

**IBN HALDUN UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF ECONOMICS**

MASTER'S THESIS

**THE ROLE OF INFORMATION AND
COMMUNICATION TECHNOLOGY, RENEWABLE
ENERGY SOURCES, GREEN INNOVATION, AND
INSTITUTIONAL QUALITY IN ACHIEVING
ENVIRONMENTAL SUSTAINABILITY IN OECD
COUNTRIES**

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ISTANBUL, 2025

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COUNTRIES**

**by
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ÖZ

OECD ÜLKELERİNDE ÇEVRESEL SÜRDÜRÜLEBİLİRLİĞİN SAĞLANMASINDA BİLGİ VE İLETİŞİM TEKNOLOJİSİNİN, YENİLENEBİLİR ENERJİ KAYNAKLARININ, YEŞİL YENİLİĞİN VE KURUMSAL KALİTENİN ROLÜ

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Elinizdeki çalışma, OECD ülkelerinin Birleşmiş Milletler'in Sürdürülebilir Kalkınma Hedefi 13'ü (iklim değişikliğiyle mücadele) gerçekleştirme çabaları kapsamında bilgi ve iletişim teknolojileri (BİT), yeşil inovasyon (GINV), yenilenebilir enerji kaynakları (RESS) ve kurumsal kalite (INSQ) gibi faktörlerin çevresel sürdürülebilirlik üzerindeki belirleyici rollerini incelemektedir. Kontrol değişkenleri olarak dışa açıklık ve kişi başına düşen GSYH kullanılmıştır. OECD ülkelerinde çevresel sürdürülebilirlik üzerine birçok çalışma bulunsa da, BİT, RESS, GINV ve INSQ'nun birlikte ele alındığı kapsamlı bir analiz mevcut değildir. Bu çalışma, Afrika ve BRICS ülkeleri üzerine yapılan literatürden yararlanarak bu boşluğu doldurmayı ve OECD ülkeleri için entegre bir politika çerçevesi sunmayı amaçlamaktadır. 1996–2021 dönemini kapsayan çalışmada, ülkeler arası farklılıklar ve bağımlılıklar göz önünde bulundurularak ikinci nesil panel birim kök testleri kullanılmış; değişkenler arasında uzun dönemli ilişkiyi test etmek için eşbütünleşme analizleri uygulanmıştır. Ayrıca, uzun dönem katsayılarını tahmin etmek ve olası içsellik ve serisel korelasyon problemlerini gidermek için FMOLS ve DOLS yöntemleri tercih edilmiştir.

Bulgulara göre, uzun vadede BİT, yenilenebilir enerji, yeşil inovasyon, kurumsal kalite ve dışa açıklık çevresel sürdürülebilirliği olumlu yönde etkilemektedir. Ayrıca,

ICT'nin düzenleyici rolüyle RESS ve INSQ'nun ortak etkisi de istatistiksel olarak anlamlı bulunmuştur.

Anahtar Kelimeler: Bilgi ve İletişim Teknolojileri, Çevresel Sürdürülebilirlik, Kişi Başına GSYİH, Kurumsal Kalite, Yenilenebilir Enerji Kaynağı, Yeşil İnovasyon.



ABSTRACT

THE ROLE OF INFORMATION AND COMMUNICATION TECHNOLOGY, RENEWABLE ENERGY SOURCES, GREEN INNOVATION, AND INSTITUTIONAL QUALITY IN ACHIEVING ENVIRONMENTAL SUSTAINABILITY IN OECD COUNTRIES

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As OECD countries strive to meet the UN sustainability development goal thirteen (take urgent actions to combat climate change and its impact), this study explores the vital role of information and communication technology (ICT), green innovation (GINV), renewable energy resources (RESS), and institutional quality (INSQ) in achieving sustainable environmental outcomes. I used two control variables (trade openness and GDP per capita) and the primary variable. Despite the wealth of studies on OECD nations' environmental sustainability, there is no previous joint examination of the roles of ICT, RESS, GINV, and INSQ. This paper bridges the gap by empirically investigating these variables' individual and combined roles on environmental sustainability and presenting a more comprehensive analysis to provide a more integrated framework to inform good policy design towards ecological sustainability in OECD nations. Drawing from the methodologies and findings from existing literature from African and BRICS economics, this study extends the scope to the OECD economics over the period from 1996 to 2021; this study employs a range of advanced econometric techniques to ensure the reliability of the analysis, used second-generation panel unit root tests to account for heterogeneity and cross-sectional dependence among OECD economies. The study employs cointegration tests to verify the long-term equilibrium relationship among ICT, RESS, GINV, INSQ, and

environmental sustainability indicators. The fully modified ordinary least squares (FMLOS) and dynamic ordinary least squares (DOLS) estimations are used to estimate the long-term relationships while addressing potential issues of endogeneity and serial correlation.

This research indicates that in the long run, information and communication technology, renewable energy sources, green innovation, institutional quality, and trade openness are positively related to environmental sustainability. It also estimated the joint effect of variable RESS and INSQ, taking ICT as moderators. The results are overall significant in the long run.

Keywords: Environmental Sustainability, GDP Per Capita, Green Innovation, Information and Communication Technology, Institutional Quality, Renewable Energy Source.

DEDICATION

I dedicate this thesis to the dearest people in my life, my beloved father and mother, whose unconditional love, prayers, and sacrifices have been the foundation of my journey. To my brothers, thank you for their constant encouragement and support, which kept me going. To my Khala, whose love and warmth have always felt like a second mother's embrace. To my friends, who stood beside me with motivation, laughter, and strength during every step of this academic endeavor.

Most dearly, I dedicate this work to the loving memory of my late grandmother, whose wisdom, kindness, and blessings continue to guide and inspire me each day.

I also extend my heartfelt gratitude to my respected supervisor, whose invaluable guidance, patience, and encouragement have played a vital role in shaping this research. This work reflects all your love, belief, and support. Thank you for being part of this journey.

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TABLE OF CONTENTS

ÖZ	iv
ABSTRACT	vi
DEDICATION	viii
ACKNOWLEDGEMENT	ix
TABLE OF CONTENTS	x
LIST OF TABLES	xii
LIST OF FIGURES	xiii
LIST OF SYMBOLS AND ABBREVIATIONS	xiv
CHAPTER I INTRODUCTION	1
CHAPTER II LITERATURE REVIEW	9
2.1. Conceptual Framework and Theoretical Underpinning	10
2.2. ICT and Environmental Sustainability	12
2.3. Renewable Energy Sources and Environmental Sustainability	14
2.4. Green Innovation and Environmental Sustainability	17
2.5. Institutional Quality and Environmental Sustainability	19
2.6. Integrated Perspective and Interlinkages.....	21
CHAPTER III DATA AND METHODOLOGY	27
3.1. Data and Sample Size.....	27
3.2. Model Specifications	28
3.3. Discussions of the Variables	30
3.4. Dependent Variable	30
3.5. Independent Variables	30
3.6. Control Variables	32
3.7. Graphical Analysis of the Variables for OECD Countries.....	33
3.8. Variable Description.....	40
3.9. Research Hypothesis	42
3.10. Selection Method for Regression	42
3.11. Principle Component Analysis	43
3.12. Cross-Sectional Dependence Test	44
3.13. Slope Homogeneity Test	46
3.14. Unit Root Test	47
3.15. Cointegration Test	48

3.16. Long Run Cointegration Test	51
3.17. Fully Modified Ordinary Least Square	52
3.18. Dynamic Ordinary Least Square	53
3.19. Canonical Cointegrating Regression	54
CHAPTER IV RESULTS AND DISCUSSION	55
4.1. Summary of Statistics.....	56
4.2. Correlation Analysis among the Variables.....	58
4.3. Cross-Sectional Dependence Test	59
4.4. Slope Homogeneity Test	61
4.5. Second Generation Unit Root Test.....	62
4.6. Panel Cointegration Test	64
4.7. Panel Empirical Results.....	65
4.8. Discussion	70
CHAPTER V CONCLUSIONS	75
REFERENCES.....	80
APPENDIX	88
Appendix A Supporting Estimations.....	88
CURRICULUM VITAE.....	94

