries contributed positively to environmental degradation. This evidence underscores the importance of regional cooperation and integration in environmental policy, as energy-related decisions in one EU member state can significantly influence environmental outcomes in others.

Brahmia and Mannai (2025) analysed the effects of ICT development, trade openness, foreign direct investment, and energy use on environmental degradation in Gulf Cooperation Council (GCC) countries using panel data from 1990 to 2022. The study validated the EKC hypothesis and found that ICT expansion and electricity consumption intensified carbon emissions, highlighting the trade-off between technological development and environmental quality. The findings also indicated that trade and FDI flows contributed to environmental degradation in line with the pollution haven hypothesis. However, the authors argued that these challenges could be mitigated through regulatory reforms and enhanced investment in renewable energy, suggesting a pathway for the GCC countries to balance economic transformation with ecological sustainability.

Erdogan, Pata, and Alola (2024) explored the dynamics of coal dependence across top coal-consuming economies from 1997 to 2021. Using panel data econometrics, the authors examined the validity of the coal-Kuznets Curve and found that economic growth initially increased coal consumption, while at higher income levels, coal demand declined, consistent with the EKC hypothesis. The study further identified that population density and industrialisation were key contributors to coal use, while demand for natural gas and renewable energy exerted a negative influence. These results provide empirical justification for policies that support the substitution of coal with cleaner energy sources and advocate for the reinvestment of economic gains into sustainable energy infrastructure.

Naimoğlu and Akal (2024) investigated the linkages among economic complexity, globalisation, energy consumption patterns, and environmental sustainability in 12 energy-importing emerging economies using panel ARDL from 1996 to 2020. The results confirmed a U-shaped relationship between economic complexity and environmental degradation,

aligning with the EKC hypothesis. Renewable energy consumption reduced emissions, while fossil fuel use had the opposite effect. The study highlighted the adverse environmental effects of economic globalisation and underscored the necessity of promoting renewable energy and carbon pricing mechanisms to ensure long-term sustainability.

Javed et al. (2024) examined the role of green technology innovation, environmental policy, and renewable energy in reducing ecological footprints across G7 economies between 1994 and 2018. Applying panel quantile regression and long-run mean estimation techniques, the study validated the EKC hypothesis and found that all three factors significantly reduced the ecological footprint across most quantiles. Although renewable energy consumption had a statistically insignificant effect at the lowest quantile, its impact was generally negative and supportive of sustainability objectives. The findings indicated that stringent environmental regulations and increased financial support for green innovation were essential for maintaining ecological sustainability across advanced economies.

Research by Destiartono (2025) assessed whether rapid urbanisation and economic growth contributed to environmental degradation in Indonesia using annual data from 1991 to 2021. The study adopted the ARDL bounds test, Zivot-Andrews stationarity check, and Toda-Yamamoto causality analysis to estimate the augmented EKC model. The results supported the EKC hypothesis and indicated that urbanisation and energy intensity significantly raised CO₂ emissions. Renewable energy consumption was associated with a reduction in emissions, while improvements in energy efficiency were found to be critical for environmental management. The study recommended a simultaneous strategy of increasing renewable energy usage and enhancing efficiency to meet Indonesia's sustainability targets.

Ikhsan and Amri (2024) analysed the effect of corruption on environmental degradation in six ASEAN countries from 1996 to 2019 using a fixed effect panel regression model. The findings provided evidence in favour of the EKC hypothesis, with renewable energy reducing emissions and urbanisation exerting a positive effect. Interestingly, corruption was also found to have a positive relationship with CO₂ emissions, implying that weak governance mechanisms undermine environmental protection. The study emphasised the importance of strengthening institutional frameworks and increasing renewable energy adoption to mitigate ecological harm.

Hacıımamoğlu and Cengiz (2024) investigated the combined impact of natural resource rents and renewable energy consumption on environmental degradation in ASEAN-5 countries using the Method of Moments Quantile Regression over the period 1990 to 2018. The study utilised a modified ecological footprint pressure index that accounts for both demand and supply sides of environmental pressure. The findings confirmed the EKC hypothesis and showed that both natural resource rents and renewable energy consistently reduced environmental degradation across all quantiles. The authors advocated for redirecting revenues from natural resources into clean energy investment to achieve long-term environmental sustainability.

Nabaweesi et al. (2024) explored the renewable energy-environmental Kuznets Curve (REKC) hypothesis in the context of East African Community countries, focusing on modern renewable energy sources exclusive of traditional biomass. Using panel data from 1996 to 2019 and employing the pooled mean group estimation within an ARDL framework, the study revealed that the REKC hypothesis is valid in this regional bloc. Financial development emerged as a critical enabler of renewable energy consumption, while urbanisation, trade openness and foreign direct investment appeared to reduce the use of modern renewables. Governance, however, did not demonstrate a significant impact. This study adds novelty by shifting focus from aggregate renewables to modern renewables, providing insights into how structural and financial variables interact with clean energy transitions in emerging African economies.

Rahman, Husnain and Azimi (2024) examined the environmental impact of overpopulation and human capital alongside energy consumption in South Asia using fixed and random effects models as well as dynamic panel causality. Drawing from panel data spanning 1972 to 2021, their findings confirmed the Environmental Kuznets Curve, with energy consumption and population density increasing carbon emissions, whereas human capital significantly reduced them. Causality tests indicated a complex dynamic, suggesting that emissions not only respond to economic and demographic factors but also exert reverse causality on human capital and population dynamics. The study concluded that strengthening educational and health systems is essential to improve environmental quality and meet international climate commitments such as the Paris Agreement.

Agusalim et al. (2025) tested the EKC and the Pollution Haven Hypothesis in 29 countries where religion is embedded in state governance. Applying the panel ARDL method

with data from 1990 to 2022, the results did not validate the EKC hypothesis across most of these countries, especially those with lower income levels. However, the long-run results supported the Pollution Haven Hypothesis, as FDI inflows were found to increase carbon emissions, particularly where environmental regulations were weak. Renewable energy consistently mitigated emissions, suggesting its potential as a counterbalance to fossil-fuel-driven development. The study also found that democratic institutions, contrary to expectations, were associated with higher emissions, indicating a possible gap between democratic norms and environmental outcomes. It proposed the adoption of faith-based economic models to align ethical values with sustainability objectives.

Hasan et al. (2024) investigated the role of environmental diplomacy and economic indicators in reducing environmental degradation in OECD countries. Using panel data econometric methods from 1991 to 2020, including FMOLS, DOLS and PMG-ARDL, the study tested the EKC hypothesis within a comprehensive policy framework. The results demonstrated that GDP, FDI, environmental diplomacy and renewable energy consumption significantly influenced carbon emissions. Specifically, renewable energy had a mitigating effect, while traditional economic expansion contributed to environmental degradation. The findings provided empirical justification for embedding environmental diplomacy in national and international policy agendas, especially when formulating sustainable growth strategies.

Lanhui and Ibrahim (2024) employed a novel ARDL model to examine the impact of trade openness on carbon emissions in South Africa over the period 1980 to 2020. The analysis confirmed the presence of the EKC, where GDP initially worsens emissions until a certain threshold, beyond which economic growth contributes to environmental improvement. Trade openness, however, was found to deteriorate environmental quality in the long-run. The study highlighted that government effectiveness has mixed effects, with political stability and control of corruption paradoxically contributing to higher emissions, while the rule of law was associated with reduced emissions. The authors recommended transitioning to a green economy by leveraging trade for environmental gains through renewable energy, recycling industries and green financing mechanisms.

Wani et al. (2024) employed a panel nonlinear ARDL model to explore asymmetric relationships between green energy and economic growth on environmental degradation in MENA countries from 1996 to 2020. The study validated the EKC hypothesis in the short-

run and found that both positive and negative shocks to green energy led to reductions in carbon emissions. In contrast, positive shocks to GDP contributed to increased emissions. The findings suggested that while economic growth remains environmental pressure, strategic investments in renewable energy can buffer this impact. Additionally, trade openness was positively associated with emissions, while FDI appeared to support environmental quality, potentially due to clean technology transfers.

Chopra et al. (2024) revisited the EKC hypothesis in the context of the COP-28 climate agenda, focusing on the top five carbon-intensive economies. The study applied the CS-ARDL technique and confirmed the EKC relationship, noting that while GDP and urbanisation positively correlated with the carbon footprint, the squared term of GDP, renewable energy, technological innovation and effective governance reduced environmental pressures. These findings were robust across MG and CCEMG estimators, underlining the importance of government effectiveness and technological capacity in managing the transition to carbon neutrality. The study offered strategic guidance for aligning economic policies with sustainable development goals under the post-COP framework.

Nica, Georgescu and Kinnunen (2024) explored the relationship between electricity access and carbon emissions in India using an ARDL model and EKC specification for the period 1990 to 2023. The results indicated an N-shaped EKC, highlighting two inflection points where, economic growth alternately increased and decreased emissions. Renewable energy consumption played a vital role in reducing emissions, particularly as it helped expand electricity access without compromising environmental integrity. The study emphasised the need for a dual strategy focused on both economic growth and energy diversification to achieve sustainable outcomes.

Khan et al. (2024) examined the impact of urbanisation, technology-driven energy deficits and renewable energy on CO₂ emissions in 48 Belt and Road Initiative economies using the system GMM approach. Their findings supported the EKC hypothesis and affirmed the Pollution Halo Hypothesis, where FDI contributed to lower emissions through cleaner technologies. Renewable energy sources were associated with significant mitigation effects, while technology-related energy deficits increased emissions. The study recommended urban development and the adoption of advanced energy solutions as pathways to environmental improvement in developing economies.

Zhou et al. (2025) investigated the role of energy intensity and renewable versus non-renewable energy in shaping environmental outcomes in highly pollutant nations. Using cross-sectional dependence and slope heterogeneity-consistent estimators on panel data from 1990 to 2021, the authors validated the EKC hypothesis in two out of three model specifications. Energy intensity was shown to increase emissions significantly, whereas renewable energy reduced them. The study highlighted a feedback relationship between emissions, economic growth and energy structure, underscoring the need for energy tax reforms and subsidies to support clean energy transitions. These policy suggestions offer a pragmatic approach to reducing emissions in economies heavily reliant on fossil fuels.

Azimi et al. (2025) investigated the impact of government effectiveness, economic complexity and state fragility on achieving Sustainable Development Goal 8 targets among G20 countries between 2000 and 2023. The authors employed the cross-sectionally augmented autoregressive distributed lags model alongside dynamic common correlated effects estimators. Their findings confirmed that institutional strength, economic complexity and renewable energy use promote economic growth and labour productivity while reducing unemployment and emissions. State fragility and primary energy consumption, in contrast, were associated with adverse outcomes. The study validated the Environmental Kuznets Curve (EKC) hypothesis by identifying a redefined turning point shaped by these governance and structural indicators.

Daga et al. (2024) assessed the determinants of CO₂ emissions in five high-emission economies, including China, the United States, India, Russia and Japan. Applying panel ARDL estimation over the period from 1990 to 2021, the study found that economic growth and resource extraction significantly contributed to environmental degradation. Technological change and renewable energy, however, exhibited the potential to mitigate emissions. Although the EKC hypothesis was not validated, the findings support a shift toward sustainable development through clean technologies.

Shouwu et al. (2024) analysed the relationship between renewable energy, environmental technologies and environmental degradation in North African countries. Using FM-OLS, D-OLS and DSUR methods, the study found that renewable energy significantly reduced emissions, while environmental technologies had a limited role. Causality tests revealed a bidirectional link between economic growth and both CO₂ emissions and renewable energy use. Despite not supporting the EKC hypothesis, the study

encouraged public investment in green technologies and adoption of international agreements. Closely related with green technology such as the green finance variable.

Wang and Xu (2024) explored the interaction between economic development, development finance and environmental quality in the Global South. Employing a simultaneous equations model, the study confirmed an inverted N-shaped EKC and emphasised the importance of renewable natural capital, human capital investment and green finance in driving low-carbon growth.

Ahmad et al. (2024) examined the asymmetrical relationship between financial development, technological innovation and carbon emissions in developing Asian countries from 1995 to 2021. Using a dynamic error correction model, the authors found that positive financial shocks are associated with increased emissions while negative shocks yield environmental gains. The EKC hypothesis was validated under these asymmetrical effects, and renewable energy use was found to be consistently effective in lowering emissions.

Issayeva et al. (2024) investigated the EKC hypothesis in Kazakhstan using the ARDL bounds test approach. The analysis incorporated GDP, renewable energy, industrial and agricultural output. The results confirmed a negative coefficient for the squared GDP term, consistent with the EKC hypothesis. Renewable energy and industrial production were found to be significant contributors to emissions, while agriculture showed no measurable effect.

Next, Dhayal et al. (2025) focused on the Sub-Saharan African region to evaluate the roles of strategic commodity extraction, policy uncertainty and renewable energy in environmental degradation. Applying the augmented mean group estimator and system GMM on a panel of thirty-nine countries, the study confirmed the EKC hypothesis. It further demonstrated that commodity exports intensified emissions, while renewable energy use and stable economic policy supported environmental improvement. Bibi et al. (2024) studied the textile and fashion industry in China, assessing how environmental regulations, innovation and renewable energy shape environmental outcomes. Using quarterly time series data and ARDL modelling, the results confirmed the EKC hypothesis. The study found that environmental regulations reduced emissions, renewable energy had immediate benefits, and technological innovation improved outcomes over time.

Some studies combine Kuznets curve with the STIRPAT model. Rokhmawati et al. (2024) used a system dynamics model integrated with the STIRPAT framework to simulate the effects of a carbon tax in Indonesia. The study tested ten scenarios and confirmed the EKC hypothesis, showing an inverted U-shaped relationship between GDP and CO₂ emissions. The fastest emission peak was projected in 2040 under scenarios involving carbon taxation and nuclear power. Renewable energy improvements and green industrial restructuring were identified as essential drivers of emission reduction. The study provides an ex-ante policy framework for Indonesia's transition toward carbon neutrality. Also related, Zeng et al. (2024) analysed a regional integrated energy system in Shanghai by applying an extended STIRPAT model and multi-objective optimisation. The study predicted carbon-peaking trajectories under different development scenarios from 2020 to 2040. The findings affirmed the EKC hypothesis and suggested that higher renewable energy penetration within clean energy configurations was critical to achieving emission reduction targets.

Next, Borsha et al. (2024) conducted a comprehensive empirical study in Bangladesh to test the Environmental Kuznets Curve (EKC) hypothesis using the STIRPAT framework. Their analysis covered the period from 1992 to 2021 and applied the ARDL technique along with pairwise Granger causality. The study confirmed the presence of a long-run relationship among CO₂ emissions, GDP per capita, its squared term, industrialisation, population, and renewable energy consumption. The results validated the EKC hypothesis, indicating that economic growth initially exacerbates environmental degradation but eventually leads to environmental improvements as income increases. A key finding was the significant negative relationship between renewable energy and CO₂ emissions, reinforcing the role of renewables in mitigating environmental harm. The study also identified industrialisation as a long-term driver of emissions, highlighting the environmental costs of industrial expansion in developing economies like Bangladesh.

Salahodjaev and Sadikov (2024) examined the interrelationship between renewable energy consumption, carbon dioxide emissions and economic factors in fifty countries experiencing high rates of coronary heart disease from 2000 to 2020. Employing a two-step system GMM approach, the authors found that renewable energy significantly reduced emissions, highlighting the importance of sustainable energy in improving environmental quality. The results supported the Environmental Kuznets Curve hypothesis, confirming an

inverted U-shaped relationship between GDP per capita and CO₂ emissions. The study further suggested that the co-benefits of renewable energy extend beyond environmental gains to include health-related outcomes in vulnerable economies.

Iqbal et al. (2025) analysed the climate Kuznets Curve (CKC) for BRICS countries between 1992 and 2020. The study applied a robust panel quantile autoregressive distributed lag model to examine the nonlinear effects of economic activity on climate indicators such as cooling degree days. The findings revealed a U-shaped CKC, but more importantly, demonstrated that renewable energy and higher education jointly moderated the negative impacts of economic growth on climate outcomes. The study called for the integration of climate-responsive curricula in education to complement renewable energy policies for long-term sustainability.

Ganda (2025) tested the Environmental Kuznets Curve hypothesis for South Africa using the ARDL approach. The study uncovered both U-shaped and inverted U-shaped curves depending on the variable configurations across short-run and long-run models. Although the impact of foreign direct investment and financial development was statistically insignificant, renewable energy exhibited a substantial negative association with environmental degradation in the long term. The findings underscored the role of human capital and clean energy in shaping South Africa's path toward environmental sustainability.

Alam et al. (2024) investigated the role of financial inclusion and information and communication technology in reducing environmental degradation in oil-producing countries. Using panel quantile regression and FMOLS techniques, the study showed that ICT and financial inclusion consistently reduced CO₂ emissions, whereas primary energy consumption and the human development index were positively associated with pollution. Although the EKC hypothesis was confirmed, renewable energy was not the focal variable. The study contributed important policy implications by emphasising the digital-financial nexus in climate mitigation for resource-rich economies.

Bektur (2024) explored the influence of economic freedom, renewable energy and economic growth on ecological sustainability among fifteen countries with the highest economic freedom from 1996 to 2018. The results of panel cointegration and long-run estimations demonstrated that renewable energy significantly reduced the ecological footprint in several countries. The Environmental Kuznets Curve hypothesis was validated

in selected cases, including Canada, Denmark and Singapore. The study concluded that economic freedom and renewable energy could jointly enhance environmental outcomes depending on national context.

Bashir et al. (2024) evaluated the relationship between energy prices, energy consumption, gold prices and economic growth in newly industrialised countries. Using CS-ARDL and a range of robustness checks, the study confirmed that renewable energy consumption reduced environmental degradation, while fossil fuel use and gold prices increased emissions. The Environmental Kuznets Curve hypothesis was supported, and the authors called for stronger green investments and structural reforms to meet sustainable development targets in industrialising economies.

Simbi et al. (2025) assessed the long-term association among CO₂ emissions, GDP and socio-economic variables in thirty-six African countries over the period from 1990 to 2020. Employing the Pooled Mean Group ARDL model and Dumitrescu and Hurlin causality tests, the study validated the EKC hypothesis. The turning point was estimated to be around USD 10,600 per capita, although most countries had not yet reached it. Renewable energy and urbanisation were negatively associated with emissions, while trade openness and economic growth had positive effects. The study advocated for green growth policies to address Africa's environmental vulnerabilities.

Alnafisah et al. (2024) applied the innovation curve theory to test the EKC in six MENA countries by examining the roles of technological innovation, economic growth and renewable energy. The study confirmed an inverted U-shaped relationship between technological innovation and carbon emissions, as captured by patent variables. Renewable energy consumption contributed to lower emissions, while the turning point for innovation-induced environmental improvements was clearly identified. These findings highlighted the dual role of innovation as both a pollutant and a long-term environmental solution.

Koçak et al. (2024) focused on the transport sector in Pakistan, analysing the relationship between non-renewable energy, urbanisation and environmental quality using the QARDL approach from 1995 to 2018. The study found strong support for the EKC in moderate to high quantiles. Urbanisation and fossil fuel use were associated with increased emissions, while renewable energy played a mitigating role. The study provided sector-

specific insights that inform climate policy in the context of Pakistan's growing urban transport system.

Bozatli and Akca (2024) examined the effects of different types of environmental regulations on sustainability in Turkey, using a Fourier ARDL model over the period 1990 to 2020. The study distinguished between market-based, command and control, and technology support regulations. Only market-based instruments were found to improve environmental quality significantly. The study validated both the Environmental Kuznets Curve and the Load Capacity Curve hypotheses and confirmed the beneficial role of renewable energy in reducing the ecological footprint.

Aruga et al. (2024) investigated the dynamic nexus between energy consumption by source and carbon dioxide emissions in Japan from January 2019 to March 2023. Using the ARDL model, the study found that photovoltaic (PV) energy had a mitigating effect on emissions in the short-run, while coal, oil, and liquefied natural gas (LNG) significantly contributed to emission increases. The study also revealed an inverted U-shaped relationship between CO₂ emissions and economic growth, captured through the Nikkei stock index, offering empirical support for the Environmental Kuznets Curve hypothesis in the context of a high-income country with mixed energy usage. The authors advocated for enhanced policy incentives in renewable energy investment, particularly PV systems, as a pathway to long-term ecological balance in line with Japan's Paris Agreement commitments.

Mahmood et al. (2024) examined the role of renewable energy transition and innovation in shaping environmental sustainability across twenty-five Western European countries during the period from 1995 to 2020. Employing techniques that account for cross-sectional dependence, the authors found strong support for the Environmental Kuznets Curve with a turning point around USD 50,287 per capita. The results showed that renewable energy transition significantly reduced CO₂ emissions in both the short and long-run. Furthermore, while innovation proxied by patent activity contributed to environmental sustainability in the long-run, it had no effect in the short-run. The study concluded that renewable energy transition and innovation serve as crucial instruments for sustaining environmental quality in advanced economies.

Xu et al. (2024) explored the asymmetrical effects of energy use, gold prices, and fossil fuel prices on environmental degradation in ten newly industrialised countries over the

period from 1995 to 2023. Using the CS-ARDL model complemented by FGLS, CS-DL, AMG, and Driscoll-Kraay estimators, the authors confirmed the validity of the Environmental Kuznets Curve. Renewable energy consumption was shown to significantly reduce emissions, while fossil fuel usage and gold prices had the opposite effect. The findings underscored the potential of renewable energy to reduce ecological harm and called for stronger structural reforms and green investment in newly industrialised economies.

Mohamed et al. (2024) re-examined the EKC hypothesis for Malaysia using time series data from 1985 to 2020. Applying the ARDL and FMOLS approaches, the study found a long-run inverted U-shaped relationship between GDP and both carbon emissions and the ecological footprint, thereby supporting the EKC hypothesis. The results revealed that electricity intensity increases emissions, while the use of renewable energy in power generation lowers them. However, when ecological footprint was considered, the signs for electricity intensity and renewable energy reversed, indicating complex environmental trade-offs. The study advocated for improved legislation on energy efficiency and the strategic management of renewable energy systems to strengthen Malaysia's path toward sustainable development.

Yusoff et al. (2024) analysed the factors influencing renewable energy consumption and environmental change in six ASEAN countries using panel data from 1990 to 2019. Employing Pedroni cointegration tests and estimation methods including FMOLS, DOLS, and POLS, the results showed a long-term positive relationship between GDP and renewable energy use. However, carbon emissions, population density, and foreign direct investment negatively influenced renewable energy demand. Although the Environmental Kuznets Curve was statistically supported, the study highlighted that economic growth in some ASEAN countries coincided with higher emissions, challenging the assumption that growth automatically drives greener transitions. This study recommended comprehensive reforms, including the restructuring of fossil fuel subsidies and promotion of clean energy investment, to align regional policy with environmental goals.

Villanthenkodath et al. (2024) assessed the influence of monetary and fiscal policies on India's ecological footprint from 1990 to 2022 using the ARDL framework. The study confirmed a significant long-run relationship among ecological footprints, GDP, renewable energy consumption, and macroeconomic policy instruments. While monetary policy showed a strong negative impact on ecological footprint, fiscal policy was statistically

insignificant in both the short and long-run. The study also validated the EKC hypothesis in the long-run and identified renewable energy as a consistent factor in improving environmental quality. These findings highlighted the need for macroeconomic coordination that integrates sustainability and renewable energy development in India's policy architecture.

Ahmed et al. (2025) explored the environmental implications of agricultural value-added, renewable energy, and GDP in Somalia from 1990 to 2020 using multiple estimators, including ARDL, CCR, DOLS, and FMOLS. The study confirmed the EKC hypothesis and established that renewable energy use reduced environmental degradation, while agricultural value-added exacerbated emissions in the long-run. The authors emphasised that despite Somalia's strong solar energy potential, underutilisation of renewable resources hampers its environmental progress. The study proposed expanding solar infrastructure as a strategic response to both economic and environmental challenges in the country.

Kitole et al. (2024) investigated the interactions between economic growth, globalisation, and environmental degradation in Tanzania from 1970 to 2022. Using the ARDL model, the study identified a long-run inverted U-shaped relationship between GDP per capita and CO₂ emissions, consistent with the EKC framework. However, short-run results indicated a weak negative relationship. Trade openness was found to significantly increase emissions, underscoring the environmental costs of globalisation. The authors recommended the promotion of green trade and investment in renewable energy infrastructure to decouple emissions from growth and align national policy with the Tanzania Development Vision 2025.

Toumi (2025) applied the panel quantile ARDL (PQARDL) method to investigate the impacts of financial development, renewable energy, and innovation on the ecological footprint of major remittance-receiving economies between 1990 and 2022. The study found that renewable energy consistently reduced the ecological footprint across all quantiles, whereas financial development and innovation had heterogeneous effects. The findings questioned the universal applicability of the EKC hypothesis, instead supporting an N-shaped relationship between income and environmental degradation. The study urged policymakers to integrate renewable energy and innovation strategies into comprehensive development agendas for long-term ecological balance.

Yahyaoui and Ghandri (2024) evaluated the effect of renewable energy, trade openness, and GDP on CO₂ emissions in MENA countries from 1990 to 2023 using FMOLS, DOLS, and SGMM techniques. The results showed that renewable energy reduced emissions, while economic growth increased them. Although trade openness had conflicting effects depending on the estimation method, the inverted U-shaped EKC hypothesis was supported in the long-run. The authors recommended the expansion of renewable energy use and the efficient regulation of GDP and trade-related emissions to improve environmental outcomes in the region.

Mohamad et al. (2023) examined the environmental implications of energy source transition in two of the world's largest carbon emitters, the United States and China. The study employed both linear and nonlinear autoregressive distributed lag (ARDL) models using annual data from 1985 to 2021 to evaluate the impact of fossil fuel and renewable energy consumption on CO₂ emissions. Their empirical findings revealed a statistically significant and positive association between fossil energy use and environmental degradation, whereas renewable energy consumption was found to have a mitigating effect on CO₂ emissions in both countries. These results were consistent across the linear and nonlinear ARDL specifications, indicating that the transition towards renewable energy sources contributes meaningfully to reducing environmental pressure over the long term.

Mohamad and Ab-Rahim (2024) assessed the environmental consequences of different energy sources in India, particularly fossil fuels, renewable energy, and nuclear power, using both linear and nonlinear ARDL models with data spanning from 1985 to 2021. Their findings revealed that fossil fuel consumption significantly increases CO₂ emissions, contributing to environmental degradation, while nuclear energy consumption was associated with a reduction in emissions. Although renewable energy was included in the analysis, its impact was less prominent in the long-run results, pointing to a complex energy-environment nexus in India. Additionally, the study incorporated GDP per capita as a control variable and found a strong positive correlation with CO₂ emissions.

Elatrroush (2025) examined whether financial development affects environmental quality across 60 developing and emerging countries from 1980 to 2021. Using Pooled Mean Group and panel quantile regression, supported by cross-sectional dependence and unit root tests, the analysis revealed heterogeneous outcomes. In several country clusters, financial development and other macroeconomic factors were found to increase CO₂ emissions, while

in others, these variables contributed to environmental improvement. The study showed that institutional, structural, and technological differences across economies explain these disparities. Although the EKC hypothesis was not explicitly validated, the study confirmed the beneficial role of renewable energy in reducing emissions. Policy recommendations include promoting financial instruments that support low-carbon technologies, encouraging investment in bioenergy, and shifting away from non-renewable energy use to meet SDGs.

Naz et al. (2024) explored the decoupling of economic growth and CO₂ emissions in emerging economic blocs, particularly the ASEAN and GCC regions. Integrating the EKC hypothesis with stakeholder and ecological modernization theories, the study applied fuzzy-set Qualitative Comparative Analysis to assess how renewable energy, economic growth, and institutional settings influence environmental outcomes. The findings confirmed the EKC in some contexts, especially where income growth was accompanied by strong environmental policy frameworks. In ASEAN countries, rapid GDP growth was associated with increased ecological footprints, signalling weak decoupling. Meanwhile, in the GCC bloc, renewable energy played a pivotal role in reducing ecological degradation. This comparative approach illustrates that achieving decoupling is contingent on region-specific policy environments and energy strategies, with renewable energy emerging as a key element for managing emissions sustainably.

2.8 A Remark

Recent empirical studies have significantly deepened the understanding of the Environmental Kuznets Curve (EKC) hypothesis while expanding its analytical scope through integration with the STIRPAT framework and an intensified focus on renewable energy as a crucial lever for sustainable development. Reviewing over a hundred contemporary studies reveals a strong consensus that the inverted U-shaped EKC relationship, in which environmental degradation initially rises with income but eventually declines after a certain threshold, remains generally valid across diverse economies and contexts.

However, this relationship is neither automatic nor universal; instead, it is highly dependent on how societies manage structural conditions such as energy composition, technological capability, governance effectiveness, trade orientation, financial development and demographic pressures. The STIRPAT framework has been instrumental in this

literature because it allows researchers to operationalise the IPAT identity flexibly, quantifying how population, affluence and technology interact in stochastic and often non-linear ways to influence environmental impacts while accommodating moderating and interaction effects. A clear and repeated finding is the pivotal role of renewable energy in shaping whether and when the EKC turning point is reached. In high-income countries with strong institutions, such as the G7, Western Europe and the Nordic region, studies consistently show that renewable energy consumption significantly reduces CO₂ emissions and ecological footprints.

These effects are often amplified when renewable energy interacts with other factors such as technological innovation, financial development and governance quality. For instance, research using ARDL and NARDL models shows that the environmental benefits of renewable energy are greater and more stable when supported by high R&D spending, advanced technological capability and robust policy frameworks. This aligns directly with the STIRPAT model's insight that technology moderates the impact of affluence and population on environmental outcomes, and that renewable energy is a key technological input that strengthens this moderation.

In contrast, studies focusing on emerging economies and large developing countries show a more complex trajectory. While many confirm the EKC pattern in principle, they reveal that the turning point often comes later because of deep reliance on fossil fuels, rapid industrialisation, insufficient regulatory enforcement and lagging renewable energy adoption. Here too, renewable energy consistently appears as a critical dampening force on emissions.

Empirical findings demonstrate that when renewable energy uptake expands alongside improvements in governance and human capital, the downward bend of the EKC can be achieved sooner. The Renewable Energy Kuznets Curve (RKC) concept refines this further by suggesting that renewable energy itself follows a Kuznets-like path, increasing with economic development until it reaches maturity. Proactive policy that promotes renewable energy early can therefore shift the EKC turning point forward, shortening the period when economic growth fuels environmental deterioration.

A major theme across these studies is the importance of variable interactions. For example, trade openness and foreign direct investment can either support or hinder environmental sustainability. In well-governed economies, they facilitate clean technology

transfer and expand green investment, which strengthens the benefits of renewable energy and supports emission reduction. In countries with weak institutions, however, trade and FDI can exacerbate emissions, supporting the pollution haven effect.

The STIRPAT framework captures these nuances by including interaction terms and stochastic estimations that reveal how governance quality and renewable energy jointly moderate the impact of economic and demographic variables. Advanced estimation methods have allowed researchers to uncover asymmetries and non-linearities in how renewable energy, governance and income growth interact to affect CO₂ emissions. Many recent papers confirm that these relationships are not constant across income groups or sectors.

Studies focusing on forestry, agriculture, logistics and urban transport show that sectoral growth pressures can override national EKC patterns if renewable energy policies and technological standards are not sector-specific and robust. Other research demonstrates that renewable energy adoption in one country can create positive spillover effects on neighbouring countries by encouraging technology transfer and policy learning.

Additionally, a substantial segment of the literature extends the classic EKC by examining other structural moderators, such as economic complexity, human capital, financial inclusion, energy security and environmental diplomacy. These factors are often found to work hand-in-hand with renewable energy to achieve environmental improvements. Countries with higher technological sophistication and capable institutions extract more environmental benefit from renewable energy than those with weaker structures. Conversely, political instability, corruption and poor institutional performance undermine the potential gains from renewable energy investment.

Although a substantial body of empirical research has validated the Environmental Kuznets Curve (EKC) hypothesis and strengthened its explanatory scope through integration with the STIRPAT framework, a critical shortcoming persists in how existing studies address the joint influence of renewable energy and governance effectiveness. Most prior studies investigate these factors in isolation or explore only simple pairwise interactions with economic growth, often using general cross-country samples without specific attention to the largest emitters. Moreover, despite the methodological advantages of dynamic models, there remains limited application of advanced panel ARDL and nonlinear ARDL (NARDL) techniques to capture both symmetric and asymmetric long-run and short-run interactions among these variables in this critical group of countries.

Addressing this gap, this study applies both the EKC and STIRPAT frameworks within a robust panel ARDL and NARDL modelling strategy to uncover how renewable energy and government effectiveness jointly condition the relationship between economic growth and CO₂ emissions in the most emission-intensive economies. By doing so, this study provides new empirical evidence and practical insights that support integrated policy efforts to manage and reduce CO₂ emissions while sustaining economic development where it matters most for global sustainability. This contribution fills a significant empirical and methodological void in the existing literature and informs targeted climate and energy policy design in high-emission contexts.

RESEARCH METHODOLOGY

3.1 Introduction

This chapter sets out the methodological framework adopted to examine the complex and evolving interrelationship between economic growth, energy consumption, and environmental sustainability. The analysis is grounded in two well-established theoretical frameworks, the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model. Together, these frameworks provide a comprehensive lens through which to assess the long-term drivers of carbon dioxide (CO₂) emissions and their implications for sustainable development.

The urgency of this investigation arises from escalating global concerns over climate change and environmental degradation. As economies expand, their energy demands increase, often at the expense of environmental quality. This is particularly evident in countries that rely heavily on fossil fuels. The need to understand the economic and environmental trade-off is especially pertinent in the world's top emitters, which collectively account for a substantial share of global CO₂ emissions. This study focuses on a panel of high-emission countries, including China, the United States, India, Russia, Japan, Iran, Germany, Indonesia, South Korea, and Saudi Arabia.

The primary objective of this study is to investigate the long-run relationship between CO₂ emissions per capita and a set of key explanatory variables. These include gross domestic product (GDP) per capita, squared GDP per capita (to capture potential non-linear effects), population, foreign direct investment (FDI), and electricity generation from fossil fuels, nuclear energy, and renewable sources. In addition, interaction terms involving government effectiveness, are introduced to examine how governance moderates the relationship between economic development and environmental performance.

To analyse these relationships, the study employs a panel data econometric approach using annual data from 1996 to 2023. This method allows for the examination of both time-based trends and cross-country differences. Recognising that some relationships may not be uniform in all directions, both linear and non-linear econometric models are applied. These include the autoregressive distributed lag (ARDL) and non-linear ARDL (NARDL) models, which are well-suited to assessing dynamic and asymmetric responses.

The structure of this chapter is organised to systematically develop the study's methodological approach. Section 3.2 introduces the theoretical foundations underpinning the research, beginning with the Environmental Kuznets Curve (EKC) hypothesis in Section 3.2.1, followed by the STIRPAT model in Section 3.2.2. Section 3.3 presents the variables employed in the analysis, detailing their definitions, transformations, sources, and the rationale for their inclusion. Section 3.4 outlines the empirical strategy, including panel unit root testing (Section 3.4.1), the specification of the Autoregressive Distributed Lag (ARDL) model (Section 3.4.2), and the non-linear ARDL model (Section 3.4.3).

The overall model specifications are described in Section 3.5, while Section 3.6 concludes the chapter and sets the stage for the empirical analysis that follows. This structured approach ensures a coherent and robust methodological foundation for examining the interlinkages between economic growth, renewable energy consumption, and environmental sustainability across the world's highest carbon-emitting economies.

3.2 Methodology

The relationship between economic growth, energy consumption, and environmental sustainability has become increasingly critical in the context of global development. Energy remains a vital input for economic activities across major sectors such as industry, transportation, and agriculture. However, the continued dependence on fossil fuel-based energy sources has led to mounting environmental pressures, particularly through increased carbon dioxide (CO₂) emissions. In light of these concerns, this study seeks to address the dual policy challenge of fostering economic growth while mitigating its environmental consequences.

The primary objective of this study is to examine the short and long-term relationship between CO₂ emissions per capita and several key economic, demographic, and institutional variables. These include gross domestic product per capita (LGDP), the square of GDP per

capita (LGDP2) to account for potential non-linear effects as posited by the Environmental Kuznets Curve hypothesis, and total population (LPOPL), which reflects the scale of human activity influencing emissions. Additionally, the model incorporates renewable energy consumption (LRE), which represents the transition towards cleaner energy sources.

To capture the institutional dimension, the variable for government effectiveness (LEIU), based on the Economist Intelligence Unit's proxy for government effectiveness, is included. This allows the study to assess whether government effectiveness can moderate the impact of economic activity on environmental outcomes. Furthermore, two interaction terms are constructed: LGDP*LEIU (GDP per capita $\times$ government effectiveness) and LRE*LEIU (renewable energy $\times$ government effectiveness). These interaction terms are intended to capture how government effectiveness conditions the relationship between both economic growth and renewable energy use with CO₂ emissions. Thus, gives more novelty and high impactful results.

All variables are sourced from reliable international databases, including the World Bank and Our World in Data, except for the interaction terms, which are computed by the author. The empirical analysis is conducted using panel data covering the period from 1996 to 2023, enabling both temporal and cross-country comparisons. This methodological framework provides a comprehensive basis for exploring the structural and institutional factors that drive environmental outcomes in high-emission economies.

3.2.1 Environmental Kuznets Curve (EKC)

The Environmental Kuznets Curve (EKC) hypothesis is a theoretical model used in environmental economics to describe the relationship between environmental degradation and economic development (Kaika & Zervas, 2013; Uchiyama, 2016; Kuznets, 2019; Mohamad et al., 2023). According to Kuznets (2019) and Mohamad & Ar-Rahim, (2024), the relationship between environmental quality and economic growth follows an inverted U-shape, meaning that environmental degradation initially increases with economic growth but eventually decreases after reaching a certain level of income per capita.