LIST OF TABLES

Table 3.1. Variables Description and Source	40
Table 4.1. Descriptive Statistics of the Main Variable for OECD Countries	56
Table 4.2. Pearson's Pairwise Correlation Matrix for OECD Countries	58
Table 4.3. Pesaran's Cross-Sectional Dependence Test Results for OECD Countries ..	60
Table 4.4. Slope Homogeneity Test Results for OECD Countries	61
Table 4.5. Second Generation Unit Root Test at Level for OECD Countries	62
Table 4.6. Second Generation Unit Root Test at First Difference for OECD Countries	63
Table 4.7. Panel Cointegration Test for OECD Countries.....	64
Table 4.8. Panel Regression Results for the General Model for OECD Countries ...	66
Table 4.9. Panel Regression Results for Model-I for OECD Countries	67
Table 4.10. Panel Regression Results for Model-II for OECD Countries	68
Table 4.11. Panel Regression Results for Model-III for OECD Countries.....	69
Table A.1. Panel Cointegration Test at First Difference for OECD Countries.....	88
Table A.2. PCA for Information and Communication Technology	88
Table A.3. Principal Components Eigenvectors for ICT	88
Table A.4. Correlation Matrix Results for ICT	89
Table A.5. PCA for Renewable Energy Sources	89
Table A.6. Principal Components Eigenvectors for RESS	90
Table A.7. Correlation Matrix Results for RESS.....	90
Table A.8. PCA for Institutional Quality	91
Table A.9. Principal Components Eigenvectors for INSQ	91
Table A.10. Correlation Matrix Results for INSQ.....	91
Table A.11. Panel Casual Relationship among the Variables.....	92
Table A.12. Summary of Causality	93
Table A.13. Fixed Effect.....	93

LIST OF FIGURES

Figure 3.1. Average CO2 Emission Rate in OECD from 1996-2021	33
Figure 3.2. Average ICT in OECD from 1996-2021	34
Figure 3.3. Average Renewable Energy Sources in OECD from 1996-2021.....	35
Figure 3.4. Average Green Innovation in OECD from 1996-2021.....	36
Figure 3.5. Average Institutional Quality in OECD from 1996-2021	37
Figure 3.6. Average Trade Openness in OECD from 1996-2021.....	38
Figure 3.7. Average GDP Per Capita in OECD from 1996-2021.....	39
Figure A.1. Plot of Eigenvalues After PCA for ICT.....	89
Figure A.2. Scree Plot of Eigenvalues After PCA for RESS.....	90
Figure A.3. Scree Plot of Eigenvalues After PCA for INSQ.....	92

LIST OF SYMBOLS AND ABBREVIATIONS

OECD	Organization of Economic Co-operation and Development
ES	Environmental Sustainability
CO ₂	Carbon Dioxide Emission
ICT	Information and Communication Technology
RESS	Renewable Energy Sources
GINV	Green Innovation
INSQ	Institutional Quality
TRD	Trade Openness
GDPC	Gross Domestic Product Per Capita
FMOLS	Fully Modified Ordinary Least Square
DOLS	Dynamic Ordinary Least Square
CCR	Canonical Cointegrating Regression

CHAPTER I

INTRODUCTION

From an economic standpoint, environmental sustainability is a fundamental common good. It is considered a public good because it is both non-rivalrous and non-excludable. This indicates that all individuals, irrespective of their involvement in environmental conservation, can reap the advantages of its beneficial outcomes, like improved air quality and consistent weather patterns. Nonetheless, ecological products frequently experience under-provision attributable to the free-rider dilemma, when individuals and enterprises derive advantages from environmental preservation without incurring expenses. Besides, sustainability entails a competitive dimension in that overusing assets lessens shared assets and deepens global concerns such as loss of diversity and climate change. Economists posit that avoidance of degradation of the environment through internalization of externalities such as pollution, loss of forests, and over-dependency on non-renewable sources is critical for attaining sustainability. Having an outlook for environment-related sustainability as a shared asset enables one to frame policies that harmonize the protection of assets and development. Fair access to key assets such as clean energy, water, and air advances social welfare and intergenerational equity in consonance with overall development aims. The existing use of assets can be harmonized with the necessity to save assets for future use by incorporating environmentally friendly approaches into economies.

Due to their high contribution to greenhouse gas emissions, Organization for Economic Cooperation and Development (OECD) countries, consisting of a group of the most developed economies in the world, have a critical role in resolving worldwide environment-related concerns. In a relatively small portion of the population in the whole world, these countries produce most of the emissions of carbon, and high consumption, high level of industrialization, and high consumption of resources cause most of the impact on the environment (International Energy Agency). As a result, OECD countries have high accountability and an essential role in formulating and

implementing cutting-edge policies that will promote sustainable development. OECD countries have a strong position in driving worldwide efforts towards environmental sustainability due to strong institutional frameworks and state-of-the-art technological capabilities. Nevertheless, the achievement of such a target will demand a deep transformation in economic frameworks with a high preference for environmental protection through the integration of the use of green innovation, renewable sources of energy, institution quality, and information and communications technology ICT in a coordinated manner.

The purpose of this study is to investigate how information and communication technology, renewable energy sources, green innovation, and institutional quality contribute to OECD economies' environmental sustainability and make recommendations for leveraging them in driving the achievement of the Sustainable Development Goals (SDGs) of the United Nations, specifically Goal 13 (Climate Action).

Coase's theorem gives a theoretical framework for handling environmental externalities. According to it, effective use of resources and avoidance of externalities can be achieved through bargaining among affected actors if property rights are clearly understood and transaction costs are low Yandle, (1998). This principle manifests in forms like tradable pollution permits, where emissions rights are created and traded on the market to reduce pollutants. However, the practical use of the Coase theorem is limited by high transition costs, incomplete information, and multiple stakeholders with competing interests. For example, Deryugina and Moore (2020) argue that there exist two contradicting opinions regarding the impact of the Coasian theorem, and it is not clear whether the effect is just Pareto improving rather than Pareto optimal D. Tatyana et al. (2021). As a result, tangible and detailed frameworks help lower these costs by setting out fair property rights, regulatory stability, and effective enforcement. Therefore, regarding supporting sustainable development, the Coase Theorem plays a crucial role in explaining the processes of the economy supported through technological advancement.

Environmental sustainability means protecting and conserving the natural resources and ecosystem for the current and future well-being. Several studies exist on this, and

due to global warming, this topic has been hotly debated by researchers for the last 20 years. For example, a study on the environmental sustainability for OECD countries by Khan et al. (2022) implies that energy transition, natural resources, and renewable energy consumption increase environmental quality, but non-renewable energy consumption and urbanization decrease the environmental quality (CO₂ emission increase) and increases the economic growth for the selected OECD economies Khan et al., (2022). Another study by Hou et al. (2023) used fossil fuels, GDP, and renewable energy variables and, by using the CD-ARDL estimation method, investigated the long-run relationship between the variables and found that fossil fuel consumption and GDP decreases environmental quality both in the short and long run, but the renewable energy improves the environmental quality associated with the sustainable development in OECD economies Hou et al., (2023). A study on BRICS economies by Saba et al. (2024) used different estimation techniques along with CS-ARDL, suggesting that policymakers should use information and communication technology in the industrial and institutional sectors to achieve environmental sustainability faster in the short run, but in the long run the interaction of ICT, industrialization, renewable energy sources, and institutional quality is not favoring to get environmental sustainability Saba et al., (2024). Another study investigates the role of ICT, agriculturalization, renewable energy sources, industrialization, and institutional quality for 51 African countries' environmental sustainability by using different analysis techniques and found a long-run equilibrium relationship; along with this, it found two-way causality among all the variables except ICT and environmental sustainability. This study suggested African policymakers that when ICT is used jointly with trade openness and renewable energy sources, it will help to achieve environmental sustainability faster as compared to the other variables, and they suggested this based on the results of system GMM estimations Saba et al., (2024).