According to Naveed et al. (2022) and Kuznets (1955), the EKC hypothesis is named after economist Simon Kuznets, who proposed a similar curve to describe the relationship between income inequality and economic development. The EKC model is an extension of

this idea to the environmental domain. The standard form of the EKC model can be represented by the following quadratic equation (1):

$$E = \alpha + \beta_1 \cdot Y_i + \beta_2 \cdot Y_i^2 + \varepsilon \quad (1)$$

Where:

E = Environmental degradation (CO₂ emissions)

Y_i = Income per capita (GDP per capita)

α = Intercept term (constant)

β_1 = Coefficient of income per capita

β_2 = Coefficient of the squared income per capita

ε = Error term (captures unexplained variation)

In the quadratic EKC model, the equation (2) is the turning point can be mathematically derived from the estimated coefficients of income (Y) and its square (Y^2):

$$Turning\ point = -\frac{\beta_1}{2\beta_2} \quad (2)$$

Where:

β_1 is the coefficient of income per capita.

β_2 is the coefficient of the squared income per capita.

The sign and magnitude of β_1 and β_2 determine the position and shape of the curve. A positive β_1 and β_2 confirm the inverted U-shape, with the turning point occurring at a specific level of income.

3.2.2 STIRPAT

The STIRPAT model, an acronym for "Stochastic Impacts by Regression on Population, Affluence, and Technology," is a widely used analytical framework in environmental studies that seeks to understand the determinants of environmental impact

(Shahbaz et al., 2016; Vélez-Henao et al., 2019; Lohwasser et al., 2020). This model builds upon the foundational IPAT equation, which expresses the environmental impact (I) as the product of Population (P), Affluence (A), and Technology (T). However, while the IPAT equation assumes a simplistic and deterministic relationship between these variables, the STIRPAT model allows for a more nuanced and flexible analysis by incorporating stochastic elements, enabling the study to account for variability and non-linear relationships. The IPAT original equation (3):

$$I = P \times A \times T \quad (3)$$

The standard form of the STIRPAT model can be expressed by the following quadratic equation (4):

$$I = a \cdot P_i^b \cdot A_i^c \cdot T_i^d \cdot \epsilon_i \quad (4)$$

Where:

I represents the environmental impact,

P^b denotes population,

A^c signifies affluence,

T^d stands for technology,

a is a constant term,

Where b, c, d are the exponents or elasticities that measure the sensitivity of environmental impact to changes in population, affluence, and technology, respectively, ϵ_i is the stochastic error term. The exponents $b, c,$ and d , are estimated using regression analysis, and they provide insight into how changes in each of the factors influence environmental impact. For example, if b is greater than one, it suggests that environmental impact increases at a faster rate than population growth, indicating a disproportionate effect of population on the environment. Similarly, if c is less than one, it implies that as affluence increases, its marginal impact on the environment decreases, which might be due to more efficient use of resources or better environmental regulations in wealthier societies.

The insights gained from STIRPAT analyses have important policy implications. For example, if the model reveals that population growth has a strong positive elasticity, it suggests that policies aimed at stabilizing or reducing population growth could be effective in mitigating environmental impacts. Similarly, if affluence is found to have a significant impact on environmental degradation, policymakers might consider strategies to promote sustainable consumption and production practices.

3.3 Justification of Variables

This study investigates the existence of short and long-run cointegration relationships using both ARDL and Non-linear ARDL models among the following variables: CO₂ emissions per capita, GDP per capita, GDP per capita squared, population, renewable energy consumption, and government effectiveness. The inclusion of these variables is theoretically grounded in the Environmental Kuznets Curve (EKC) hypothesis, which postulates an inverted U-shaped relationship between income and environmental degradation, as well as in the broader literature on government effectiveness and renewable energy transitions. To explore the moderating role of institutional factors, the study also includes two interaction terms: GDP per capita $\times$ government effectiveness (LGDP*LEIU) and renewable energy $\times$ government effectiveness (LRE*LEIU).

3.3.1 CO₂ Emissions Per Capita (LCO₂)

CO₂ emissions per capita is essential for understanding the varying contributions of different countries to global climate change. While total CO₂ emissions offer an absolute measure of a country's greenhouse gas output, the per capita metric allows for a more equitable comparison by accounting for population size. For example, countries like China and India, with their large populations, contribute significantly to global CO₂ emissions, but their per capita emissions are lower than those of smaller, more industrialized nations like the United States or Australia. This metric is crucial because it highlights the disparities in carbon footprints across regions.

High per capita emissions often indicate a greater reliance on fossil fuels, intensive industrial activities, and energy-consuming lifestyles. In contrast, lower per capita emissions might reflect a higher use of renewable energy, more energy-efficient technologies, or a less industrialized economy. Recognizing these differences is vital for developing fair and

effective climate policies that address the unique needs and capacities of different countries. By focusing on CO₂ emissions on a per capita basis, researchers and policymakers can gain valuable insights into the environmental impact of individual lifestyles, consumption patterns, and the overall efficiency and sustainability of an economy. Understanding CO₂ emissions per capita is vital for developing effective and equitable climate policies.

It underscores the need for differentiated responsibilities in international climate agreements, where countries with higher per capita emissions are expected to take on more significant commitments to reduce their carbon footprints. This approach is reflected in frameworks like the Paris Agreement, which emphasizes the principle of common but differentiated responsibilities and respective capabilities. This measure not only reflects a country's economic activities but also provides a window into its technological progress, energy usage, and the effectiveness of its environmental policies.

3.3.2 Economic Growth (LGDP and LGDP²)

GDP is a fundamental indicator that reflects economic activity within a country. It is calculated by adding up consumption, investment, government spending, and net exports (exports minus imports). GDP per capita, which divides the GDP by the population, offers a perspective on the standard of living in different countries. Moreover, the Gross Domestic Product (GDP) is a key measure that represents the economic performance of a country. It sums up the total value of goods and services produced within a country's borders over a specific period, usually a year. GDP is widely used to assess the economic health of a nation, with higher GDP indicating stronger economic performance. However, when exploring the relationship between economic growth and environmental impact, researchers also consider the square of GDP.

In environmental studies, GDP per capita is often used as a proxy for economic growth. As a country's GDP per capita increases, it typically experiences industrialization, urbanization, and higher energy consumption, all of which can lead to increased environmental degradation, such as pollution and higher CO₂ emissions. However, the relationship between GDP per capita and environmental degradation is not straightforward, which is where the square of GDP per capita becomes relevant. This quadratic relationship is essential in understanding the Environmental Kuznets Curve (EKC) hypothesis, which

suggests that environmental degradation initially increases with economic growth, but after a certain income level is reached, further growth leads to environmental improvements.

3.3.3 Population (LPOPL)

Population size and growth are critical factors that significantly influence environmental degradation. As the global population continues to rise, the demand for resources such as food, water, energy, and land increases, leading to greater environmental stress. Meaning, as the population grows, so does the need for natural resources. A larger population means more mouths to feed, more homes to power, and more goods to produce, all of which require energy, land, and other resources. This heightened demand often leads to environmental challenges like deforestation, soil degradation, water pollution, and increased greenhouse gas emissions. This relationship between population and environmental degradation is complex, with multiple interacting factors such as consumption patterns, technological advancements, and economic structures playing pivotal roles.

In many developing nations, rapid population growth exacerbates these environmental issues. These countries often rely heavily on natural resources for their economic growth, leading to unsustainable practices such as overfishing, overgrazing, and deforestation. For example, as more land is cleared for agriculture to feed a growing population, forests are cut down, resulting in biodiversity loss and higher carbon emissions. Population density and urbanization are also critical in understanding environmental degradation. High population density in urban areas often leads to more pollution, higher waste production, and greater stress on infrastructure. The process of urbanization typically involves transforming natural landscapes into built environments, which can lead to habitat destruction and reduced biodiversity.

Additionally, the concentration of people in cities drives up the demand for energy, mostly sourced from fossil fuels, contributing to air pollution and climate change. However, urbanization can also present opportunities for more efficient resource use and lower environmental impact per person. Cities can achieve economies of scale in areas such as energy distribution, public transportation, and waste management, potentially reducing the environmental footprint per capita, even as the total population grows.

3.3.4 Renewable Energy Consumption (LRE)

Renewable energy is becoming increasingly critical in the global pursuit of sustainable development. As the world grapples with the challenges of climate change, resource depletion, and environmental degradation, renewable energy sources like solar, wind, and hydro offer a promising pathway to a cleaner, more sustainable future. These energy sources are not only abundant and inexhaustible, but they also play a crucial role in reducing greenhouse gas emissions, decreasing pollution, and promoting energy security.

As economies grow, the demand for energy rises. Historically, this demand has been met predominantly by fossil fuels, which are associated with significant environmental impacts, including greenhouse gas emissions, air and water pollution, and ecosystem disruption. However, the integration of renewable energy can decouple economic growth from environmental degradation. This study particularly focusing the renewable energy from sources like solar, wind, and hydro, is increasingly significant in the study of the Environmental Kuznets Curve (EKC).

These energy sources represent a critical shift in how societies power their economies, moving away from fossil fuels and toward more sustainable energy systems. Understanding the role of renewable energy is essential in the EKC framework because it not only offers a pathway to reducing environmental degradation as economies grow but also helps in achieving long-term sustainability.

3.3.5 Government Effectiveness (LEIU)

Government effectiveness plays a central role in determining a country's environmental outcomes, particularly in the implementation and success of climate-related policies. It encompasses the quality of public services, the competence and independence of civil servants, the reliability of infrastructure, the efficiency of bureaucratic processes, and the credibility of a government's commitment to long-term development objectives. Within the context of this study, government effectiveness is essential for understanding how government effectiveness influences the relationship between economic development, energy use, and environmental sustainability.

In environmental governance, effective governments are capable of designing coherent policies, ensuring timely implementation, and enforcing environmental regulations. This includes setting emission standards, monitoring pollution, promoting the use of clean

energy, and coordinating with various stakeholders such as industries, energy producers, and civil society. Strong institutional frameworks help avoid policy reversals, reduce administrative delays, and ensure long-term investment in green infrastructure. When governments are effective, they can support the adoption of renewable energy, enhance energy efficiency, and facilitate a structural shift towards low-carbon economies.

The presence of effective governance is particularly critical in maximising the environmental benefits of renewable energy. Even with an increase in the share of renewable energy in the energy mix, the actual environmental gains depend on the government's ability to manage integration into the grid, provide technical support, and address intermittency issues. Moreover, policy consistency, financial incentives, and regulatory clarity are all necessary for renewable energy to displace fossil fuels. Without effective governance, these benefits may not materialise fully, and the environmental impact of energy consumption may remain high.

From an analytical perspective, including government effectiveness as a variable allows the study to capture institutional factors that often shape the success or failure of environmental policies. This is particularly relevant in the framework of the Environmental Kuznets Curve (EKC), where it is hypothesised that environmental degradation initially rises with economic growth and eventually falls after reaching a certain income level. In countries with stronger institutions, this turning point may occur earlier because such governments are more capable of enforcing environmental standards, investing in clean technologies, and engaging in international cooperation.

In empirical studies, government effectiveness is measured using global indices such as the Economist Intelligence Unit Riskwire and Democracy Index. In this study, the selected measure is derived from the Economist Intelligence Unit, which captures various aspects of administrative capacity and policy effectiveness. It reflects how well governments manage environmental challenges and deliver services related to energy, climate policy, and environmental protection.

Recognising the role of governance improves the explanatory power of the econometric model. It helps explain why countries at similar levels of income and energy consumption may experience different environmental outcomes. For instance, two countries with comparable GDP per capita and renewable energy capacities might show divergent emission patterns due to differences in institutional effectiveness. This variable also provides

the foundation for interaction terms that examine whether the effects of GDP and renewable energy on emissions are influenced by the government effectiveness.

In sum, government effectiveness is not only an important standalone predictor of environmental performance but also a key moderating factor in the broader economic and energy-environment relationship. Including this variable allows for a more accurate and policy-relevant analysis of long-term carbon emissions and the institutional conditions under which sustainable development becomes achievable.

3.3.6 Interaction Terms (LGDP*LEIU) and (LRE*LEIU)

To further explore the conditional role of government effectiveness, this study incorporates two interaction terms: the interaction between GDP per capita and government effectiveness (LGDP*LEIU), and the interaction between renewable energy consumption and government effectiveness (LRE*LEIU). These variables are constructed to assess whether the effects of economic development and renewable energy on CO₂ emissions are influenced by the strength and effectiveness of governance. The inclusion of these terms introduces an important dimension that acknowledges how institutional environments shape the outcomes of economic and environmental policies.

The interaction term LGDP*LEIU captures how the impact of income levels on environmental quality varies depending on the administrative capacity and regulatory performance of the state. In countries with high government effectiveness, rising income is more likely to be accompanied by investments in clean technologies, enforcement of environmental regulations, and the transition toward more sustainable production processes. These countries are also better equipped to integrate environmental concerns into national development strategies, manage pollution control systems, and foster green innovation.

As a result, economic growth in these contexts may lead to a reduction in emissions after a certain income threshold, supporting the Environmental Kuznets Curve hypothesis. Conversely, in countries with low government effectiveness, income growth may exacerbate environmental degradation due to the absence of proper controls, regulatory oversight, and accountability mechanisms. The second interaction term, LRE*LEIU, evaluates whether the environmental effectiveness of renewable energy consumption depends on the government effectiveness. Renewable energy adoption alone may not yield significant emission reductions unless supported by government effectiveness that can ensure proper integration,

operation, and scaling of renewable energy systems. In countries with strong governance, policy frameworks are typically more consistent and long-term, encouraging investment in renewables and ensuring their effective use. These governments can facilitate grid modernisation, enforce renewable energy quotas, manage subsidies transparently, and coordinate efforts across agencies and regions.

On the other hand, in environments with weak governance, renewable energy development may be plagued by mismanagement, poor maintenance, policy inconsistencies, and a lack of enforcement, which diminish the potential environmental benefits. Including these interaction terms strengthens the explanatory capacity of the model by acknowledging that the effects of economic and energy variables do not occur in isolation. Instead, their influence on CO₂ emissions is shaped by the broader institutional context. The interactions help identify whether governance can serve as an enabling factor that enhances the positive environmental impact of income and renewable energy or whether its absence may limit or reverse those effects. This approach offers a more realistic and policy-relevant understanding of the dynamics underlying carbon emissions and the transition to a low-carbon economy. Through these variables, the study contributes to a more refined analysis of the Environmental Kuznets Curve framework.

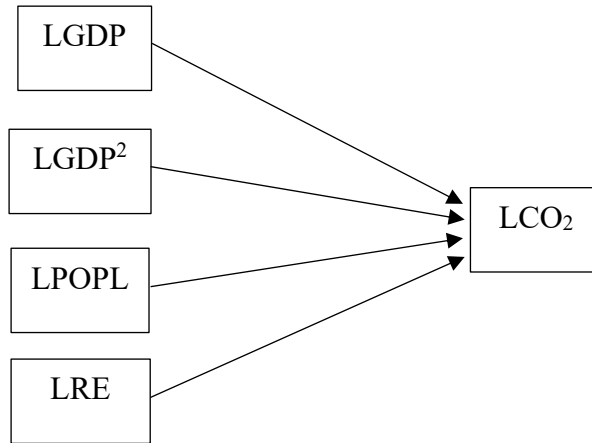
It highlights the importance of institutional capacity in ensuring that economic and technological advances translate into genuine environmental improvements. The results derived from these interaction terms will offer valuable insights into how countries can align governance reforms with climate strategies to achieve more effective and sustainable outcomes. Table 3.1 shows the detailed description for each variable used in this study and also the respective data sources.

Table 3.1:
Description of Variables

Short Form	Variable's description	Data Sources
LCO ₂	CO ₂ Emissions Per Capita (mt)	Our World in Data
LGDP	Gross Domestic Product Per Capita (\$)	World Bank
LGDP ²	Gross Domestic Product Per Capita Square (\$)	World Bank
LPOPL	Population (total)	World Bank
LRE	Renewable Energy Consumption (exajoules)	Our World in Data
LEIU	Government effectiveness (Economist Intelligence Unit Riskwire & Democracy Index)	World Bank
LGDP*LEIU	Interaction: GDP per capita × government effectiveness	Author calculation
LRE*LEIU	Interaction: Renewable energy × government effectiveness	Author calculation

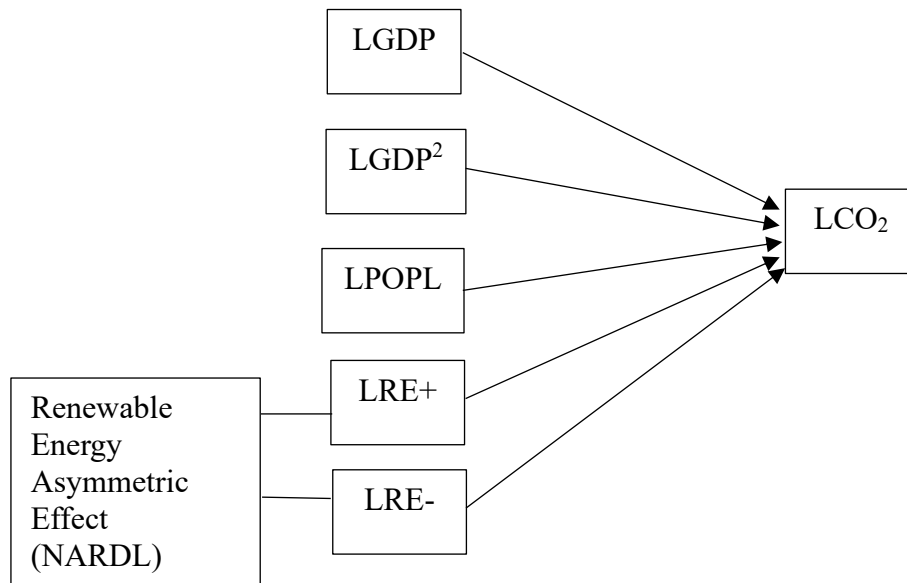
3.3.7 Concept Framework

Figure 3.1:
Model 1 Panel ARDL Approach



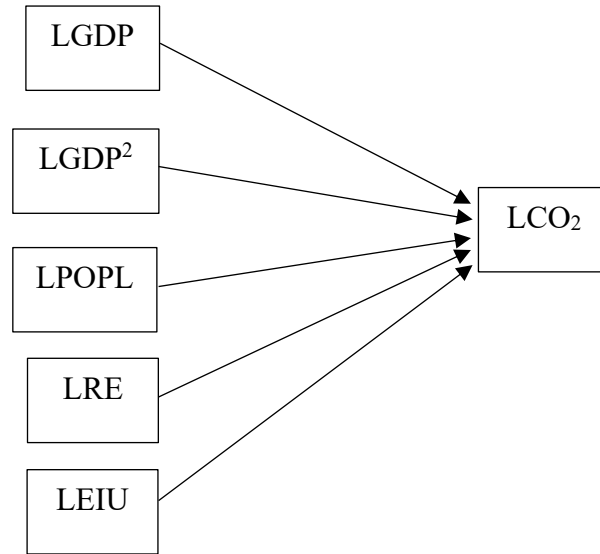
$$LCO_2 = LGDP + LGDP^2 + LPOPL + LRE$$

Figure 3.2:
Model 2 Panel NARDL Approach



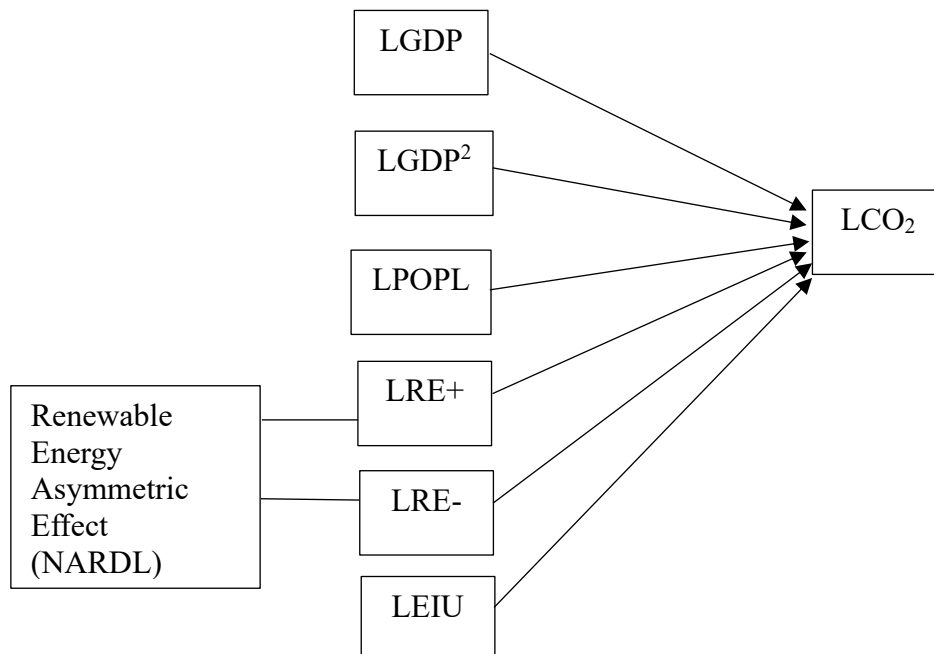
$$LCO_2 = LGDP + LGDP^2 + LPOPL + (LRE+) + (LRE-)$$

Figure 3.3:
Model 3 Panel ARDL Approach



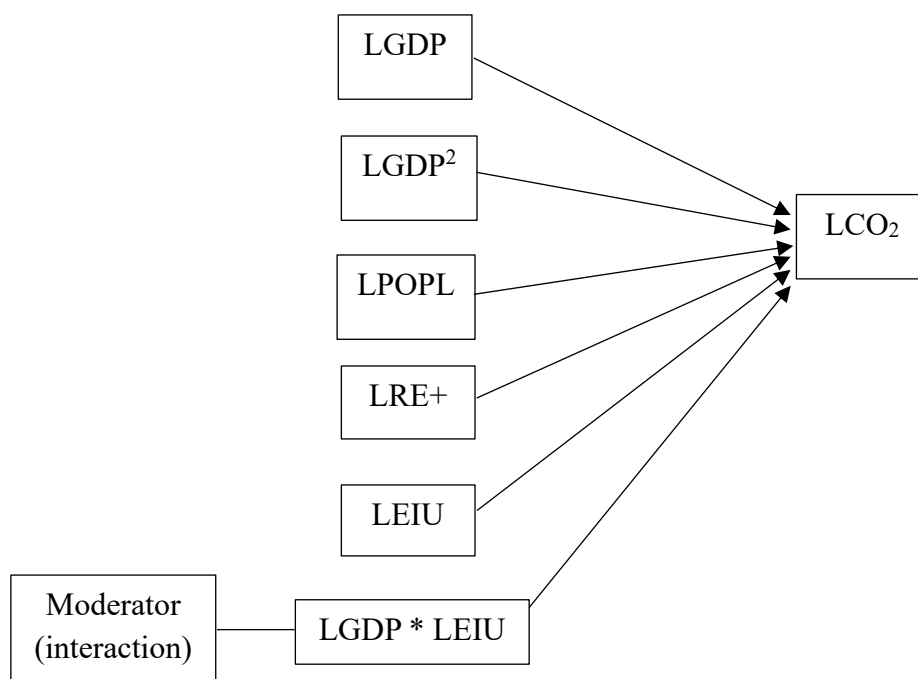
$$LCO_2 = LGDP + LGDP^2 + LPOPL + LRE + LEIU$$

Figure 3.4:
Model 4 Panel NARDL Approach



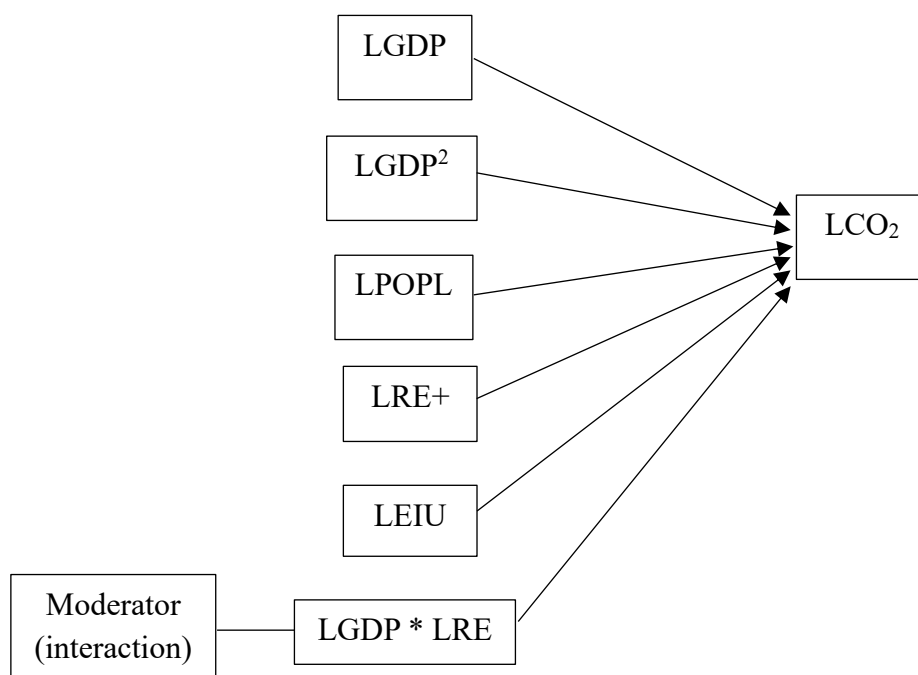
$$LCO_2 = LGDP + LGDP^2 + LPOPL + (LRE+) + (LRE-) + LEIU$$

Figure 3.5:
Model 5 Panel ARDL Approach (moderator LGDP*LEIU)



$$LCO_2 = LGDP + LGDP^2 + LPOPL + LRE + LEIU + (LGDP*LEIU)$$

Figure 3.6:
Model 6 Panel ARDL Approach (moderator LGDP*RE)



$$LCO_2 = LGDP + LGDP^2 + LPOPL + LRE + LEIU + (LGDP*RE)$$

3.4 Panel Data Analysis

Panel analysis is an econometric method that combines time series and cross-sectional data, enabling the examination of variables over time across multiple entities, such as countries or firms. This dual-dimensional approach allows researchers to track how variables evolve both within individual entities and across different entities over a specified period. The principal benefit of panel analysis is its capacity to control for unobserved heterogeneity and variations that are specific to each entity but remain constant over time. By accounting for these entity-specific factors, panel analysis yields more precise and reliable estimates.

In the context of this study, the panel analysis enables to isolate the effects of various energy sources on CO₂ emissions while controlling for factors unique to each country that could influence these relationships. Additionally, panel analysis enhances statistical power and flexibility by pooling data across entities and time periods. This aggregation improves the efficiency of estimates and facilitates a nuanced exploration of both short-term and long-term effects. This is particularly valuable for capturing the intricate dynamics of how changes in energy consumption impact CO₂ emissions over time and across different countries.

3.4.1 Cross-Sectional Dependence Tests

Cross-sectional dependence (CSD) describes a situation in which observations across units such as countries, firms, or regions are interrelated within a panel dataset. When this interdependence exists but is ignored, it may distort test statistics and lead to unreliable conclusions. This issue is particularly common in macroeconomic panels where global shocks, unobserved common factors, or spillover effects often occur (Pesaran, 2004; De Hoyos and Sarafidis, 2006). For this reason, identifying CSD is an essential first step before selecting estimation methods that assume independence across units.

To detect such dependence, several statistical procedures have been developed. A well-known option is the Lagrange Multiplier (LM) test by Breusch and Pagan (1980). This test is appropriate for panels with a small number of cross-sectional units and a relatively long-time dimension. The LM statistics are given by:

$$LM = T \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{p}_{ij}^2 \quad (5)$$

where $\hat{\rho}_{ij}$ represents the estimated pairwise correlation between residuals for units i and j .

However, when the number of cross-sectional units is large compared to the time periods, the LM statistic becomes impractical because it requires calculating a large number of pairwise correlations. To address this, Pesaran (2004) proposed the CD test which is more robust for panels with both large N and large T . The CD statistics are defined as:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij}^2 \quad (6)$$

Under the null hypothesis of cross-sectional independence, this statistic is asymptotically standard normal. Its simplicity and flexibility make it a popular choice in empirical panel studies. In addition, Pesaran (2014) introduced a bias-corrected version of the CD test, often referred to as CD_{LM} . This version improves the test's accuracy for unbalanced panels and models with nonstationary data. It also adjusts for potential biases from residual serial correlation and unobserved common factors.

If the test rejects the null hypothesis of independence, researchers should use estimators that can handle cross-sectional dependence. Suitable choices include the Common Correlated Effects (CCE) estimator by Pesaran (2006), spatial econometric models, or factor-augmented panel approaches. Therefore, checking for cross-sectional dependence is a critical diagnostic step in panel data analysis. It ensures that subsequent estimations are reliable and that the chosen methods properly reflect the characteristics of the data.

3.4.2 Panel data and Pedroni Tests

When working with panel data, it is essential to verify whether the variables move together in the long-run, even if each series on its own may not be stationary. To assess this, the Pedroni cointegration approach is applied. Introduced by Pedroni (1999, 2001), this method builds on classical cointegration ideas but adapts them for panel datasets by accommodating possible differences across countries or units. It allows each cross-section to have its own intercept and trend term, making it well-suited for studies involving multiple economies with varying structural and institutional contexts.

The core purpose of the Pedroni test is to determine whether there is a consistent long-run association among the selected variables. It does so by testing the null hypothesis that no cointegration exists, using a range of statistical measures that capture both the collective behaviour across the panel (within-dimension) and individual unit-specific relationships (between-dimension). Confirming cointegration is a key step to ensure that estimated long-term coefficients are reliable and not the result of spurious correlations. As such, the Pedroni test serves as an important diagnostic before moving on to estimating long-run dynamics and applying further models in this study.

3.4.3 Panel Unit Root Tests

Panel unit root tests are used to assess the stationarity of panel data, which is essential for ensuring valid econometric analysis. Stationarity implies that the statistical properties of a time series, such as its mean and variance, are consistent over time. For accurate modelling and inference, it is crucial to ensure that the variables in a panel dataset are stationary. In this study, panel unit root tests are utilized to check the stationarity of key variables such as CO₂ emissions per capita, GDP per capita, FDI, and energy consumption.

Among the common tests employed are the Lee and Lee (2009) and Im et al. (2003) test, which evaluates whether variables possess unit roots, indicating non-stationarity across the panel. If non-stationarity is detected, necessary transformations, such as differencing or logarithmic transformations, are applied to achieve stationarity. Conducting panel unit root tests is vital for ensuring that the data used in the panel analysis is appropriate for econometric modelling.

First-generation panel unit root tests, such as the Levin, Lin and Chu (LLC), assume cross-sectional independence. The LLC test imposes a common unit root process across all units. The concept of unit root testing originates from time series econometrics, where early developments such as the Dickey and Fuller (DF) test played a central role in determining the stationarity of economic variables. The DF test was designed to evaluate whether a stochastic process follows a random walk, with the null hypothesis indicating the presence of a unit root, implying non-stationarity.

This test was later extended to the Augmented Dickey-Fuller (ADF) test, which incorporates lagged differences of the dependent variable to account for serial correlation in the residuals. The ADF test is commonly specified as equation (7):

$$\Delta y_{it} = \alpha_{it} + \gamma_i y_{it-1} + \sum_{j=0}^p \beta_{ij} \Delta y_{it-j} + \varepsilon_{it} \quad (7)$$

where y_{it} represents the value of the variable for cross-sectional unit i at time t , and $\gamma_i=0$ under the null hypothesis of a unit root.

Complementing this approach, the Phillips-Perron (PP) test offers a non-parametric correction for serial correlation and heteroskedasticity, providing similar conclusions without requiring lagged difference terms. While both ADF and PP tests are widely used in time series analysis, they are not directly applicable in panel data settings, as they do not consider the cross-sectional dimension. To address this, panel unit root tests have been developed by extending the logic of time series tests to datasets that contain both cross-sectional and time series dimensions. In panel data analysis, which typically involves multiple cross-sectional units such as countries or firms observed over several time periods, panel unit root tests improve statistical power by pooling information across units.

3.4.4 Mean Group (MG) and Pooled Mean Group (PMG) Estimation

The MG approach discovered by Pesaran and Smith (1995) and the PMG estimator developed by Pesaran, Shin, and Smith (1999), are suitable methods for capturing both short-run heterogeneity and long-run homogeneity across countries or sectors. In this study, both estimators are utilised to explore the dynamic impact of energy consumption and economic output on CO₂ emissions for the overall economy and individual sectors.

Selecting an appropriate lag length for both MG and PMG models is crucial to ensure robust results. To decide which estimator provides more reliable estimates, the Hausman test is conducted, following Pesaran, Shin, and Smith (1999). The Hausman test determines whether the difference in estimated coefficients between MG, DFE and PMG is statistically significant. If the test result indicates significance, the MG or DFE estimator is preferred because it remains consistent when regressors are correlated with the error term. Conversely, if the test statistic is insignificant, the PMG estimator is favoured for its efficiency under the assumption of long-run homogeneity.

When there is no correlation between the regressors and the error term, the PMG estimator yields consistent estimates, whereas the MG estimator does not. However, if correlation exists, the MG estimator remains consistent while the PMG does not. Under the null hypothesis of no correlation, there should be no systematic difference between the estimators. Therefore, the Hausman test compares the difference in coefficients ($\hat{\beta}^{PMG} - \hat{\beta}^{MG}$) and evaluates its covariance. By construction, the covariance of an efficient estimator with its difference from an inefficient estimator should be zero. The test statistic is then computed in equation (11) as:

$$H = (\hat{\beta}^{PMG} - \hat{\beta}^{MG})' [Var(\hat{\beta}^{PMG} - \hat{\beta}^{MG})]^{-1} (\hat{\beta}^{PMG} - \hat{\beta}^{MG}) \quad (11)$$

A non-significant result suggests that PMG is preferable due to its efficiency, while a significant outcome supports using MG for consistency. The MG model equation (12) is as follows:

$$a_i(Q)y_{it} = b_i(Q)x_{it} + d_i z_{it} + e_{it} \quad (12)$$

Let Q denote output, i represent to the long-run parameter for each sector $i=1,2,\dots, N$ and t indicate the time frame $t = 1,2,\dots,T$. The long-run coefficient for each sector is given by $\theta_i = \frac{bi(1)}{di(1)}$. Then, the mean Group (MG) estimator for the error correction coefficient across the entire panel is calculated as $\theta = \frac{1}{N} \sum_{i=1}^N \hat{\theta}_i$ and the variance estimated by $\hat{\Delta}_{\hat{\theta}} = \frac{1}{N(N-1)} \sum_{i=1}^N (\hat{\theta}_i - \hat{\theta})^2$.

However, Pesaran, Shin, and Smith (1999) integrated multiple datasets and developed the Pooled Mean Group (PMG) estimator. This approach enables the estimation of both short-run and long-run coefficients. As described by Pesaran, Shin, and Smith (1999), the maximum likelihood (ML) method is applied within the PMG framework to estimate the long-run parameter, denoted as θ . The unrestricted ARDL model is specified for time periods $t = 1, 2, \dots, T$. The sectors $i=1, 2, \dots, N$, leading to the following equation (13):

$$y_{it} = \alpha_{it} + \sum_{j=1}^m \beta_{ij} y_{it-j} + \sum_{j=0}^n \lambda_{ij} x_{it-j} + \mu_{it} + \varepsilon_{it} \quad (13)$$

where x_{ij} denotes the vector of explanatory variables, which has dimensions, $(k \times 1)$ for group i and μ_i refers to fixed effects. The parameters for the Vector Error Correction Model (VECM) are defined as follows equation (14):

$$\Delta y_{it} = \theta_i (y_{it-1} - \lambda_i x_{it-1}) + \sum_{j=1}^{m-1} \gamma_{it} \Delta y_{it-j} + \sum_{j=1}^{n-1} \lambda_{ij} x_{it-j} + \sum_{j=1}^{p-1} \delta_{it} z_{it-j} + \mu_{it} + \varepsilon_{it} \quad (14)$$

In this context, λ_i denotes the long-run parameter, while Δy_{it} represent the short-run coefficient vectors. The term y_{it} indicates the dependent variables, which include $\ln Q$ and $\ln CO_2$. The expression x_{it-j} corresponds to the vector of non-stationary variables, whereas z_{it-j} denotes the stationary variables. The parameter μ captures the fixed effects, ε is the error term, and θ_i is the error correction coefficient. The PMG estimation approach is constructed within the framework of the Vector Error Correction Model (VECM).

3.4.5 Autoregressive Distributed Lag Model (ARDL)

The Autoregressive Distributed Lag (ARDL) model is an econometric technique widely utilised in the analysis of dynamic relationships between time series variables. It is particularly well-suited for scenarios where the variables under consideration exhibit different orders of integration, allowing researchers to explore both short-term and long-term interactions. The ARDL approach, initially introduced by Pesaran and Shin (1995), has gained popularity due to its flexibility, especially when dealing with small sample sizes and mixed integration orders among the variables.

According to Pesaran and Shin (1996, 2001) and further extended by Pesaran et al. (1999), the primary advantage of the panel ARDL model lies in its ability to accommodate variables that are integrated of different orders, such as $I(0)$ and $I(1)$, without requiring pre-testing for unit roots. This flexibility is particularly important in panel datasets where variables often exhibit mixed integration properties across countries. Unlike traditional time series approaches, which focus on a single country, the panel ARDL framework enables the analysis of both short-run and long-run dynamics across multiple cross-sectional units while accounting for heterogeneity in slope coefficients.

The model also addresses some of the limitations of conventional panel cointegration methods, such as Pedroni or Kao, which assume homogeneous long-run relationships and may not adequately reflect country-specific differences. By employing estimators such as the Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE), the panel ARDL approach allows for flexibility in capturing both common long-run relationships and heterogeneous short-run adjustments across countries. This feature makes

it particularly suitable for this study, which investigates the top ten CO₂-emitting countries with diverse economic structures, energy mixes, and governance capacities.

Therefore, the use of panel ARDL in this study ensures that the empirical analysis is consistent with the characteristics of the data, robust to mixed integration orders, and capable of capturing both homogeneity and heterogeneity in the dynamic relationships under study. The application of the ARDL model in empirical research, particularly in the context of environmental economics, offers valuable insights into the dynamics of economic growth and environmental sustainability. For instance, when investigating the Environmental Kuznets Curve (EKC) hypothesis, which postulates an inverted U-shaped relationship between environmental degradation and economic growth, the ARDL model enables researchers to explore both the short-term and long-term effects of economic growth on CO₂ emissions.

In the short-run, an increase in GDP might lead to higher CO₂ emissions due to the expansion of industrial activities and energy consumption. However, in the long-run, as a country becomes wealthier, investments in cleaner technologies, stricter environmental regulations, and a shift towards renewable energy sources might result in a reduction of emissions. The ARDL model allows researchers to identify this turning point and quantify the change, offering a more comprehensive understanding of the EKC hypothesis.

3.4.6 Nonlinear Autoregressive Distributed Lag Model (NARDL)

The NARDL model is especially useful in situations where the response of the dependent variable to increases in an explanatory variable differs from its response to decreases (Shin et al., 2014). Traditional linear models, such as the standard ARDL, assume that the impact of changes is symmetric, meaning that the effects of positive and negative changes are mirror images of each other. However, in many real-world scenarios, this assumption does not hold.

For instance, in studies examining the impact of economic growth on environmental sustainability, it is plausible that the effects of economic expansion on environmental degradation might differ from those of economic contraction. Economic growth might lead to higher CO₂ emissions due to increased industrial activity, but economic downturns might not result in proportionate decreases in emissions, especially if industries are slow to scale

down production or if governments implement stimulus measures that prioritize economic recovery over environmental concerns.

By employing the NARDL model, researchers can gain a more comprehensive understanding of these asymmetric dynamics. For example, the NARDL model can reveal whether positive changes in GDP (economic growth) have a larger or smaller impact on CO₂ emissions compared to negative changes (economic contraction). This insight is critical for formulating effective environmental policies, as it highlights the potential for different strategies to be required during periods of economic expansion versus contraction. This feature is particularly useful for policymakers who need to understand the pace of economic adjustment in response to both positive and negative economic shocks.

3.4.7 Justification for Using the NARDL Model

The selection of the Nonlinear Autoregressive Distributed Lag (NARDL) model in this study is grounded in both the nature of the theories applied and the characteristics of the key variables under investigation. Conventional symmetric econometric specifications can provide broad insights, but they often impose restrictive assumptions that fail to capture the complexity of environmental, economic, and institutional dynamics. Since this study is framed within the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT model, the choice of NARDL is not only methodologically appropriate but also theoretically consistent.

The EKC hypothesis is inherently non-linear, postulating an inverted U-shaped relationship between income and emissions. At early stages of growth, economic expansion intensifies environmental degradation, while at higher income levels, cleaner technologies, structural transformation, and stronger regulations are expected to reduce emissions. This theoretical structure implies turning points and asymmetric responses because the effect of rising income is not the same as the effect of declining or stabilising income. A linear ARDL model may fail to capture this theoretical complexity, while NARDL is specifically designed to test and estimate such asymmetries.

The STIRPAT framework conceptualises environmental pressure as a stochastic function of population, affluence, and technology. Within this model, renewable energy serves as a proxy for technological progress, but its effects are unlikely to be symmetric.

Increases in renewable energy adoption may lead to gradual and sustained reductions in emissions, while reductions in renewable energy usage may generate sharper environmental deterioration due to reliance on fossil fuels and infrastructure lock-in. Similarly, population dynamics may produce non-linear effects, with urbanisation and demographic transitions amplifying or moderating the scale of emissions differently at various stages. These theoretical expectations justify the use of NARDL to test for non-linear and asymmetric impacts.

From an econometric perspective, NARDL provides methodological advantages that align with the theoretical requirements of EKC and STIRPAT. The model can handle regressors integrated of mixed orders $I(0)$ and $I(1)$, which is suitable for environmental and economic data where unit root properties vary across variables. Moreover, it estimates both short-run and long-run asymmetric effects within a single framework, thereby capturing dynamic adjustment processes consistent with the non-linearities implied by EKC and STIRPAT.

The adoption of NARDL also positions this study within the latest methodological developments in environmental economics. Recent literature increasingly recognises the importance of capturing asymmetry and non-linearity when testing environmental hypotheses (Bekun et al., 2024; Odei et al., 2025; Su et al., 2025). By employing NARDL, this study ensures that the empirical strategy is not only robust but also fully consistent with the theoretical foundations of the EKC and STIRPAT models.

In this study, Models 2 and 4 are estimated using NARDL to capture these asymmetric dynamics. However, for Models 5 and 6, which incorporate moderator effects through the interaction of governance effectiveness with income and renewable energy, the study did not obtain statistically significant results for the symmetry tests. This suggests that while asymmetry is evident in the base models, the moderating role of governance may not operate through asymmetric effect, highlighting the complexity of institutional effects in shaping environmental outcomes.

In summary, the justification for using NARDL arises directly from the theoretical character of the EKC and STIRPAT models, which both imply non-linear and asymmetric environmental dynamics. Alongside the asymmetric behaviour of renewable energy, economic growth, and governance effectiveness, the NARDL approach provides the most

appropriate and theoretically consistent method for analysing the determinants of CO₂ emissions in the top ten emitting countries.

3.4.8 Error Correction Term (ECT)

The Error Correction Term (ECT) is essential for describing how short-term variations are reconciled with the underlying long-run equilibrium. Once a cointegration test confirms that a stable long-run association exists among the variables, the ECT is constructed and integrated into the error correction model (ECM) structure. The ECT coefficient quantifies how much of the imbalance from the previous period is adjusted in the current period, helping the system return towards its equilibrium path.

A negative and significant ECT coefficient demonstrates that the model effectively captures this self-correcting behaviour, meaning that any short-run shocks are gradually absorbed as the dependent variable adjusts to restore balance. In this study, the ECT connects short-run dynamics with the established long-run relationship, adding depth and reliability to the interpretation of the results. The error correction representation for the panel ARDL model applied in this study is specified equation (15) as:

$$\Delta Y_{it} = \beta_i + \gamma ECT_{it-1} + \sum_{i=1}^p \gamma_{1i} \Delta Z_{it-i} + \varepsilon_{it} \quad (15)$$

Where ΔY_{it} denotes the change in the dependent variable for unit i at time t , then ECT_{it-1} represents the lagged error correction term, which measures the extent of deviation from the long-run equilibrium. ΔZ_{it-i} stands for the lagged first differences of the explanatory variables, β_i captures the individual-specific effects, and ε_{it} is the stochastic error term. The ECT is derived as the residual from the estimated long-run relationship as equation (16):

$$\Delta Y_{it} = \beta_i + \sum_{k=1}^k \gamma_1 Z_{kit-i} + \varepsilon_{it} \quad (16)$$

Where Y_{it} is the level of the dependent variable and Z_{kit-i} are the explanatory variables in levels. This framework allows the model to describe how short-run adjustments

interact with the long-run equilibrium, ensuring that any temporary shocks are gradually corrected over time.

3.5 Model Specification

The study examines the impact of renewable energy consumption on CO₂ emissions in a panel of 10 countries. Using annual data from 1996 to 2023 (28 years), the analysis investigates the relationship between renewable energy and environmental degradation, focusing on how renewable energy consumption influences CO₂ emissions per capita.

3.5.1 Model 1: Baseline Model Using Aggregate Renewable Energy

This model is developed to examine the long-run relationship between carbon dioxide emissions per capita and key explanatory variables, which include gross domestic product per capita, the square of GDP per capita, total population, and aggregate renewable energy consumption. The empirical investigation utilises panel data and applies the Autoregressive Distributed Lag (ARDL) approach as introduced by Pesaran et al. (2001).

This approach is suitable for estimating both long-run and short-run dynamics using variables that are integrated of order I(0) and I(1), without requiring that all variables be stationary at the same level. The main objective of this model is to identify whether a cointegrating relationship exists among the variables, particularly focusing on the long-run effects. All data series are transformed into their natural logarithmic form to standardise their distribution, reduce heteroscedasticity, and enable the interpretation of coefficients in terms of elasticities. The ARDL Model 1 specification is presented below equation (17):

$$\begin{aligned} \Delta LCO_2 = & \beta_{0i} + \gamma ECT_{it-1} + \beta_1 LCO_{2\ it-1} + \beta_2 LGDP_{it-1} + \beta_3 LGDP^2_{it-1} \\ & + \beta_4 LPOPL_{it-1} + \beta_5 LRE_{it-1} + \sum_{i=1}^p \gamma_{1i} \Delta LCO_{2\ it-i} + \sum_{i=0}^q \gamma_{2i} \Delta LGDP_{it-i} \\ & + \sum_{i=0}^r \gamma_{3i} \Delta LGDP^2_{it-i} + \sum_{i=0}^s \gamma_{4i} \Delta LPOPL_{it-i} + \sum_{i=0}^k \gamma_{5i} \Delta LRE_{it-i} \\ & + \varepsilon_{it} \quad (17) \end{aligned}$$

In this equation all variables are in log form, LCO₂ refers to carbon dioxide emissions per capita measured in metric tonnes, LGDP represents gross domestic product per capita in

US dollars, and LGDP² is included to capture potential non-linear effects based on the Environmental Kuznets Curve (EKC) hypothesis. The variable LPOP denotes total population, and RE represents the total consumption of renewable energy measured in exajoules. The error term ε_{it} captures the unobserved factors affecting emissions. The coefficients $\beta_0 - \beta_6$ measure the long-run relationships, while the summation terms with coefficients $\gamma_{1i} - \gamma_{5i}$ account for the short-run dynamics of the system.

Model 1 acts as the baseline specification from which further disaggregated models are developed. In subsequent models, the aggregate renewable energy variable is replaced by individual renewable energy sources, namely solar, wind, and hydro energy consumption. This disaggregation enables the study to assess the differentiated impacts of each renewable energy type on carbon emissions. As such, Model 1 provides the foundation for understanding the broader dynamics between macroeconomic activity, population, and renewable energy use in relation to environmental sustainability.

3.5.2 Model 2: Asymmetric Impact of Renewable Energy on CO₂ Emissions

Following the baseline specification in Model 1, Model 2 extends the analysis by allowing for potential asymmetries in the impact of renewable energy consumption on carbon dioxide emissions. The central motivation of this model is to explore whether increases and decreases in renewable energy usage have different effects on environmental outcomes. To capture this possibility, the model employs a Nonlinear Autoregressive Distributed Lag (NARDL) approach, which distinguishes between the positive and negative changes in renewable energy consumption.

The nonlinear ARDL is an extension to the ARDL technique where Granger and Yoon (2002) develop the concept of “hidden cointegration,” wherein cointegrating relationships between the positive and negative components of the underlying variables can be identified (Shin et al., 2014). Shin et al. (2014) approach will be used to decompose variables as electricity power consumption with positive and negative shocks. The variables are as follows in equations (18 & 19):

$$RE^+ = \sum_{i=1}^t \Delta RE^+_i = \sum_{i=1}^t \max(\Delta RE^+_i, 0) \quad (18)$$

$$RE^- = \sum_{i=1}^t \Delta RE^-_i = \sum_{i=1}^t \min(\Delta RE^-_i, 0) \quad (19)$$

All variables are expressed in natural logarithmic form to ensure scale consistency and elasticity-based interpretation, and the model is estimated using annual panel data. The focus of this model remains on identifying long-run cointegration relationships, in line with the objective of assessing how renewable energy consumption influences CO₂ emissions differently when it rises versus when it falls. The asymmetric ARDL Model 2 is specified as follows in equation (20):

$$\begin{aligned} \Delta LCO_2 = & \beta_{0i} + \gamma ECT_{it-1} + \beta_1 LCO_{2\ it-1} + \beta_2 LGDP_{it-1} + \beta_3 LGDP^2_{it-1} + \beta_4 LPOPL_{it-1} \\ & + \beta_5 LRE^+_{it-1} + \beta_6 LRE^-_{it-1} + \sum_{i=1}^p \gamma_{1i} \Delta LCO_{2\ it-i} + \sum_{i=0}^q \gamma_{2i} \Delta LGDP_{it-i} \\ & + \sum_{i=0}^r \gamma_{3i} \Delta LGDP^2_{it-i} + \sum_{i=0}^s \gamma_{4i} \Delta LPOPL_{it-i} + \sum_{i=0}^k \gamma_{5i} \Delta RE^+_{it-1} \\ & + \sum_{i=0}^l \gamma_{6i} \Delta RE^-_{it-1} + \varepsilon_{it} \end{aligned} \quad (20)$$

In this model, renewable energy is disaggregated into two separate partial sum processes: RE⁺ and RE⁻, which represent the positive and negative changes in renewable energy consumption over time. This structure allows the estimation to capture whether an increase in renewable energy use leads to a greater or lesser reduction in emissions compared to an equivalent decrease.

By identifying these asymmetric effects, Model 2 provides a more nuanced understanding of the role of renewable energy in emissions reduction, which may be relevant for designing policies that encourage consistent investment and usage in renewable energy sectors. It also offers a robust check to the symmetric structure assumed in Model 1.

3.5.3 Model 3: The Role of Government Effectiveness in the Renewable Energy

In this model, the analysis is extended by incorporating government effectiveness as an institutional determinant that may influence the relationship between renewable energy consumption and carbon dioxide emissions. The variable for government effectiveness,

denoted as LEIU, is sourced from the Economist Intelligence Unit's Riskwire and Democracy Index. It reflects the government effectiveness, policy implementation capacity, and the effectiveness of public institutions in managing development and environmental challenges. By including this variable, Model 3 seeks to explore whether stronger governance frameworks can enhance the environmental benefits of renewable energy deployment.

The empirical strategy adopts the ARDL approach with panel data, focusing on both long-run equilibrium and short-run dynamics. As in previous models, all series are transformed into their natural logarithmic forms to normalise distribution, reduce heteroscedasticity, and interpret coefficients as elasticities. The primary aim is to examine how macroeconomic indicators, renewable energy use, and government effectiveness interact in determining per capita carbon emissions. The Model 3 is specified as follows in equation (21):

$$\begin{aligned}
\Delta LCO_2 = & \beta_{0i} + \gamma ECT_{it-1} + \beta_1 LCO_{2\ it-1} + \beta_2 LGDP_{it-1} + \beta_3 LGDP^2_{it-1} + \beta_4 LPOPL_{it-1} \\
& + \beta_5 LRE_{it-1} + \beta_6 LEIU_{it-1} + \sum_{i=1}^p \gamma_{1i} \Delta LCO_{2\ it-i} + \sum_{i=0}^q \gamma_{2i} \Delta LGDP_{it-i} \\
& + \sum_{i=0}^r \gamma_{3i} \Delta LGDP^2_{it-i} + \sum_{i=0}^s \gamma_{4i} \Delta LPOPL_{it-i} + \sum_{i=0}^k \gamma_{5i} \Delta LRE_{it-i} \\
& + \sum_{i=0}^l \gamma_{6i} \Delta LEIU_{it-i} + \varepsilon_{it} \quad (21)
\end{aligned}$$

The inclusion of LEIU recognises the importance of governance in shaping environmental outcomes. An effective government can implement and enforce policies that promote renewable energy development, ensure regulatory compliance, and coordinate intersectoral planning. In contrast, weak governance may limit the efficiency of policy instruments, reduce investor confidence in clean energy, and hinder environmental progress. Therefore, this model examines whether higher levels of government effectiveness moderate the impact of renewable energy on CO₂ emissions, potentially strengthening its mitigating effect. Thus, Model 3 offers a broader perspective by integrating government effectiveness into the empirical framework, contributing to a better understanding of how renewable energy and governance jointly influence environmental sustainability.

3.5.4 Model 4: Asymmetric of Renewable Energy and Government Effectiveness

Model 4 extends the previous specifications by simultaneously incorporating asymmetric effects of renewable energy consumption and government effectiveness (LEIU) into the emissions model. This formulation is intended to capture the differentiated impact of increases and decreases in renewable energy use on carbon dioxide emissions, while also accounting for the role of government effectiveness. Government effectiveness is measured through the Economist Intelligence Unit's Riskwire and Democracy Index, reflects the capacity of public institutions to implement environmental policies, regulate the energy market, and support the adoption of renewable technologies.

This model employs the Nonlinear Autoregressive Distributed Lag (NARDL) approach to evaluate whether the relationship between renewable energy and emissions behaves asymmetrically, depending on the direction of change. All variables are expressed in natural logarithmic form to facilitate interpretation in terms of elasticity, reduce heteroscedasticity, and normalise skewed data distributions. The analysis continues to focus on long-run equilibrium relationships while also capturing short-run dynamics. The functional form of Model 4 is specified as follows in equation (22):

$$\begin{aligned}
\Delta LCO_2 = & \beta_{0i} + \gamma ECT_{it-1} + \beta_1 LCO_{2\ it-1} + \beta_2 LGDP_{it-1} + \beta_3 LGDP^2_{it-1} \\
& + \beta_4 LPOPL_{it-1} + \beta_5 LEIU_{it-1} + \beta_6 LRE^+_{it-1} + \beta_7 LRE^-_{it-1} \\
& + \sum_{i=1}^p \gamma_{1i} \Delta LCO_{2\ it-i} + \sum_{i=0}^q \gamma_{2i} \Delta LGDP_{it-i} + \sum_{i=0}^r \gamma_{3i} \Delta LGDP^2_{it-i} \\
& + \sum_{i=0}^s \gamma_{4i} \Delta LPOPL_{it-i} + \sum_{i=0}^k \gamma_{5i} \Delta LEIU_{it-i} + \sum_{i=0}^l \gamma_{6i} \Delta RE^+_{it-1} \\
& + \sum_{i=0}^m \gamma_{7i} \Delta RE^-_{it-1} + \varepsilon_{it}
\end{aligned} \tag{22}$$

Model 4 captures a more realistic scenario in which renewable energy impacts on emissions are not necessarily symmetric. For instance, a rise in renewable energy adoption may result in a more substantial reduction in emissions compared to the increase in emissions resulting from a decline in renewable usage. Additionally, the inclusion of government effectiveness serves to assess whether the institutional context enhances or mitigates these asymmetric effects. A country with higher governance capacity may be more successful in

translating renewable energy investment into environmental benefits due to better regulation, enforcement, and policy support.

This model thus offers a more comprehensive understanding of how renewable energy dynamics, when examined alongside government effectiveness, can influence the trajectory of CO₂ emissions. It helps identify whether policy interventions must account for asymmetries and institutional readiness when designing sustainable energy transitions.

3.5.5 Model 5: Interaction of Economic Growth and Government Effectiveness

Model 5 expands the empirical framework by introducing an interaction term between GDP per capita and government effectiveness, denoted as LGDP*LEIU. This interaction variable is calculated by the author and represents the joint effect of economic performance and government effectiveness on environmental outcomes. The aim of this model is to assess whether the environmental impact of economic growth is conditioned by the level of governance effectiveness.

In particular, the inclusion of LGDP*LEIU makes it possible to determine whether countries with stronger government experience less environmental degradation from economic expansion, compared to those with weaker institutional capacity. As with the earlier models, the estimation adopts the Autoregressive Distributed Lag (ARDL) approach using panel data, allowing for a mix of I(0) and I(1) variables and focusing on the identification of long-run cointegration relationships. All variables are expressed in their natural logarithmic forms to account for scale effects, stabilise variances, and interpret the estimated coefficients as elasticities. The functional form of Model 5 is specified as follows in equation (23):

$$\begin{aligned}
\Delta LCO_2 = & \beta_{0i} + \gamma ECT_{it-1} + \beta_1 LCO_{2it-1} + \beta_2 LGDP_{it-1} + \beta_3 LGDP^2_{it-1} \\
& + \beta_4 LPOPL_{it-1} + \beta_5 LRE_{it-1} + \beta_6 LEIU_{it-1} + \beta_7 LGDPEIU_{it-1} \\
& + \sum_{i=1}^p \gamma_{1i} \Delta LCO_{2it-i} + \sum_{i=0}^q \gamma_{2i} \Delta LGDP_{it-i} + \sum_{i=0}^r \gamma_{3i} \Delta LGDP^2_{it-i} \\
& + \sum_{i=0}^s \gamma_{4i} \Delta LPOPL_{it-i} + \sum_{i=0}^k \gamma_{5i} \Delta LRE_{it-i} + \sum_{i=0}^l \gamma_{6i} \Delta LEIU_{it-i} \\
& + \sum_{i=0}^m \gamma_{7i} \Delta LGDP * LEIU_{it-i} + \varepsilon_{it}
\end{aligned} \tag{23}$$

The interaction term $LGDP*LEIU$ is expected to provide insights into how institutional effectiveness influences the growth–emissions nexus. In countries with high governance scores, economic growth may be associated with cleaner technologies, more efficient public infrastructure, and stricter environmental regulations, all of which could mitigate carbon emissions. Conversely, in settings with weaker institutions, growth may exacerbate environmental degradation due to inadequate enforcement and policy fragmentation. Model 5 therefore contributes to a more nuanced understanding of how economic and institutional factors jointly shape environmental performance. It also serves to inform policymakers that economic growth alone is not sufficient for environmental improvement unless accompanied by effective governance structures.

3.5.6 Model 6: Interaction of Renewable Energy and Government Effectiveness

Model 6 further extends the empirical investigation by incorporating an interaction term between renewable energy consumption and government effectiveness, denoted as $LRE*LEIU$. This variable, calculated by the author, reflects the combined effect of clean energy usage and government effectiveness on carbon dioxide emissions per capita. The rationale behind including this interaction term is to assess whether the environmental effectiveness of renewable energy is enhanced or diminished depending on the strength of governance. In other words, the model aims to identify whether countries with higher government effectiveness are more capable of translating renewable energy investments into measurable reductions in emissions.

The model is estimated using the ARDL framework with annual panel data. The analysis continues to focus on long-run cointegration, supported by short-run dynamics. All variables are transformed into natural logarithmic form to stabilise variance, correct for skewness, and allow for elasticity-based interpretations. The functional form of Model 6 is specified as follows in equation (24):

$$\begin{aligned}
\Delta LCO_2 = & \beta_{0i} + \gamma ECT_{it-1} + \beta_1 LCO_{2\ it-1} + \beta_2 LGDP_{it-1} + \beta_3 LGDP^2_{it-1} \\
& + \beta_4 LPOPL_{it-1} + \beta_5 LRE_{it-1} + \beta_6 LEIU_{it-1} + \beta_7 LREEIU_{it-1} \\
& + \sum_{i=1}^p \gamma_{1i} \Delta LCO_{2\ it-i} + \sum_{i=0}^q \gamma_{2i} \Delta LGDP_{it-i} + \sum_{i=0}^r \gamma_{3i} \Delta LGDP^2_{it-i} \\
& + \sum_{i=0}^s \gamma_{4i} \Delta LPOPL_{it-i} + \sum_{i=0}^k \gamma_{5i} \Delta LRE_{it-i} + \sum_{i=0}^l \gamma_{6i} \Delta LEIU_{it-i} \\
& + \sum_{i=0}^m \gamma_{7i} \Delta LRE * LEIU_{it-i} + \varepsilon_{it}
\end{aligned} \tag{24}$$

This model captures the notion that the presence of strong governments may amplify the positive environmental effects of renewable energy, by enabling better regulation, infrastructure support, and enforcement mechanisms. Conversely, in countries with weaker governance, even high levels of renewable energy deployment may not effectively reduce emissions due to implementation inefficiencies or policy misalignment. Model 6 thus completes the series of empirical models by combining clean energy policy and government effectiveness into a unified analytical framework. It provides important insights for policymakers regarding the institutional prerequisites for ensuring that renewable energy investments lead to genuine environmental improvements.

3.6 A Remark

This chapter has outlined the methodological framework designed to investigate the complex dynamics between economic growth, energy consumption, and environmental sustainability in ten high-emission countries over the period 1996–2023. The study is theoretically grounded in the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT model, both of which provide complementary perspectives on the drivers of carbon dioxide (CO₂) emissions. By integrating these frameworks, the research is equipped

to capture non-linear, structural, and institutional factors influencing environmental degradation.

The empirical strategy adopts a panel data approach, enabling simultaneous consideration of cross-country variations and temporal trends. A series of econometric models, including both linear and non-linear Autoregressive Distributed Lag (ARDL and NARDL) specifications, are applied to capture both short- and long-run relationships. The variable selection reflects both theoretical relevance and empirical rigour. Core variables include GDP per capita, its squared term, population, and renewable energy consumption. Government effectiveness is introduced to reflect government effectiveness, with interaction terms between governance and both economic development ($LGDP*LEIU$) and renewable energy ($LRE*LEIU$) enriching the analysis by accounting for conditional effects.

Six model specifications are constructed to incrementally address the study's research objectives. The models not only test the EKC hypothesis but also examine the asymmetric impact of renewable energy, the role of government effectiveness, and how government effectiveness moderates the influence of economic and energy variables on CO₂ emissions. This layered modelling approach enhances the study's capacity to generate policy-relevant insights. In sum, this chapter provides a methodologically foundation for the empirical analysis in the next chapter

FINDINGS AND DISCUSSIONS

4.1 Introduction

This chapter presents the empirical results of the panel econometric analysis conducted to examine the relationship between carbon dioxide (CO₂) emissions and key explanatory variables, including economic growth, population, renewable energy consumption, and government effectiveness, across ten of the world's highest carbon-emitting countries. The analysis is based on the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT model, which together provide a theoretical basis for understanding the influence of economic and structural factors on environmental outcomes.

The findings are organised into six models. Models 1 and 2 assess the EKC hypothesis using linear and non-linear autoregressive distributed lag (ARDL and NARDL) models, with Model 2 specifically testing for asymmetries in the effects of renewable energy consumption. Models 3 and 4 incorporate government effectiveness to explore whether government effectiveness influences the relationship between economic development and environmental performance. Models 5 and 6 extend this analysis by including interaction terms between government effectiveness and income, as well as between government effectiveness and renewable energy consumption, in order to identify moderating effects.

Prior to presenting estimation results, several diagnostic procedures were performed. Section 4.2 presents descriptive statistics that summarise the distributional characteristics, variability, and statistical properties of the variables used. Section 4.3 reports the results of panel unit root tests, confirming that all variables are either stationary at level or become stationary after first differencing, thus meeting the integration requirements for the ARDL and NARDL frameworks. Section 4.4 outlines the outcomes of cross-sectional dependence tests, which support the assumption of cross-sectional independence and validate the

application of first-generation estimators. Section 4.5 presents the results of the Pedroni cointegration tests, providing robust evidence of long-run equilibrium relationships among the variables across all model specifications.

The estimation results for Models 1 through 6. Each model is estimated using three alternative techniques: the Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE) estimators. The Hausman test guides the selection of the appropriate estimator, with the PMG approach generally preferred due to its capacity to accommodate short-run heterogeneity while imposing long-run homogeneity. The empirical findings reveal several key patterns: confirmation of the Environmental Kuznets Curve (EKC) hypothesis in multiple models, a persistent positive relationship between population and carbon emissions, asymmetric effects of renewable energy consumption on environmental outcomes, and the conditional role of government effectiveness in moderating these relationships.

4.1.1 Descriptive Introduction

Table 4.1 provides the summary statistics for the variables employed in the empirical analysis. All variables are expressed in natural logarithmic form to reduce skewness, ensure comparability, and allow interpretation in terms of elasticities. The variables include carbon dioxide emissions per capita (LCO_2), GDP per capita ($LGDP$), GDP per capita squared ($LGDP^2$), population ($LPOPL$), renewable energy consumption (LRE), government effectiveness ($LEIU$), and two interaction terms: $LRE*LEIU$ (renewable energy $\times$ government effectiveness) and $LGDP*LEIU$ (GDP per capita $\times$ government effectiveness).

Table 4.1:
Descriptive Statistics

	LCO_2	$LGDP$	$LGDP^2$	$LPOPL$	LRE	$LEIU$	$LRE*LEIU$	$LGDP*LEIU$
Mean	0.8529	5.8954	36.5289	8.2198	2.1183	-0.3886	-0.7309	-2.3800
Med.	0.9889	5.2670	27.7759	8.1310	2.4781	-0.4260	-0.5087	-2.1312
Max.	1.3518	8.2634	68.2839	9.1578	3.8846	0.0000	1.6673	0.0000
Min.	-0.0754	4.0594	16.4787	7.1409	-2.7694	-1.2041	-3.2615	-7.4207
Std. Dev.	0.3857	1.3338	16.5765	0.5416	1.1253	0.2509	0.6824	1.7451
Skew.	-0.9062	0.4555	0.5944	0.3412	-1.5356	-0.3005	-0.1915	-0.6733
Kurt.	2.7030	1.6327	1.8162	2.2877	6.0585	2.5646	4.3084	2.7879
Jarque-Bera	39.3482	31.4912	32.8340	11.3520	219.177	6.4262	21.6839	21.6816
Prob.	0.0000	0.0000	0.0000	0.0034	0.0000	0.0402	0.0000	0.0000

The dependent variable, LCO_2 , has a mean of 0.8529, with values ranging from -0.0754 to 1.3518 and a standard deviation of 0.3857. The distribution is left-skewed (-0.9062), and the Jarque-Bera test confirms non-normality ($p = 0.0000$), reflecting considerable variation in per capita carbon emissions across the sample. LGDP, a proxy for income level, has a mean of 5.8954 and shows moderate dispersion (standard deviation = 1.3338). Its squared term ($LGDP^2$) has a much wider spread (standard deviation = 16.5765), with a mean of 36.5289. The positive skew and non-normality (Jarque-Bera $p < 0.01$) reinforce the appropriateness of testing a non-linear Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted-U shaped relationship between income and environmental degradation.

LPOPL (log of population) displays a relatively balanced distribution, with a mean of 8.2198, low standard deviation (0.5416), and only mild skewness (0.3412). However, the Jarque-Bera test ($p = 0.0034$) still indicates a statistically significant deviation from normality. LRE (log of renewable energy consumption) reveals considerable heterogeneity, with values spanning from -2.7694 to 3.8846. The mean of 2.1183 and negative skewness (-1.5356) suggest that the majority of observations fall at the lower end of the renewable energy spectrum. High kurtosis (6.0585) implies the presence of extreme values, likely countries with disproportionately high adoption of renewables.

LEIU, representing government effectiveness as sourced from World bank data, the Economist Intelligence Unit (EIU) Riskwire and Democracy Index, has a mean of -0.3886 and values ranging from -1.2041 to 0.0000. This distribution, though only slightly skewed (-0.3005), confirms that a large portion of the sample comprises countries with weaker institutional performance. The Jarque-Bera test is marginally significant ($p = 0.0402$), indicating modest departure from normality.

$LRE*LEIU$, the interaction between renewable energy consumption and government effectiveness, captures the joint impact of energy policy and government effectiveness. The mean of -0.7309, combined with a broad range (-3.2615 to 1.6673), suggests that in many contexts, the benefits of renewable energy are potentially undermined by weak governance. This variable exhibits mild left-skewness and leptokurtosis (kurtosis = 4.3084), pointing to a dense clustering of observations around the mean with several outliers.

As the LGDP*LEIU, the interaction between income and governance effectiveness, reflects how government effectiveness mediates the environmental effects of economic growth. With a mean of -2.3800 and standard deviation of 1.7451, the variable shows a left-skewed distribution (-0.6733) and modest tail thickness (kurtosis = 2.7879). This supports the hypothesis that higher income alone does not guarantee better environmental performance unless accompanied by effective governance. Most variables significantly deviate from normality, as indicated by Jarque-Bera statistics ($p < 0.01$), except for LEIU, which is borderline at the 5% level. These results highlight the heterogeneity of the sample and justify the use of estimation techniques that can account for non-normal distributions, such as panel ARDL or NARDL models with robust standard errors and interaction effects.

4.2 Panel Unit Root Test Results

Before estimating the long-run and short-run dynamics between carbon emissions, economic growth, renewable energy consumption, population, and governance, it is essential to determine the time-series properties of the panel data. Specifically, identifying the order of integration of each variable is necessary to ensure the validity of the econometric approach. In Table 4.2, three panel unit root tests were employed: the Levin, Lin and Chu (LLC) test, the Augmented Dickey-Fuller Fisher test (ADF-Fisher), and the Phillips-Perron Fisher test (PP-Fisher). These tests allow for the examination of both common and individual unit root processes across the cross-sectional units.

Table 4.2:
Unit Root Results

Variable	Form	LLC		ADF		PP	
		Stat.	Prob.	Stat.	Prob.	Stat.	Prob.
LCO ₂	Level	-0.3125	0.3773	13.8586	0.8376	17.5363	0.6179
	1 st Dif	-13.7718 ***	0.0000	180.5055 ***	0.0000	203.7683 ***	0.0000
LGDP	Level	-3.5308 ***	0.0002	26.9793	0.1358	32.3932 **	0.0393
	1 st Dif	-11.0215 ***	0.0000	132.3182 ***	0.0000	148.7949 ***	0.0000
LGDP ²	Level	-2.6188	0.0044	23.4703	0.2663	29.4776	0.0788
	1 st Dif	-11.3535 ***	0.0000	133.0120 ***	0.0000	151.3932 ***	0.0000
LPOPL	Level	-7.3757 ***	0.0000	67.8500 ***	0.0000	111.6148 ***	0.0000
	1 st Dif	-1.9703 **	0.0244	70.1135 ***	0.0000	48.9303 ***	0.0003
LRE	Level	0.3224	0.6264	9.4405	0.9772	9.6714	0.9737

	1 st Dif	-15.3304 ***	0.0000	180.2813 ***	0.0000	213.3002 ***	0.0000
LEIU	Level	0.1989	0.5788	51.0229 ***	0.0002	33.4945 **	0.0298
	1 st Dif	-7.9632 ***	0.0000	187.5706 ***	0.0000	155.5801 ***	0.0000
LGDP*LEIU	Level	0.7145	0.7626	53.3338 ***	0.0001	37.3330 **	0.0107
	1 st Dif	-10.2677 ***	0.0000	227.9948 ***	0.0000	187.4484 ***	0.0000
LRE*LEIU	Level	-0.6845	0.2468	61.4182 ***	0.0000	45.0786 ***	0.0011
	1 st Dif	-9.4017 ***	0.0000	204.1930 ***	0.0000	189.4247 ***	0.0000

Note: *, **, and *** denote 10 %, 5 %, and 1 % significance levels, respectively

The results, presented in Table 4.2, indicate that the majority of variables are non-stationary at level but become stationary after first differencing, suggesting that they are integrated of order one, $I(1)$. For the dependent variable, carbon dioxide emissions per capita (LCO_2), all three tests fail to reject the null hypothesis of a unit root at level, with p-values far exceeding the 5 percent significance threshold. However, at the first difference, the test statistics are strongly significant across all three methods, confirming that LCO_2 is $I(1)$.

Similarly, both GDP per capita (LGDP) and its squared term ($LGDP^2$) show mixed evidence at level. The LLC test rejects the null of a unit root for both variables, but the ADF and PP tests provide less conclusive support for stationarity. In light of these mixed results, and in line with standard practice, these variables are conservatively treated as $I(1)$, particularly because they are clearly stationary at first difference according to all three tests. Log of population (LPOPL) is the only variable that is stationary at level according to all three-unit root tests, with highly significant statistics. This indicates that LPOPL is integrated of order zero, $I(0)$. This is acceptable in the context of ARDL-type models, which allow for a combination of $I(0)$ and $I(1)$ variables, provided none are $I(2)$.

Renewable energy consumption (LRE) is found to be non-stationary at level in all three tests but becomes strongly stationary after first differencing, thus confirming it is $I(1)$. Government effectiveness (LEIU) also presents mixed results at level such as the LLC does not reject the null, but the ADF and PP tests indicate stationarity. However, as with LGDP, the variable is treated as $I(1)$ due to strong stationarity after first differencing. The two interaction terms, LRE*LEIU (the product of renewable energy and governance effectiveness) and LGDP*LEIU (the product of GDP and governance), are both non-stationary at level but clearly stationary at the first difference across all tests. This further

confirms their integration at order one. Overall, the findings from Table 4.2 establish that all variables in the dataset are either $I(0)$ or $I(1)$, with none integrated of order two. According to Pesaran et al. (2001) and Afroz and Muhibbullah (2022), validates the use of dynamic panel models such as the panel ARDL and its non-linear extension, the panel NARDL. These models are particularly appropriate for analysing both long-run cointegrating relationships and short-run when variables are of mixed integration orders but exclude $I(2)$.

4.3 Analysis of ARDL (Model 1) and NARDL (Model 2)

4.3.1 Cross-Sectional Dependence Tests (Models 1 and 2)

Before proceeding to panel ARDL or NARDL estimations, it is essential to verify the presence or absence of cross-sectional dependence (CSD) in the panel dataset. Cross-sectional dependence arises when the residuals of different cross-sectional units (e.g., countries) are correlated due to common shocks, unobserved global factors, or spatial linkages (Ertur & Musolesi, 2017). If not addressed, such dependence can lead to biased standard errors and invalid inference in panel estimations. To assess this issue, three standard CSD tests were employed in Table 4.3, the Breusch-Pagan LM test, the Pesaran Scaled LM test, and the Pesaran CD test. These tests examine whether the residuals of individual panel equations are significantly correlated.