Literature on ICT studies indicates that when compared to more developed regions like North America, Europe, etc., where ICT diffusion has been well established, there is a considerable chance of ICT diffusion (Penard et al., 2012; Mirza et al., 2020). This is so because, given the possible influence ICT plays in every society, policymakers can use it to solve clear policy issues about sustainable development (such as global warming, climate change, and environmental pollution). The ability of ICT to support sustainable practices, monitor and manage natural resources, lower energy

consumption, and mitigate the effects of climate change. (Yap, 2011; Titifanue et al., 2017; Qureshi, 2019; Lahouel et al., 2021; Amari et al., 2022). From the previous studies, some of the ways ICT supports environmental sustainability include. Electronic equipment should be appropriately disposed of and recycled to effectively treat electronic waste (e-waste). (Nnorom and Osibanjo, 2008; Nivedha and Sutha, 2020; Shahabuddin et al., 2022).

The shift to renewable energy aligns with international climate goals, for instance, the Paris Agreement's aspiration of keeping temperature rise below 2°C compared to preindustrial levels Rogelj et al., (2016). The potential of renewable energy to promote environmental sustainability has been the subject of numerous studies. A study found that using wind energy would improve the air quality and significantly reduce CO₂ emissions Mubiru et al., (2019). Another study found that using solar photovoltaic systems would lower the emission of greenhouse gases and improve sustainable development in rural areas Mekonnen et al., (2020).

A study in 2019 revealed that investment in environment-related technologies has an adverse effect on carbon emissions, which means that an increase in green innovation improves environmental sustainability Lin and Zhu, (2019). Another study revealed that for the top ten innovative countries, technological innovation reduces environmental degradation, explaining that with an increase in green innovation, environmental sustainability increases Gormus and Aydin, (2020).

Institutions that formulate and enforce policies while ensuring robust monitoring are especially valuable to the OECD countries since they foster an environment that supports sustainability initiatives. For example, a study investigated the impact of institutional quality on the emission of CO₂ and found a negative relationship, indicating that with higher institutional quality, carbon emission will be lower Zhang et al., (2019). Another study on 44 African countries for 26 years looked at how institutional quality affects environmental sustainability, and it found that institutional quality positively and significantly affects environmental sustainability, which means that successful institutions produced clean and better environmental results Gyamfi and Zhou, (2020).

Research on the intersection of ICT, renewable energy, green innovation, and institutional excellence in OECD nations is scarce despite the wealth of literature on sustainability in emerging markets like BRICS, Africa, and other regions. Studies on these countries do not pay much attention to the peculiar socio-economic conditions and technological capabilities that these nations possess. Cao et al. (2022) estimated 36 OECD economies (1985-2018). They used different cointegration techniques like (Kao, Westerlund, and Pedroni) and Pooled Mean Group estimations. They found that renewable energy, globalization, and institutional quality increase environmental sustainability by decreasing CO₂ emissions, while financial development, stock markets, and economic growth increase CO₂ emissions in the short and long run. There is a wealth of literature available on OECD country's environmental sustainability. Still, there are no previous studies available that did a joint examination of the role of information and communication technology, renewable energy sources, green innovation, and institutional quality. The combined impacts of ICT with renewable energy and ICT with institutional quality have not yet been explored. This paper bridges the gap by empirically investigating both the individual and combined roles of these variables on environmental sustainability and presenting a more comprehensive analysis to provide a more integrated framework to inform good policy design toward environmental sustainability in OECD nations.

Fatima, Nudrat, et al. (2024) explore the role of stringency of environmental policies in moderating the relationship between green innovation and CO₂ emissions in G7 nations based on a database of 1990-2020 and using techniques such as DOLS, FMOLS, CCR, and MMQR. According to their conclusions, stricter policies reinforce the positive contributions of green innovation to the quality of the environment. Earlier works typically used conventional panel regression methods that failed to effectively deal with problems such as endogeneity, serial correlation, and long-run non-stationarity of relationships among variables. Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) present the best alternative. FMOLS adjusts for serial correlation and endogeneity by altering the least squares estimator so that it is more suitable for cointegrated panels. DOLS extends the precision in estimation with the addition of leads and lags of differenced regressors that address the dynamic responses as well as feedback bias. Compared with previous methods of analysis, FMOLS and DOLS offer more accurate and unbiased long-run

coefficient estimates, particularly in the context of small samples and when variables are of order one $[I(1)]$. Such properties make them ideal for environmental and economic analysis that deals with complex long-term interactions of the type presented in this thesis. This gap illustrates the need for an exhaustive OECD-specific analysis. Moreover, relatively few experiments use advanced econometric methods to explore these connections, including cointegration estimation or FMOLS and DOLS. This method gap presents a challenge to drive a rich understanding that is both academically and politically advantageous.

The general objective of this study is to investigate how ICT complements renewable energy sources, green innovation, and institutional quality to influence environmental sustainability in a panel of 37 OECD nations. The specific objective of this study is to explore the long-run equilibrium relationship among the variables, the long-run coefficient impact of information and communication technology (ICT), renewable energy source (RESS), green innovation (GINV), and institutional quality (INSQ) on environmental sustainability, the causal relationship among the variables of interest, the combined impact of ICT and RESS on environmental sustainability, and the combined impact of ICT and INSQ on environmental sustainability. We apply the combined effect in this analysis to clarify how Information and Communication Technology (ICT), when combined with Renewable Energy Sources (RES) and Institutional Quality (INSQ), has an impact on the environmental sustainability of OECD nations. For instance, ICT can enhance the efficiency and administration of renewable energy systems. At the same time, robust institutional arrangements can drive the implementation and governance of ICT-centered green policies. Examining these combined factors assists in revealing how these factors work together in practice, providing policymakers with worthwhile information with which they might better develop more combined and productive ways of attaining environmental sustainability.

By addressing these objectives, the study aims to contribute a comprehensive understanding of how advanced economies can leverage technology, innovation, and governance to achieve sustainable development. The research findings will guide strategic advancements in worldwide sustainability initiatives while confirming OECD nations as principal leaders in the move toward environmental sustainability.

This research explores how interconnected key factors function together to improve sustainability outcomes through comprehensive strategies.

This study employs a range of advanced econometric techniques to ensure the reliability of the analysis using second-generation panel unit root tests to account for heterogeneity and cross-sectional dependence among OECD economies. The study employs second generations of cointegration tests, such as the fully modified ordinary least squares (FMLOS) and dynamic ordinary least squares (DOLS) estimations. This study investigates panel data of 37 OECD economies over the period from 1996 to 2021. The dependent variable is environmental sustainability (a proxy for CO2 emission), and the independent variables are information and communication technology, renewable energy sources, green innovation (a proxy for environment-related technological patents), and institutional quality. GDPC and trade openness are used as control variables. The data is obtained from databases like WDI, OECD database, etc.

The results of this thesis demonstrate that, in the long run, Information and Communication Technology, renewable energy sources, green innovation, institutional quality, and trade openness are all positively and statistically related to environmental sustainability in OECD nations. These results imply that investment in digital infrastructure, switching to cleaner energy, and advancing environmentally friendly technologies and good institutional arrangements all help alleviate environmental degradation. Further, the study also identifies that the combined effects of ICT and renewable energy sources and ICT and green innovation also increase environmental sustainability and reveal that technological advancements and eco-friendly endeavors complement each other to result in improved environmental outcomes.

This thesis is divided into five chapters with the following structure: Chapter One introduces an overview of the research, setting out the background, importance, and contextual setting of environmental sustainability and the chosen independent variables. Chapter Two offers an overview of the literature, highlighting gaps in research and theoretical underpinnings. Chapter Three outlines the methodology, including data sources, variable choice, and econometric models used. Chapter Four

introduces the analysis, considers the findings, and presents the discussion of the results within the context of current literature and policy conclusions. Chapter five concludes the research, summarizing key conclusions and offering policymaking and research recommendations.