Table 4.3:
Cross-Section Dependence Results (Models 1 and 2)

Test	Statistic	d.f.	Prob.
Breusch-Pagan LM	30.1082		0.9567
Pesaran scaled LM	-1.5697	45	0.1165
Pesaran CD	-0.5183		0.6042

The Breusch-Pagan LM test produced a test statistic of 30.1082 with a corresponding p-value of 0.9567, which is well above the conventional significance levels (1%, 5%, and 10%). This suggests that the study fail to reject the null hypothesis of cross-sectional independence. Similarly, the Pesaran scaled LM test yields a statistic of -1.5697 with a p-value of 0.1165, again failing to reject the null. Lastly, the Pesaran CD (cross-sectional dependence) test reports a statistic of -0.5183 with a p-value of 0.6042, further confirming the absence of statistically significant cross-sectional dependence.

Collectively, the results from all three tests indicate that cross-sectional dependence is not present in Models 1 and 2. This outcome implies that shocks or innovations affecting one country do not systematically influence other countries within the sample. From a methodological standpoint, this finding is favourable, as it justifies the use of first-generation panel estimation techniques such as the panel ARDL model, without needing to control for cross-sectional dependence using second-generation estimators. Thus, the dataset for Models 1 and 2 satisfies the assumption of cross-sectional independence, reinforcing the robustness of the chosen econometric approach for estimating both short-run and long-run relationships among the variables.

4.3.2 Pedroni Cointegration Test (Models 1 and 2)

To determine the existence of a long-run equilibrium relationship between carbon emissions and its explanatory variables, the Pedroni residual cointegration test was conducted. The Pedroni test is widely used in panel data analysis to assess cointegration in settings where heterogeneity is allowed both across cross-sections and over time. The test evaluates the null hypothesis of no cointegration against the alternative that a cointegrating relationship exists among the variables.

Table 4.4:
Pedroni Residual Cointegration Results (Models 1 and 2)

Alternative hypothesis: common AR coefs. (within-dimension)		
Test	Statistic	Prob.
Panel v-Statistic	2.9750	0.0015
Panel rho-Statistic	-1.0569	0.1453
Panel PP-Statistic	-3.6943	0.0001
Panel ADF-Statistic	-3.8336	0.0001
Alternative hypothesis: individual AR coefs. (between-dimension)		
Test	Statistic	Prob.
Group rho-Statistic	0.7375	0.7696
Group PP-Statistic	-2.4252	0.0077
Group ADF-Statistic	-3.1536	0.0008

Table 4.4 presents the results for both the within-dimension (panel statistics) and between-dimension (group statistics) approaches. The within-dimension statistics assume a common autoregressive coefficient across all panel units, while the between-dimension approach allows this coefficient to vary across countries. These two dimensions provide

complementary evidence regarding the presence of cointegration. For the within-dimension approach, the Panel v -statistic is 2.9750 with a p -value of 0.0015, indicating strong rejection of the null hypothesis at the 1% level. This test is particularly sensitive to positive cointegration and supports the presence of a long-run relationship. Similarly, the Panel PP-statistic (-3.6943 , $p = 0.0001$) and the Panel ADF-statistic (-3.8336 , $p = 0.0001$) also reject the null of no cointegration at the 1% significance level, reinforcing the robustness of the cointegration results under the common autoregressive coefficient assumption.

The between-dimension results further corroborate these findings. The Group PP-statistic of -2.4252 ($p = 0.0077$) and the Group ADF-statistic of -3.1536 ($p = 0.0008$) both reject the null hypothesis at the 1% and 5% levels, respectively. These results demonstrate that even when allowing for heterogeneity in the autoregressive parameters, there is strong statistical evidence in favour of cointegration across panel units. Taken together, the Pedroni test results provide consistent and compelling evidence that carbon emissions, economic growth, population, and renewable energy consumption share a stable long-run relationship in Models 1 and 2. This finding justifies the application of panel ARDL estimation, which relies on the assumption of cointegration among variables to estimate both the short-run adjustments and the long-run elasticities.

4.3.3 Panel ARDL Estimation Results (Model 1)

Table 4.5 presents the results of the dynamic panel ARDL estimation for Model 1, which investigates the relationship between carbon dioxide emissions per capita (LCO_2) and its primary determinants: income level (LGDP), the square of income (LGDP^2), population size (LPOPL), and renewable energy consumption (LRE). The estimation was conducted using three techniques: the Pooled Mean Group (PMG), the Mean Group (MG), and the Dynamic Fixed Effects (DFE) estimators. Each method allows for different assumptions about heterogeneity across countries, with the PMG estimator assuming homogeneity in the long-run coefficients while allowing for heterogeneity in the short-run dynamics and error variances.

Table 4.5:
Panel ARDL (Model 1)

Long-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Std. error	Coefficient	Std. error
LGDP	2.4366	0.0010	26.9554	0.3430	0.8666	0.3223

LGDP ²	-0.1948	0.0033	-2.9272	0.3420	-0.0061	0.9403

LPOPL	0.1954	0.0327	1.9989	0.2034	-0.8060	0.3438
	**					
LRE	-0.0038	0.6900	-0.0725	0.4878	-0.0769	0.3060
Short-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Variable	Coefficient	Std. error
COINTEQ	-0.1835	0.0119	-0.6382	0.0000	-0.0541	0.0426
	**		***		**	
D(LCO ₂ (-1))	-0.0103	0.8885	0.0912	0.1183	-0.1274	0.0230
					**	
D(LGDP)	-22.8265	0.2140	-30.2572	0.0039	1.4376	0.0013
			***		***	
D(LGDP ²)	1.7940	0.1566	2.4892	0.0007	-0.0602	0.0860
			***		*	
D(LPOPL)	-2.4186	0.2581	4.0568	0.4851	0.1439	0.7234
D(LRE)	-0.0633	0.0040	-0.0298	0.1942	0.0004	0.9459

C	-1.4797	0.0091	-12.8554	0.6520	0.1454	0.6632
Hausman			4.4947		15.9867	
p-Value			(0.3432)		(0.0030)	

Note: *, **, and *** denote 10 %, 5 %, and 1 % significance levels, respectively

In the long-run, the PMG estimator produces results that are theoretically consistent and statistically robust. The coefficient for LGDP is positive and statistically significant, with a value of 2.4366. In contrast, the coefficient for LGDP² is negative and significant at -0.1948. This pattern confirms the existence of an inverted U-shaped relationship between income and emissions, providing strong empirical support for the Environmental Kuznets Curve (EKC) hypothesis. These findings similar with (Javed et al., 2024; Chopra et al., 2024), on average, carbon emissions initially increase with economic growth but begin to decline once a certain income is reached.

The coefficient of population (LPOPL) is also positive and statistically significant in the long-run. The estimate of 0.1954 implies that an increase in population contributes to higher emissions, consistent with the scale effect in environmental economics. According to Zarco-Soto et al. (2021), larger populations tend to consume more energy and generate more waste, which puts upward pressure on emission levels. Conversely, the coefficient for renewable energy consumption (LRE) is negative, although statistically insignificant. This finding suggests that while renewable energy has the expected direction of effect in the long term, its contribution to emissions reduction has not been substantial or consistent across countries. This could reflect the limited share of renewables in national energy mixes, technical constraints, or variation in policy enforcement (Rogge et al., 2017; Borozan, 2022;

Falcone, 2023). However, in short-run, the renewable energy does impact to reduce the CO₂ emissions as similar result with study by Pata et al. (2025), which found the renewable energy reduces carbon emissions in USA.

Comparing across estimators, the MG method generates extremely large coefficient estimates, such as 26.9554 for LGDP, which may reflect strong heterogeneity in the panel. Meanwhile, the DFE approach imposes homogeneity across both short- and long-run coefficients, yielding smaller and less theoretically consistent results, including an insignificant LGDP² coefficient. Among the three methods, the PMG estimator offers the most plausible and theoretically valid set of long-run coefficients.

In the short-run dynamics, the error correction term (COINTEQ) is negative and statistically significant under all three estimators. Under PMG, its value is -0.1835 , indicating that approximately 18 percent of the deviation from the long-run equilibrium is corrected in each period. This adjustment speed confirms the presence of a stable long-run relationship among the variables in the model. The MG estimator reports a faster speed of adjustment, while the DFE estimator shows a slower correction rate. The short-run coefficients for the first lag of the dependent variable ($D(LCO_2(-1))$) are insignificant under PMG and MG, though significant under DFE. The coefficient of $D(LGDP)$ is negative under both PMG and MG and statistically significant only under MG. This suggests that in the short-run, temporary economic expansions may coincide with emission reductions, potentially due to structural shifts, temporary clean investments, or cyclical effects. $D(LGDP^2)$ is positive and statistically significant, reinforcing the short-run non-linearity in the income–emissions relationship. However, the magnitude of the short-run effects is smaller than the long-run effects.

The short-run coefficients for $D(LPOPL)$ and $D(LRE)$ are generally insignificant, except for $D(LRE)$ under the PMG model. The PMG estimate of -0.0633 for $D(LRE)$ is significant at the one percent level, indicating that increases in renewable energy consumption have a modest but statistically meaningful immediate effect in lowering carbon emissions. The Hausman test was employed to determine the appropriate estimator between PMG and MG. The test statistic of 4.4947 with a p-value of 0.3432 indicates that the null hypothesis cannot be rejected, meaning that PMG is the preferred estimator over MG in this context. The PMG approach is thus selected for interpreting the long-run coefficients and adjustment mechanisms in this model.

Therefore, the results of Model 1 support the Environmental Kuznets Curve hypothesis, reveal that population growth continues to contribute to environmental degradation, and highlight the modest but statistically significant short-run impact of renewable energy. Model 1 results is supported by studies by Ozkan and Okay (2024) and Kalim et al. (2024). These findings reinforce the relevance of long-run growth and structural energy policy in shaping the environmental trajectory of countries.

4.3.4 Nonlinear Adjustment and Coefficient Symmetry Test (Model 2)

To examine the possibility of asymmetric effects of renewable energy consumption on carbon emissions, a nonlinear panel ARDL (NARDL) model was estimated. The model distinguishes between positive and negative changes in renewable energy consumption, thereby allowing the analysis to capture whether increases and decreases in renewable energy use have differential impacts on environmental outcomes. This is particularly important in environmental policy evaluation, where behavioural and structural responses to renewable energy expansion may differ from those associated with contraction or policy rollback.

Table 4.6:
Coefficient Symmetry (Model 2)

Variable	Statistic	Value	Probability
LRE	F-statistic	9.6979	0.0021
	Chi-square	9.6979	0.0018

The results of the coefficient symmetry test for the renewable energy variable (LRE) are reported in Table 4.6. Both the F-statistics and the Chi-square statistics are used to test the null hypothesis of symmetry, which posits that the effects of positive and negative changes in renewable energy are equal in magnitude but opposite in direction. The F-statistic value is 9.6979, with an associated p-value of 0.0021. The Chi-square statistics yield the same value, with a p-value of 0.0018. In both cases, the p-values are below the conventional 1 percent significance level. This leads to a strong rejection of the null hypothesis of symmetry. According to same panel NARDL method by (Sheikh et al., 2020) and Ramos-Herrera (2024), these results confirm the presence of significant asymmetric effects of renewable energy consumption on carbon emissions. Specifically, the impact of an increase in renewable energy consumption is not equal to the impact of a decrease.

4.3.5 Panel Asymmetric ARDL Estimation Results (Model 2)

Table 4.7 shows the Model 2 extends the baseline Environmental Kuznets Curve framework by introducing a nonlinear structure to examine whether increases and decreases in renewable energy consumption have asymmetric effects on carbon dioxide emissions. The analysis uses the Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE) estimators. The PMG estimator is the preferred specification based on the Hausman test, which fails to reject the null hypothesis of efficiency at the five percent level (p-value = 0.0500).

Table 4.7:
Panel NARDL (Model 2)

Long-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Std. error	Coefficient	Std. error
LGDP	2.3193 ***	0.0019	31.7678 **	0.0333	0.7332	0.3500
LGDP ²	-0.1815 ***	0.0063	-2.7607 *	0.0577	0.0019	0.9790
LPOPL	0.5431 ***	0.0000	0.4591	0.7427	0.0634	0.9541
LRE+	-0.0237 ***	0.0044	0.0587	0.5354	-0.1063	0.2090
LRE-	0.0131 *	0.0900	-0.6075	0.3845	-0.0093	0.9141
Short-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Variable	Coefficient	Std. error
COINTEQ	-0.2216 **	0.0210	-0.7248 ***	0.0000	-0.0604 **	0.0287
D(LCO2(-1))	0.0153	0.8345	0.1269 **	0.0190	-0.1255 **	0.0256
D(LGDP)	-23.4767	0.1893	-39.4776 ***	0.0014	1.3489 ***	0.0030
D(LGDP ²)	1.7647	0.1479	3.4090 ***	0.0025	-0.0540	0.1307
D(LPOPL)	-2.7855	0.2523	9.0854	0.3078	0.1973	0.6414
D(LRE+)	-0.0050	0.8785	-0.0341	0.2941	0.0160	0.3246
D(LRE-)	-0.6568	0.1225	-0.1587	0.1163	-0.0033	0.6650
C	-2.3367 **	0.0146	-39.3189	0.1490	-0.2463	0.6691
Hausman			11.0681		44.2206	
p-Value			(0.0500)		(0.0000)	

Note: *, **, and *** denote 10 %, 5 %, and 1 % significance levels, respectively

In the long-run, the PMG results again confirm the validity of the Environmental Kuznets Curve hypothesis. The coefficient for LGDP is positive and statistically significant (2.3193), while LGDP² is negative and significant (-0.1815). This pattern reinforces the

earlier finding that economic growth initially contributes to environmental degradation, but beyond a certain income level, further growth reduces emissions.

Population (LPOPL) has a significant positive long-run coefficient (0.5431), suggesting that an increase in population contributes meaningfully to higher emissions over time. This result supports the view that demographic growth intensifies environmental pressures, primarily through increased energy demand and consumption (Wang et al., 2022). Importantly, the asymmetric decomposition of renewable energy reveals that only positive changes in renewable energy consumption (LRE^+) are statistically significant in the long-run, which similar results with Kalim et al. (2024) and Alnour et al. (2024). The coefficient is negative (-0.0237) and significant at the one percent level, implying that increases in renewable energy use reduce emissions.

In the short-run dynamics, the error correction term (COINTEQ) is negative and statistically significant (-0.2216), confirming the existence of a stable long-run equilibrium. Approximately 22 percent of the short-run disequilibrium is corrected each period. This finding aligns with the earlier model and strengthens confidence in the cointegration relationship. Under the Mean Group (MG) estimator, additional significant short-run dynamics emerge. $D(LGDP)$ and $D(LGDP^2)$ are both statistically significant, with negative and positive coefficients respectively, again suggesting short-run non-linear effects of income on emissions. $D(LCO_2(-1))$ is also significant in the MG model, indicating moderate autoregressive behaviour in emissions. However, for consistency and robustness, the interpretation remains focused on the PMG results.

Taking together, the significant results from Model 2 confirm three key patterns. First, the EKC hypothesis remains valid under both symmetric and asymmetric specifications. Clarify similar findings as closely relevant past studies also prove the existence of EKC in South Asia (Rahman et al., 2024b), European countries (Horobet et al., 2024), and emerging market regions (Odei et al., 2025). Second, population continues to play a significant role in long-run environmental degradation (Wang et al., 2022). Third, increases in renewable energy consumption contribute to emissions reduction, and not reductions, highlighting a critical asymmetric effect (Alnour et al., 2024). This implies that promoting renewable energy expansion yields positive environmental outcomes, consistent with the EKC–STIRPAT perspective where technological progress and structural change drive decarbonisation at higher income levels.

However, inconsistent policy support such as abrupt withdrawal of subsidies, unstable regulatory frameworks, or delayed infrastructure development can undermine these gains by discouraging private investment and slowing the diffusion of clean technologies. Although a temporary reduction in renewable investment may not immediately raise emissions, it creates policy uncertainty that weakens long-run environmental performance. Therefore, governments must strengthen governance effectiveness by ensuring coherent, transparent, and long-term renewable energy policies that reduce investment risk, sustain technological innovation, and reinforce the trajectory towards lower emissions in line with sustainable growth objectives.

4.4 Analysis ARDL (Model 3) and NARDL (Model 4)

4.4.1 Cross-Section Dependence Test Results (Model 3 and Model 4)

To ensure the validity of the panel data estimation for Models 3 and 4, tests for cross-sectional dependence were conducted. Cross-sectional dependence arises when the residuals of individual cross-sectional units, such as countries, are correlated due to common shocks, spillover effects, or unobserved global factors. Ignoring such dependence can lead to biased coefficient estimates and misleading inference, particularly in dynamic panel models. Therefore, three standard tests were employed: the Breusch-Pagan LM test, the Pesaran scaled LM test, and the Pesaran CD test.

Table 4.8:
Cross-Section Dependence Results (Models 3 and 4)

Test	Statistic	d.f.	Prob.
Breusch-Pagan LM	38.9478		0.7250
Pesaran scaled LM	-0.6380	45	0.5235
Pesaran CD	-0.4181		0.6758

As reported in Table 4.8, the results consistently indicate the absence of cross-sectional dependence. The Breusch-Pagan LM test yielded a statistic of 38.9478 with a p-value of 0.7250, well above the conventional significance levels. This shows fail to reject the null hypothesis of cross-sectional independence. The Pesaran scaled LM test, which adjusts for the number of cross-sectional units and time dimensions, produced a statistic of -0.6380 with a p-value of 0.5235. Similarly, the Pesaran CD test, which directly assesses

the average correlation of residuals across panels, reported a statistic of -0.4181 and a corresponding p-value of 0.6758 . In all three cases, the high p-values confirm that the residuals across countries are not significantly correlated.

The absence of cross-sectional dependence in both models has important methodological implications. According to Mensah and Abdul-Mumuni (2023), the results validate the use of first-generation panel data techniques such as the panel ARDL and panel NARDL estimators, which assume cross-sectional independence. Furthermore, it implies that shocks or innovations affecting one country in the sample do not systematically spill over to others in a way that would violate the independence assumption. Consequently, the empirical results of Models 3 and 4 can be interpreted with greater confidence, without the need to apply more complex second-generation estimators that are explicitly correct for cross-sectional dependence.

4.4.2 Pedroni Residual Cointegration Test Results (Model 3 and Model 4)

To verify the existence of a stable long-run relationship between carbon dioxide emissions and their explanatory variables in Models 3 and 4, the Pedroni residual cointegration test was conducted. Both perspectives provide robust and complementary insights into the existence of cointegration.

Table 4.9:
Pedroni Residual Cointegration Results (Models 3 and 4)

Alternative hypothesis: common AR coefs. (within-dimension)		
Test	Statistic	Prob.
Panel v-Statistic	1.8291	0.0337
Panel rho-Statistic	0.0068	0.5027
Panel PP-Statistic	-3.5910	0.0002
Panel ADF-Statistic	-4.1480	0.0000
Alternative hypothesis: individual AR coefs. (between-dimension)		
Test	Statistic	Prob.
Group rho-Statistic	1.8897	0.9706
Group PP-Statistic	-3.0579	0.0011
Group ADF-Statistic	-4.4770	0.0000

As shown in Table 4.9, the within-dimension test statistics provide strong evidence of cointegration. The Panel v-Statistic is 1.8291 with a p-value of 0.0337 , indicating significance at the 5 percent level. More compelling are the Panel PP-Statistic and Panel

ADF-Statistic, which are both highly significant, with p-values of 0.0002 and 0.0000, respectively. These results lead to a rejection of the null hypothesis of no cointegration, confirming that the variables in the model are bound by a long-run equilibrium relationship. The between-dimension results further support this conclusion. The Group PP-Statistic is – 3.0579 and the Group ADF-Statistic is –4.4770, with p-values of 0.0011 and 0.0000, respectively. These values also strongly reject the null hypothesis and indicate that the cointegration relationship holds even when allowing for country-specific heterogeneity in the autoregressive dynamics.

Taken together, the Pedroni test results confirm that both Model 3 and Model 4 exhibit robust cointegration among the included variables. This finding is methodologically important, as it validates the use of the panel ARDL and panel NARDL estimators, both of which rely on the assumption of long-run equilibrium among the dependent and explanatory variables. The presence of cointegration also implies that any short-run deviations in emissions from their long-run equilibrium path are expected to be temporary and self-correcting over time. Thus, the results from the Pedroni test provide strong statistical support for the existence of a long-run equilibrium relationship between carbon emissions, income, population, renewable energy consumption, and government effectiveness across countries.

4.4.3 Panel ARDL Estimation Results (Model 3)

Model 3 in Table 4.10 extends the Environmental Kuznets Curve (EKC) framework by including government effectiveness (LEIU) to assess whether government effectiveness significantly influences carbon dioxide emissions. Estimations were performed using the Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE) estimators. The Hausman test strongly favours the PMG estimator, with a test statistic of 38.3900 and a p-value of 0.0000, indicating that long-run homogeneity should be imposed for more efficient and consistent estimates.

Table 4.10:
Panel ARDL (Model 3)

Long-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Std. error	Coefficient	Std. error
LGDP	2.4107 ***	0.0015	37.5650	0.1653	0.8290	0.3503
LGDP ²	-0.1952 **	0.0038	-3.6815	0.2115	-0.0004	0.9963

LPOPL	0.1950 **	0.0332	1.4596	0.2895	-0.7912	0.3530
LRE	-0.0057	0.5609	-0.0764	0.3749	-0.0750	0.3193
LEIU	0.0308 ***	0.0013	-0.1407 **	0.0170	-0.0737	0.7547
Short-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Variable	Coefficient	Std. error
COINTEQ	-0.2046 **	0.0211	-0.7869 ***	0.0000	-0.0541 **	0.0442
D(LCO ₂ (-1))	0.0185	0.8243	0.1124 *	0.0916	-0.1252 **	0.0266
D(LGDP)	-22.1797	0.2251	-30.4605 ***	0.0053	1.4800 ***	0.0011
D(LGDP ²)	1.7427	0.1623	2.6404 ***	0.0013	-0.0636 *	0.0737
D(LPOPL)	-2.4136	0.2464	3.7152	0.5849	0.1357	0.7399
D(LRE)	-0.0692 ***	0.0039	-0.0398	0.1334	0.0005	0.9421
D(LEIU)	-0.0237	0.1587	0.0582 **	0.0421	0.0085	0.4386
C	-1.6107 ***	0.0184	-30.4318	0.2724	0.1377	0.6823
Hausman			38.3900		16.6125	
p-Value			(0.0000)		(0.0053)	

Note: *, **, and *** denote 10 %, 5 %, and 1 % significance levels, respectively

In the long-run, the PMG estimation yields results that are theoretically consistent with the EKC hypothesis. The coefficient for LGDP is positive and statistically significant (2.4107), while LGDP² is negative and significant (−0.1952), confirming the inverted U-shaped relationship between income and emissions. This result is similar finding as Cutcu et al. (2025), which is conducted a study related to geopolitical risk, renewable energy and EKC using panel data of 17 countries.

These results found that carbon emissions increase during the early stages of economic growth but begin to decline once a critical income level is reached. This supports studies by (Lin et al., 2022) and (Gao et al., 2025), as the proposition that economic development, when advanced beyond a certain threshold, can facilitate environmental improvements through structural shifts and cleaner technologies.

Population (LPOPL) is also statistically significant in the long-run with a positive coefficient (0.1950), indicating that increases in population contribute to higher per capita emissions. This finding is consistent with the evident of scale effect in environmental economics, as larger populations increase energy consumption and associated emissions (Bu et al., 2022). Although LEIU was included in the long-run specification, it is not statistically

significant under the PMG estimator. This suggests that government effectiveness, as measured in this model, does not have a direct long-run impact on emissions after controlling for income, population, and renewable energy.

In the short-run, the error correction term (COINTEQ) is negative and highly significant (-0.2046), confirming the presence of a stable long-run equilibrium relationship. The magnitude of the coefficient implies that approximately 20 percent of deviations from equilibrium are corrected in each year. Among the short-run variables, the first difference of renewable energy consumption ($D(LRE)$) is statistically significant and negative (-0.0692), indicating that increases in renewable energy have a measurable and immediate effect in reducing emissions (Mohamad et al., 2023; Ahmad et al., 2024; Azimi et al., 2025). This finding highlights the relevance of renewable energy in short-run emission management, even though its long-run effect is statistically insignificant in this specification.

The first differences of GDP and GDP squared are not statistically significant under PMG, but they become significant under the MG estimator, suggesting heterogeneity in short-run dynamics across countries. The short-run coefficient for government effectiveness ($D(LEIU)$) is not statistically significant, implying that short-term changes in governance effectiveness do not produce immediate changes in emissions, at least not within the same year. This aligns with the notion that governance effects are often realised more gradually through institutional reforms, policy implementation, and behavioural change (Haque & Ntim, 2018; Teng & Wang, 2021).

Overall, the results from Model 3 confirm the robustness of the EKC hypothesis and reinforce the importance of demographic pressure in environmental degradation. While government effectiveness does not exhibit a statistically significant direct effect in this model, the significant short-run influence of renewable energy underscores the relevance of clean energy transitions in achieving immediate environmental gains.

4.4.4 Coefficient Symmetry Test Results (Model 4)

To evaluate whether increases and decreases in renewable energy consumption exert symmetric effects on carbon dioxide emissions, a coefficient symmetry test was conducted in the context of Model 4, which incorporates an asymmetric specification of the renewable energy variable. In this model, renewable energy consumption is decomposed into its

positive changes (LRE^+) and negative changes (LRE^-) using the nonlinear ARDL framework. The coefficient symmetry test assesses whether the impact of LRE^+ is statistically equal in magnitude and opposite in direction to that of LRE^- .

Table 4.11:
Coefficient Symmetry (Model 4)

Variable	Statistic	Value	Probability
LRE	F-statistic	8.5487	0.0038
	Chi-square	8.5487	0.0035

As reported in Table 4.11 shows both the F-statistic and Chi-square statistical values of 8.5487, with corresponding p-values of 0.0038 and 0.0035, respectively. These results are statistically significant at the 1 percent level, indicating a strong rejection of the null hypothesis of coefficient symmetry. Therefore, it can be concluded that the effects of increasing and decreasing renewable energy consumption on carbon emissions are not symmetric. The confirmed asymmetry in the effect of renewable energy changes thus supports the methodological use of the nonlinear ARDL model and highlights the necessity for policymakers to design energy strategies that encourage sustained, rather than fluctuating, growth in renewable energy investment.

4.4.5 Panel Asymmetric ARDL Estimation Results (Model 4)

In Table 4.12 shows the Model 4 adopts a nonlinear ARDL framework to examine the asymmetric impact of renewable energy consumption on carbon dioxide emissions, distinguishing between positive changes (LRE^+) and negative changes (LRE^-). This model also includes economic growth (LGDP and LGDP2), population (LPOPL), and government effectiveness (LEIU). Estimations were conducted using the Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE) estimators. The Hausman test indicates that the PMG estimator is appropriate, as the null hypothesis of efficient and consistent estimation is not rejected (p-value = 0.1454). Hence, the interpretation is based primarily on the PMG results.

Table 4.12:
Panel NARDL (Model 4)

Long-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Std. error	Coefficient	Std. error

LGDP	2.5726 ***	0.0009	43.7925 *	0.0882	0.7023	0.3785
LGDP ²	-0.2072 ***	0.0025	-3.8623 *	0.0879	0.0067	0.9287
LPOPL	0.5147 ***	0.0001	1.5217	0.3947	0.0640	0.9541
LEIU	0.0354 ***	0.0029	-0.6656	0.1804	-0.0631	0.7646
LRE+	-0.0247 ***	0.0040	0.3404	0.3632	-0.1040	0.2195
LRE-	0.0113	0.1586	-1.1436	0.1850	-0.0081	0.9257
Short-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Variable	Coefficient	Std. error
COINTEQ	-0.2326 **	0.0246	-0.8394 ***	0.0000	-0.0604 **	0.0300
D(LCO ₂ (-1))	0.0433	0.5864	0.1372 **	0.0151	-0.1231 **	0.0297
D(LGDP)	-23.0320	0.1986	-44.4922 ***	0.0010	1.3912 ***	0.0025
D(LGDP ²)	1.7266	0.1555	4.0254 ***	0.0033	-0.0573	0.1128
D(LPOPL)	-2.8035	0.2498	8.0810	0.4512	0.1916	0.6530
D(LEIU)	-0.0261 **	0.0897	0.0632 ***	0.0052	0.0085	0.4388
D(LRE+)	0.0051	0.8363	-0.0414	0.2983	0.0162	0.3210
D(LRE-)	-0.6560 *	0.0929	-0.1812	0.2221	-0.0034	0.6643
C	-2.5337 **	0.0197	-45.3875 **	0.0293	-0.2478	0.6687
Hausman p-Value			9.5411 (0.1454)		119.2316 (0.0000)	

Note: *, **, and *** denote 10 %, 5 %, and 1 % significance levels, respectively

In the long-run, the coefficients for LGDP and LGDP² are statistically significant, with LGDP positively associated with emissions (2.5726) and LGDP² negatively associated (-0.2072). These findings provide further confirmation of the Environmental Kuznets Curve (EKC) hypothesis, suggesting that emissions rise during early stages of economic development but decline beyond a certain income threshold. Population (LPOPL) also has a significant positive long-run effect (0.5147), meaning reinforcing the notion that demographic expansion intensifies environmental pressures through increased energy demand (Liu et al., 2021).

Ali et al. (2022) reported outcomes consistent with those in Model 4, focusing on how economic growth, fossil fuel use, and population density influence CO₂ emissions in India, Pakistan, and Bangladesh. Their analysis identified a long-run relationship between population and emissions through the ARDL framework and revealed a U-shaped

Environmental Kuznets Curve, indicating that as population increases, CO₂ emissions tend to rise. According to Luqman et al. (2023), the intensifying urban sprawl in developing nations with high population growth has emerged as a critical driver of increased CO₂ emissions.

Among the renewable energy terms, only positive changes in renewable energy consumption (LRE⁺) are statistically significant in the long-run. The coefficient of LRE⁺ is -0.0247 , indicating same finding as (Alnour et al., 2024; Lu et al., 2024; Liu et al., 2024) which indicates the increases in renewable energy use reduce carbon emissions over time. In contrast, LRE⁻ is statistically insignificant, confirming the presence of asymmetry in the impact of renewable energy, as supported by the coefficient symmetry test (Table 4.11) presented earlier. This result implies that while expanding renewable energy adoption contributes to long-term emissions reduction, declines or stagnation in renewable energy usage do not exert an equal and opposite effect (Yuan et al., 2022; Copley, 2023). The error correction term is negative and statistically significant (-0.2326), confirming the existence of a stable long-run equilibrium relationship. Approximately 23 percent of short-term deviations from the long-run equilibrium are corrected each period, suggesting moderate convergence toward equilibrium.

In the short-run, one additional statistically significant result emerges. The first difference of government effectiveness (D(LEIU)) is significant under the Mean Group estimator (coefficient = 0.0632 , p-value = 0.0052), suggesting that short-term improvements in governance may contribute to emissions reduction in some countries, though this effect is not significant in the PMG results. Additionally, D(LGDP²) is significant in the MG model, reinforcing short-run non-linearity between income and emissions. While short-run coefficients for renewable energy components are not statistically significant in the PMG results, it is noteworthy that the long-run impact of renewable energy expansion remains robust. The significant long-run reduction in emissions from increases in renewable energy, alongside the insignificant effect from reductions, underscores the asymmetric influence of energy transitions on environmental outcomes.

Therefore, the findings from Model 4 provide strong support for the EKC hypothesis, highlight the contribution of population growth to emissions, and, crucially, confirm that only increases in renewable energy consumption reduce emissions in the long-run. Relatively, this finding supported by similar results as studies by (Luqman et al., 2023; Liu

et al., 2021; Alnour et al., 2024). These results emphasise the need for continuous policy commitment to expanding renewable energy capacity rather than merely maintaining current levels.

4.5 Analysis of ARDL (Model 5)

4.5.1 Cross-Section Dependence Test Results (Model 5)

Before proceeding to estimate the long-run and short-run relationships in Model 5, it is important to verify whether the panel data exhibit cross-sectional dependence. This diagnostic step is essential, as the presence of correlated errors across countries could arise from shared global shocks, regional policy spillovers, or unobserved common factors. If uncorrected, such dependence may bias the results and compromise the reliability of inference in panel data models. Table 4.13 indicate the Model 5 introduces an interaction term between GDP per capita and government effectiveness (LGDP*LEIU), intended to capture how governance moderates the environmental effects of economic growth. Given this specification, the possibility of inter-country dependence must be tested explicitly.

Table 4.13:
Cross-Section Dependence Results (Model 5)

Test	Statistic	d.f.	Prob.
Breusch-Pagan LM	39.6720		0.6965
Pesaran scaled LM	-0.5616	45	0.5744
Pesaran CD	-0.4239		0.6717

The Table 4.13 reports the results of three standard tests: the Breusch-Pagan LM test, the Pesaran scaled LM test, and the Pesaran CD test. The Breusch-Pagan LM statistic is 39.6720 with a p-value of 0.6965, indicating that the null hypothesis of cross-sectional independence cannot be rejected. Similarly, the Pesaran scaled LM statistic is -0.5616 with a p-value of 0.5744, and the Pesaran CD statistic is -0.4239 with a p-value of 0.6717. All three tests consistently show p-values well above the conventional threshold of 0.05, confirming the absence of statistically significant cross-sectional dependence in the residuals.

4.5.2 Pedroni Residual Cointegration Test Results (Model 5)

To evaluate the existence of a stable long-run relationship among the variables specified in Model 5, the Pedroni residual cointegration test was employed. This model incorporates an interaction term between GDP per capita and government effectiveness (LGDP*LEIU), aiming to assess whether government effectiveness alters the environmental impact of economic growth. Establishing cointegration is essential before applying long-run estimators such as the panel ARDL, as it confirms that the variables move together over time and share a common equilibrium path. The Pedroni test examines the null hypothesis of no cointegration against the alternative that the variables are cointegrated.

Table 4.14:
Pedroni Residual Cointegration Results (Model 5)

Alternative hypothesis: common AR coefs. (within-dimension)		
Test	Statistic	Prob.
Panel v-Statistic	1.2308	0.1092
Panel rho-Statistic	0.2733	0.6077
Panel PP-Statistic	-4.3984	0.0000
Panel ADF-Statistic	-4.7076	0.0000
Alternative hypothesis: individual AR coefs. (between-dimension)		
Test	Statistic	Prob.
Group rho-Statistic	2.0159	0.9781
Group PP-Statistic	-4.4697	0.0000
Group ADF-Statistic	-4.9841	0.0000

As shown in Table 4.14, the within-dimension statistics provide strong evidence of cointegration. The Panel PP-statistic is -4.3984 with a probability value of 0.0000 , and the Panel ADF-statistic is -4.7076 with a probability value of 0.0000 . Both results indicate statistical significance at the one percent level and lead to rejection of the null hypothesis. This confirms the presence of a long-run equilibrium relationship under the assumption of common dynamics across countries. The between-dimension results reinforce this conclusion. The Group PP-statistic is -4.4697 with a p-value of 0.0000 , and the Group ADF-statistic is -4.9841 with a p-value of 0.0000 .

These results confirm that cointegration holds even when heterogeneity across countries is allowed in the autoregressive process. The consistent rejection of the null hypothesis across all four test statistics offers robust evidence that carbon emissions, income,

renewable energy use, population, government effectiveness, and the income-governance interaction share a long-run relationship. This validates the use of panel ARDL estimation for Model 5 and ensures that long-run coefficients derived from the model reflect meaningful equilibrium dynamics rather than spurious associations. Thus, the Pedroni test results strongly support the existence of cointegration among the variables in Model 5. This finding confirms that the relationship among economic, demographic, institutional, and environmental factors is stable over time, justifying the estimation of both short-run and long-run dynamics using the ARDL framework.

4.5.3 Panel ARDL Estimation Results (Model 5)

Model 5 in Table 4.15, introduces a governance-moderated Environmental Kuznets Curve by including an interaction term between income and government effectiveness (LGDP*LEIU). The estimation was conducted using the Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE) estimators. The Hausman test supports the use of the PMG estimator, as the p-value of 0.1115 indicates that the assumption of long-run homogeneity cannot be rejected.

The PMG results provide strong empirical evidence in support of the EKC hypothesis. Both the coefficient for GDP per capita (LGDP) and the squared term (LGDP²) are statistically significant at the one percent level. LGDP is positively associated with emissions, while LGDP² is negative, confirming the inverted U-shaped relationship between economic growth and environmental degradation. These findings are consistent with the theory that emissions initially increase with economic growth but begin to decline after surpassing a certain income threshold (Ikhsan & Amri, 2024; Hasan et al., 2024; Chopra et al., 2024).

Table 4.15:
Panel ARDL (Model 5)

Long-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Std. error	Coefficient	Std. error
LGDP	0.7846 ***	0.0000	146.8402 *	0.0593	0.4178	0.6896
LGDP ²	-0.0456 ***	0.0000	-14.6179 *	0.0538	0.0264	0.7828
LPOPL	1.0855 ***	0.0000	3.4215	0.2403	-0.5940	0.4272

LRE	0.0369 ***	0.0000	0.8523	0.3611	-0.0230	0.7490
LEIU	0.0558	0.1173	550.5049	0.3286	0.8784	0.5076
LGDP*LEIU	-0.0045	0.4056	-81.6429	0.3393	-0.1606	0.4732
Short-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Variable	Coefficient	Std. error
COINTEQ	-0.3645 **	0.0309	-0.9364 ***	0.0000	-0.0601 **	0.0281
D(LGDP)	-0.1280	0.9939	-156.3314	0.2531	1.6148 ***	0.0006
D(LGDP(-1))	9.7955	0.7970	-100.4396	0.1818	0.1011	0.8298
D(LGDP ²)	-0.1684	0.9048	15.0974	0.2566	-0.0716 *	0.0508
D(LGDP ² (-1))	-0.9600	0.7920	9.6945	0.1883	-0.0277	0.4530
D(LPOPL)	1.9849	0.4434	6.8300	0.1128	0.2161	0.6111
D(LPOPL(-1))	-3.6806	0.4374	-7.7779	0.3342	-0.1441	0.7248
D(LRE)	-0.1001 ***	0.0015	-0.1025	0.1920	-0.0018	0.7815
D(LRE(-1))	-0.0160	0.4810	-0.0550	0.1256	-0.0103	0.1192
D(LEIU)	-5.7135	0.4096	19.7492	0.6187	-0.0525	0.4972
D(LEIU(-1))	-18.7249 **	0.0483	-1.6566	0.9459	-0.0738	0.3067
D(LGDP*LEIU)	0.6000	0.5777	-4.6122	0.5541	0.0103	0.4298
D(LGDP*LEIU(-1))	3.4318 *	0.0510	-0.1644	0.9708	0.0123	0.3108
C	-4.1669 **	0.0290	-319.8715	0.2381	0.1373	0.7259
Hausman			10.3272		6.0138	
p-Value			(0.1115)		(0.4216)	

Note: *, **, and *** denote 10 %, 5 %, and 1 % significance levels, respectively

Population (LPOPL) also has a significant positive long-run effect, with a coefficient of 1.0855. This implies that an increase in population is associated with higher per capita carbon emissions, a finding that supports the scale effect in environmental literature (Rehman & Rehaman, 2022; Liu et al., 2021). Similarly, renewable energy consumption (LRE) has a statistically significant positive coefficient of 0.0369 in the long-run. While this result may appear counterintuitive, it is likely driven by countries in which renewable energy development is still insufficient to displace fossil fuels on a large scale (Ahmed et al., 2021; Rahman et al., 2022). The long-run coefficient for government effectiveness (LEIU) and its interaction with income (LGDP*LEIU) are not statistically significant, suggesting that government effectiveness alone or its interaction with income does not directly moderate long-term emissions in this model specification.

The short-run results show a significant error correction term with a value of -0.3645 and a p-value below one percent. This indicates that approximately 36 percent of deviations

from the long-run equilibrium are corrected each year, confirming the presence of a stable and adjusting relationship among the variables. Among the short-run dynamics, the first difference of renewable energy consumption ($D(LRE)$) is statistically significant and negative, with a coefficient of -0.1001 . This implies that increases in renewable energy use reduce emissions in the short-run, and constant with the past studies (Azimi et al., 2025; Zhou et al., 2025). Additionally, one lag of the squared income term ($D(LGDP^2)$) is significant under the DFE estimator, but not under PMG.

Furthermore, the first lag of the interaction term $D(LGDP*LEIU(-1))$ is significant in the PMG model, with a coefficient of 3.4318 and a p-value of 0.0510 . This suggests that, in the short-run, changes in the interaction between income and governance may influence emissions, although the result borders conventional significance levels. However, based on the Hausman test, both PMG and DFE are not able to be interpreted.

Thus, Model 5 provides further validation of the Environmental Kuznets Curve, while highlighting the importance of population dynamics in shaping emissions. Although government effectiveness does not exhibit a direct significant long-run effect, its interaction with income may exert influence in the short term. The consistent significance of the error correction term reinforces the validity of using the panel ARDL approach and suggests a meaningful long-run equilibrium exists among the variables. The finding that renewable energy contributes to emissions reduction in the short-run, but not the long-run, points to the need for scaling up renewables to produce more transformative long-term effects.

A key contribution of Model 5 is to test whether governance (proxied by government effectiveness, $LEIU$) alters the timing of the EKC turning point. The turning point is calculated as $-(\beta_1 / 2\beta_2)$, where β_1 is the coefficient of $LGDP$ and β_2 is the coefficient of $LGDP^2$. Using the PMG long-run estimates, the coefficients are $\beta_1 = 0.7846$ for $LGDP$ and $\beta_2 = -0.0456$ for $LGDP^2$, which implies a turning point of: $\text{Turning point} = -\frac{0.7846}{2 \times -0.0456} \approx 8.6$.

This corresponds to a GDP per capita of around USD 5,400–5,500 (2015 constant prices), suggesting that on average, the top emitters begin to reduce emissions only after reaching upper-middle income levels. However, the coefficient for the interaction term $LGDP*LEIU$ is statistically insignificant in the long-run, meaning that governance does not systematically accelerate (earlier turning point) or delay (later turning point) the EKC threshold across these economies. In the short-run, the lagged interaction term shows

borderline significance ($p = 0.051$ under PMG), which indicates that governance shocks may temporarily influence emissions trajectories.

Numerically, if governance were significant and negative, the turning point would shift downward (e.g., from $\log 8.6 \approx \text{USD } 5,400$ to perhaps $\log 8.3 \approx \text{USD } 4,000$), enabling countries to peak emissions at a lower income level. A positive coefficient would instead delay the turning point to higher income levels (e.g., from $\log 8.6 \approx \text{USD } 5,400$ up toward $\text{USD } 7,000\text{--}8,000$). This study estimates show no long-run effect, thus conclude that governance does not consistently alter the EKC transition in the top 10 emitters, though short-run interactions suggest some potential influence.

4.6 Analysis of ARDL (Model 6)

4.6.1 Cross-Section Dependence Test Results (Model 6)

Before estimating the long-run and short-run dynamics of Model 6, it is necessary to assess the presence of cross-sectional dependence in the panel data. Table 4.16 report Model 6 includes an interaction term between renewable energy consumption and government effectiveness (LRE*LEIU), which captures how government effectiveness moderates the environmental impact of renewable energy use. Given that institutional characteristics and energy policy outcomes may exhibit regional spillover effects, it is important to test whether such dependence is statistically evident in the data. To this end, three widely accepted diagnostic tests were applied: the Breusch-Pagan LM test, the Pesaran scaled LM test, and the Pesaran CD test.

Table 4.16:
Cross-Section Dependence Results (Model 6)

Test	Statistic	d.f.	Prob.
Breusch-Pagan LM	39.5952		0.6996
Pesaran scaled LM	-0.5697	45	0.5689
Pesaran CD	0.0678		0.9459

As reported in Table 4.16, all three tests consistently fail to reject the null hypothesis of cross-sectional independence. The Breusch-Pagan LM statistic is 39.5952 with a p-value of 0.6996, indicating no significant cross-sectional dependence. Similarly, the Pesaran

scaled LM statistic is -0.5697 with a p-value of 0.5689 , and the Pesaran CD statistic is 0.0678 with a p-value of 0.9459 , further confirming the absence of statistically significant correlation in the residuals across countries.

These results indicate that the panel data used in Model 6 satisfy the assumption of cross-sectional independence. This justifies the use of first-generation panel estimation techniques, including the panel ARDL approach, without the need to control for spatial or contemporaneous correlation across cross-sectional units. Furthermore, the absence of cross-sectional dependence suggests that the interaction between renewable energy and governance effectiveness operates independently across countries in the panel and is not driven by common regional dynamics or global shocks. The diagnostic tests confirm that the estimation of Model 6 can proceed without concerns of cross-sectional dependence. This finding enhances the credibility of the empirical results that follow and reinforces the structural soundness of the model.

4.6.2 Pedroni Residual Cointegration Test Results (Model 6)

To confirm the existence of a long-run equilibrium relationship among the variables in Model 6, the Pedroni residual cointegration test was applied. This model incorporates an interaction term between renewable energy consumption and government effectiveness (LRE*LEIU) in addition to standard EKC variables, with the aim of examining whether government effectiveness strengthens the environmental benefits of renewable energy.

Table 4.17:
Pedroni Residual Cointegration Results (Model 6)

Alternative hypothesis: common AR coefs. (within-dimension)		
Test	Statistic	Prob.
Panel v-Statistic	0.4793	0.3159
Panel rho-Statistic	0.3186	0.6250
Panel PP-Statistic	-3.9555	0.0000
Panel ADF-Statistic	-3.8727	0.0001
Alternative hypothesis: individual AR coefs. (between-dimension)		
Test	Statistic	Prob.
Group rho-Statistic	2.2428	0.9875
Group PP-Statistic	-3.8522	0.0001
Group ADF-Statistic	-3.6931	0.0001

The Pedroni test evaluates the null hypothesis of no cointegration against the alternative that a stable long-run relationship exists among the variables. The results, as presented in Table 4.17, offer strong and consistent support for cointegration. The within-dimension Panel PP-statistic is -3.9555 with a p-value of 0.0000 , and the Panel ADF-statistic is -3.8727 with a p-value of 0.0001 . These results lead to the rejection of the null hypothesis at the one percent level, indicating that the variables in Model 6 are cointegrated under the assumption of common dynamics. The between-dimension results reinforce this conclusion. The Group PP-statistic is -3.8522 with a p-value of 0.0001 , and the Group ADF-statistic is -3.6931 with a p-value of 0.0001 . These values also indicate strong statistical significance, suggesting that the existence of cointegration is robust even when allowing for country-specific variations in the adjustment process. Taken together, the findings from the Pedroni test confirm that carbon emissions, income, population, renewable energy use, government effectiveness, and their interaction are bound by a stable long-run relationship.

This result validates the use of the panel ARDL framework in estimating both the short-run and long-run dynamics in Model 6. Moreover, it supports the theoretical proposition that the interplay between government effectiveness and renewable energy consumption plays a sustained role in shaping environmental outcomes over time. Therefore, the cointegration results confirm the structural validity of Model 6 and provide a strong empirical foundation for interpreting the estimated long-run coefficients in the subsequent ARDL analysis.

4.6.3 Panel ARDL Estimation Results (Model 6)

Table 4.18 presents the estimation results of Panel ARDL Model 6 using the Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE) estimators to evaluate the long-run and short-run relationships between economic growth, population, renewable energy, institutional effectiveness, and environmental sustainability. The model includes interaction effects between renewable energy and government effectiveness to assess how governance moderates the role of clean energy in mitigating environmental degradation. The selection between estimators is guided by the Hausman test as robustness check, which assesses whether the homogeneity restrictions imposed by the PMG estimator are valid.

Table 4.18: (Model 6)
Panel ARDL

Long-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Std. error	Coefficient	Std. error
LGDP	-0.8360 ***	0.0070	64.1541 *	0.0721	1.1814 **	0.0315
LGDP ²	0.0991 ***	0.0002	-6.3190 *	0.0790	-0.0347	0.4879
LPOPL	0.5281 ***	0.0000	1.6948	0.3248	-0.1390	0.7307
LRE	0.0695 ***	0.0006	-0.5558 *	0.0713	-0.2336 **	0.0124
LEIU	-0.2470 ***	0.0003	1.3073	0.5276	0.7481 **	0.0427
LRE*LEIU	0.1007 ***	0.0001	-0.4691	0.5248	-0.3051 **	0.0373
Short-run	Pooled mean group		Mean group		Dynamic fixed effects	
Variable	Coefficient	Std. error	Coefficient	Variable	Coefficient	Std. error
COINTEQ	-0.2803 ***	0.0336	-0.6437 ***	0.0000	-0.0927 ***	0.0006
D(LGDP)	-11.8363	0.4359	-39.0206	0.2081	1.5025 ***	0.0014
D(LGDP ²)	1.3000	0.3548	3.6880	0.2362	-0.0640 *	0.0859
D(LPOPL)	-0.6380	0.6921	2.2907	0.7432	0.4037	0.3462
D(LRE)	-0.2142 ***	0.0002	0.0103	0.9477	0.0111	0.3989
D(LEIU)	0.5447 ***	0.0045	-0.2270	0.7181	-0.0423	0.3669
D(LRE*LEIU)	-0.2875 ***	0.0000	-0.0477	0.8739	0.0204	0.2749
C	-0.6865	0.0639	-83.2323	0.1280	-0.2976	0.3676
Hausman			22.6696		28.7677	
p-Value			(0.0009)		(0.0001)	

Note: *, **, and *** denote 10 %, 5 %, and 1 % significance levels, respectively

The Hausman test results ($\chi^2 = 22.6696$, $p = 0.0009$ for MG; $\chi^2 = 28.7677$, $p = 0.0001$ for DFE) strongly reject the null hypothesis of slope homogeneity, indicating that the MG and DFE estimators are statistically preferable to PMG. This suggests substantial heterogeneity in the long-run relationships across countries in the panel, and thus, the MG estimator provides more robust estimation and reliable coefficient estimates.

In the long-run equation, the PMG estimator yields statistically significant coefficients for all core variables. Specifically, the coefficient of LGDP is negative (-0.8360, $p < 0.01$), while the coefficient of LGDP² is positive (0.0991, $p < 0.01$), confirming fail to proven U-shaped Environmental Kuznets Curve (EKC) relationship. However, the MG

which more accurate model estimator shows the opposite signs, with an implausibly large positive coefficient for LGDP (64.1541) and a negative sign for LGDP² (-6.3190). This indicates the existence of U-Shaped EKC, and constants with the previous studies (Alnour et al., 2024; Kalim et al., 2024; Bucak et al., 2024).

Population (LPOPL) is positively and significantly associated with emissions in the PMG model (0.5281, $p < 0.01$), indicating that population pressures exacerbate environmental degradation. However, in MG and DFE, the effects are statistically insignificant. Renewable energy consumption (LRE) is positively associated with environmental quality in the PMG model (0.0695, $p < 0.01$), suggesting that a transition to renewable sources contributes to emission reductions in the long-run. The results supported by similar finding related to renewable energy relatively reduce the CO₂ emissions (Horobet et al., 2024; Mohamad et al., 2023; Ahmed et al., 2025).

Government effectiveness (LEIU) plays a crucial role in shaping environmental outcomes. In the PMG specification, LEIU has a significant negative coefficient (-0.2470, $p < 0.01$), implying that stronger governance frameworks lead to reductions in emissions. Moreover, the interaction term between renewable energy and government effectiveness (LRE*LEIU) is positively significant in the PMG model (0.1007, $p < 0.01$), which suggests that good governance enhances the positive environmental impact of renewable energy deployment. This moderating role of government effectiveness is also supported in the DFE model, where LRE*LEIU remains significantly negative, indicating that when institutions are weaker, renewable energy adoption may be less effective or even counterproductive in reducing emissions (Abdmouleh et al., 2015; Bhandary et al., 2021; Salvador & Sancho, 2021).

Turning to the short-run dynamics, the error correction term (COINTEQ) is negative and statistically significant across all estimators, confirming the presence of long-run cointegration. The PMG estimate of -0.2803 ($p < 0.01$) indicates that approximately 28% of the deviation from the long-run equilibrium is corrected each year. In the MG model, the adjustment speed is even higher (-0.6437), suggesting a faster convergence process in heterogeneous panels. The short-run coefficients generally exhibit less statistical significance.

Notably, the first-differenced renewable energy variable ($D(LRE)$) is negative and significant in the PMG model (-0.2142 , $p < 0.01$), indicating that abrupt changes in renewable energy use might initially increase emissions, possibly due to transitional inefficiencies or delays in technology adaptation. Similarly, the interaction term $D(LRE*LEIU)$ is negative and significant (-0.2875 , $p < 0.01$), reinforcing the notion that government effectiveness is vital for immediate environmental benefits from renewable energy. In terms of long-run elasticities, population exerts the strongest upward pressure on emissions (0.53%), followed by governance as the most powerful mitigating factor (-0.25%). Renewable energy alone has a modest effect (0.07%), but its impact is significantly amplified by good governance (0.10%), underscoring that institutional quality is decisive in maximising the environmental benefits of energy transitions. In the short-run, shocks correct by $\sim 28\%$ annually; a 1% increase in renewables cuts emissions by $\sim 0.21\%$, governance shocks alone raise emissions by $\sim 0.54\%$ due to transition frictions, while coordinated RE–governance changes yield an extra $\sim 0.29\%$ abatement effect.

In contrast, the MG and DFE estimates for the short-run effects are mostly insignificant, further supporting the preference for long-run analysis in drawing policy implications. Therefore, the findings from Model 6 underscore the robustness of the EKC hypothesis in the long-run and the importance of institutional effectiveness in enhancing the environmental benefits of renewable energy. These results suggest that policy efforts to decouple economic growth from environmental degradation should not only focus on energy transitions but also on strengthening institutional frameworks to ensure effective implementation and monitoring. The interaction between governance and renewable energy is particularly critical, as stronger government appear to amplify the environmental gains from clean energy investments.

The significant interaction between renewable energy and government effectiveness ($LRE*LEIU$) suggests that stronger institutions amplify the environmental benefits of clean energy. This operates through several mechanisms. First, effective governance reduces corruption and rent-seeking in the renewable energy sector, ensuring that funds are allocated efficiently and projects are completed on time rather than delayed or mismanaged. Second, governments with higher institutional quality are better equipped to design and enforce regulatory frameworks, such as renewable portfolio standards, grid integration protocols, and subsidy reforms, which accelerate the scaling-up of renewables.

Third, stronger institutions facilitate greater transparency and accountability, which improves investor confidence and attracts both domestic and foreign capital into renewable energy markets. This enables faster diffusion of advanced technologies, lowering transitional inefficiencies that otherwise raise emissions in the short-run. Finally, effective governance enhances monitoring and evaluation of renewable energy projects, allowing policymakers to quickly identify bottlenecks and correct implementation failures.

By contrast, in countries with weaker governance, renewable energy deployment may suffer from corruption in procurement, lack of enforcement capacity, and grid mismanagement, which diminishes its immediate impact on emissions and sometimes leads to rebound effects. This explains why, in the short-run, the PMG estimates show negative coefficients for $\Delta LRE * LEIU$: better institutions help ensure that the environmental dividends of renewable energy are realised more quickly, rather than delayed by inefficiencies or policy failures.

4.7 Discussions of the Results

This study provides a comprehensive empirical analysis of the Environmental Kuznets Curve (EKC) and the extended STIRPAT framework, focusing on how population growth, economic affluence, renewable energy use and government effectiveness interact to influence carbon dioxide emissions in the world's ten highest carbon-emitting countries. By applying both linear and nonlinear panel ARDL and NARDL models across six carefully structured specifications, the findings confirm core theoretical expectations while revealing important nuances about the circumstances under which renewable energy and governance produce real environmental benefits.

In Model 1, the standard STIRPAT structure is validated. The results show that population and income significantly increase emissions, while the squared term of income is negative and significant. It suggests that in the early stages of economic growth, the scale effect dominates, leading to higher emissions, but at higher income levels structural changes and cleaner technologies begin to reverse this trend (Naveed et al., 2022; Alnour et al., 2024). However, renewable energy as a technological factor is found to be insignificant in the long-run and only significant in the short-run. This implies that the renewable energy share in these countries remains insufficient to cause permanent structural shifts in carbon emissions, a pattern noted by Pata et al. (2025).

Model 2 tests for asymmetric effects by decomposing renewable energy into positive and negative changes. The findings reveal that only positive changes in renewable energy significantly reduce emissions in the long-run, while reductions in renewable energy use do not have an equal and opposite effect. This confirms the asymmetric STIRPAT framework that technological interventions like renewable energy expansion generate cumulative benefits that are not easily undone in reverse. Such path dependency is consistent with observations by Sheikh et al. (2020) and Alnour et al. (2024), who argue that once a country invests in modern renewables and infrastructure, some benefits persist even if policy support weakens temporarily. Therefore, maintaining continuous expansion of renewable energy capacity is more effective than merely preventing its decline.

Model 3 integrates government effectiveness to examine whether stronger institutional quality directly lowers emissions or strengthens the effect of renewable energy. While the inclusion of governance aligns with theoretical expectations from Haque and Ntim (2018) and Zhao et al. (2022), the coefficient for government effectiveness is insignificant in the long-run. This suggests that better governance alone does not guarantee emission reductions unless it is explicitly directed toward environmental policy implementation and technological adoption. Renewable energy remains insignificant in the long-run under this specification too, which supports findings by Teng and Wang (2021) that governance needs concrete policy channels to affect environmental performance.

Model 4 explores the interaction between renewable energy and governance quality. Interestingly, both renewable energy and its interaction term with governance emerge as positively significant under the PMG estimator. This counterintuitive outcome may reflect that in some contexts; renewable energy expansion still relies heavily on biomass or low-efficiency technologies which can increase local emissions if governance frameworks do not steer the energy mix towards modern renewables. The reversal of the EKC shape in this model, with income negatively associated and its squared term positively associated with emissions, reinforces concerns raised by Borožan (2022) and Ahmed et al. (2021) about policy misalignment. This result highlights that renewable energy expansion alone can produce mixed outcomes if governance is not well targeted.

Model 5 examines whether governance moderates the income-emissions link by including an interaction term between income and government effectiveness. The results confirm the EKC pattern once again, with income positively linked to emissions and the

squared term negatively linked, consistent with Cutcu et al. (2025) and Ikhsan and Amri (2024). However, the interaction term between income and governance is insignificant, indicating that governance does not fundamentally alter the turning point of the EKC within this sample. Renewable energy remains positively significant, which supports the idea that in fossil fuel-dominant economies, renewable energy adoption may not yet be sufficient to offset growing energy demand, as noted in Rahman et al. (2022) and Kalim et al. (2024).

Model 6 combines renewable energy and governance interaction again but estimates the model using the Mean Group estimator, which is more appropriate given the heterogeneity across these countries. This model shows the strongest evidence that effective governance enhances the environmental benefit of renewable energy. The interaction term between renewable energy and government effectiveness is negative and significant, indicating that strong institutional quality ensures that renewable energy deployment translates into actual emission reductions.

This finding aligns with the conclusions of Abdmouleh et al. (2015) and Salvador and Sancho (2021), who argue that institutional frameworks determine whether clean energy investments deliver real carbon benefits. The short-run PMG results also confirm that both changes in renewable energy and its governance interaction reduce emissions, underscoring the immediate importance of governance in ensuring renewable energy policy effectiveness.

Synthesising these six models reveals three core insights. First, the EKC hypothesis is robust for the world's largest emitters, but the point at which income leads to environmental improvement is shaped by structural and policy factors. This supports recent multi-country evidence showing that the EKC is more a result of deliberate policy than an automatic outcome of income growth, as suggested by Odei et al. (2025) and Horobet et al. (2024). Second, renewable energy acts as a critical technological lever in the extended STIRPAT framework but is highly conditional on both its expansion trajectory and the strength of governance. The consistent asymmetry observed confirms that policy must prioritise ongoing renewable energy growth rather than assume static capacity will suffice. Third, population remains a persistent driver of emissions, highlighting the importance of demographic pressures as emphasised in the original STIRPAT literature (York et al., 2003) and recent regional studies by Liu et al. (2021) and Rehman and Rehman (2022).

Together, these results make clear that renewable energy transitions are not a stand-alone solution for decarbonising the top emitters. These countries need to have a strong governance to ensure that investments in renewables are effectively integrated into national energy systems and are capable of displacing high-carbon sources. Policymakers should therefore focus on expanding clean energy capacity while simultaneously strengthening institutions that can enforce standards, manage subsidies and regulate the energy market transparently. The asymmetric finding further suggests that once momentum in renewable expansion is lost, simply stopping the rollback does not immediately restore environmental gains, highlighting the need for continuous policy commitment.

4.8 A Remark

This chapter has presented the empirical results derived from six panel econometric models examining the relationship between carbon dioxide (CO₂) emissions and a set of key determinants, including income, population, renewable energy consumption, and government effectiveness, across ten high-emission countries over the period 1996 to 2023. The estimations were grounded in the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT framework, with an emphasis on capturing both linear and non-linear dynamics, as well as moderation effects through interaction terms.

The results from the baseline models (Models 1 and 2) provide strong support for the EKC. Increases in income initially lead to higher emissions, but this trend reverses after a certain income threshold is reached, indicating that economic growth can contribute to environmental improvement in the long-run. Model 2 further confirms the existence of asymmetric effects of renewable energy, where increases in renewable energy consumption reduce emissions more effectively than decreases cause deterioration, highlighting the importance of sustained renewable energy expansion.

Models 3 and 4 introduce government effectiveness as a factor that potentially influences environmental outcomes. While government effectiveness does not exert a consistent direct effect on emissions in all cases, its significance in the short-run and in combination with renewable energy suggests that governance plays an enabling role in shaping environmental performance, particularly in the early phases of policy implementation.

Models 5 and 6 incorporate interaction terms to test whether the effect of income and renewable energy on emissions is conditional on government effectiveness. The findings reveal that the relationship between income and emissions may change in the presence of stronger or weaker governance, although the results are nuanced. In particular, Model 6 shows that government effectiveness enhances the short-run impact of renewable energy in reducing emissions, even if the long-run effects are less straightforward.

Across all models, population remains a significant driver of emissions in the long-run, reinforcing the scale effect observed in environmental economics. Renewable energy shows consistent short-run benefits, but its long-run effectiveness depends on the broader energy mix and institutional context. The absence of cross-sectional dependence and the confirmation of long-run cointegration in all models validate the use of the panel ARDL and NARDL approaches adopted in this study.

In sum, the empirical findings confirm the validity of the EKC hypothesis, underscore the environmental benefits of renewable energy, and highlight the importance of government effectiveness as a moderating factor. These results provide a robust empirical foundation for the policy recommendations and theoretical reflections that will be developed in the following chapter.

CHAPTER 5:

CONCLUSIONS

5.1 Introduction

This chapter concludes the thesis by integrating the main findings, theoretical insights, and policy implications that have emerged from the analysis. The study set out to explore the dynamic relationships between carbon dioxide emissions, economic growth, renewable energy consumption, population, and government effectiveness across the ten highest carbon-emitting countries during the period from 1996 to 2023. This study was guided by two principal theoretical frameworks, namely the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT model. These frameworks provided a structured foundation for understanding how economic, demographic, renewable energy consumption, and government effectiveness.

The purpose of this chapter is to summarise the study's main contributions and evaluate how effectively the research objectives have been achieved. Section 5.2 present the summary of the Interpretation of STIRPAT and EKC Validity. Section 5.3 extends the summary of key findings and links to research objectives. Section 5.4 extends the policy implications with specific reference to the 5.4.1, Kyoto Protocol and 5.4.2, Carbon Pollution Reduction Scheme. Section 5.5 outlines the study's limitations, and Section 5.6 offers recommendations for future research. The chapter concludes with Section 5.7, which provides a final reflection on the study's significance and overall contribution to the field of environmental economics.

5.2 Summary of the Findings

The extended STIRPAT models provide a comprehensive evaluation of how environmental degradation is shaped by population growth, economic affluence and technological factors. Analysis across all six models consistently highlights renewable energy as a crucial technological variable within the STIRPAT framework, yet its environmental effectiveness is shown to depend strongly on structural factors and the quality of governance. The results demonstrate that while population and income growth generally intensify environmental pressures, the adoption of renewable energy can mitigate emissions, although this effect is not uniform across countries and is highly sensitive to whether institutions support sustained clean energy deployment and effective regulation.

This section provides a detailed in-depth evaluation of both the STIRPAT framework (Section 5.2.1) and the Environmental Kuznets Curve (Section 5.2.2), drawing together insights from each model to explain how the key variables interact and under what conditions the anticipated environmental benefits can be realized.

5.2.1 In-Depth Evaluation of the STIRPAT Framework

The STIRPAT model is a stochastic extension of the classic IPAT identity, which expresses environmental impact (I) as a function of population (P), affluence (A), and technology (T). STIRPAT departs from the rigid proportionality of IPAT by allowing for elasticities to be estimated empirically and incorporating stochastic variation. In log-linear form, it enables testing of how population size, economic development, and technological change influence environmental degradation, often operationalised using carbon emissions. This study applies the STIRPAT framework across six dynamic panel ARDL models, each incorporating different theoretical refinements to test not only the standard P–A–T relationship but also the role of asymmetric adjustments, government effectiveness, and interaction effects.

5.2.1.1 Model 1: *STIRPAT Baseline* $LCO_2 = LGDP + LGDP^2 + LPOPL + LRE$

Model 1 captures the core components of the STIRPAT model: Population (P) is represented by LPOPL. Affluence (A) is proxied by LGDP and $LGDP^2$, then, Technology (T) is indirectly captured by LRE, with $LGDP^2$ included to test for non-linear income effects. Empirical findings from this model strongly support the STIRPAT framework. LPOPL has

a positive and significant coefficient, affirming that population growth intensifies environmental impact through the scale effect. LGDP is positive and significant, while LGDP² is negative and significant, indicating a non-linear affluence–impact relationship consistent with the Environmental Kuznets Curve (EKC).

LRE (renewable energy) is statistically insignificant in the long-run but significant in the short-run under PMG. This suggests that technological change, as captured by renewable energy deployment, does not have a consistent long-run effect across all countries, possibly due to variation in energy mix or institutional context. Nonetheless, the model adheres well to the STIRPAT structure.

5.2.1.2 Model 2: STIRPAT with Asymmetric Technological Adjustment – LRE⁺ and LRE⁻

Model 2 extends the STIRPAT framework by decomposing technological change into positive (LRE⁺) and negative (LRE⁻) adjustments. This allows the model to detect whether improvements and regressions in renewable energy adoption have asymmetric environmental consequences. The affluence and population variables behave consistently with STIRPAT expectations. LGDP remains positive and significant, and LGDP² remains negative and significant, reaffirming the EKC-type affluence–impact relationship.

LPOPL is positive and significant in the long-run. The asymmetric decomposition of LRE reveals that only LRE⁺ (positive changes in renewable energy) is statistically significant and negative in the long-run under PMG. LRE⁻ is not significant, suggesting that increases in renewable energy reduce emissions, but reductions in renewable energy capacity do not immediately result in an equivalent rise in emissions. This asymmetry aligns with the revised STIRPAT literature that advocates for directional sensitivity in technology’s impact.

5.2.1.3 Model 3: STIRPAT with government effectiveness (LEIU)

Model 3 incorporates government effectiveness (LEIU) as a governance-based extension of the technology component in STIRPAT. It acknowledges that institutional capacity plays a critical role in determining how effectively societies can deploy clean technologies and regulate environmental outcomes. LGDP and LGDP² remain significant and correctly signed. LPOPL continues to show a positive effect. LRE is insignificant in the long-run. LEIU, the government effectiveness is statistically insignificant in the long-run. While the inclusion of LEIU enriches the “Technology” pillar conceptually, the empirical evidence does not show a direct and significant long-run effect. However, its presence in the

model acknowledges that governance should be considered a mediator of technological effectiveness, even if its independent statistical influence varies.

5.2.1.4 Model 4: STIRPAT with Asymmetric Technology and Governance effectiveness (LRE^+ , LRE^- , $LEIU$, $LRE*LEIU$)

Model 4 presents an advanced STIRPAT specification by allowing governance to moderate the effects of technological change. It introduces an interaction term ($LRE*LEIU$) between renewable energy and government effectiveness. Empirical results reveal a significant U-shaped affluence, with $LGDP$ negative and $LGDP^2$ positive. This result deviates from the STIRPAT expectation that affluence eventually mitigates environmental degradation and instead suggests emissions rise again at higher income levels. Population retains a positive effect.

Both LRE and $LRE*LEIU$ are statistically significant. LRE is positive, while $LRE*LEIU$ is also positive. These signs imply that renewable energy, particularly when implemented in strong institutional contexts, may be associated with higher emissions. This could be due to transitional technologies, institutional focus on growth over sustainability, or incomplete clean energy transitions. This model suggests a conditional failure of the STIRPAT “T” pillar. Technological progress (as proxied by renewable energy use) does not automatically reduce environmental pressure unless accompanied by deep structural changes in energy systems and regulatory design.

5.2.1.5 Model 5: STIRPAT with Affluence–Governance effectiveness ($LGDP*LEIU$)

Model 5 tests whether governance moderates the impact of affluence on emissions. The interaction term $LGDP*LEIU$ reflects this mechanism. Both $LGDP$ and $LGDP^2$ remain statistically significant with the expected signs, affirming the inverted U-shaped EKC relationship. $LPOPL$ is also significant and positive. LRE is positive and significant, suggesting that renewable energy expansion may still coexist with emissions growth if renewables are not dominant in the overall energy mix. The interaction term $LGDP*LEIU$ is statistically insignificant in both the short and long-run, indicating that government effectiveness does not significantly moderate the affluence–emissions relationship. Despite this, the STIRPAT structure holds firmly: affluence, population, and technology are retained with interpretable and statistically strong effects.

5.2.1.6 Model 6: STIRPAT with Renewable Energy–Governance effectiveness (LRE*LEIU)

Model 6 assesses whether governance effectiveness influences the environmental impact of renewable energy using a STIRPAT framework with interaction effects. The MG estimator is preferred based on the Hausman test, indicating heterogeneous long-run relationships across countries. Under the MG estimator, the results support a U-shaped EKC, with a large positive coefficient on income and a negative squared term. However, these signs differ from the PMG estimates, which show a statistically significant but reversed pattern. Population effects are only significant in PMG.

Renewable energy (LRE) is positively associated with emissions in PMG, while the interaction term (LRE*LEIU) is also positive, implying that weakly targeted governance may reduce the effectiveness of clean energy. In contrast, the MG and DFE estimators suggest that government effectiveness can mitigate this effect, with LRE*LEIU turning negative and significant under DFE. Short-run estimates from PMG show that both $D(LRE)$ and $D(LRE*LEIU)$ are negative and significant, suggesting that clean energy backed by institutional support can reduce emissions immediately. The significant error correction terms confirm long-run equilibrium across all estimators. These findings highlight that renewable energy policies must be paired with strong governance to achieve meaningful environmental outcomes.

5.2.2 In-Depth Evaluation of the EKC

The Environmental Kuznets Curve (EKC) hypothesis is a widely studied proposition in environmental economics that links economic development to environmental degradation. The EKC posits a non-linear, as the inverted U-shaped relationship between per capita income and environmental, which typically proxied by CO₂ emissions. In the initial phases of growth, pollution rises with income due to industrialisation, energy use, and urbanisation. However, beyond a certain income threshold, structural shifts toward services, regulatory reforms, and technological advancements lead to declining emissions. This implies that economic growth can be both a cause of and solution to environmental degradation.

5.2.2.1 Model 1: Baseline EKC Specification (PMG)

Model 1 establishes the classical EKC framework by regressing carbon emissions (LCO_2) on GDP per capita ($LGDP$), its squared term ($LGDP^2$), population ($LPOPL$), and renewable energy consumption (LRE). Estimation using the Pooled Mean Group (PMG) approach produces statistically significant coefficients with expected signs for both income variables: $LGDP$ is positive, and $LGDP^2$ is negative. This confirms an inverted U-shaped income between and CO_2 emissions curve, thus supporting the EKC hypothesis in the long-run. The findings are consistent with the canonical EKC literature, indicating that emissions tend to increase with economic growth at early stages but decline as economies mature and adopt cleaner technologies. However, renewable energy consumption (LRE) is statistically insignificant in the long-run, suggesting that income-driven structural changes are the primary determinants of emission dynamics in this baseline specification.

5.2.2.2 Model 2: EKC with Asymmetric Renewable Energy (PMG)

Building upon the baseline, Model 2 introduces asymmetry in renewable energy use by decomposing LRE into positive (LRE^+) and negative (LRE^-) changes. The EKC structure remains robust, with $LGDP$ and $LGDP^2$ maintaining their expected signs and statistical significance. Notably, LRE^+ is significantly negative, indicating that increases in renewable energy consumption contribute to emission reductions. Conversely, LRE^- is insignificant, suggesting that reductions in renewable energy do not correspond to proportional increases in emissions. This asymmetric impact confirms the stability of the EKC hypothesis under more refined energy dynamics and implies that policy interventions should focus on expanding renewable capacity, as the environmental gains are primarily associated with positive shifts.

5.2.2.3 Model 3: EKC with Government Effectiveness (MG)

Model 3 (MG) augments the EKC with government effectiveness ($LEIU$) in the long-run equation. The EKC pattern remains intact and statistically strong as the $LGDP$ is positive and $LGDP^2$ is negative (both significant), confirming the inverted-U. Unlike the PMG case, under the MG estimator $LEIU$ is significantly negative in the long-run, indicating that better governance directly reduces emissions rather than merely shifting income dynamics; in other words, institutional quality operates as a structural mitigation lever alongside growth. Short-run MG dynamics show rapid error-correction toward equilibrium and some persistence in emissions, but contemporaneous shocks are mostly insignificant, underscoring that the

environmental payoff of governance is primarily long-run and structural rather than driven by transient fluctuations.

5.2.2.4 Model 4: EKC with Asymmetric Renewable Energy and Governance (PMG)

In Model 4, the specification is extended further by combining LRE^+ , LRE^- , $LEIU$, and their interaction term ($LRE*LEIU$). This more complex model leads to a reversal in the EKC relationship: $LGDP$ becomes negative and significant, while $LGDP^2$ is positive and significant. The result produces a U-shaped income and CO_2 emissions curve, indicating that emissions decline during early development but rise again at higher income levels. This outcome contradicts the EKC hypothesis and suggests that advanced economies may face renewed environmental pressure due to high consumption, energy-intensive industries, or rebound effects from efficiency gains.

The significant positive coefficient of $LRE*LEIU$ implies that good governance may amplify the effects of renewable energy deployment, but not always in a manner that reduces emissions. These results reflect the nuanced interplay between government effectiveness and clean energy, challenging the assumption that economic growth alone leads to environmental improvements.