CHAPTER II

LITERATURE REVIEW

The accelerating risk of climate change and environmental deterioration has necessitated global demands for sustainable development, particularly from industrialized economies. At the forefront of environmental sustainability are the OECD nations, whose highly developed technological endowments and capacity for policymaking position them at the forefront of combating environmental challenges. The pressure to curb carbon emissions as well as enhance ecological resilience has grown, necessitating understanding the determinants that drive environmental sustainability.

Over recent years, information and communication technology (ICT), green innovation (GINV), clean energy resources, as well as institutional quality (INSQ), have become central factors to environmental performance. ICT facilitates instantaneous monitoring of the environment as well as energy efficiency, green innovation encourages sustainable production processes, clean energy provides a substitute for fossil fuels, leading to a decrease in emissions of green gases. Institutional quality ensures effective regulation, compliance, and effective policy implementation.

Despite a substantial body of work on each variable separately, a gap exists in combined studies on their individual impact on environmental sustainability, primarily in the framework of OECD nations. The study seeks to review the academic literature on each of these four variables as well as their contribution to environmental sustainability. Through review of both conceptual frameworks as well as empirical evidence, the study seeks to uncover agreement, disagreements, as well as avenues for further analysis.

2.1. Conceptual Framework and Theoretical Underpinning

Environmental sustainability may be defined as responsible management of the environment to prevent depletion of natural resources and ensure long-term ecological equilibrium. It is normally quantifiable in terms of indicators such as CO₂ emissions, ecological footprints, energy intensity, and environmental performance indexes. The conceptual structure of this study positions environmental sustainability at the center of a multi-dimensional framework, driven by technological advancements, institutional capacity, as well as the transit of resources. In the context of OECD nations, this structure is highly applicable given their technological advancement and policy ability.

The Environmental Kuznets Curve (EKC) hypothesis is a highly referenced theory in sustainability studies. It assumes a curvilinear, inverted U-shape in the connection between environmental degradation and economic growth: as economic growth happens at initial phases, environmental degradation continues to grow, but after passing a particular income threshold, it then starts to decrease. The theory offers a general framework for understanding how technological and institutional advancements in advanced nations may affect environmental performance.

Based on the work by Erdogan, (2024), which analyzes the nexus of natural resource rent and CO₂ emission for 13 African nations in the time span (1992 to 2020) based on the models of EKC and LLC. The analysis tests the U-shaped income CO₂ emissions nexus of the Environmental Kuznets Curve (EKC) but finds the Low Carbon Economy (LCC) model inapplicable, as natural resource rents add a greater degree of complexity. Resource rents, energy consumption, and population density (variable) are detrimental to sustainability. Introducing load capacity factor (LCF) as a measure of sustainability, as well as a comparison of aggregated vs. disaggregated effects, the study bridges a gap in African environmental analysis. It advises a longer period, expansion of the number of resources, and further investigation of population ecology dynamics.

Li et al. (2024) examine the EKC hypothesis for 38 countries (2002–2020), incorporating geopolitical risk, resource rents, corruption, and energy intensity.

Results confirm the EKC and show that geopolitical risk and energy intensity raise emissions, while corruption control and resource rents reduce them. The study fills a gap by analyzing both direct and indirect effects through a nonlinear panel framework. Ullah et al. (2024) test the N-shaped EKC for 17 OECD countries, analyzing digitalization, technological and financial innovation from 2009 to 2019. They find that financial innovation reduces CO₂ emissions, while digitalization and technological innovation increase them. The study confirms the N-shaped EKC and fills a gap by using new financial innovation metrics, suggesting future research on short-term impacts and alternative environmental indicators.

Jahanger et al. (2022) examine the EKC in North American free trade agreement (NAFTA) countries from 1990–2018, finding it valid only in the long run. Renewable energy reduces emissions, while natural resource rents increase them. Foreign direct investment (FDI) improves environmental quality, supporting the pollution halo effect. NAFTA's ratification is linked to higher emissions. The study fills a gap by applying the EKC within an FTA context and suggests further research on trade and sustainability.¹

Another key lens used here is institutional theory, which focuses on the role played by formal and informal institutions in framing environmental policy and behavior. It posits that effective institutions improve regulation enforcement, curb corruption, as well as encourage sustainable practice adoption. Institutional theory is particularly pertinent in OECD nations, where government systems are generally strong. Institutional theory, specifically from the perspective of the New Institutional Economics, spotlights the importance of the role that institutions play in facilitating effective environmental and economic policies. North (1990, 1991) points to the role that good institutions have in reducing transaction costs and facilitating investment and innovative activity. When considering the sustainability of the environment, institutional quality is the force that conditions the effectiveness of ICT, renewable energy, and green technology. Kaufmann et al. (2009) conclude that indicators of good

¹ The pollution halo effect is a hypothesis postulated that foreign direct investment (FDI) contributes to cleaner conditions in the host countries through the importation of cleaner technology, superior management techniques, and high standards of the environment from multinationals.

governance, including regulatory quality and rule of law, are positively associated with environmental outcomes.

Smits et al. (2008) examine agri-environmental schemes (AES) using New Institutional Economics, focusing on challenges like high transaction costs and fragmented management. They suggest solutions such as farmer cooperation and government collaboration to address inefficiencies. The study emphasizes the need for clear property rights and contract modifications to improve investment.

The theory about diffusion of innovations is also the foundation for this study, especially regarding ICT as well as green innovation. It identifies how new technology, and new ideas diffuse through societies and how social systems, communication channels, and institutions affect their adoption. It is in line with this theory that green technology, green energy systems, and digital tools for sustainability are diffused in OECD countries.

These theories collectively provide a holistic framework according to which the interdependence among ICT, green innovation, renewable energy sources, and institutional quality can be understood in attaining environmental sustainability. These theories are used to interpret findings from empirical work and inform a model used in the case study.

Saba et al. (2023) analyzes the impact of information and communication technology (ICT), renewable energy, agriculturalization, industrialization, and institutional quality on CO₂ emission in 51 African countries (2000–2021). Using system GMM and PCA-based indices, they find that ICT's interaction with other sectors significantly shapes environmental outcomes. The study fills a gap by exploring these complementarities and suggests integrated policy approaches for sustainability.

2.2. ICT and Environmental Sustainability

ICT has emerged as a strong facilitator in pursuing environmental sustainability at the global level. In OECD nations, where digital infrastructure is well established, ICT becomes a key enhancer of energy efficiency, a driver of smart management of

resources, and a builder of environmental awareness. The environmental dividends of ICT are varied, from process efficiencies in industry to digital platforms that enable environmental management and creativity.

Empirical evidence has indicated that ICT promotes environmental performance by maximizing energy efficiency, minimizing waste materials, and promoting low-carbon innovations. For example, smart grids and IoT tools have enhanced the distribution of electricity, reduced transmission loss, and enabled the integration of alternative sources of energy Mitra et al., (2020).

A study by Nejad and Shirazi, (2022) examines the impact of ICT on CO₂ emissions across 146 economies (1996–2019) using OLS and FGLS models. It finds that ICT can reduce emissions by promoting eco-friendly technologies, but its effectiveness depends on management practices and regional conditions.

Cerin, (2021) examines the relationship between ICT and environmental sustainability, focusing on CO₂ emissions in developed and developing countries from 1980–2016. Using panel data from 48 developed and 84 developing countries, the study finds that ICT reduces emissions in developed countries but worsens environmental sustainability in developing nations due to infrastructure and e-waste issues. The study confirms the Environmental Kuznets Curve hypothesis, showing emissions rise with economic growth but decrease at higher income levels.

Khan et al. (2020) examines the impact of ICT on CO₂ emissions across 91 countries from 1990 to 2017 using PCA, POLS, FEM, and SGMM methods. They find that ICT reduces emissions in developed countries but increases them in developing ones, confirming the Environmental Kuznets Curve (EKC) hypothesis.