5.2.2.5 Model 5: EKC with Income–Governance Interaction (PMG)

To test whether governance moderates the impact of economic growth on emissions, Model 5 introduces an interaction term ($LGDP*LEIU$) between income and governance effectiveness. The EKC pattern is reaffirmed: $LGDP$ is positive and significant, $LGDP^2$ is negative and significant, and the interaction term is statistically insignificant. This suggests that while governance might affect emissions through channels such as policy enforcement or innovation support, it does not shift the structural relationship between income and emissions. The EKC hypothesis, therefore, holds in its original form even when the government effectiveness is considered.

5.2.2.6 Model 6: EKC with Renewable Energy–Governance Interaction (MG)

Model 6 presents the most intricate scenario, incorporating renewable energy, governance, and their interaction term ($LRE*LEIU$), but estimated using the Mean Group (MG) estimator to account for country-specific long-run heterogeneity. The Hausman test supports the use of MG over PMG. The results under MG estimation confirm a inverted U-

shaped relationship: LGDP is positive and significant, and LGDP² is negative and significant. In the short-run under PMG, both D(LRE) and D(LRE*LEIU) are negative and significant, suggesting that clean energy backed by strong governance does reduce emissions in the short term. The divergence between short- and long-run effects signals the presence of lagged structural constraints, rebound effects, or delayed policy impacts that may undermine long-term environmental gains.

Table 6.1:
Summary of EKC

Model	Specification	Long-run	Short-run
Model 1 (PMG)	Baseline EKC: LGDP, LGDP ² , LPOPL, LRE	PMG Estimation	
		EKC shape: LGDP +2.4366*, LGDP ² -0.1948* → inverted- U EKC confirmed. Population (LPOPL): +0.1954 (**) → 1% ↑ population ⇒ ~0.20% ↑ CO ₂ .	Adjustment speed: ECM -0.1835 () → ~18%** of disequilibrium corrected per year. (ΔLRE): -0.0633* → 1% ↑ RE ⇒ ~0.06% immediate ↓ CO ₂ .
Model 2 (PMG)	EKC with Asymmetric Renewable Energy: LRE ⁺ , LRE ⁻	PMG Estimation	
		EKC shape: LGDP +2.3193*, LGDP ² -0.1815* → inverted- U EKC confirmed. Population (LPOPL): +0.5431* → 1% ↑ population ⇒ ~0.54% ↑ CO ₂ . Renewables – positive change (LRE ⁺): -0.0237* → expansions of RE reduce emissions in LR. Renewables – negative change (LRE ⁻): +0.0131* → cuts/slowdowns in RE raise emissions in LR.	Adjustment speed: ECM -0.2216 (significant) → system converges back to LR equilibrium. Persistence: ΔLCO ₂ (-1) +0.8345 (sig.) → emissions show state dependence/inertia. ΔLRE ⁺ , ΔLRE ⁻ and other SR covariates: mostly not significant under PMG.
Model 3 (MG)	EKC with Governance Effectiveness (LEIU)	MG Estimation	
		(LEIU): -0.1407 (**) → 1% ↑ governance ⇒ ~0.14% ↓ CO ₂ (significant mitigation).	Adjustment speed: ECM -0.7869* → ~79% of disequilibrium corrected within a year. Inertia: ΔLCO ₂ (-1) +0.1124* → emissions show persistence. Growth nonlinearity: ΔLGDP ² +2.6404* → positive SR pressure from the income nonlinearity. Governance shock (ΔLEIU): +0.0582 (**) → small SR uptick (transition/enforcement effects) despite LR mitigation.

Model	EKC with	PMG Estimation	
4 (PMG)	LRE ⁺ , LRE ⁻ , and LEIU	EKC shape: LGDP +2.5726*, LGDP ² -0.2072* → inverted- U EKC confirmed. (LPOPL): +0.5147* → 1% ↑ population ⇒ ~0.51% ↑ CO ₂ . (LEIU): +0.0354* → small positive LR coefficient (context-specific; governance rises with activity/emissions in the long-run for top emitters). (LRE ⁺): -0.0247* → expansions of RE reduce emissions in the long-run.	Adjustment speed: ECM -0.2326 () → ~23%** of disequilibrium corrected per year. (ΔLEIU): -0.0261 (**) → small immediate reduction in emissions when governance improves. (ΔLRE ⁻): -0.6560 (*) → significant asymmetric SR response (negative when RE contracts), indicating transitional dynamics. Example; also some country like Indonesia renewable energy still producing CO ₂ , however less than fossil energy.
Model	EKC with GDP	PMG Estimation	
5 (PMG)	× Governance (LGDP*LEIU)	EKC shape: LGDP +0.7846*, LGDP ² -0.0456* → inverted- U EKC confirmed. (LPOPL): +1.0855* → 1% ↑ population ⇒ ~1.09% ↑ CO ₂ (largest LR driver). Renewables (LRE): +0.0369* (small, positive sign; interpreted as RE not yet displacing fossils at scale in some countries.	EKC shape: LGDP +0.7846*, LGDP ² -0.0456* → inverted-U EKC confirmed. (ΔLRE): -0.1001* → 1% ↑ RE ⇒ ~0.10% immediate ↓ CO ₂ . Renewables (ΔLRE): -0.1001* → 1% ↑ RE ⇒ ~0.10% immediate ↓ CO ₂ . Interaction Δ(LGDP×LEIU)(-1): +3.4318 (*) → borderline, suggests temporary governance-income effects.
Model	EKC with	MG estimation	
6 (MG)	LRE*LEIU	LGDP: +64.1541* → positive (supports EKC with LGDP ²). LGDP ² : -6.3190* → negative (confirms inverted-U EKC). LRE (renewables): -0.5558* → 1% ↑ RE → ~0.56% ↓ emissions.	Error-correction term (ECM): -0.6437*** → ~64% of disequilibrium corrected within a year.

Note: EKC Validity is confirmed when LGDP is positive and LGDP² is negative (inverted U-shape).

MG = Mean Group; PMG = Pooled Mean Group.

(The summary only reports the variable that has a significant value)

5.3 Summary of Key Findings

The empirical results obtained in this study comprehensively fulfil the general aim and each specific research objective by providing robust evidence on how renewable energy deployment, economic growth, governance quality, and demographic trends collectively shape CO₂ emissions in the world's ten highest carbon-emitting countries over the period from 1996 to 2023. By applying an integrated framework that combines the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT model, the study generates nuanced insights that extend and contextualise existing findings in environmental economics and sustainability studies.

In addressing the first objective, which is to investigate the effect of renewable energy on CO₂ emissions, the findings reveal a multi-layered narrative. The baseline models (Models 1 and 3) indicate that renewable energy does not yet exert a robust long-run effect on emissions, which reflects the empirical reality that many large emitters continue to rely predominantly on fossil fuels despite modest increases in renewable energy capacity. This aligns with prior evidence suggesting that renewable energy must reach a critical scale and efficiency threshold to exert a transformative impact on national carbon footprints (Pata et al., 2025).

Importantly, the asymmetric specifications (Models 2 and 4) provide fresh empirical insight by decomposing renewable energy changes into positive and negative shocks. These results show that increases in renewable energy usage significantly contribute to long-run emissions reductions, while decreases do not produce equivalent emissions growth, highlighting an asymmetric and path-dependent relationship. This finding resonates with recent work emphasising the non-linear effectiveness of clean energy deployment (Sheikh et al., 2020; Pata & Aydin, 2020). Moreover, Model 6 demonstrates that renewable energy's mitigation effect is significantly stronger when institutional frameworks are sufficiently robust to ensure that clean energy expansion is well-managed, integrated, and consistently regulated. This highlights a key policy implication: technological solutions such as renewables cannot deliver their full environmental benefit in isolation but require supportive governance structures to maximise their impact.

The second objective which tests the validity of the Environmental Kuznets Curve (EKC) hypothesis, is addressed consistently across the models. Results from Models 1, 2, 3, 5, and 6 reveal a significant positive coefficient for income and a significant negative

coefficient for its squared term. This empirical pattern confirms the inverted U-shaped relationship predicted by the EKC, reinforcing the view that economic growth initially accelerates environmental degradation through industrial expansion and rising energy demand, but at higher income levels, structural change, technological advancement, and stronger regulation contribute to emissions reductions (Dinda, 2004; Odei et al., 2025). Notably, Model 4 highlights a deviation: a U-shaped income–emissions relationship emerges when renewable energy and governance interact ineffectively. This suggests that poorly designed clean energy policies or weak institutional alignment with decarbonisation goals may undermine the EKC dynamic, resulting in renewed environmental pressures at higher income levels. Such evidence supports recent literature questioning the automatic validity of the EKC in the presence of rebound effects and unsustainable consumption patterns in advanced economies (Borozan, 2022).

The third objective which evaluates the effect of population size on CO₂ emissions within the STIRPAT framework, is also consistently supported by the results. Across all models, population exerts a positive and significant effect, confirming the scale effect central to the STIRPAT perspective (York et al., 2003). This finding highlights demographic pressure as a structural driver of emissions, implying that mitigation strategies must be complemented by demographic management and urban planning measures if sustainability goals are to be achieved. The fourth objective, which investigates the moderating role of government effectiveness in the renewable energy–emissions nexus, is directly addressed through the inclusion of governance variables and interaction terms in Models 5 and 6.

In Model 3, government effectiveness by itself does not exhibit a significant direct long-run effect on CO₂ emissions, suggesting that institutional quality alone, without targeted environmental policies or technology-specific strategies, may not suffice to reduce emissions in high-carbon economies. However, when the interaction between renewable energy and governance effectiveness is introduced (Models 4 and 6), a more nuanced picture emerges. In Model 4, the interaction term is unexpectedly positive under the PMG estimator, indicating that in contexts where governance frameworks are fragmented or where the renewable sector still depends on low-efficiency resources such as traditional biomass, clean energy deployment may coincide with persistently high emissions.

This aligns with the observation that simply expanding nominal renewable capacity does not guarantee deep decarbonisation if the supporting institutional and regulatory

environment is weak (Ahmed et al., 2021; Mensah et al., 2023). In contrast, Model 6, estimated using the Mean Group estimator to account for heterogeneity, shows that when governance is effective and well-coordinated, it significantly amplifies the emissions-reducing impact of renewable energy.

This confirms theoretical expectations and empirical evidence in the literature suggesting that institutional capacity is a key enabler for translating clean technology investments into measurable environmental gains (Abdmouleh et al., 2015; Salvador & Sancho, 2021). The short-run results from the PMG estimator further reinforce this point, demonstrating that immediate policy action combining renewable energy expansion with good governance yields quick emissions reductions, although maintaining these benefits over the long term depends on sustained institutional support and policy coherence.

Overall, the study's findings demonstrate clear coherence with the stated research objectives. They validate the EKC and STIRPAT frameworks in the context of the world's top emitters but extend them by highlighting the crucial conditionality of technological and institutional factors. Renewable energy is shown to be an effective tool for decarbonisation only when its expansion is sustained and embedded in robust governance systems. Population growth continues to exacerbate emissions, confirming its central role in environmental impact assessments and supporting calls for integrated demographic, urban, and energy policy interventions.

In summary, this study provides a holistic and empirically grounded understanding of the drivers of CO₂ emissions in the world's largest carbon emitters. It contributes to the literature by confirming well-established hypotheses while also offering novel insights into the asymmetric, conditional, and interaction effects that must be addressed to ensure that economic growth, clean energy expansion, and governance reforms collectively lead to meaningful and sustained reductions in carbon emissions. These insights offer valuable guidance for policymakers designing integrated climate and energy strategies aligned with global sustainability targets.

5.4 Policy Implications

The empirical findings of this study provide vital guidance for international climate policy, particularly in the context of high-emission economies. The results confirm that

renewable energy consumption significantly contributes to reducing carbon emissions, especially when supported by high institutional effectiveness. These insights align directly with Sustainable Development Goal 7 (SDG 7), which advocates for clean and affordable energy, and SDG 13, which emphasises urgent climate action. However, the study also highlights that the mere availability of renewable energy is insufficient without robust governance to ensure consistent implementation, enforcement, and accountability.

Given the strategic importance of the ten highest CO₂-emitting countries in global mitigation efforts, the findings underscore the need to integrate government effectiveness considerations into the design and execution of climate policies. This is particularly relevant when evaluating the effectiveness of international agreements such as the Kyoto Protocol and domestic mechanisms like the Carbon Pollution Reduction Scheme. The following sections explore how the study's findings reinforce and expand upon these policy frameworks, offering recommendations that bridge empirical insights with actionable climate governance in high-emission contexts.

5.4.1 Policy Implication Related to Kyoto Protocol

The Kyoto Protocol, adopted in 1997 under the United Nations Framework Convention on Climate Change (UNFCCC), represented the first legally binding international agreement aimed at mitigating greenhouse gas emissions. It introduced the principle of common but differentiated responsibilities, placing the obligation of emissions reductions primarily on developed nations based on their historical contributions to climate change. To facilitate compliance, the Protocol established several mechanisms, including emissions trading, the Clean Development Mechanism, and joint implementation.

Despite its legal force and wide ratification, the practical impact of the Kyoto Protocol on the world's top carbon dioxide emitting countries has been uneven. The ten highest emitters which are China, the United States, India, Russia, Japan, Indonesia, Iran, Germany, Saudi Arabia, and South Korea, collectively account for the majority of global emissions. However, their trajectories since the Protocol's adoption vary significantly. Countries such as Japan and Germany, with strong regulatory government and substantial investment in low-carbon technologies, have made measurable progress in stabilising or reducing emissions. Others, including China, India, and Indonesia, have continued to

experience substantial growth in emissions, largely due to rapid industrialisation and continued dependence on fossil fuels.

This variation in outcomes points to a critical weakness in the design and enforcement of the Kyoto Protocol. While the agreement established a global framework for emissions reduction, it lacked robust mechanisms to ensure consistent implementation at the national level. Many countries adopted the Protocol but failed to translate its commitments into effective domestic policy. Moreover, the absence of binding targets for developing countries meant that the largest sources of emissions growth were not adequately constrained.

The empirical results of this study, based on the STIRPAT and Environmental Kuznets Curve frameworks, reinforce the limitations of purely formal international agreements in driving environmental performance. The analysis demonstrates that carbon dioxide emissions in the ten highest-emitting countries are driven by a combination of population growth, economic development, and energy consumption patterns. The Environmental Kuznets Curve is confirmed, with emissions rising in the early stages of income growth and declining beyond a certain threshold. However, the turning point is not guaranteed without deliberate policy interventions.

A key finding is the asymmetric role of renewable energy in emissions reduction. Only consistent positive changes in renewable energy consumption significantly reduce emissions in the long-run. Reductions or stagnation in renewable energy expansion do not produce symmetrical increases in emissions, but they do erode the momentum necessary for long-term climate targets. This highlights the need for policies that not only adopt renewable energy frameworks but actively sustain their growth over time.

Another crucial dimension revealed by the study is the role of governance. The interaction between renewable energy and institutional effectiveness is found to be significant in explaining variation in emissions performance. Countries with high governance capacity are more likely to convert renewable energy investments into actual emissions reductions. In contrast, in countries with weak institutional structures, renewable energy deployment may have limited or even counterproductive effects due to inefficiencies in policy execution, lack of regulatory enforcement, and misaligned energy strategies.

These findings suggest that for the Kyoto Protocol or any subsequent international climate agreement to be effective in high-emitting countries, several enhancements are necessary. First, emissions reduction commitments must be aligned with sector-specific targets, particularly for the energy, industrial, and transportation sectors which contribute most to emissions in these countries. Second, national governments should establish autonomous monitoring bodies capable of verifying compliance with international targets. Third, technical and policy assistance from countries with successful implementation histories should be integrated into bilateral and multilateral cooperation frameworks.

Therefore, the Kyoto Protocol remains a landmark in international environmental law, but its success within the ten highest carbon dioxide emitting countries depends on institutional capacity, targeted policy design, and the sustained growth of renewable energy. The agreement must evolve from a framework of formal commitment into a platform for measurable, sectoral, and governance-linked climate action. Only then can its objectives be realised in practice and contribute meaningfully to the global effort to combat climate change.

5.4.2 Policy Implication related to Carbon Pollution Reduction Scheme

The continued dominance of China and the United States in global carbon dioxide emissions places these two countries at the centre of international climate policy discussions. Together, they contribute over 40 percent of total global CO₂ emissions, making their mitigation strategies essential to the success or failure of global climate targets. While both countries have made progress in expanding renewable energy and implementing partial mitigation frameworks, the scale of their emissions necessitates more integrated, enforceable, and outcome-driven approaches.

One such approach is the Carbon Pollution Reduction Scheme, which has been discussed and implemented in various forms in different jurisdictions. This scheme comprises two primary components: carbon footprint monitoring and carbon taxation. These tools function together to ensure that emissions are not only measured accurately but also regulated through economic instruments that discourage excessive pollution and promote cleaner energy transitions.

In China, rapid industrialisation and energy-intensive development have led to steep increases in emissions over the past three decades. While the country has invested heavily in wind, solar, and hydroelectric infrastructure, coal remains the predominant energy source. Several provinces have piloted regional carbon markets, and a national emissions trading system for the power sector has been launched. However, the absence of a comprehensive, nationwide carbon tax continues to limit the country's ability to apply uniform pricing to carbon emissions. Adopting a full carbon pollution reduction framework that combines carbon accounting with progressive carbon taxation would allow China to align its domestic emissions control mechanisms with international standards while strengthening its long-term energy transition strategy.

The United States presents a different but equally complex scenario. Although emissions have stabilised or declined in some sectors due to fuel switching and technological improvements, federal climate policy has been marked by inconsistency. Some states, notably California and members of the Regional Greenhouse Gas Initiative, have established carbon pricing systems. However, there is no unified federal carbon tax or emissions cap. Implementing a nationwide carbon pollution reduction scheme would provide a consistent and credible framework for managing emissions, unify fragmented state-level initiatives, and reinforce the country's international climate commitments. A federal carbon tax coupled with robust emissions tracking would not only internalise environmental costs but also create incentives for low-carbon innovation and infrastructure.

Other top emitters such as India, Russia, Indonesia, and Iran face their own challenges in adopting such a framework. These include reliance on subsidised fossil fuels, limited regulatory capacity, and political sensitivities around energy taxation. Nonetheless, the principles of the carbon pollution reduction scheme can be adapted to these contexts. Starting with carbon footprint monitoring in emission-intensive sectors, followed by phased carbon pricing mechanisms, would provide a manageable pathway toward more comprehensive regulation.

Successful implementation of this scheme in any high-emitting country depends on three key conditions. First, there must be a legally mandated system for transparent and regular carbon accounting, covering major sectors such as electricity generation, manufacturing, and transportation. Second, carbon taxes must be designed to reflect the real cost of emissions, while considering economic impacts on vulnerable groups and regions.

Third, revenues collected from carbon taxes should be reinvested into clean energy development, energy efficiency programs, and institutional strengthening to support enforcement and compliance.

Additionally, both China and the United States would benefit from linking their national schemes to international carbon markets. Trading emissions credits with countries or firms that exceed their own targets can improve cost efficiency, provide financial incentives for early mitigation, and facilitate cross-border technology transfers. As these two countries lead global emissions, their adoption of such market-based instruments would significantly influence the trajectory of international climate policy.

In conclusion, the carbon pollution reduction scheme offers a coherent and practical framework for controlling emissions in the ten highest-emitting countries. For China and the United States in particular, embracing this approach would demonstrate global leadership, enable more consistent policy coordination, and contribute directly to the achievement of international climate goals. The integration of carbon footprint tracking and carbon taxation within a unified national strategy holds the potential to transform how emissions are managed, regulated, and ultimately reduced across the most critical global economies.

5.5 Limitations of the Study

While this study is grounded in strong theoretical foundations including the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT model and employs advanced panel econometric techniques such as ARDL and NARDL estimators, several limitations should be acknowledged to frame the scope and applicability of its findings. One major limitation concerns the selection of countries included in the analysis. This study focuses exclusively on ten of the world's highest carbon-emitting economies: China, the United States, India, Russia, Japan, Iran, Germany, Indonesia, South Korea, and Saudi Arabia.

These countries play a critical role in shaping global emissions trends and are therefore suitable for analysing the relationship between economic growth, energy consumption, government effectiveness, and environmental sustainability. However, this focus on high emitters inherently restricts the generalisability of the results to a broader set of countries. The patterns observed in this study may not apply to economies with lower

emission levels, different stages of industrialisation, or more limited institutional capacity. As such, caution is required when extending the conclusions to countries outside the selected sample, particularly those in the Global South, small island developing states, or regions with unique structural and environmental characteristics.

A second limitation arises from the assumption of cross-sectional independence embedded in the econometric design. The panel ARDL and NARDL models used in this study treat each country as an independent unit of analysis, unaffected by the environmental or policy developments occurring in other countries. In practice, however, national economies are increasingly interconnected through global trade, investment flows, technology transfer, and transboundary environmental effects.

For instance, a country's emissions performance may be influenced by the outsourcing of carbon-intensive production to other nations, or by regional energy agreements and shared resource management. By not accounting for spatial dependence or spillover effects, the study may overlook key mechanisms that drive emissions outcomes across borders. This methodological constraint implies that the estimated relationships reflect only internal national dynamics, potentially omitting external influences that are relevant in a globalised context.

Another limitation relates to the use of an aggregated measure of renewable energy consumption. The data used in this study, sourced from Our World in Data, combine various types of renewable energy including hydro, wind, solar, bioenergy, and geothermal into a single variable. While this allows for simplification and comparability across countries, it does not account for the fact that different countries rely on different renewable energy sources. Each source has distinct characteristics in terms of emissions mitigation potential, technological complexity, investment requirements, and integration with the national grid.

For example, hydroelectric power is dominant in some countries, while others focus on solar and wind due to resource availability and policy incentives. The assumption that all renewable energy types contribute equally to emissions reduction may lead to an oversimplified understanding of their environmental impact. In a panel setting where countries are structurally diverse, this aggregation may dilute the accuracy of the model in capturing the true effect of renewable energy on carbon emissions.

Finally, the study is constrained by data availability, particularly with regard to government effectiveness and renewable energy use in the early years of the sample. The analysis covers the period from 1996 to 2023 because government effectiveness data from the World Bank's Worldwide Governance Indicators is only available beginning in 1996. This temporal limitation means that any institutional developments or environmental reforms occurring prior to 1996 are excluded from the analysis, potentially missing important historical context.

In addition, the renewable energy consumption data for certain countries, especially Saudi Arabia, are sparse or negligible during the early years of the sample. For much of the late 1990s and early 2000s, Saudi Arabia's renewable energy use was either minimal or not consistently reported, resulting in limited variation and potentially weaker coefficient estimates for that country. These early data constraints may affect the precision of long-run estimations and reduce the robustness of the results for countries with delayed renewable energy development.

Taken together, these limitations underscore the importance of interpreting the results within the context of the countries studied, the model assumptions adopted, and the structure of the available data. While the findings provide useful insights into the role of economic growth, renewable energy, and governance in shaping environmental outcomes, they are not without caveats. A careful and context-sensitive interpretation is essential when drawing conclusions or making policy recommendations based on this analysis.

5.6 Future Research Recommendations

To advance the academic discourse and policy relevance of renewable energy research, future studies should prioritise areas that address the structural, methodological, and data-related constraints identified in this study. These recommendations are intended to support the development of more robust, context-sensitive, and policy-driven insights into the role of renewable energy in achieving environmental sustainability.

A key priority is the disaggregation of renewable energy sources. Instead of treating renewable energy as a single aggregated variable, future research should differentiate between solar, wind, hydro, biomass, and geothermal energy. Each source has unique environmental, technological, and economic characteristics. Solar and wind energy, for

instance, involve issues related to intermittency and grid integration, while hydro and biomass present concerns about land use, water consumption, and ecosystem disruption. By disaggregating these sources, researchers can better identify which technologies contribute most effectively to reducing carbon emissions under different national and regional conditions. This level of detail is essential for producing actionable knowledge that can inform targeted policy interventions, energy investment strategies, and technology deployment.

It is also essential for future research to examine the effectiveness of renewable energy within diverse institutional and policy environments. This study highlights the role of government effectiveness, but future work should go further by exploring how regulatory frameworks, financial incentives, energy market structures, and public-private partnerships influence the performance and adoption of renewable energy. Comparative analysis across countries with similar income levels but different institutional capacities would be particularly valuable. Such studies can help clarify whether the success of renewable energy transitions depends more on technological availability or on the strength of the enabling environment.

In addition, spatial and regional dynamics should be incorporated into the analysis of renewable energy development. Energy systems are not confined by national borders, and many countries participate in regional energy grids, cross-border electricity trading, and shared renewable infrastructure. Future research should apply spatial econometric models that account for these cross-border linkages. Doing so would provide a clearer understanding of how renewable energy policies and investments in one country can influence outcomes in neighbouring countries. This is especially important in regions such as ASEAN, the European Union, and Sub-Saharan Africa, where regional energy cooperation is expanding.

Another critical direction is the use of more granular and high-frequency data. Many national statistics are now available at quarterly intervals and often include sector-specific energy use. Employing such data would allow researchers to capture the immediate effects of policy changes, seasonal demand fluctuations, and short-term market shocks. Furthermore, integrating satellite data, smart grid metrics, or renewable energy project-level information could significantly enrich the empirical analysis. This level of granularity is increasingly important in evaluating the real-world impact of renewable energy deployment and monitoring the progress toward climate targets.

Finally, future studies should adopt modelling approaches that recognise the non-linearity and transitional nature of energy systems. The global shift from fossil fuels to renewables involves periods of uncertainty, rapid technological evolution, and structural economic change. Models that allow for time-varying parameters, regime shifts, or threshold effects can capture these dynamics more effectively than static linear models. In doing so, researchers will be better equipped to reflect the complexity of energy transitions and offer deeper insight into the long-term sustainability of different renewable energy pathways.

By addressing these critical areas, future research can play a transformative role in shaping the renewable energy agenda. It can bridge the gap between empirical findings and strategic decision-making, support more nuanced international comparisons, and ultimately contribute to accelerating the global transition toward low-carbon and resilient energy systems.

5.7 Conclusion

This chapter has presented and interpreted the empirical findings derived from a panel dataset consisting of the ten highest carbon-emitting countries over the period 1996 to 2023. The analysis employed both linear and non-linear panel autoregressive distributed lag (ARDL and NARDL) models to examine the short-run and long-run dynamics between carbon dioxide emissions, economic growth, renewable energy consumption, population, and government effectiveness. The theoretical framework guiding the analysis was grounded in the Environmental Kuznets Curve (EKC) hypothesis and the STIRPAT model, both of which provided complementary lenses for understanding the environmental impacts of demographic, economic, and technological factors.

The results from the baseline models confirmed the presence of an inverted U-shaped relationship between income per capita and carbon emissions, thus supporting the EKC hypothesis. In the early stages of economic growth, emissions tend to rise with increased industrial activity and energy consumption. However, after reaching a certain income threshold, further growth is associated with a decline in emissions, likely due to technological improvements, structural economic transformation, and stronger environmental regulation. This finding affirms the idea that economic development, when combined with appropriate policy and institutional measures, can eventually lead to environmental improvements.

The application of the STIRPAT model allowed for a more flexible estimation of the environmental effects of population, affluence, and technology. Consistent with STIRPAT expectations, population growth was found to exert a positive and statistically significant impact on carbon emissions, illustrating the scale effect of human activity on environmental degradation. Affluence, proxied by GDP per capita and its squared term, further clarified the non-linear trajectory of emissions along the development path. Renewable energy, representing a key technological factor in the STIRPAT framework, was generally associated with emissions reduction in the short-run, although its long-run impact was less robust across countries and specifications. This indicates that the environmental benefits of renewable energy are context-dependent and may require sustained commitment, investment, and policy continuity.

The government effectiveness played a critical role in shaping environmental outcomes. The interaction terms introduced into the models revealed that stronger governance enhances the effectiveness of both economic development and renewable energy in mitigating emissions. Specifically, the interaction between renewable energy and government effectiveness showed that institutional capacity significantly conditions the extent to which clean energy transitions result in tangible environmental gains. Likewise, the moderating effect of governance on the income-emissions relationship highlighted the importance of capable government in facilitating a faster and more stable movement toward the EKC turning point.

The inclusion of non-linear modelling through the NARDL approach revealed important asymmetries, particularly in how positive and negative changes in renewable energy consumption affect emissions. The findings suggested that increases in renewable energy usage have a more substantial impact on reducing emissions than the effect of equivalent decreases in renewable use. This asymmetry reflects the importance of policy stability and the cumulative nature of clean energy transitions, where sustained momentum yields stronger environmental outcomes.

From an econometric standpoint, the study ensured methodological rigour through a series of diagnostic procedures. Stationarity of the panel data was verified using unit root tests, confirming the appropriateness of the dynamic panel ARDL and NARDL models employed. These tests ensured that the long-run and short-run relationships among variables were estimated without spurious regression issues. Additionally, model robustness was

assessed through sensitivity checks, including alternative specifications and lag structures. Full statistical results, including stationarity diagnostics and model fit indicators, are provided in the appendices. These steps strengthen the validity of the empirical findings and reinforce the reliability of the policy recommendations derived from the models.

In summary, the empirical findings of this chapter underscore the interconnected roles of economic growth, demographic trends, renewable energy deployment, and institutional effectiveness in shaping the trajectory of carbon emissions. By integrating the EKC and STIRPAT frameworks within a dynamic panel econometric setting, the analysis offers a multidimensional understanding of environmental change across the world's most emission-intensive economies. These results contribute to the empirical literature on sustainable development and provide actionable insights for policymakers seeking to design integrated strategies that balance economic performance with long-term environmental goals.

REFERENCES

- Abdmouleh, Z., Alammari, R. A., & Gastli, A. (2015). Review of policies encouraging renewable energy integration & best practices. *Renewable and Sustainable Energy Reviews*, 45, 249-262. <https://doi.org/10.1016/j.rser.2015.01.035>
- Acemoğlu, D., & Robinson, J.A. (2016). Paths to Inclusive Political Institutions. In: Eloranta, J., Golson, E., Markevich, A., Wolf, N. (eds) *Economic History of Warfare and State Formation*. Studies in Economic History. Springer, Singapore. https://doi.org/10.1007/978-981-10-1605-9_1
- Adam, M. R., El-badawy, T., Shamsudin, M. S., Hubadillah, S. K., Jamalludin, M. R., Abd Aziz, M. H., & Nasir, A. M. (2024). Deforestation influence on climate change. In *Advances and Technology Development in Greenhouse Gases: Emission, Capture and Conversion* (pp. 169-183). Elsevier. <https://doi.org/10.1016/B978-0-443-19066-7.00010-2>
- Afroz, R., & Muhibbullah, M. (2022). Dynamic linkages between non-renewable energy, renewable energy and economic growth through nonlinear ARDL approach: evidence from Malaysia. *Environmental Science and Pollution Research*, 29(32), 48795-48811. <https://doi.org/10.1007/s11356-022-19346-0>
- AghaKouchak, A., Chiang, F., Huning, L. S., Love, C. A., Mallakpour, I., Mazdiyasni, O., ... & Sadegh, M. (2020). Climate extremes and compound hazards in a warming world. *Annual Review of Earth and Planetary Sciences*, 48(1), 519-548. <https://doi.org/10.1146/annurev-earth-071719-055228>
- Agusalim, L., Karim, M., Irfany, M. I., Lestari, A. V. A., & Pebrianti, H. (2025). Economic development and climate change: Insights from religious countries. *International Journal of Energy Economics and Policy*, 15(2), 32–39. <https://doi.org/10.32479/ijeep.17975>
- Ahmad, M., Balbaa, M. E., Zikriyoev, A., Nasriddinov, F., & Kuldasheva, Z. (2024). Energy efficiency, technological innovation, and financial development-based EKC premise: Fresh asymmetric insights from developing Asian regions. *Environmental Challenges*, 18, 100947. <https://doi.org/10.1016/j.envc.2024.100947>
- Ahmed, S., Abdi, A. H., Sodal, M., Yusuf, O. A., & Mohamud, M. H. (2025). Assessing the energy-economy-environment nexus in Somalia: The impact of agricultural value added on CO₂ emissions. *International Journal of Energy Economics and Policy*, 15(2), 143–150. <https://doi.org/10.32479/ijeep.17426>
- Ahmed, Z., Cary, M., Shahbaz, M., & Vo, X. V. (2021). Asymmetric nexus between economic policy uncertainty, renewable energy technology budgets, and environmental sustainability: Evidence from the United States. *Journal of Cleaner Production*, 313, 127723. <https://doi.org/10.1016/j.jclepro.2021.127723>
- Alam, I., Shichang, L., Muneer, S., Alshammary, K. M., & Rehman, M. Z. U. (2024). Does financial inclusion and information communication technology affect environmental degradation in oil-producing countries? *PLOS ONE*, 19(3), e0298545. <https://doi.org/10.1371/journal.pone.0298545>

- Ali, E. B. & Anufriev, V. P. (2023). Revisiting the energy consumption, economic growth and the environmental Kuznets curve in developing countries. *Economy of Regions*, 19(1), 75-84. <https://doi.org/10.17059/ekon.reg.2023-1-6>
- Ali, I. M. A. (2023). Income inequality and environmental degradation in middle-income countries: a test of two competing hypotheses. *Social Indicators Research*, 166(2), 299-321. <https://doi.org/10.1007/s11205-023-03068-y>
- Ali, M. U., Gong, Z., Ali, M. U., Asmi, F., & Muhammad, R. (2022). CO2 emission, economic development, fossil fuel consumption and population density in India, Pakistan and Bangladesh: a panel investigation. *International Journal of Finance & Economics*, 27(1), 18-31. <https://doi.org/10.1002/ijfe.2134>
- Allison, I., Paul, F., Colgan, W., & King, M. (2021). Ice sheets, glaciers, and sea level. In *Snow and ice-related hazards, risks, and disasters* (pp. 707-740). Elsevier. <https://doi.org/10.1016/B978-0-12-817129-5.00013-5>
- Alnafisah, N., Alsmari, E., Alshehri, A., & Binsuwadan, J. (2024). Assessing the impacts of technological innovation on carbon emissions in MENA countries: Application of the innovation curve theory. *Energies*, 17(4), 904. <https://doi.org/10.3390/en17040904>
- Alnour, M., Önden, A., Hasseb, M., Önden, İ., Rehman, M. Z., Esquivias, M. A., & Hossain, M. E. (2024). The asymmetric role of financial commitments to renewable energy projects, public R&D expenditure, and energy patents in sustainable development pathways. *Sustainability*, 16(13), 5503. <https://doi.org/10.3390/su16135503>
- Al-Mulali, U., Raboshuk, A., Ibrahim, R. L., & Saboori, B. (2024). Evaluating the asymmetric effect of patents driven environmental technologies on environmental degradation in the E7 countries: An extended model of STIRPAT. In *Natural Resources Forum*. Oxford, UK: Blackwell Publishing Ltd. <https://doi.org/10.1111/1477-8947.12439>
- Amer, E. A. A. A., Meyad, E. M. A., Meyad, A. M., & Mohsin, A. K. M. (2024). Impacts of renewable and disaggregated non-renewable energy consumption on CO2 emissions in GCC countries: A STIRPAT model analysis. *Heliyon*, 10(9). <https://doi.org/10.1016/j.heliyon.2024.e30154>
- Amin, A., Yusoff, N. Y. B. M, Yousaf, H., Peng, S., Işık, C., Akbar, M., & Abbas, S. (2023). The influence of renewable and non-renewable energy on carbon emissions in Pakistan: evidence from stochastic impacts by regression on population, affluence, and technology model. *Frontiers in Environmental Science*, 11, 1182055. <https://doi.org/10.3389/fenvs.2023.1182055>
- Andersson, F. N. (2024). Economic inequality and the ecological footprint: Time-varying estimates for four developed economies, 1962–2021. *Ecological Economics*, 220, 108185. <https://doi.org/10.1016/j.ecolecon.2024.108185>
- Aquilas, N. A., Ngangnchi, F. H., & Mbella, M. E. (2024). Industrialization and environmental sustainability in Africa: The moderating effects of renewable and non-renewable energy consumption. *Heliyon*, 10(4). <https://doi.org/10.1016/j.heliyon.2024.e25681>
- Aruga, K., Islam, M. M., & Jannat, A. (2024). Assessing the CO₂ emissions and energy source consumption nexus in Japan. *Sustainability*, 16(13), 5742. <https://doi.org/10.3390/su16135742>