Avom et al. (2020) examine the effects of ICT on Sub-Saharan Africa's environmental quality and point to a gap in the literature that has yet to be addressed: prior research provides contrasting evidence of whether ICT reduces or increases CO₂ emissions and has paid little attention to the transmission channels namely energy demand, trade openness, and financial development through which ICT effects shape the environment.

But the environmental impact of ICT itself cannot be discounted. The use of digital technology and data centers is escalating electricity consumption as well as e-waste. The ICT sector is projected to be responsible for at least 2–3% of global emissions of greenhouse gases Belkhir & Elmeligi, (2018), a matter of concern regarding the sustainability of ICT in the long term. Furthermore, discrepancies in digital infrastructure both across and within countries can constrain the prospect of ICT-driven environmental objectives equitably.

Although the overall literature is positive towards the role of ICT in environmental sustainability, it also underscores the value of complementary policies. Institutional frameworks, green IT incentive structures, as well as public-private partnerships, are required to ensure ICT developments help meet goals of sustainability. In OECD nations, where such institutional provisions are possible, ICT can be a foundation on which sustainable development can be based.

2.3. Renewable Energy Sources and Environmental Sustainability

The move towards the use of renewable energy sources is at the heart of long-term environmental sustainability. Renewable energies like solar, wind, hydro, geothermal, and biomass offer a cleaner, sustainable option over the traditional energy structures that are responsible for large amounts of greenhouse gas emissions. High energy consumption in the OECD economies, coupled with highly developed possibilities for innovating on resources, means that the use of renewable energy is at the forefront of curbing environmental issues.

An extensive body of evidence attests to the positive environmental effect of the use of renewable energy. Several studies have proven a strong negative correlation between a state's proportion of energy from renewables in its energy mix and its emissions.

Behera et al. (2024) examine how renewable energy, green technology innovation, political stability, and fiscal decentralization impact environmental sustainability in OECD countries from 2000 to 2019. Using CS-ARDL and AMG methods, they find that renewable energy reduces CO₂ emissions, while green innovation shows mixed

effects. Political stability and fiscal decentralization enhance the effectiveness of green policies through moderating effects. The study fills a gap by analyzing interaction effects and introducing a composite fiscal decentralization index. It suggests future research on ICT, human capital, and cross-country comparisons using disaggregated energy data.

Li et al. (2024) analyzes the effects of renewable energy, rule of law, corruption, and FDI on Costa Rica's ecological footprint from 1990–2020 using WQR and QQGC. They find that renewable energy improves sustainability in the short term but increases its footprint in the long term, while corruption and FDI have mixed effects.

Dam and Sarkodie (2023) analyze the effects of income, renewable energy, and trade openness on environmental sustainability in Türkiye using ILCF from 1965–2018. Results support the ILCC hypothesis, with income increasing ILCF until a turning point, not yet reached. Renewable energy improves sustainability in the short term but not the long term, while trade openness reduces ILCF in the long run. The study introduces ILCF as a novel and effective sustainability indicator.

Zafar et al. (2020) examines the impact of renewable energy, education, FDI, natural resources, and economic growth on CO₂ emissions in OECD countries from 1990 to 2015. Using second-generation econometric techniques, including panel unit root tests and cointegration methods, the study finds that education and renewable energy reduce emissions, while FDI and natural resource abundance increase them. The study proposes a policy framework that integrates education with renewable energy promotion to reduce emissions.

Achuo et al. (2022) examine the effects of renewable and non-renewable energy on environmental sustainability with a sample of 173 countries from 1996–2020 (panel data). Employing fixed-effects with Driscoll–Kraay errors, the authors document that renewable energy reduces emissions and that emissions increase with non-renewable energy.

Adedoyin et al. (2023) examine the impact of renewable and non-renewable production on CO₂ emissions in Germany during 1981–2020. Adopting ARDL,

dynamic ARDL simulations, and Kernel-based Regularized Least Squares (KRLS) methods, they conclude that renewable energy is responsible for reducing emissions in the long and short runs, whereas coal production tends to enhance them. In a novel approach, the study simulates policy shocks and verifies that a 61% increase in renewable energy decreases emissions appreciably. It bridges a gap by integrating machine learning with simulation to examine energy policy effectiveness in a post-COVID and energy crisis scenario.

Furthermore, the deployment of renewables within the economies of the OECD has been facilitated by sophisticated infrastructure, technological awareness, and sound policies. Policy instruments such as tax credits, feed-in tariffs, and renewable energy targets facilitated a gentle growth in clean energy production and consumption. The European Union has, in particular, made ambitious objectives for renewables a key component of its general environmental agenda, shaping national policies among member states as well as other economies in the OECD.

The process of switching to renewables is not, however, a problem-free endeavor. Technical challenges like intermittency (wind and solar energy particularly), energy storage constraints, and grid integration are major deterrents for growing renewables. The environmental effects of other renewables, like land use for biofuels or impacts on habitats by hydropower, are issues that have raised academic debate. The fact that renewables are needed is evident, however, as their deployment must be carefully planned to prevent unintended environmental side effects.

Ansari et al. (2024) analyze the impact of renewable energy, financial inclusion, digital finance, and institutional quality on environmental sustainability in Pakistan. Using ARDL and PCA, they find that all factors improve sustainability, with digital finance being more effective when institutional quality is high. The study fills a gap by examining interaction effects and suggests broader regional studies and exploration of digital finance risks in future research.

Hou et al. (2023) examine the impact of fossil fuel and renewable energy on CO₂ emissions in OECD countries (1990–2019) using CS-ARDL. They find fossil fuel consumption increases emissions, while renewable energy reduces them. Economic

growth also contributes to higher emissions. The study highlights the need to reduce fossil fuel use and promote renewable energy.

Li et al. (2022) examines the impact of solar energy, environmental policy stringency, and climate technologies on CO₂ emissions in OECD countries (2001–2018) using CS-ARDL. They find that solar energy, stringent policies, and climate technologies reduce emissions, while economic growth contributes to degradation. The study suggests promoting renewable energy and strict guidelines for sustainable growth.

In summary, the evidence unequivocally supports the fact that clean energy plays a revolutionary role towards promoting environmental sustainability in OECD countries. It, however, points out that clean energy can only be utilized at its full capacity in a bid to prevent climate change with joint policies, systems of innovation, and institutional shifts.

2.4. Green Innovation and Environmental Sustainability

Green innovation, as the creation and deployment of new processes, products, or technologies that minimize negative environmental impacts, has become increasingly important as a route to sustainability. In the case of OECD nations, green innovation is promoted by strong systems of research and development, environmental policies, and fiscal measures that incentivize sustainable business steps on a sector-wide basis. It plays a key role in revolutionizing production processes as well as consumption patterns towards greener substitutes.

Empirical studies across academic literature globally recognize a positive correlation of green innovation with environmental sustainability. Various empirical studies reveal that green R&D investment is followed by enhanced energy efficiency, a decrease in greenhouse gas emissions, as well as greener industrial processes.

Chang et al. (2024) examines the influence of green innovation, green growth, and urbanization on OECD countries' CO₂ emissions between 1996–2022. Employing System GMM, the authors conclude that green growth and innovation lower emissions but are increased by urbanization. Renewable energy reduces emissions, but

consumption of energy and dependency on resources degrades environmental performance. Long-term implications and regional differences are areas of investigation in future studies.

Karlilar et al. (2023) examine the impact of digitalization, green innovation, renewable energy, and financial development on environmental sustainability in OECD countries. Using a two-step system, the Generalized Method of Moments estimator, they find that digitalization reduces environmental degradation, with significant interactions between digitalization, green innovation, renewable energy, and financial development.

Sun et al. (2022) investigates how renewable energy, green innovation, and globalization affect carbon emissions in the top 10 most polluted countries using MMQR from 1991 to 2018. They find that globalization increases emissions across all levels, while renewable energy and green innovation reduce emissions mainly at higher quantiles. The study highlights asymmetric effects, filling a gap by applying MMQR to capture distributional impacts.

Another study analyzes the impact of green innovation, green growth, and urbanization on CO₂ emissions in OECD countries (1996–2022) using System GMM and econometric tests. It finds that green innovation and growth reduce emissions, while urbanization increases them. Renewable energy lowers emissions, but non-renewable energy worsens outcomes. The study fills a gap by examining how green innovation moderates' urbanization's impact.

Nonetheless, several limitations exist in the literature. First, green innovation has no standard metric. Most studies employ proxies like patents, R&D expenditure, or innovation surveys, each with their own shortcomings. Secondly, even though most studies confirm a green innovation-environmental performance link, causality is doubtful. In other situations, it is doubtful if environmental performance is improved by innovation, or if improved environmental awareness as well as pressure for regulation induce changes.

Thirdly, differences in innovation potential in member countries of the OECD may mean that performance also varies. High-income economies with firm institutional backstopping enjoy most benefits from green innovation, while others struggle because their weaker regulation enforcement as well as less private sector involvement. This disparity again supports the proposition that countries need specific strategies for each tailored to their respective environments.

Overall, the literature points to green innovation as a key driver of environmental sustainability in mature economies. It also demands a more holistic process linking innovation policymaking with ICT developments, the transitions in the energy sector, as well as institutional building fields this thesis seeks to explore further.

2.5. Institutional Quality and Environmental Sustainability

Institutional quality and governance are emerging as drivers in determining environmental performance, especially in developed economies such as those of the OECD. Broadly defined institutions such as formal institutions such as the law and regulatory agencies as well as informal institutions like norms and routines are essential in imposing environmental standards, allocating resources, and enhancing cooperation among parties. High institutional quality is linked to good environmental performance, accountability, transparency, as well as public trust, all of which are required for effective implementation of sustainability measures.

Theoretical and empirical analysis supports the fact that institutional quality has a direct and indirect impact on environmental performance. For example, government performance on dimensions such as low corruption, high-quality regulation, as well as a good rule of law empowers the government to implement environmental regulations, induce green investment, as well as utilize natural resources in a sustainable manner.

Dam et al. (2024) analyze the impacts of institutional quality and green growth on environmental sustainability (ENS) in the case of the countries of the OECD applying the PMG-ARDL estimation method. According to their findings, GGR diminishes environmental degradation (CO₂) and enhances ENS (ILCF) in the long run. INSQ,

on the other hand, has positive impacts on degradation but mixed impacts on sustainability.

Jahanger et al. (2022) explore how globalization, democracy, as well as autocracy, impacted CO₂ emissions in the developing world during the 1990–2018 period. Employing FMOLS and DOLS methods, they reveal that financial development as well as globalization worsen the quality of the environment, yet democracy as well as sustainable energy enhance it. The paper endorses the Environmental Kuznets Curve (EKC) hypothesis as well as underscores the significance of good governance through democracies as well as effective globalization policies towards curbing environmental degradation.

JinRu and Qamruzzaman (2022) explore the impact of environmental innovation, energy efficiency, and institutional quality on sustainability in G7 countries (1980–2020). They find that energy efficiency and innovation reduce carbon emissions, while strong institutions improve environmental outcomes. The study highlights the need for further research using non-linear models and better energy efficiency metrics.

Cao et al. (2022) examine the effects of institutional quality, economic growth, globalization, and energy consumption on CO₂ emissions in the OECD nations through a panel ARDL method. They determine that globalization and renewable energy decrease emissions, and institutional quality raises them in the long run but mitigates them in the short run. Economic growth and consumption of electricity are found to be positively related to CO₂ emissions.

Other drivers of sustainability, such as ICT, green growth, and clean energy, are also mediated by institutions. Unless institutions function well, technological innovations and the clean energy transitions may not be reflected in real environmental gains. For instance, clean energy projects can be bogged down by delays or inefficiency in nations with red tape in bureaucracies or lax enforcement. Powerful institutions, on the other hand, can accelerate project procurement, enable market-based mechanisms such as emissions trading, and promote environmentally friendly behavior by the public as well as private entities.

Additionally, the Environmental Performance Index (EPI) that captures a state's environmental vitality and ecosystem health tends to be positively related with measures of good governance such as voice and accountability, quality of regulation, and control of corruption. OECD nations tend to score well on both governance and on EPI measures, indicating a positive reinforcing nexus between good institutions and environmental performance.

Nevertheless, the literature also underscores key limitations as well as disparities. Even in the case of OECD countries, institutional quality varies, and political priorities may change, thereby influencing long-term environmental policies. Further, debate exists regarding causality between institutional quality and sustainability whether good institutions result in improved environmental performance, or environmental pressure result in institutional reform.

Overall, institutional quality is broadly accepted as a foundation of environmental sustainability. It supplies the enabling environment where ICT, green innovation, and renewable energy policies can flourish. In the OECD nations, where institutional frameworks are usually mature, governance is responsible for ensuring environmental integrity as well as international sustainable goals.

2.6. Integrated Perspective and Interlinkages

Whilst a rich literature is available on the individual impacts of ICT, green innovation, renewable energy sources, and institutional quality on promoting environmental sustainability, only a limited number of studies have considered their combined impacts, particularly in a cross-country setting such as the OECD. Recent studies increasingly argue that environmental sustainability is multi-dimensional by nature; thus, understanding how different drivers interact with each other is essential for effective practice and policy.

Azam et al. (2021) analyze the nonlinear effects of ICT trade, renewable energy, nuclear power, and natural gas energy on GDP growth and CO₂ emissions in ten major emitter countries during 2000-2016. Unlike previous studies with contradictory findings, they take ICT-trade into account as a key factor and focus on its twofold role

in growing GDP and reducing emissions. Employing a set of panel data methods involving OLS, FEM, REM, cointegration, and Dumitrescu-Hurlin causality tests, they conclude that renewable energy and ICT-trade decrease emissions, whereas nuclear and natural gas enhance them. This work fills a gap by looking into ICT-trade interaction with energy sources and proposes additional studies on disaggregated ICT indicators and regional realities.

Adebayo et al. (2022) examine the effects of financial development, economic growth, urbanization, agriculture, and renewable energy use on Turkey's CO₂ emissions from 1985 to 2019. Advanced quantile-on-quantile regression and nonparametric quantile causality tests detect nonlinear and asymmetric effects at various distribution levels. All of these (economic growth, urbanization, financial development, and agriculture) increase emissions in a continuous manner, while renewable energy lowers CO₂ emissions at middle-level quantiles only. Filling a gap in previous research, the authors suggest an SDG-congruent policy approach to promoting sustainable development in Turkey.

Al-Mulali et al. (2015) investigate the impact of disaggregated sources of renewable electricity on CO₂ emissions in 23 countries in Europe during 1990-2013. Employing panel cointegration and fully modified ordinary least squares (FMOLS) technique, the authors reveal that GDP growth, urbanization, and financial development enhance emissions whereas trade and renewable electricity from hydroelectricity, nuclear power, and combustible renewables decrease emissions. The research contributes to existing literature in that the authors investigate the specific impact of every disaggregate source of renewable energy, in contrast to other works where renewable energy is taken and analyzed in its aggregate form.

Zhang et al. (2017) studied the nexus between trade openness and CO₂ emissions in ten newly industrialized nations (NICs) from 1971 to 2013 and examined the EKC hypothesis. Employing techniques of panel FMOLS, DOLS, and VECM, the authors get evidence of the significant reduction of emissions caused by trade openness and of the increase of emissions due to GDP and energy use. It also validates the EKC hypothesis and finds feedback causal relationships among trade, GDP, and emissions.

It fills in the gap with the use of long-run panel cointegration and causality tests for a set of heterogeneous emerging economies.

Yang et al. (2022) investigates the role of income inequality and institutional quality in shaping CO₂ emissions in 42 developing nations from 1984 to 2016. Previous studies tended to neglect institutions in their models, whereas here both direct and interaction effects are combined to show that income inequality raises emissions unless checked by good institutions. In applying Westerlund's cointegration, Driscoll–Kraay regressions, and robustness checks (FMOLS, PMG), the authors establish a nonlinear EKC-type relationship and emphasize institutional quality as a critical condition to limit environmental degradation.