- Auteri, M., Mele, M., Ruble, I., & Magazzino, C. (2024). The double sustainability: The link between government debt and renewable energy. *Journal of Economic and Administrative Sciences*, 40(1), e00356. <https://doi.org/10.1016/j.jeca.2024.e00356>
- Azimi, M. N., Rahman, M. M., & Maraseni, T. (2025). Advancing sustainable development goal 8 targets: The role of institutional quality, economic complexity, and state fragility in G20 nations (2000–2023). *Resources, Conservation and Recycling: Global Perspectives*, 1, 100278. <https://doi.org/10.1016/j.resglo.2025.100278>
- Aziz, G., Sarwar, S., Hussan, M. W., & Saeed, A. (2023). The importance of extended-STIRPAT in responding to the environmental footprint: Inclusion of environmental technologies and environmental taxation. *Energy Strategy Reviews*, 50, 101216. <https://doi.org/10.1016/j.esr.2023.101216>
- Bakry, W., Nghiem, X.-H., Bhatti, M. I., Al-Mohamad, S., & Cui, L. (2024). *Digital finance and sustainable development: Evidence from developing nations*. *Public Administration Review*. <https://doi.org/10.1177/00368504241278823>
- Balsalobre-Lorente, D., Nur, T., Topaloglu, E. E., & Evcimen, C. (2024). Assessing the impact of economic complexity on the ecological footprint in G7 countries: Fresh evidence under human development and energy innovation processes. *Global Responsibility Journal*, 50, 100182. <https://doi.org/10.1016/j.gr.2023.03.017>
- Bashir, M. F., Bashir, M. A., Raza, S. A., Bilan, Y., & Vasa, L. (2024). Linking gold prices, fossil fuel costs and energy consumption to assess progress towards sustainable development goals in newly industrialized countries. *Geoscience Frontiers*, 15(1), 101755. <https://doi.org/10.1016/j.gsf.2023.101755>
- Bektur, Ç. (2024). The role of economic freedom in achieving the environmental sustainability for the highest economic freedom countries: Testing the environmental Kuznets curve hypothesis. *Environmental Science and Pollution Research*, 31, 8426–8444. <https://doi.org/10.1007/s11356-023-29120-5>
- Bekun, F. V., Gyamfi, B. A., Olasehinde-Williams, G., & Yadav, A. (2024). Revisiting the foreign direct investment-CO2 emissions nexus within the N-EKC framework: Evidence from South Asian countries. *Sustainable Futures*, 6, 100357. <https://doi.org/10.1016/j.sftr.2024.100357>
- Bhandary, R. R., Gallagher, K. S., & Zhang, F. (2021). Climate finance policy in practice: A review of the evidence. *Climate Policy*, 21(4), 529–545. <https://doi.org/10.1080/14693062.2020.1871313>
- Bibi, S., Khan, A., Fubing, X., Jianfeng, H., Hussain, S., & Khan, A. N. (2024). Impact of environmental policies, regulations, technologies, and renewable energy on environmental sustainability in China's textile and fashion industry. *Frontiers in Environmental Science*, 12, 1496454. <https://doi.org/10.3389/fenvs.2024.1496454>
- Bisset, T. (2023). N-shaped EKC in sub-Saharan Africa: the three-dimensional effects of governance indices and renewable energy consumption. *Environmental Science and Pollution Research*, 30(2), 3321–3334. <https://doi.org/10.1007/s11356-022-22394-1>
- Borozan, D. (2022). Detecting a structure in the European energy transition policy instrument mix: What mix successfully drives the energy transition?. *Renewable and Sustainable Energy Reviews*, 165, 112621. <https://doi.org/10.1016/j.rser.2022.112621>
- Borsha, F. H., Voumik, L. C., Rashid, M., Das, M. K., Stępnicka, N., & Zimon, G. (2024). An empirical investigation of GDP, industrialization, population, renewable energy and

- co2 emission in Bangladesh: bridging EKC-STIRPAT models. *International Journal of Energy Economics and Policy*, 14(3), 560-571. <https://doi.org/10.32479/ijeep.15423>
- Bozatli, O., & Akca, H. (2024). Does the composition of environmental regulation matter for ecological sustainability? Evidence from Fourier ARDL under the EKC and LCC hypotheses. *Clean Technologies and Environmental Policy*, 26, 1143–1160. <https://doi.org/10.1007/s10098-024-02838-7>
- Brahmia, S. Y., & Mannai, S. (2025). Environmental degradation in Gulf Cooperation Council: Role of ICT development, trade, FDI, and energy use. *Sustainability*, 17(1), 54. <https://doi.org/10.3390/su17010054>
- Breusch, T. S., and Pagan, A. R. (1980). The Lagrange Multiplier test and its applications to model specification in econometrics. *The Review of Economic Studies*, 47(1), 239–253. <https://doi.org/10.2307/2297111>
- Bu, Y., Wang, E., Qiu, Y., & Möst, D. (2022). Impact assessment of population migration on energy consumption and carbon emissions in China: A spatial econometric investigation. *Environmental Impact Assessment Review*, 93, 106744. <https://doi.org/10.1016/j.eiar.2022.106744>
- Bucak, Ç., Önder, A. Ö., & Çatık, A. N. (2024). Spatial effects of renewable and fossil energy consumption on the ecological footprint for the EU countries. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-024-34803-8>
- Byaro, M., Dimoso, P., & Rwezaula, A. (2024). Are clean energy technologies a panacea for environmental sustainability in sub-Saharan African countries? *Environmental Science and Pollution Research*, 31(13), 13784–13802. <https://doi.org/10.1007/s11356-023-28438-4>
- Campos-Romero, H., & Rodil-Marzábal, Ó. (2024). Environmental effects of growth and global value chains: The case of East and Southeast Asian economies. *Sustainable Development*, 32(2), 431–448. <https://doi.org/10.1002/sd.2877>
- Cao, Y., Jamaani, F., & Qin, B. (2024). Modern methodological approaches for evaluating energy efficiency and environmental pollution: Emerging trends and technological innovation perspectives. *Energy Strategy Reviews*, 50, 101557. <https://doi.org/10.1016/j.esr.2024.101557>
- Çatık, A. N., Bucak, Ç., Ballı, E., Manga, M., & Destek, M. A. (2024). How do energy consumption, globalization, and income inequality affect environmental quality across growth regimes?. *Environmental Science and Pollution Research*, 31(7), 10976-10993. <https://doi.org/10.1007/s11356-023-31797-7>
- Celik, A., Kostekci, A., & Alola, A. A. (2024). Carbon neutrality implication of material productivity, total factor productivity and renewable energy uptake in the Nordics. *Ecological Indicators*, 160, 111813. <https://doi.org/10.1016/j.ecolind.2024.111813>
- Chopra, R., Rehman, M. A., Yadav, A., & Bhardwaj, S. (2024). Revisiting the EKC framework concerning COP-28 carbon neutrality management: Evidence from Top-5 carbon embittering countries. *Journal of Environmental Management*, 352, 120690. <https://doi.org/10.1016/j.jenvman.2024.120690>
- Chou, C. H., Ngo, S. L., & Tran, P. P. (2023). Renewable energy integration for sustainable economic growth: Insights and challenges via bibliometric analysis. *Sustainability*, 15(20), 15030. <https://doi.org/10.3390/su152015030>

- Chowdhury, R. R., & Moran, E. F. (2012). Turning the curve: A critical review of Kuznets approaches. *Applied Geography*, 32(1), 3-11. <https://doi.org/10.1016/j.apgeog.2010.07.004>
- Copley, J. (2023). Decarbonizing the downturn: addressing climate change in an age of stagnation. *Competition & change*, 27(3-4), 429-448. <https://doi.org/10.1177/10245294221120986>
- Coskey, S. K. M. & Kao, C. (1998). A Residual-base Test of the Null of Cointegration in Panel Data. *Econometric Reviews*, 17 (1), 57 – 84. <https://doi.org/10.1080/07474939808800403>
- Cutcu, I., Altiner, A., & Bozkurt, E. (2025). The impact of economic policy uncertainty and geopolitical risk on environmental quality: An analysis of the Environmental Kuznets Curve hypothesis with the novel QRPD approach. *Sustainability*, 17(1), 269. <https://doi.org/10.3390/su17010269>
- Daga, S., Yadav, K., Lakshmi, V., & Singh, P. (2024). Growth vs. green: Unpacking the economic–environmental dilemma in major carbon emitters with panel ARDL analysis. *Environmental Systems and Decisions*. <https://doi.org/10.1007/s44274-024-00173-8>
- De Hoyos, R. E., and Sarafidis, V. (2006). Testing for cross-sectional dependence in panel-data models. *The Stata Journal*, 6(4), 482–496. <https://doi.org/10.1177/1536867X0600600403>
- Delbeke, J., Runge-Metzger, A., Slingenberg, Y., & Werksman, J. (2019). The paris agreement. In *Towards a climate-neutral Europe* (pp. 24-45). Routledge.
- Destiariono, M. E. (2025). Do economic growth and urbanization drive CO2 emissions? Role of renewable energy and energy efficiency in Indonesia. *International Journal of Energy Economics and Policy*, 15(1), 245–254. <https://doi.org/10.32479/ijeep.18354>
- Destiariono, M. E., & Firmansyah. (2024). Does the linkage between GDP, renewable energy, and methane validate the EKC hypothesis? Evidence from Indonesia. *International Journal of Energy Economics and Policy*, 14(1), 38–47. <https://doi.org/10.32479/ijeep.15075>
- Dhayal, K. S., Enyoghasim, M. O., Anyanwu, K. C., Onwe, J. C., & Giri, A. K. (2025). Impact of green energy, strategic commodities and economic policy uncertainty towards environmental sustainability for Sub-Saharan Africa. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s43621-025-01023-0>
- Dinda, S. (2004). Environmental Kuznets curve hypothesis: a survey. *Ecological economics*, 49(4), 431-455. <https://doi.org/10.1016/j.ecolecon.2004.02.011>
- Doğan, N., & Dalkılıç, İ. (2024). Ink and influence: The role of media on climate policy understanding. *CINEJ Cinema Journal*, 13(1), Article 645. <https://doi.org/10.5195/cinej.2024.645>
- Du, J., Ahmad, M., Uddin, I., Xu, H., & Gu, X. (2023). From growth to sustainability: investigating N-shaped EKC and the role of energy productivity, technological advancement, and human capital in OECD economies. *Environmental Science and Pollution Research*, 30(46), 102374-102388. <https://doi.org/10.1007/s11356-023-29514-5>
- Duong, K., & Flaherty, E. (2023). Does growth reduce poverty? The mediating role of carbon emissions and income inequality. *Economic Change and Restructuring*, 56(5), 3309-3334. <https://doi.org/10.1007/s10644-022-09462-9>

- Dzwigol, H., Kwilinski, A., Lyulyov, O., & Pimonenko, T. (2023). The role of environmental regulations, renewable energy, and energy efficiency in finding the path to green economic growth. *Energies*, 16(7), 3090. <https://doi.org/10.3390/en16073090>
- Ebhota, W. S., & Jen, T. C. (2020). Fossil fuels environmental challenges and the role of solar photovoltaic technology advances in fast tracking hybrid renewable energy system. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 7, 97-117. <https://doi.org/10.1007/s40684-019-00101-9>
- Ehigiamusoe, K. U., & Dogan, E. (2022). The role of interaction effect between renewable energy consumption and real income in carbon emissions: evidence from low-income countries. *Renewable and Sustainable Energy Reviews*, 154, 111883. <https://doi.org/10.1016/j.rser.2021.111883>
- El-Hawwary, A., Brenzinger, K., Lee, H. J., Veraart, A. J., Morriën, E., Schlöter, M., ... & Ho, A. (2022). Greenhouse gas (CO₂, CH₄, and N₂O) emissions after abandonment of agriculture. *Biology and Fertility of Soils*, 58(5), 579-591. <https://doi.org/10.1007/s00374-022-01644-x>
- Elatrroush, I. (2025). Does financial development influence environmental quality? Evidence from emerging and developing countries. *Environment, Development and Sustainability*, 1-51. <https://doi.org/10.1007/s10668-024-05873-y>
- Erdogan, S., Pata, U. K., & Alola, A. A. (2024). Where do we stand on cutting coal dependency? Evidence from the top coal-dependent economies. *Energy Strategy Reviews*, 49, 101444. <https://doi.org/10.1016/j.esr.2024.101444>
- Ertur, C., & Musolesi, A. (2017). Weak and strong cross-sectional dependence: A panel data analysis of international technology diffusion. *Journal of Applied Econometrics*, 32(3), 477-503. <https://doi.org/10.1002/jae.2538>
- Eyuboglu, K., & Uzar, U. (2025). The social, economic, and environmental drivers of renewable energy: Is income inequality a threat to renewable energy transition?. *Journal of Cleaner Production*, 490, 144780. <https://doi.org/10.1016/j.jclepro.2025.144780>
- Falcone, P. M. (2023). Sustainable energy policies in developing countries: a review of challenges and opportunities. *Energies*, 16(18), 6682. <https://doi.org/10.3390/en16186682>
- Feng, M. Q., Morake, O., Sampene, A. K., & Agyeman, F. O. (2024). Trade openness, human capital, natural resource, and carbon emission nexus: A CS-ARDL assessment for Central Asian economies. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-024-33059-6>
- Filonchik, M., Peterson, M. P., Zhang, L., Hurynovich, V., & He, Y. (2024). Greenhouse gases emissions and global climate change: Examining the influence of CO₂, CH₄, and N₂O. *Science of The Total Environment*, 173359. <https://doi.org/10.1016/j.scitotenv.2024.173359>
- Ganda, F. (2025). Testing the environmental Kuznets curve hypothesis in South Africa using the ARDL approach. *Natural Resources Forum*. <https://doi.org/10.1111/1477-8947.12377>
- Gao, J., Hua, G., & Huo, B. (2025). Green Climate Finance Development and Environmental Air Quality Improvement: Unveiling the Role of Green Technological Progress and

- Industrial Symbiotic Agglomeration. *Business Strategy and the Environment*, 34(2), 1669-1690. <https://doi.org/10.1002/bse.4060>
- Gazeloğlu, C., & Erkılıç, E. (2025). Economic development, renewable energy use, and international tourism: Strategic approaches to carbon emission reduction in SICA countries. *Sustainability*, 17(5), 1995. <https://doi.org/10.3390/su17051995>
- Georgescu, I., Nica, I., & Kinnunen, J. (2024). Towards sustainability: Understanding Norway's ecological footprint through the framework of the Environmental Kuznets Curve. *Energies*, 17(23), 6074. <https://doi.org/10.3390/en17236074>
- Global Carbon Project (2022). Retrieve from <https://emissions.globalcarbonatlas.org/index.php#> (accessed 21 July 2024)
- Golledge, N. R. (2020). Long-term projections of sea-level rise from ice sheets. *Wiley Interdisciplinary Reviews: Climate Change*, 11(2), e634. <https://doi.org/10.1002/wcc.634>
- Granger, C. W., & Yoon, G. (2002). Hidden cointegration. U of California, Economics Working Paper, 2002-02.
- Gyamfi, B. A., Agozie, D. Q., Ali, E. B., Bekun, F. V., & Asongu, S. A. (2024). Assessment of the influence of institutions and globalization on environmental pollution for open and closed economies. *Quality & Quantity*, 58(5), 4353-4381. <https://doi.org/10.1007/s11135-024-01859-0>
- Hacıimamoglu, T. (2025). Investigating the EKC and LCC hypotheses for BRICS countries: The role of economic complexity in environmental degradation. *Natural Resources Forum*. <https://doi.org/10.1111/1477-8947.70013>
- Hacıimamoğlu, T., & Cengiz, V. (2024). Are natural resource rents and renewable energy consumption solutions for environmental degradation? Fresh insights from a modified ecological footprint model. *Sustainability*, 16(7), 2736. <https://doi.org/10.3390/su16072736>
- Hasan, M. M., Nan, S., & Rizwanullah, M. (2024). The role of environmental diplomacy and economic factors on environmental degradation. *Heliyon*, 10(5), e24642. <https://doi.org/10.1016/j.heliyon.2024.e24642>
- Hasanov, F. J., Mukhtarov, S., Suleymanov, E., & Shannak, S. (2024). The role of renewable energy and total factor productivity in reducing carbon emissions: A case of top-ranked nations in the renewable energy country attractiveness index. *Journal of Environmental Management*, 339, 121220. <https://doi.org/10.1016/j.jenvman.2024.121220>
- Heggelund, G. M. (2021). China's climate and energy policy: at a turning point?. *International Environmental Agreements: Politics, Law and Economics*, 21, 9-23.
- Haque, F., & Ntim, C. G. (2018). Environmental policy, sustainable development, governance mechanisms and environmental performance. *Business Strategy and the Environment*, 27(3), 415-435. <https://doi.org/10.1002/bse.2007>
- Herrera-García, G., Ezquerro, P., Tomás, R., Béjar-Pizarro, M., López-Vinielles, J., Rossi, M., ... & Ye, S. (2021). Mapping the global threat of land subsidence. *Science*, 371(6524), 34-36. <https://doi.org/10.1126/science.abb8549>
- Horobet, A., Belascu, L., Radulescu, M., Balsalobre-Lorente, D., Botoroga, C.-A., & Negreanu, C.-C. (2024). Exploring the nexus between greenhouse emissions,

- environmental degradation and green energy in Europe: A critique of the Environmental Kuznets Curve. *Energies*, 17(20), 5109. <https://doi.org/10.3390/en17205109>
- Huang, J., Zheng, B., & Du, M. (2025). How digital economy mitigates urban carbon emissions: The green facilitative power of industrial coagglomeration. *Applied Economics*, 1-19. <https://doi.org/10.1080/00036846.2025.2486785>
- Ikhsan, I., & Amri, A. (2024). Corruption and environmental damage: Evidence from panel data in ASEAN-6. *International Journal of Energy Economics and Policy*, 14(1), 70–76. <https://doi.org/10.32479/ijeep.15208>
- Im, K. S., Pesaran, M. H., & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of econometrics*, 115(1), 53-74. [https://doi.org/10.1016/S0304-4076\(03\)00092-7](https://doi.org/10.1016/S0304-4076(03)00092-7)
- International Energy Agency (IEA). (2020). *World Energy Outlook 2020*. Retrieve from <https://www.iea.org/reports/world-energy-outlook-2020>
- IPCC. (2022). Intergovernmental Panel on Climate Change. Sixth Assessment Report, Climate Change 2022: Impacts, Adaptation and Vulnerability, the Working Group II contribution. Retrieve from <https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/>
- Iqbal, M., Ul-Durar, S., Arshed, N., Shahzad, K., & Ayub, U. (2025). Connecting higher education and renewable energy to attain sustainability for BRICS countries: A climate Kuznets curve perspective. *International Journal of Emerging Markets*. <https://doi.org/10.1108/IJOEM-04-2023-0555>
- Issayeva, G., Zhussipova, E. Y., & Pazilov, G. A. (2024). Examining the Environmental Kuznets Curve hypothesis in energy, agriculture, and industry sectors: The case of Kazakhstan. *International Journal of Energy Economics and Policy*, 14(3), 62–70. <https://doi.org/10.32479/ijeep.16005>
- Javed, A., Rapposelli, A., Khan, F., Javed, A., & Abid, N. (2024). Do green technology innovation, environmental policy, and the transition to renewable energy matter in times of ecological crises? A step towards ecological sustainability. *Technological Forecasting and Social Change*, 202, 123638. <https://doi.org/10.1016/j.techfore.2024.123638>
- Kaika, D., & Zervas, E. (2013). The Environmental Kuznets Curve (EKC) theory—Part A: Concept, causes and the CO₂ emissions case. *Energy policy*, 62, 1392-1402. <https://doi.org/10.1016/j.enpol.2013.07.131>
- Kalim, R., Ul-Durar, S., Iqbal, M., Arshed, N., & Shahbaz, M. (2024). Role of knowledge economy in managing demand-based Environmental Kuznets Curve. *Geosystem Frontiers*, 11(1), 101594. <https://doi.org/10.1016/j.gsf.2023.101594>
- Ketchoua, G. S., Arogundade, S., & Mduduzi, B. (2024). Revaluating the sustainable development thesis: Exploring the moderating influence of technological innovation on the impact of foreign direct investment (FDI) on green growth in the OECD countries. *Discover Sustainability*, 5, Article 433. <https://doi.org/10.1007/s43621-024-00433-w>
- Khan, S. U., & Cui, Y. (2022). Identifying the impact factors of sustainable development efficiency: integrating environmental degradation, population density, industrial structure, GDP per capita, urbanization, and technology. *Environmental Science and Pollution Research*, 29(37), 56098-56113. <https://doi.org/10.1007/s11356-022-19809-4>

- Khan, S., Yuan, H., Yahong, W., & Ahmad, F. (2024). Environmental implications of technology-driven energy deficit and urbanization: Insights from the environmental Kuznets and pollution hypothesis. *Environmental Technology & Innovation*, 35, 103554. <https://doi.org/10.1016/j.eti.2024.103554>
- Kitole, F. A., Sesabo, J. K., Adesiyan, O. F., Ige, A. O., Ojo, T. O., Emenike, C. U., Khumalo, N. Z., Kassem, H. S., & Elhindi, K. M. (2024). Greening the growth: A comprehensive analysis of globalization, economic performance, and environmental degradation in Tanzania. *Sustainability*, 16(24), 10983. <https://doi.org/10.3390/su162410983>
- Kongkuah, M., Yao, H., & Yilanci, V. (2022). The relationship between energy consumption, economic growth, and CO₂ emissions in China: the role of urbanisation and international trade. *Environment, Development and Sustainability*, 1-25. <https://doi.org/10.1007/s10668-021-01628-1>
- Koçak, S., Bandy, T. P., & Awan, A. (2024). Is the environmental Kuznets curve valid for transport sector in Pakistan? New evidence for non-renewable energy and urbanization using the QARDL approach. *Environmental Science and Pollution Research*, 31, 2425–2443. <https://doi.org/10.1007/s11356-023-27255-z>
- Kao, C. & Chiang, M. H. (2000). On the Estimation and Inference of a Cointegrated Regression in Panel Data. *Advances in Econometrics*, 15, 179-222. [https://doi.org/10.1016/S0731-9053\(00\)15007-8](https://doi.org/10.1016/S0731-9053(00)15007-8)
- Kuldasheva, Z., Ahmad, M., Salahodjaev, R., & Fahlevi, M. (2023). Do tourism and renewable energy influence co₂ emissions in tourism-dependent countries?. *International Journal of Energy Economics and Policy*, 13(6), 146-152. <https://doi.org/10.32479/ijeep.14410>
- Kulmer, V., Seebauer, S., Hinterreither, H., Kortschak, D., Theurl, M. C., & Haas, W. (2022). Transforming the s-shape: Identifying and explaining turning points in market diffusion curves of low-carbon technologies in Austria. *Research Policy*, 51(1), 104371. <https://doi.org/10.1016/j.respol.2021.104371>
- Kumar, V., Ranjan, D., & Verma, K. (2021). Global climate change: the loop between cause and impact. In *Global climate change* (pp. 187-211). Elsevier. <https://doi.org/10.1016/B978-0-12-822928-6.00002-2>
- Kus, B., & Jackson, G. (2025). Green Transitions: Rethinking Political Economy in the Context of Climate Change. *Regulation & Governance*, 19(2), 287-302. <https://doi.org/10.1111/rego.70013>
- Kuznets, S. (1955). International differences in capital formation and financing. In *Capital formation and economic growth* (pp. 19-111). Princeton University Press.
- Kuznets, S. (1964). *Postwar Economic Growth: Four Lectures*. Harvard University Press.
- Kuznets, S. (1971). *Economic growth of nations: Total output and production structure*. Harvard University Press
- Kuznets, S. (2019). Economic growth and income inequality. In *The gap between rich and poor* (pp. 25-37). Routledge.
- Lanhui, W., & Ibrahim, A. S. (2024). Unraveling the environmental consequences of trade openness in South Africa: A novel approach using ARDL modeling. *Environmental Research Communications*, 6(5), 055002. <https://doi.org/10.1088/2515-7620/ad46ef>

- Le, T. T. (2022). How do corporate social responsibility and green innovation transform corporate green strategy into sustainable firm performance?. *Journal of Cleaner Production*, 362, 132228. <https://doi.org/10.1016/j.jclepro.2022.132228>
- Leal, P. H., & Marques, A. C. (2022). The evolution of the environmental Kuznets curve hypothesis assessment: A literature review under a critical analysis perspective. *Heliyon*, 8(11). <https://doi.org/10.1016/j.heliyon.2022.e11521>
- Lee, C. C., & Lee, J. D. (2009). Income and CO2 emissions: evidence from panel unit root and cointegration tests. *Energy policy*, 37(2), 413-423. <https://doi.org/10.1016/j.enpol.2008.09.053>
- Leitão, N. C. (2024). The link between human development, foreign direct investment, renewable energy, and carbon dioxide emissions in G7 economies. *Energies*, 17(5), 978. <https://doi.org/10.3390/en17050978>
- Li, P., He, Q., Zhang, J., & Xia, Q. (2024). Analyzing the impact of energy synergy and renewable energy generation on energy security: Empirical evidence from China's Yangtze River Delta region. *Energy*, 297, 131868. <https://doi.org/10.1016/j.energy.2024.131868>
- Liao, C., Erbaugh, J. T., Kelly, A. C., & Agrawal, A. (2021). Clean energy transitions and human well-being outcomes in Lower and Middle Income Countries: A systematic review. *Renewable and Sustainable Energy Reviews*, 145, 111063. <https://doi.org/10.1016/j.rser.2021.111063>
- Lin, T., Wang, L., & Wu, J. (2022). Environmental regulations, green technology innovation, and high-quality economic development in China: Application of mediation and threshold effects. *Sustainability*, 14(11), 6882. <https://doi.org/10.3390/su14116882>
- Liu, J., Li, M., & Ding, Y. (2021). Econometric analysis of the impact of the urban population size on carbon dioxide (CO2) emissions in China. *Environment, Development and Sustainability*, 23(12), 18186-18203. <https://doi.org/10.1007/s10668-021-01433-w>
- Liu, P., Ur Rahman, Z., Jóźwik, B., & Doğan, M. (2024). Determining the environmental effect of Chinese FDI on the Belt and Road countries' CO2 emissions: An EKC-based assessment in the context of pollution haven and halo hypotheses. *Environmental Sciences Europe*, 36, Article 66. <https://doi.org/10.1186/s12302-024-00866-0>
- Lohwasser, J., Schaffer, A., & Brieden, A. (2020). The role of demographic and economic drivers on the environment in traditional and standardized STIRPAT analysis. *Ecological economics*, 178, 106811. <https://doi.org/10.1016/j.ecolecon.2020.106811>
- Lu, R., Yang, Y., Liu, J., & Ayub, A. (2024). Exploring the impact of financial globalization, good governance and renewable energy consumption on environmental pollution: Evidence from BRICS-T countries. *Heliyon*, 10(6), e33398. <https://doi.org/10.1016/j.heliyon.2024.e33398>
- Luqman, M., Rayner, P. J., & Gurney, K. R. (2023). On the impact of urbanisation on CO2 emissions. *NPJ Urban Sustainability*, 3(1), 6. <https://doi.org/10.1038/s42949-023-00084-2>
- Mahmood, H. (2024). Military expenditures and the environment in MENA region: The interaction effects of wars and conflicts. *International Journal of Sustainable Development and Planning*, 19(10), 3397–3406. <https://doi.org/10.18280/ijstdp.191024>

- Mahmood, H., Irshad, A. R., & Tanveer, M. (2024). Do innovation and renewable energy transition play their role in environmental sustainability in Western Europe? *Humanities and Social Sciences Communications*, 11, 42. <https://doi.org/10.1057/s41599-023-02539-4>
- Malik, K., Capareda, S. C., Kamboj, B. R., Malik, S., Singh, K., Arya, S., & Bishnoi, D. K. (2024). Biofuels production: a review on sustainable alternatives to traditional fuels and energy sources. *Fuels*, 5(2), 157-175. <https://doi.org/10.3390/fuels5020010>
- Mamkhezri, J., & Khezri, M. (2024). Assessing the spillover effects of research and development and renewable energy on CO2 emissions: international evidence. *Environment, Development and Sustainability*, 26(3), 7657-7686. <https://doi.org/10.1007/s10668-023-03026-1>
- Martínez-Navarro, D., Amate-Fortes, I., & Guarnido-Rueda, A. (2020). Inequality and development: is the Kuznets curve in effect today?. *Economia Politica*, 37, 703-735. <https://doi.org/10.1007/s40888-020-00190-9>
- Martins, T., Barreto, A. C., Souza, F. M., & Souza, A. M. (2021). Fossil fuels consumption and carbon dioxide emissions in G7 countries: Empirical evidence from ARDL bounds testing approach. *Environmental Pollution*, 291, 118093. <https://doi.org/10.1016/j.envpol.2021.118093>
- Mata, J. P. V., Bautista, M. G. G., Granda, L. E. S., & Moreano, E. G. Z. (2024). Evaluating the Environmental Kuznets Curve: The role of renewable energy, economic growth, urban density and trade openness on CO2 emissions. An analysis for high-income countries using the CS-ARDL model. *International Journal of Energy Economics and Policy*, 14(2), 211–221. <https://doi.org/10.32479/ijeep.16740>
- Matemilola, S., & Alabi, H. A. (2023). Greenhouse effect. In *Encyclopedia of Sustainable Management* (pp. 1810-1813). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-25984-5_517
- Mensah, B. D., & Abdul-Mumuni, A. (2023). Asymmetric effect of remittances and financial development on carbon emissions in sub-Saharan Africa: an application of panel NARDL approach. *International Journal of Energy Sector Management*, 17(5), 865-886. <https://doi.org/10.1108/IJESM-03-2022-0016>
- Menyari, Y. E. (2024). The impact of tourism, foreign direct investment, trade, economic growth, and renewable energy on carbon emissions: The case of Mediterranean countries. *Journal of Economic and Social Studies*, 17(1), 313–337. <https://doi.org/10.70908/2232-6022/17.313-337>
- Michaelowa, A., Shishlov, I., & Brescia, D. (2019). Evolution of international carbon markets: lessons for the Paris Agreement. *Wiley Interdisciplinary Reviews: Climate Change*, 10(6), e613. <https://doi.org/10.1002/wcc.613>
- Mohamad, A. H. H. B., & Ab-Rahim, R. (2024). Do the various sources of energy consumption affect the environmental degradation in India?. *International Journal of Renewable Energy Development*, 13(2), 168-178. <https://doi.org/10.61435/ijred.2024.55836>
- Mohamad, A. H. H., & Ab-Rahim, R. (2025). Mapping the research landscape of energy market and renewable energy: A bibliometric analysis. *International Journal of Renewable Energy Development*, 14(4), 703-716. <https://doi.org/10.61435/ijred.2025.61058>

- Mohamad, A. H. H., Zainuddin, M. R. K. V., & Ab-Rahim, R. (2023). Does Renewable Energy Transition in the USA and China Overcome Environmental Degradation?. *International Journal of Energy Economics and Policy*, 13(6), 234–243. <https://doi.org/10.32479/ijeep.14840>
- Mohamed, E. F., Abdullah, A., Jaaffar, A. H., & Osabohien, R. (2024). Reinvestigating the EKC hypothesis: Does renewable energy in power generation reduce carbon emissions and ecological footprint? *Energy Strategy Reviews*, 53, 101387. <https://doi.org/10.1016/j.esr.2024.101387>
- Mohsin, M., Naseem, S., Sarfraz, M., & Azam, T. (2022). Assessing the effects of fuel energy consumption, foreign direct investment and GDP on CO2 emission: New data science evidence from Europe & Central Asia. *Fuel*, 314, 123098. <https://doi.org/10.1016/j.fuel.2021.123098>
- Muhammad, F., Qayyum, A., Bawazir, A. A., Jan, M., & Ahmed, N. (2024). Assessing the tri-dimensional nexus of energy, environment, and economic growth in Pakistan: An empirical study. *International Journal of Energy Economics and Policy*, 14(2), 331–338. <https://doi.org/10.32479/ijeep.16128>
- Nabaweesi, J., Kigongo, T. K., Buyinza, F., Adaramola, M. S., Namagembe, S., & Nkote, I. N. (2024). Investigating the modern renewable energy-environmental Kuznets curve (REKC) hypothesis for East Africa Community (EAC) countries. *Technological Sustainability*, 3(1), 76-95. <https://doi.org/10.1108/TECHS-09-2023-0037>
- Naseem, S., Mohsin, M., Zia-UR-Rehman, M., Baig, S. A., & Sarfraz, M. (2021). The influence of energy consumption and economic growth on environmental degradation in BRICS countries: an application of the ARDL model and decoupling index. *Environmental Science and Pollution Research*, 1-14. <https://doi.org/10.1007/s11356-021-16533-3>
- Naveed, A., Ahmad, N., Aghdam, R. F., & Menegaki, A. N. (2022). What have we learned from Environmental Kuznets Curve hypothesis? A citation-based systematic literature review and content analysis. *Energy Strategy Reviews*, 44, 100946. <https://doi.org/10.1016/j.esr.2022.100946>
- Naimoğlu, M., & Akal, M. (2024). Relationship between economic complexity, globalization, energy sources and environmental sustainability. *Politická Ekonomie*, 72(3), 249–275. <https://doi.org/10.18267/j.polek.1446>
- Naz, F., Tanveer, A., Karim, S., & Dowling, M. (2024). The decoupling dilemma: Examining economic growth and carbon emissions in emerging economic blocs. *Energy Economics*, 126, 107848. <https://doi.org/10.1016/j.eneco.2024.107848>
- Nica, I., Georgescu, I., & Kinnunen, J. (2024). An autoregressive distributed lag and environmental Kuznets curve approach: Linking CO2 emissions and electricity access in India. *Sustainability*, 16(24), 11278. <https://doi.org/10.3390/su162411278>
- Njie, Y., Wang, W., Liu, L., & Abdullah. (2024). Unveiling the nexus: Analyzing foreign direct investment and energy consumption in shaping carbon footprints across Africa's leading CO2-emitting countries. *International Journal of Renewable Energy Development*, 13(2), 60315. <https://doi.org/10.61435/ijred.2024.60315>
- Nugroho, A. D. (2024). Impact of agricultural technical efficiency on farm-gate emission: An implementation of Environmental Kuznets Curve in Asian developing countries.