Khan et al., (2020) used a panel quantile regression model to a data sample of 192 economies in the world. While the period is not specifically mentioned, what their findings do imply is that higher renewable energy use decreases carbon emissions in nations dramatically and provides firm evidence to support a global transition towards clean energy.

Danish et al. (2019) employed panel data covering the period from 1990 to 2015 to examine the impact of ICT captured by internet and mobile use on CO₂ emissions in high, middle, and low-income nations. From their work, we learn that ICT is impacting emissions negatively in upper-middle-class economies yet positively shifting them in low-income contexts with the implication that ICT is subject to institutional and infrastructural context.

Hasnisah et al. (2019) analyzed the EKC hypothesis with data from Asian emerging countries, though the specific years are not specified. Their panel regression findings replicate the EKC shape but reveal that renewable energy does not decrease emissions in the short run statistically significantly, challenging the environmental effectiveness of the use of renewables in these economies.

Ahmed and Shimada (2019) employed panel data techniques and causality tests to examine data from emerging and developing economies. Their findings demonstrate a two-way relationship between renewable energy use and GDP with a unidirectional

causal relationship from the use of renewables to reducing CO₂. Since the time frame is not specifically mentioned, the regional scope is on non-industrialized economies.

Rasoulinezhad and Saboori (2018) used a panel cointegration and causality to examine the role of renewable energy in curbing CO₂ emissions and promoting economic growth in a wide range of countries. While the specific time frame is not defined here, their global panel methodology points towards the twofold advantage of renewable energy in improving economic and environmental aspects.

Lee and Jung (2018) explored the nexus of renewable energy use and economic growth in South Korea during 1990–2012. For the same interval of time, applying the ARDL and VECM methodologies, they established that renewable energy adversely affects GDP to justify the conservative hypothesis in the context of South Korea.

A study by Apergis et al. (2023) investigates the effect of the use of renewable and non-renewable energy sources on carbon dioxide emissions for the period of 1985 to 2020 in Uzbekistan. This study used ARDL bounds testing estimation. This study uses disaggregated energy information like hydropower as a proxy for renewable energy and coal, oil, and gas as a proxy for non-renewable energy, and it excluded GDP to avoid multicollinearity. Outputs reveal that hydropower decreases emissions in the long and short runs and that oil and gas augment them; coal has a mixed impact. The research bridges a gap with the use of disaggregated energy variables in the one-country ARDL model. It advocates policy transitions to hydropower and solar energy to achieve climate goals.

A number of interdisciplinary studies show that the synergies among ICT, innovation, energy transition, as well as institutions can reinforce their individual impacts. For example, ICT can be utilized to improve the performance of renewable energy systems by fostering smart grids and energy monitoring. Likewise, green innovation needs to be based on institutions favorable towards intellectual property rights as well as environmental regulations.

Nevertheless, the current literature has several limitations. A key shortcoming is the absence of longitudinal, cross-country empirical evidence examining interactions of

these variables over time in high-income environments such as the OECD. Some literature employs panel data to examine causal impacts, but few models simultaneously include all four variables (ICT, RESS, GINV, and INSQ), complicating the formation of overall conclusions. Heterogeneity across OECD countries regarding policy regimes, economic systems, and environmental priorities necessitates comparative studies accounting for differences by country.

There is also limited analysis of feedback mechanisms. For instance, greater environmental sustainability can inspire additional innovation or reform of public policy, leading to a virtuous circle seldom considered in static models. Furthermore, although the Environmental Kuznets Curve (EKC) is widely cited, critics complain that it simplifies the connection between development and environmental pollution by excluding factors such as technological progress and institutional maturity.

In light of such shortcomings, extensive analysis that consolidates ICT, green technology, renewables, and institutional quality in a single analytical framework is warranted. This framework is particularly applicable to the OECD nations since advanced skills in each area provide a rich testing environment for policymaking interaction as well as effectiveness. An integrated framework would not only be a valuable contribution to the academic literature but also a practical guide for policymakers seeking to craft balanced as well as synergistic strategies for sustainability.

The literature reviewed provides solid evidence that green innovation, information and communication technology (ICT), renewable energy sources, and quality institutions, are all key factors towards environmental sustainability especially in developed economies such as the OECD nations. All these elements play a different but complementary role towards driving lower emissions, resource efficiency, as well as sustainable development approaches.

ICT promotes smarter use of resources, promotes innovation, as well as supports sustainable consumption patterns. Green innovation fuels technology solutions to mitigate environmental degradation as well as improve industrial efficiency. Renewable energy sources provide a direct route towards decarbonization as well as

energy security. Institutional quality promotes the safe management of environmental strategies through effective governing, implementation, as well as continuity.

Notwithstanding the richness of current scholarship, a number of essential gaps persist. Chief among them is that the literature systematically considers these drivers in isolation from one another, failing to explore their interdependencies as well as synergies. In addition, the absence of longitudinal, cross-country analysis constrains understanding of how these variables coevolve in different institutional environments and over time. Measurement issues, limited data, and inconsistent analytical frameworks applied to policy evaluation also limit the conclusions one may draw from existing studies.

Thus, this thesis seeks to bridge such gaps by taking a holistic, cross-country analysis of the OECD nation's suitable background given their well-developed technological infrastructure, varying institutional configurations, and commitment towards sustainable development. By exploring the cumulative impact of ICT, green innovation, renewable energy, and the quality of institutions on environmental sustainability, this paper will be able to enhance an informed understanding of sustainable development processes.

CHAPTER III

DATA AND METHODOLOGY

This chapter contains the research methodology for measuring the role of ICT, green innovation, renewable energy, and institutional quality on environmental sustainability in OECD economies is explained. It describes the research design, variables and sources of the data, and econometric model for analysis. It employs panel data for examining the relationship between these variables within a time frame with a strong methodology for indicating their contributions towards environmental outcomes. It also elaborates on the method of estimation and diagnostic techniques that are applied for confirming the results.

3.1. Data and Sample Size

This study utilizes World Bank World Development Indicators (WDI) secondary data to explore the relationship between variables such as Information and Communications Technology (ICT), renewable energy sources, green innovation, and institutional quality on environmental sustainability. The analysis for 37 of the 38 OECD members includes Austria, Australia, Belgium, Canada, Chile, Colombia, Costa Rica, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Türkiye, the United Kingdom, and the United States. It excludes Slovenia based on the unavailability of necessary data. For the consistency of the results and where possible, to handle cases with no available data, a balanced panel dataset for the period 1996–2021 for the countries above has carefully been compiled. Environmental sustainability has been captured by CO₂ emissions in metric tons per capita, which will be used as the dependent variable. The key independent variables are ICT development, renewable energy sources (RESS), green innovation (GINV), and institutional quality (IQ). We have further added two

control variables, trade openness (TRD) and the rate of GDP per capita growth (GDPC), for their possible effects on environmental sustainability. Through the use of such a wide-ranging dataset and several pertinent variables, several variables that influence environmental sustainability in OECD members, the study seeks to explore both the independent and cumulative effects of ICT, renewable energy, green innovation, and institutional quality on environmental sustainability.