- Caraka Tani: Journal of Sustainable Agriculture*, 39(2), 248–257.
<https://doi.org/10.20961/carakatani.v39i2.84098>
- Nunes, L. J. (2023). The rising threat of atmospheric CO₂: a review on the causes, impacts, and mitigation strategies. *Environments*, 10(4), 66.
<https://doi.org/10.3390/environments10040066>
- Odei, S. A., Dunyo, S. K., & Anderson, H. J. (2025). Research and development, economic growth, CO₂ emissions and environmental Kuznets curve. *Sustainable Futures*, 9, 100541. <https://doi.org/10.1016/j.sftr.2025.100541>
- Okesiji, S. O. (2025). Decentralized Renewable Energy Systems: A Pathway to Climate Resilience in Low-Income Regions. *Sustainability and Climate Change*, 18(2), 119–131. <https://doi.org/10.1089/scc.2025.0014>
- Okoth, E., & Omar, A. E. (2025). Urban Expansion, Governance, and Environmental Quality: Decoding the Drivers of Human Development in SADC Countries (2000–2020). *SAGE Open*, 15(2), 21582440251335192.
<https://doi.org/10.1177/21582440251335192>
- Omran, A., & Schwarz-Herion, O. (2020). Deforestation in Malaysia: the current practice and the way forward. *Sustaining our Environment for Better Future: Challenges and Opportunities*, 175–193. https://doi.org/10.1007/978-981-13-7158-5_11
- Omri, A., & Jabeur, S. B. (2024). Climate policies and legislation for renewable energy transition: The roles of financial sector and political institutions. *Technological Forecasting and Social Change*, 203, 123347.
<https://doi.org/10.1016/j.techfore.2024.123347>
- Otim, J., Mutumba, G. S., Watundu, S., Mubiinzi, G., & Kaddu, M. (2022). The effects of gross domestic product and energy consumption on carbon dioxide emission in Uganda (1986–2018). *International Journal of Energy Economics and Policy*, 12(1), 427–435.
<https://doi.org/10.32479/ijeep.12552>
- Our World in Data (2023). Carbon intensity of electricity. Retrieve from <https://ourworldindata.org/> (accessed 17 March 2023).
- Pal, S., & Mahalik, M. K. (2025). Role of Digitalization and Government Effectiveness in Sustainable Energy Transition: Evidence from Asian Economies. *International Social Science Journal*. <https://doi.org/10.1111/issj.12556>
- Pan, W., Han, H., & Ullah, S. (2024). *A Step Toward Green Sustainability: Revisiting the Environmental Kuznets Curve Nexus in Light of the Forestry Trade*. *Forests*, 15(12), 2089. <https://doi.org/10.3390/f15122089>
- Pata, U. K., Bulut, U., Balsalobre-Lorente, D., & Chovancová, J. (2025). Does income growth affect renewable energy or carbon emissions first? A Fourier-based analysis for renewable and fossil energies. *Energy Strategy Reviews*, 51, 101615.
<https://doi.org/10.1016/j.esr.2024.101615>
- Pedroni, P. (1999). Critical Values for Cointegration Tests in Heterogenous Panel with Multiple Regressors. *Oxford Bulletin of Economics and Statistics*, 61, 653–670.
<https://doi.org/10.1111/1468-0084.0610s1653>
- Pedroni, P. (2001). Fully Modified OLS for Heterogenous Cointegrated Panels. *Advances in Econometrics*, 15, 93 – 130. [https://doi.org/10.1016/S0731-9053\(00\)15004-2](https://doi.org/10.1016/S0731-9053(00)15004-2)

- Pesaran, M. H. (2004). General diagnostic tests for cross-sectional dependence in panels. *CESifo Working Paper Series* No. 1229.
- Pesaran, M. H. (2006). Estimation and inference in large heterogeneous panels with a multifactor error structure. *Econometrica*, 74(4), 967–1012. <https://doi.org/10.1111/j.1468-0262.2006.00692.x>
- Pesaran, M. H. (2014). Testing weak cross-sectional dependence in large panels. *Econometric Reviews*, 34(6–10), 1089–1117. <https://doi.org/10.1080/07474938.2014.956623>
- Pesaran, M. H., & Shin, Y. (1995). *An autoregressive distributed lag modelling approach to cointegration analysis* (Vol. 9514, pp. 371–413). Cambridge, UK: Department of Applied Economics, University of Cambridge.
- Pesaran, M. H., & Shin, Y. (1996). Cointegration and speed of convergence to equilibrium. *Journal of Econometrics*, 71(1–2), 117–143. [https://doi.org/10.1016/0304-4076\(94\)01697-6](https://doi.org/10.1016/0304-4076(94)01697-6)
- Pesaran, M. H., Shin, Y. & Smith, R. (1999). Pooled Mean Group Estimation of Dynamic Heterogeneous Panels. *Journal of the American Statistical Association*. vol. 94, 621–634. <https://doi.org/10.1080/01621459.1999.10474156>
- Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of applied econometrics*, 16(3), 289–326. <https://doi.org/10.1002/jae.616>
- Phillips, P. (1995). Fully Modified Least Squares and Vector Autoregression. *Econometrica*, vol. 63, 1023–1078. <https://doi.org/10.2307/2171721>
- Phillips, P., & Hansen, B. (1990). Statistical Inference in Instrumental Variables Regression with I (1) Processes. *Review of Economic Studies*, vol. 57, 99–125. <https://doi.org/10.2307/2297545>
- Piccolroaz, S., Woolway, R. I., & Merchant, C. J. (2020). Global reconstruction of twentieth century lake surface water temperature reveals different warming trends depending on the climatic zone. *Climatic Change*, 160(3), 427–442. <https://doi.org/10.1007/s10584-020-02663-z>
- Primbetova, M., Sharipov, K., Allayarov, P., & Haq, I. U. (2022). Investigating the impact of globalization on environmental degradation in Kazakhstan. *Frontiers in Energy Research*, 10. <https://doi.org/10.3389/fenrg.2022.896652>
- Ozkan, C., & Okay, N. (2024). Renewable energy, economic policy uncertainty and climate policy uncertainty: New evidence for Environmental Kuznets Curve from emerging and developed countries. *Sustainability*, 16(14), 6049. <https://doi.org/10.3390/su16146049>
- Rafindadi, A. A., Aliyu, I. B., & Usman, O. (2022). Revisiting the electricity consumption-led growth hypothesis: is the rule defied in France?. *Journal of Economic Structures*, 11(1), 27. <https://doi.org/10.1186/s40008-022-00290-8>
- Rahman, M. H., Voumik, L. C., Rahman, M. M., & Majumder, S. C. (2024a). Scrutinizing the existence of the Environmental Kuznets Curve in the context of foreign direct investment, trade, and renewable energy in Bangladesh: Impending from ARDL method. *Environment, Development and Sustainability*, 26(5), 9217–9244. <https://doi.org/10.1007/s10668-023-03940-4>

- Rahman, M. M., Khan, I., Field, D. L., Techato, K., & Alameh, K. (2022). Powering agriculture: Present status, future potential, and challenges of renewable energy applications. *Renewable Energy*, 188, 731-749. <https://doi.org/10.1016/j.renene.2022.02.065>
- Rahman, M. M., Husnain, M. I. U., & Azimi, M. N. (2024b). An environmental perspective of energy consumption, overpopulation, and human capital barriers in South Asia. *Scientific Reports*, 14, Article 10636. <https://doi.org/10.1038/s41598-024-53950-z>
- Ramos-Herrera, M. D. C. (2024). Economic growth and deviations from the equilibrium exchange rate: a panel ARDL and panel NARDL approach. *Applied Economic Analysis*. <https://doi.org/10.1108/AEA-02-2024-0065>
- Ratnadewati, A., Mafruhah, I., & Gravitiani, E. (2024). Multi-analysis environmental Kuznets curve for developing country in Southeast Asia: Using macro economics perspective. *International Journal of Environmental Science and Development*, 15(5), 1494. <https://doi.org/10.18178/ijesd.2024.15.5.1494>
- Rehman, E., & Rehman, S. (2022). Modeling the nexus between carbon emissions, urbanization, population growth, energy consumption, and economic development in Asia: Evidence from grey relational analysis. *Energy Reports*, 8, 5430-5442. <https://doi.org/10.1016/j.egyr.2022.03.179>
- Reis, E., & Guzman, R. (2023). An econometric model of Amazon deforestation. In *The causes of tropical deforestation* (pp. 172-191). Routledge.
- Rena, Yadav, S., Patel, S., Killedar, D. J., Kumar, S., & Kumar, R. (2022). Eco-innovations and sustainability in solid waste management: An Indian upfront in technological, organizational, start-ups and financial framework. *Journal of Environmental Management*, 302, 113953. <https://doi.org/10.1016/j.jenvman.2021.113953>
- Ritu, R. K., & Kaur, A. (2024). Testing the agriculture-induced Environmental Kuznets Curve with moderation effect of human capital and renewable energy: insights from BRICS economies. *Environmental Science and Pollution Research*, 31(37), 49529-49545. <https://doi.org/10.1007/s11356-024-34478-1>
- Rogge, K. S., Kern, F., & Howlett, M. (2017). Conceptual and empirical advances in analysing policy mixes for energy transitions. *Energy research & social science*, 33, 1-10. <https://doi.org/10.1016/j.erss.2017.09.025>
- Rokhmawati, A., Sarasi, V., & Berampu, L. T. (2024). Scenario analysis of the Indonesia carbon tax impact on carbon emissions using system dynamics modeling and STIRPAT model. *GeoJournal of Sustainability and Transition*, 3(3), 100070. <https://doi.org/10.1016/j.geosus.2024.07.003>
- Romm, J. J. (2022). *Climate change: What everyone needs to know*. Oxford University Press.
- Roy-Mukherjee, S., & Udeogu, E. (2021). Neo-liberal globalization and income inequality: panel data evidence from OECD and Western Balkan countries. *Journal of Balkan and Near Eastern Studies*, 23(1), 15-39. <https://doi.org/10.1080/19448953.2020.1852004>
- Said, R. (2024). Financial inclusion and environmental pollution in sub-Saharan Africa: Moderating effects of economic growth and renewable energy. *Environmental Science and Pollution Research*, 31(43), 55346-55360. <https://doi.org/10.1007/s11356-024-34785-7>

- Saidi, K. & Mbarek, M. B. (2016). Nuclear energy, renewable energy, CO₂ emissions, and economic growth for nine developed countries: evidence from panel granger causality tests. *Progress in Nuclear Energy*, 88, 364-374. <https://doi.org/10.1016/j.pnucene.2016.01.018>
- Salahodjaev, R., & Sadikov, A. (2024). Examining the nexus between renewable energy, CO₂ emissions, and economic factors: Implications for countries marked by high rates of coronary heart disease. *Energies*, 17(23), 6057. <https://doi.org/10.3390/en17236057>
- Salvador, M., & Sancho, D. (2021). The role of local government in the drive for sustainable development public policies. An analytical framework based on institutional capacities. *Sustainability*, 13(11), 5978. <https://doi.org/10.3390/su13115978>
- Shahbaz, M., Loganathan, N., Muzaffar, A. T., Ahmed, K., & Jabran, M. A. (2016). How urbanization affects CO₂ emissions in Malaysia? The application of STIRPAT model. *Renewable and Sustainable Energy Reviews*, 57, 83-93. <https://doi.org/10.1016/j.rser.2015.12.096>
- Shahgedanova, M. (2021). Climate change and melting glaciers. In *The impacts of climate change* (pp. 53-84). Elsevier. <https://doi.org/10.1016/B978-0-12-822373-4.00007-0>
- Shin, Y., Yu, B., & Greenwood-Nimmo, M. (2014). Modelling asymmetric cointegration and dynamic multipliers in a nonlinear ARDL framework. *Festschrift in honor of Peter Schmidt: Econometric methods and applications*, 281-314. https://doi.org/10.1007/978-1-4899-8008-3_9
- Sheikh, U. A., Tabash, M. I., & Asad, M. (2020). Global financial crisis in effecting asymmetrical co-integration between exchange rate and stock indexes of South Asian region: Application of panel data NARDL and ARDL modelling approach with asymmetrical granger causality. *Cogent Business & Management*, 7(1), 1843309. <https://doi.org/10.1080/23311975.2020.1843309>
- Shouwu, J., Xu, T., Shehzad, K., Zaman, B. U., & Wuyue, L. (2024). The role of environmental technologies and clean energy transition in shaping the N-shaped Environmental Kuznets Curve: A North African perspective. *Environmental Technology & Innovation*, 33, 103463. <https://doi.org/10.1016/j.eti.2023.103463>
- Shrimali, G., & Kniefel, J. (2011). Are government policies effective in promoting deployment of renewable electricity resources?. *Energy Policy*, 39(9), 4726-4741. <https://doi.org/10.1016/j.enpol.2011.06.055>
- Simbi, C. H., Yao, F., & Zhang, J. (2025). Sustainable development in Africa: A comprehensive analysis of GDP, CO₂ emissions, and socio-economic factors. *Sustainability*, 17(2), 679. <https://doi.org/10.3390/su17020679>
- Sobirov, Y., Makhmudov, S., Saibniyazov, M., Tukhtamurodov, A., Saidmamatov, O., & Marty, P. (2024). Investigating the impact of multiple factors on CO₂ emissions: Insights from quantile analysis. *Sustainability*, 16(6), 2243. <https://doi.org/10.3390/su16062243>
- Soeder, D. J. (2025). Greenhouse gas and climate change. In *Energy futures: The story of fossil fuel, greenhouse gas, and climate change* (pp. 97-141). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-83603-9_5
- Stern, D. I. (2017). The environmental Kuznets curve after 25 years. *Journal of Bioeconomics*, 19, 7-28. <https://doi.org/10.1007/s10818-017-9243-1>

- Su, X., Raza, K., Waseem, L. A., & Waheed, R. (2025). Fostering a green tomorrow: Exploring the impact of economic fitness on CO2 reduction along the Environmental Kuznets Curve with capital and renewable energy. *Polish Journal of Environmental Studies*, 34(2). <https://doi.org/10.15244/pjoes/188187>
- Sun, J., & Qamruzzaman, M. (2025). Technological innovation, trade openness, natural resources, clean energy on environmental sustainability: a competitive assessment between CO2 emission, ecological footprint, load capacity factor and inverted load capacity factor in BRICS+ T. *Frontiers in Environmental Science*, 12, 1520562. <https://doi.org/10.3389/fenvs.2024.1520562>
- Sun, Y., Usman, M., Radulescu, M., Pata, U. K., & Balsalobre-Lorente, D. (2024). New insights from the STIPART model on how environmental-related technologies, natural resources and the use of the renewable energy influence load capacity factor. *Gondwana Research*, 129, 398-411. <https://doi.org/10.1016/j.gr.2023.05.018>
- Suyanto, Almughni, M. A. A., Suprijati, J., Standsyah, R. E., & Dwiningwarni, S. S. (2024). Institutional quality and government expenditure: An empirical study of the Environmental Kuznets Curve (EKC) in G20 countries. *Ekonomia i Środowisko*, 90(3), 883. <https://doi.org/10.34659/eis.2024.90.3.883>
- Taher, H. (2024). The influence of renewable energy and financial development on testing the Environmental Kuznets Curve in Lebanon: ARDL approach. *Environmental Economics*, 15(2), 93–103. [https://doi.org/10.21511/ee.15\(2\).2024.09](https://doi.org/10.21511/ee.15(2).2024.09)
- Tebaldi, C., Ranasinghe, R., Voutsoukas, M., Rasmussen, D. J., Vega-Westhoff, B., Kirezci, E., ... & Mentaschi, L. (2021). Extreme sea levels at different global warming levels. *Nature Climate Change*, 11(9), 746-751. <https://doi.org/10.1038/s41558-021-01127-1>
- Teklie, D. K. and Yağmur, M. H. (2024). Effect of economic growth on co2 emission in Africa: do financial development and globalization matter?. *International Journal of Energy Economics and Policy*, 14(1), 121-140. <https://doi.org/10.32479/ijee.15141>
- Teng, F., & Wang, P. (2021). The evolution of climate governance in China: drivers, features, and effectiveness. *Environmental Politics*, 30(sup1), 141-161. <https://doi.org/10.1080/09644016.2021.1985221>
- Toumi, S. (2025). Unveiling impact of financial development, renewable energy, and technological innovation on ecological footprint in major remittance-receiving economies – A PQARDL approach. *International Journal of Renewable Energy Development*, 14(1), 1–15. <https://doi.org/10.61435/ijred.2025.60762>
- Tudor, C., & Sova, R. (2021). On the impact of GDP per capita, carbon intensity and innovation for renewable energy consumption: worldwide evidence. *Energies*, 14(19), 6254. <https://doi.org/10.3390/en14196254>
- Uchiyama, K. (2016). *Environmental Kuznets curve hypothesis* (pp. 11-29). Springer Japan. https://doi.org/10.1007/978-4-431-55921-4_2
- Ullah, A., Dogan, M., Pervaiz, A., Bukhari, A. A. A., Akkus, H. T., & Dogan, H. (2024). The impact of digitalization, technological and financial innovation on environmental quality in OECD countries: Investigation of N-shaped EKC hypothesis. *Technology in Society*, 77, 102484. <https://doi.org/10.1016/j.techsoc.2024.102484>
- Usman, M., & Hammar, N. (2021). Dynamic relationship between technological innovations, financial development, renewable energy, and ecological footprint: fresh

- insights based on the STIRPAT model for Asia Pacific Economic Cooperation countries. *Environmental Science and Pollution Research*, 28(12), 15519-15536. <https://doi.org/10.1007/s11356-020-11640-z>
- Vélez-Henao, J. A., Vivanco, D. F., & Hernández-Riveros, J. A. (2019). Technological change and the rebound effect in the STIRPAT model: A critical view. *Energy Policy*, 129, 1372-1381. <https://doi.org/10.1016/j.enpol.2019.03.044>
- Villanthenkodath, M. A., Pal, S., & Ansari, M. A. (2024). Unlocking sustainable development: Evaluating the impact of monetary and fiscal policies on ecological footprint in India. *World Development Sustainability*, 3, 100186. <https://doi.org/10.1016/j.wds.2024.100186>
- Wahyudi, H., Wiryawan, D., Leny, S. M., Said, U. B., & Abdurahman. (2025). Carbon emission control mechanism: Analysing the role of growth of the transportation and warehousing sector, GDP, and renewable energy consumption. *International Journal of Energy Economics and Policy*, 15(1), 18018. <https://doi.org/10.32479/ijee.18018>
- Wang, F., & Taghvaei, V. M. (2023). Impact of technology and economic complexity on environmental pollution and economic growth in developing and developed countries: using IPAT and STIRPAT models. *Environmental Science and Pollution Research*, 30(29), 73349-73360.
- Wang, J., & Azam, W. (2024). Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries. *Geoscience Frontiers*, 15(2), 101757. <https://doi.org/10.1016/j.gsf.2023.101757>
- Wang, J., Guan, Y., Wu, L., Guan, X., Cai, W., Huang, J., ... & Zhang, B. (2021). Changing lengths of the four seasons by global warming. *Geophysical Research Letters*, 48(6), e2020GL091753. <https://doi.org/10.1029/2020GL091753>
- Wang, Q., Wang, X., & Li, R. (2022). Does population aging reduce environmental pressures from urbanization in 156 countries?. *Science of the Total Environment*, 848, 157330. <https://doi.org/10.1016/j.scitotenv.2022.157330>
- Wang, W., Imran, M., Ali, K., & Sattar, A. (2025). Green policies and financial development in G7 economies: An in-depth analysis of environmental regulations and green economic growth. In *Natural resources forum* (Vol. 49, No. 2, pp. 1081-1107). Oxford, UK: Blackwell Publishing Ltd. <https://doi.org/10.1111/1477-8947.12424>
- Wang, Y., & Xu, Y. (2024). Green natural capital, the Environmental Kuznets Curve and development financing in the Global South. *iScience*, 27(2), 109562. <https://doi.org/10.1016/j.isci.2024.109562>
- Wani, M. J. G., Alamir, I. A., Ghazwani, M., Ahmed, I., Alkaraan, F., & Khan, M. A. (2024). Asymmetric effect of green energy and economic growth on the environmental deterioration and the environmental Kuznets curve validation in MENA countries. *International Journal of Finance & Economics*. <https://doi.org/10.1002/ijfe.3079>
- Warsame, A. A., Daror, H. O., & Abdullahi, A. M. (2025). Unraveling the environmental Kuznets curve in IGAD countries: interplay between ecological footprint, economic growth, renewable energy, and globalization. *Environmental Research Communications*, 7(1), 015031. <https://doi.org/10.1088/2515-7620/adaac7>
- World Bank Data (2023). Retrieve from <https://data.worldbank.org/> (accessed 17 March 2023).

- Wu, R., Wang, J., Wang, S., & Feng, K. (2021). The drivers of declining CO₂ emissions trends in developed nations using an extended STIRPAT model: A historical and prospective analysis. *Renewable and Sustainable Energy Reviews*, 149, 111328. <https://doi.org/10.1016/j.rser.2021.111328>
- Wu, X. F., & Chen, G. Q. (2017). Global primary energy use associated with production, consumption and international trade. *Energy Policy*, 111, 85-94. <https://doi.org/10.1016/j.enpol.2017.09.024>
- Xing, L., Khan, Y. A., Arshed, N., & Iqbal, M. (2023). Investigating the impact of economic growth on environment degradation in developing economies through STIRPAT model approach. *Renewable and Sustainable Energy Reviews*, 182, 113365. <https://doi.org/10.1016/j.rser.2023.113365>
- Xiong, S. H., Xiong, X., Li, G., Pedrycz, W., Deveci, M., & Chen, Z. S. (2024). Green production of airport terminals considering carbon footprint and indoor air quality: A multi-objective optimization perspective. *Building and Environment*, 263, 111859. <https://doi.org/10.1016/j.buildenv.2024.111859>
- Xu, T., Feng, C., Guluzada, E., & Chao, C. (2024). Evaluating the advancement of sustainable development objectives in recently industrialized nations by tying gold prices, fossil fuel prices, and energy use. *Energy Strategy Reviews*, 52, 101575. <https://doi.org/10.1016/j.esr.2024.101575>
- Yahyaoui, I., & Ghandri, M. (2024). Assessing the relationship between CO₂ emissions, renewable energy, trade openness and economic growth: MENA countries analysis. *International Journal of Energy Economics and Policy*, 14(1), 85-92. <https://doi.org/10.32479/ijeep.16173>
- Yang, S., & Park, S. (2020). The effects of renewable energy financial incentive policy and democratic governance on renewable energy aid effectiveness. *Energy Policy*, 145, 111682. <https://doi.org/10.1016/j.enpol.2020.111682>
- Yasmin, N., Jamuda, M., Panda, A. K., Samal, K., & Nayak, J. K. (2022). Emission of greenhouse gases (GHGs) during composting and vermicomposting: Measurement, mitigation, and perspectives. *Energy Nexus*, 7, 100092. <https://doi.org/10.1016/j.nexus.2022.100092>
- York, R., Rosa, E. A., & Dietz, T. (2002). Bridging environmental science with environmental policy: Plasticity of population, affluence, and technology. *Social Science Quarterly*, 83(1), 18-34. <https://doi.org/10.1111/1540-6237.00068>
- York, R., Rosa, E. A., & Dietz, T. (2003). STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts. *Ecological economics*, 46(3), 351-365. [https://doi.org/10.1016/S0921-8009\(03\)00188-5](https://doi.org/10.1016/S0921-8009(03)00188-5)
- Yu, S., Zhang, Q., Hao, J. L., Ma, W., Sun, Y., Wang, X., & Song, Y. (2023). Development of an extended STIRPAT model to assess the driving factors of household carbon dioxide emissions in China. *Journal of Environmental Management*, 325, 116502. <https://doi.org/10.1016/j.jenvman.2022.116502>
- Yuan, B., & Cao, X. (2022). Do corporate social responsibility practices contribute to green innovation? The mediating role of green dynamic capability. *Technology in Society*, 68, 101868. <https://doi.org/10.1016/j.techsoc.2022.101868>
- Yuan, X., Su, C. W., Umar, M., Shao, X., & LobonT, O. R. (2022). The race to zero emissions: Can renewable energy be the path to carbon neutrality?. *Journal of*

- Yusoff, N. Y. M., Aris, H., Nasiruddin, W. H. M., Rusli, A. K. C., Yurnaidi, Z., Safrina, R., Utama, N. A., & Rosalia, S. A. (2024). The driving forces behind renewable energy consumption: A comprehensive analysis of key determinants and environmental concerns in ASEAN countries. *Environmental Science and Pollution Research*, 31, 8912–8930. <https://doi.org/10.1007/s11356-024-34358-8>
- Zahra, S., Selvanathan, E. A., Gupta, R., & Jayasinghe, M. S. (2025). Green growth transition and carbon neutrality nexus: A comparative study on the top carbon emitters. *Journal of Environmental Management*, 353, 124228. <https://doi.org/10.1016/j.jenvman.2025.124228>
- Zarco-Soto, I. M., Zarco-Periñán, P. J., & Sánchez-Durán, R. (2021). Influence of cities population size on their energy consumption and CO 2 emissions: The case of Spain. *Environmental Science and Pollution Research*, 28, 28146-28167. <https://doi.org/10.1007/s11356-021-12624-3>
- Zaman, K. (2018). The impact of hydro-biofuel-wind energy consumption on environmental cost of doing business in a panel of BRICS countries: evidence from three-stage least squares estimator. *Environmental Science and Pollution Research*, 25, 4479-4490. <https://doi.org/10.1007/s11356-017-0797-1>
- Zeng, Y., Dai, Y., Shu, Y., & Yin, T. (2024). Carbon emission analysis of low-carbon technology coupled with a regional integrated energy system considering carbon-peaking targets. *Applied Sciences*, 14(18), 8277. <https://doi.org/10.3390/app14188277>
- Zhang, M., Chen, Y., Lyulyov, O., & Pimonenko, T. (2022). Interactions between economic growth and environmental degradation toward sustainable development. *Systems*, 11(1), 13. <https://doi.org/10.3390/systems11010013>
- Zhang, X., Hasan, M. M., & Waris, U. (2024). Assessing the nexus between natural resources and government effectiveness: role of green innovation in shaping environmental sustainability of BRICS nations. *Resources Policy*, 93, 105024. <https://doi.org/10.1016/j.resourpol.2024.105024>
- Zhou, Z. Z., Hassan, M. S., Saeed, M. I., Mahmood, H., Kalim, R., & Houaneb, A. (2025). From pollution to sustainable environment: Unlocking the role of energy intensity and renewable energy in highly pollutant nations. *Environmental Research Communications*, 7(2), 025001. <https://doi.org/10.1088/2515-7620/adac38>
- Zhu, Y., Feng, C., Liu, X., Zhang, T., & Wang, X. (2025). An Analysis of the Factors Influencing Energy Consumption Based on the STIRPAT Model: A Case Study of the Western Regions of China. *Energies*, 18(9), 2379. <https://doi.org/10.3390/en18092379>

Appendix 1:
Summarise of EKC and Renewable energy

(Author, Year)	Region/Countries	EKC Validated	Renewable Energy	Notes
Sun & Qamruzzaman (2024)	BRICS + T	✓ Yes	✓ Yes	EKC validated for CO ₂ , EF, LCF, ILCF
Odei et al. (2025)	Emerging markets	✓ Yes	✓ Yes	R&D shortens EKC turning point
Pan et al. (2024)	Global	✓ Yes	✓ Yes	EKC with forest-product trade
Gyamfi et al. (2024)	Open vs Closed economy	✓ Yes	✓ Yes	RE reduces CO ₂ in open economies
Bakry et al. (2024)	52 developing nations	✓ Yes	✓ Yes	Digital finance supports EKC
Warsame et al. (2025)	IGAD	✓ Yes	✓ Yes	EKC with ecological footprint
Mamkhezri & Khezri (2024)	54 countries	✓ Yes	✓ Yes	R&D + RE spillovers effective
Suyanto et al. (2024)	G20	✗ No	✓ Yes	EKC not supported, institutions matter
Said (2024)	SSA	✓ Yes	✓ Yes	Financial inclusion ↑ CO ₂ , RE moderates
Lu et al. (2024)	BRICS-T	✓ Yes	✓ Yes	CS-ARDL shows RE reduces pollution
Leitão (2024)	G7	✓ Yes	✓ Yes	HDI & RE improve air quality
Haciimamoglu (2025)	BRICS	✓ Yes	✓ Yes	EKC & LCC both valid, RE always effective

Doğan & Dalkılıç (2024)	USA	✓ Yes	✓ Yes	Media + RE reduce CO ₂
Ratnadewati et al. (2024)	ASEAN	✗ No	✓ Yes	RE needed but EKC not found
Su et al. (2025)	121 countries	✓ Yes	✓ Yes	High economic fitness ↓ CO ₂ , EKC turning point varies
Bekun et al. (2024)	South Asia	✓ Yes	✓ Yes	Cubic EKC (N-shaped); RE critical for FDI impact
Mahmood (2024)	MENA	✓ Yes	✓ Yes	Military spending ↑ emissions, RE helps locally
Çatık et al. (2024)	49 countries	✗ No	✓ Yes	RE helps but EKC not validated
Menyari (2024)	Mediterranean (17)	✓ Yes	✓ Yes	Tourism, FDI, RE ↓ CO ₂
Mata et al. (2024)	30 high-income	✓ Yes	✓ Yes	CS-ARDL confirms EKC & RE effectiveness
Zahra et al. (2025)	China, USA, India	✓ Yes	✗ Not included	RE not significant, EKC confirmed via green growth, tech
Balsalobre-Lorente et al. (2024)	G7	✗ No	✓ Yes	EKC not found, RE reduces EF
Kalim et al. (2024)	147 countries	✓ Yes	✓ Yes	Demand-based EKC; knowledge economy & RE reduce CO ₂
Njie et al. (2024)	Africa	✓ Yes	✓ Yes	Energy & FDI EKC validated; RE needed to curb emissions
Ketchoua et al. (2024)	OECD	✓ Yes	✓ Yes	FDI harms green growth unless moderated by tech & RE
Wahyudi et al. (2025)	Indonesia	✓ Yes	✓ Yes	Transport ↑ CO ₂ ; RE lowers it; FMOLS confirms EKC

Alnour et al. (2024)	34 countries	✓ Yes	✓ Yes	PNARDL confirms RE & R&D ↓ CO ₂ in long-run
Hasanov et al. (2024)	Renewable Energy Country Attractiveness Index (RECAI)	✓ Yes	✓ Yes	TFP + RE reduce CO ₂ ; pooled and country-specific results
Gazeloğlu & Erkişiç (2025)	Central American SICA countries	✓ Yes	✓ Yes	Tourism + RE reduce emissions; FGLS used
Nugroho (2024)	Asia (25 countries)	✓ Yes	✓ Yes	Agricultural technical efficiency + RE considered
Cutcu et al. (2025)	17 countries	✓ Yes	✓ Yes	QRPD confirms EKC; RE offset geopolitical risks
Taher (2024)	Lebanon	✓ Yes	✓ Yes	ARDL confirms EKC; RE consistently reduces CO ₂
Sobirov et al. (2024)	Asia (14 countries)	✓ Yes	✓ Yes	MMQR, FMOLS, DOLS support RE's negative effect
Destiartono & Firmansyah (2024)	Indonesia	✓ Yes	✓ Yes	EKC confirmed for methane; RE reduces CH ₄
Rahman et al. (2024a)	Bangladesh	✓ Yes	✓ Yes	EKC validated; RE and FDI reduce emissions
Liu et al. (2024)	Belt & Road	✓ Yes	✓ Yes	RE reduces CO ₂ in both BRI panels; CoFDI mixed
Georgescu et al. (2024)	Norway	✓ Yes	✓ Yes	EKC with ecological footprint; RE reduces EF
Auteri et al. (2024)	G7	✗ No	✓ Yes	RE linked to government debt; no EKC tested directly
Campos-Romero & Rodil-Marzábal (2024)	East/South Asia	✓ Yes	✓ Yes	GVCs & RE reduce emissions; EKC validated
Pata et al. (2025)	USA	✓ Yes	✓ Yes	EKC and RKC validated; income → RE → CO ₂ ↓

Celik et al. (2024)	Nordics	✓ Yes	✓ Yes	RE + TFP improve carbon neutrality
Byaro et al. (2024)	Sub-Saharan Africa	✓ Yes	✓ Yes	EKC and LCC validated; RE + clean cooking ↓ EF
Ozkan & Okay (2024)	Emerging & Developed countries	✓ Yes	✓ Yes	PMG model: RE ↓ CO ₂ ; EKC only in EMEs
Feng et al. (2024)	Central Asia	✓ Yes	✓ Yes	EKC validated; RE + HCI reduce emissions
Cao et al. (2024)	China	✓ Yes	✓ Yes	FMOLS confirms EKC; RE + tech can mitigate CO ₂
Horobet et al. (2024)	Europe	✓ Yes	✓ Yes	Mixed EKC by region; RE effective short-term
Rokhmawati et al. (2024)	Indonesia	✓ Yes	✓ Yes	STIRPAT + system dynamics; carbon tax + RE policy modeled
Li et al. (2024)	China (YRD)	✗ No	✓ Yes	REG improves energy security, U-shaped with ESL
Muhammad et al. (2024)	Pakistan	✓ Yes	✓ Yes	EKC with hydro/nuclear; RE advocated for policy
Bucak et al. (2024)	EU (26 countries)	✓ Yes	✓ Yes	Spatial spillovers: RE ↓ EF, fossil ↑ EF
Brahmia & Mannai (2025)	GCC	✓ Yes	✓ Yes	EKC confirmed; RE needed against ICT + FDI emissions
Erdogan et al. (2024)	Coal-dependent countries	✓ Yes	✓ Yes	Coal-Kuznets Curve validated; RE/NatGas displace coal
Naimoğlu & Akal (2024)	Emerging economies	✓ Yes	✓ Yes	RE ↓ CO ₂ ; globalization ↑ CO ₂ ; EKC confirmed
Javed et al. (2024)	G7	✓ Yes	✓ Yes	RE, green tech & policy ↓ EF; EKC holds across quantiles

Destiartono (2025)	Indonesia	✓ Yes	✓ Yes	ARDL confirms EKC; RE + efficiency reduce CO ₂
Ikhsan & Amri (2024)	ASEAN-6	✓ Yes	✓ Yes	FEM confirms EKC; RE ↓ CO ₂ , urbanisation ↑ CO ₂
Hacıııımođlu & Cengiz (2024)	ASEAN-5	✓ Yes	✓ Yes	MMQR: REC + NRR ↓ EF; EKC validated across quantiles
Nabaweesi et al. (2024)	EAC (5 countries)	✓ Yes	✓ Yes	REKC validated; finance ↑ RE, FDI ↓ RE
Rahman et al. (2024b)	South Asia (5 countries)	✓ Yes	✗ No	Human capital reduces CO ₂ ; energy and population increase CO ₂
Agusalim et al. (2025)	Religious countries (29)	✓ Yes	✓ Yes	PHH supported; EKC not valid in low-income nations; RE reduces CO ₂ ; faith-based policies
Hasan et al. (2024)	OECD	✓ Yes	✓ Yes	Environmental diplomacy and RE help reduce emissions
Lanhui & Ibrahim (2024)	South Africa	✓ Yes	✓ Yes	Trade openness and GDP increase CO ₂ ; RE and rule of law reduce it
Wani et al. (2024)	MENA	✓ Yes	✓ Yes	Positive/negative RE shocks reduce CO ₂ ; GDP and trade openness increase emissions
Chopra et al. (2024)	Top-5 emitters	✓ Yes	✓ Yes	GDP, urbanisation ↑ CO ₂ ; RE, tech innovation ↓ CO ₂ ; EKC confirmed
Nica et al. (2024)	India	✓ Yes	✓ Yes	N-shaped EKC; RE lowers emissions and supports electricity access
Khan et al. (2024)	48 BRI countries	✓ Yes	✓ Yes	Tech energy deficit ↑ CO ₂ ; urbanisation and RE ↓ CO ₂ ; EKC and

				Pollution Halo supported
Zhou et al. (2025)	Highly pollutant nations	✓ Yes	✓ Yes	Energy intensity ↑ CO ₂ ; RE ↓ CO ₂ ; EKC supported in 2 out of 3 models
Azimi et al. (2025)	G20	✓ Yes	✓ Yes	EKC redefined by government effectiveness, RE, and economic complexity
Daga et al. (2024)	China, US, India, Russia, Japan	✗ No	✓ Yes	No EKC; GDP and resource rents ↑ CO ₂ ; RE and tech ↓ CO ₂
Shouwu et al. (2024)	North Africa	✗ No	✓ Yes	No EKC; RE reduces CO ₂ ; environmental tech has limited effect
Wang & Xu (2024)	Global South	✓ Yes	✓ Yes	Inverted N-shaped EKC; development finance, RE, and natural capital promote sustainability
Ahmad et al. (2024)	Developing Asia (15)	✓ Yes	✓ Yes	EKC with asymmetric FD shocks; RE and innovation reduce emissions
Issayeva et al. (2024)	Kazakhstan	✓ Yes	✓ Yes	EKC holds; agriculture neutral; RE and industry have strong environmental impact
Dhayal et al. (2025)	Sub-Saharan Africa (39)	✓ Yes	✓ Yes	Strategic commodities ↑ CO ₂ ; RE and policy stability ↓ CO ₂
Bibi et al. (2024)	China (Textile Sector)	✓ Yes	✓ Yes	RE ↓ CO ₂ ; env. policy, tech improve emissions; industry sensitive to regulations
Zeng et al. (2024)	China (Shanghai RIES)	✓ Yes	✓ Yes	EKC via STIRPAT; RE in clean RIES reduces emissions under carbon-peaking scenarios
Salahodjaev & Sadikov (2024)	50 CHD-prone countries	✓ Yes	✓ Yes	EKC confirmed; RE reduces CO ₂ ; RE tied to

				better health outcomes in high-CHD nations
Iqbal et al. (2025)	BRICS	✓ Yes	✓ Yes	Climate Kuznets Curve (CKC); education & RE moderate climate damage from growth
Ganda (2025)	South Africa	✓ Yes	✓ Yes	U-shaped and inverted-U EKC; RE helps in long-run; short-run effects mixed
Alam et al. (2024)	Oil-producing countries (10)	✓ Yes	✗ No	EKC confirmed; ICT, financial inclusion ↓ CO ₂ ; energy consumption & HDI ↑ CO ₂
Bektur (2024)	High economic freedom countries	✓ Yes	✓ Yes	EKC valid in Canada, Denmark, Singapore; RE ↓ EF in 6 countries; mixed role of economic freedom
Bashir et al. (2024)	NIC economies	✓ Yes	✓ Yes	CS-ARDL confirms EKC; RE and energy prices ↓ CO ₂ ; fossil & gold prices ↑ CO ₂
Simbi et al. (2025)	Africa (36 countries)	✓ Yes	✓ Yes	EKC weakly valid; RE and urbanisation ↓ CO ₂ ; trade and GDP ↑ CO ₂
Alnafisah et al. (2024)	MENA (6 countries)	✓ Yes	✓ Yes	Innovation Curve EKC valid; patents initially ↑ then ↓ CO ₂ ; RE has reducing effect
Koçak et al. (2024)	Pakistan (transport sector)	✓ Yes	✓ Yes	QARDL confirms EKC for transport; urbanisation & fossil fuels ↑ emissions
Bozatli & Akca (2024)	Turkey	✓ Yes	✓ Yes	EKC and LCC valid; market-based policies & RE ↓ EF; command & tech support policies ineffective
Aruga et al. (2024)	Japan	✗ No	✓ Yes	PV ↓ CO ₂ ; coal, oil, LNG ↑ CO ₂ ; inverted-

				U via Nikkei index, not confirmed EKC
Mahmood et al. (2024)	Western Europe (25 countries)	✓ Yes	✓ Yes	EKC with turning point ~50,287 USD; RET ↓ CO ₂ ; innovation helps long-run sustainability
Xu et al. (2024)	NICs (10 countries)	✓ Yes	✓ Yes	EKC supported; RE ↓ CO ₂ ; fossil & gold prices ↑ pollution; structural reform needed
Mohamed et al. (2024)	Malaysia	✓ Yes	✓ Yes	EKC confirmed; RE ↓ CO ₂ but ↑ EF; electricity intensity ↑ emissions
Yusoff et al. (2024)	ASEAN (6 countries)	✓ Yes	✓ Yes	EKC transition noted; GDP ↑ RE; emissions & FDI ↓ RE; policy gaps in RE investment
Mohamad et al. (2023)	USA and China	✓ Yes	✓ Yes	Linear and nonlinear ARDL confirm: fossil ↑ CO ₂ , RE ↓ CO ₂ ; RE transition reduces long-term emissions
Villanthenkodath et al. (2024)	India	✓ Yes	✓ Yes	Long-run EKC valid; RE reduces EF; monetary policy ↓ EF; fiscal policy insignificant
Ahmed et al. (2025)	Somalia	✓ Yes	✓ Yes	EKC confirmed; agriculture ↑ CO ₂ ; RE ↓ CO ₂ ; solar potential underutilized
Kitole et al. (2024)	Tanzania	✓ Yes	✓ Yes	EKC partially valid; RE and FDI suggested; globalization ↑ emissions
Toumi (2025)	Remittance economies (9)	✓ Yes	✓ Yes	N-shaped EKC; RE ↓ EF; mixed impacts from finance and innovation across quantiles
Yahyaoui & Ghandri (2024)	MENA	✓ Yes	✓ Yes	EKC valid; RE ↓ CO ₂ ; GDP and trade

				openness show model-dependent results
Borsha et al. (2024)	Bangladesh	✓ Yes	✓ Yes	EKC supported; RE ↓ CO ₂ ; industrialisation ↑ CO ₂ ; STIRPAT used
Elatroush (2025)	Developing & emerging (60)	✗ No	✓ Yes	EKC not universal; RE ↓ CO ₂ in some clusters; FD has mixed effects by region
Naz et al. (2024)	ASEAN, GCC	✓ Yes	✓ Yes	EKC valid; ASEAN ↑ EF via GDP; RE helps decouple growth and emissions in GCC