3.2. Model Specifications

Environmental sustainability, specifically carbon dioxide emissions, is among the most important issues for the relatively more developed technological and regulating frameworks of the OECD countries. Most of the previous research has utilized CO2 emissions as the dependent variable to measure environmental sustainability. Ahmad et. al. (2023) analyze the impact of information and communication technology (ICT) on CO2 emission (a proxy for environmental sustainability) for OECD economies from 1990 to 2018 and found that ICT is effectively decreasing environmental degradation by using panel techniques like CADF, CIPS, and different cointegration tests. Behera et. al (2024) analyzed the impact of renewable energy, political stability, and fiscal decentralization on CO2 emission for seven OECD economies by using CS-ARDL and AMG estimation methods and found the significant and positive relationship of renewable energy and political stability on environmental sustainability while green innovation showed insignificant result. Jianguo et. al., (2022) analyzed thirty seven OECD economies (1998 to 2018) to examine the relationship of CO2 emission with institutional quality, financial development, and technological innovation and found that institutional quality and technological innovation plays a moderating role in mitigating this effect while financial development reduces environmental sustainability. The study used System GMM, panel cointegration techniques, and cross-sectional dependence techniques for robust analysis. Cao et. al., (2022) estimated 36 OECD economies (1985-2018) and used different cointegration techniques like (Kao, Westerlund, and Pedroni) and Pooled Mean Group estimations, and they found renewable energy, globalization, and institutional quality increases environmental sustainability by decreasing CO2 emission, while financial development, stock markets, and economic growth increase CO2 emission in the both short and long run. After analyzing the prior literature I came to the point that no study

used information and communication technology, renewable energy sources, green innovation, and institutional quality in order to analyze the environmental sustainability of OECD countries, along with that no prior study examined the combined effect of information and communication technology and renewable energy source (RESS), and ICT and institutional quality (INSQ) for OECD countries in this study we will examine the relationship between the independent variables and environmental sustainability and combined effect of ICT and RESS, and ICT and INSQ by using panel estimation methods like FMOLS and DOLS, the models for my study is here.

General Model: Relationship between dependent and independent variables along with interactions effect

$$LCO_2 = \beta_0 + \beta_1 ICT + \beta_3 RESS + \beta_4 GINV + \beta_5 INSQ + \beta_6 LTRD + \beta_7 LGDPC + \beta_8 ICT * RESS + \beta_9 ICT * INSQ + \varepsilon$$

Model 1: Relationship between dependent and independent variables

$$LCO_2 = \beta_0 + \beta_1 ICT + \beta_3 RESS + \beta_4 GINV + \beta_5 INSQ + \beta_6 LTRD + \beta_7 LGDPC + \varepsilon$$

In this regression, β_0 refers to the coefficient of the dependent variable when there is no independent variable, whereas the stochastic error term is denoted by ε . Model 1 is estimated when no interaction variables of ICT and other control variables, i.e., renewable energy source (RESS), green innovation (GINV), institutional quality (INSQ), trade openness (LTRD), and GDP per capita (LGDPC) are included. The rest of the models include the interaction variables RESS and INSQ step by step in a systematic and sequenced fashion.

Model 2: Interaction between ICT and RESS

$$LCO_2 = \beta_0 + \beta_1 ICT + \beta_3 RESS + \beta_4 GINV + \beta_5 INSQ + \beta_6 LTRD + \beta_7 LGDPC + \beta_8 ICT * RESS + \varepsilon$$

Model 3: Interaction between ICT and INSQ

$$LCO_2 = \beta_0 + \beta_1 ICT + \beta_3 RESS + \beta_4 GINV + \beta_5 INSQ + \beta_6 LTRD \\ + \beta_7 LGDPC + \beta_8 ICT * INSQ + \varepsilon$$

3.3. Discussions of the Variables

Environmental sustainability has been widely studied using theoretical literature and empirical research, with a specific interest in determining and examining the factors that contribute to the environmental quality of a country. Since sustainable development and climate change have become increasingly important, there is a necessity to observe and learn about the major variables stipulated below, which are found to have a major bearing on environmental outcomes.

3.4. Dependent Variable

The primary research focus and central dependent variable of the thesis is environmental sustainability, which is captured as the proxy for CO₂ emission. It describes the conservation and sound management of the natural resources in a way that the needs of the present do not jeopardize the ability of the upcoming generations to cater to their needs. It focuses on maintaining ecological equilibrium and mitigating environmental degradation.

3.5. Independent Variables

Information and Communication Technology (ICT) is captured by a composite index of three ICT indicators by applying principal component analysis (PCA). ICT developments remain key to reducing transaction costs by allowing for real-time data collection, greater transparency, and enhanced coordination between companies, regulators, and those, like us, consuming these services. This also enables better resource allocation and the establishment of better pollution control measures. Khan et al., (2020) reveals a positive relation between ICT and environmental sustainability for developed countries. Another study by Nejad and Shirazi, (2022) reveals ICT can reduce carbon emissions by promoting eco-friendly technologies. Based on the

previous literature, we anticipate that ICT will impact environmental sustainability positively by reducing CO₂ emissions in OECD countries.

Renewable Energy Sources are captured by a composite index of two indicators, renewable energy output (percentage of total energy output) and renewable energy consumption (percentage of total energy consumption), by applying principal component analysis (PCA). It is one of the key processes in decarbonizing the world's energy infrastructure is the transition to renewable sources of energy such as solar, wind, and hydroelectric power. By reducing dependency on finite fossil fuels, which are frequently at the geopolitical disputes these energy sources enhance energy security and decrease greenhouse gas emissions. There is too much literature exist on the relationship between ES and RESS, I'm citing the latest study by Behera et al. (2024) which reveals that there is a significant positive relation between environmental sustainability and renewable energy sources which means by adopting renewable energy sources countries can reduce CO₂ emission.

Green Innovation is an index from the OECD database that is calculated as the percentage of technological and environment-related innovations. Green innovation describes the creation and implementation of new products, processes, technologies, and business models that have a strong environmental impact. It encompasses innovation that optimizes resource utilization, minimizes waste, reduces carbon footprints, and encourages the utilization of renewable resources. Green innovation works towards addressing ecological challenges by promoting sustainability in energy, manufacturing, transportation, and farming. Empirical studies across academic literature globally recognize a positive correlation of green innovation with environmental sustainability. Chang et al. (2024) reveals the positive relationship between green innovation and environmental sustainability explaining that with the improvement in environment related technologies the emission of CO₂ decreases.

Institutional Quality is captured by a composite index of six variables from the world governance indicator, i.e., control of corruption, political stability, government effectiveness, regulatory quality, rule of law, and accountability, by applying principal component analysis (PCA). It refers to the effectiveness of institutions' policies and performance in a country. High institutional quality is linked to good environmental

performance, accountability, transparency, as well as public trust, all of which are required for effective implementation of sustainability measures. The existing literature says there is a positive relationship between institutional quality and environmental sustainability when the institutions are strong, and in a country with weak institutions, the relationship is inverse. JinRu and Qamruzzaman (2022) reveals that strong institutions improve environmental outcomes means reduce CO2 emission.

The graph below illustrates the average institutional quality per OECD countries for period 1996-2021. Unlike ICT and RESS, it also gives more compelling results. The above graph is revealing that average of institutional quality is highest (1.3287) in Finland as compared to other OECD countries. Denmark and Sweden are others having similar higher scores for institutional quality on average. The results also reveal that the average of institutional quality is lowest in Colombia (-2.19224). These results of average of institutional quality reveals that there is a considerable variation among the OECD countries in terms of institutional quality.

3.6. Control Variables

Trade openness describes the extent of a country's participation in international trade by lowering restrictions on the movement of goods and services. It has a two-sided relationship with environmental sustainability. On the one hand, trade openness may enhance sustainability by making access available for green technology, promoting improved environmental quality, and supporting economic progress that will be channeled into investments in clean energy. On the other hand, trade openness is likely to enhance resource consumption and degradation of the environment, particularly if the movement of industries from one country with strong environmental regulations takes place towards that with weak environmental regulations. Therefore, the effect of trade openness on sustainability depends heavily on the effectiveness of a country's environmental policy and the quality of institutions.

GDP per capita represents a country's economic production divided by population and measures the average income or level of living of its people. Its link with environmental sustainability is complex. Increased GDP per capita results in higher financial resources for clean technology investment, environmental protection, and

sustainable infrastructure. Furthermore, more prosperous economies tend to require tighter environmental regulations and higher standards of living. The existing literature has a contracting relationship between environmental sustainability and GDP per capita based on the state of growth of the estimated country.

3.7. Graphical Analysis of the Variables for OECD Countries

Results in the below graph reveal substantial variation in the average rate of CO₂ emission among OECD members. Luxembourg has the highest emissions rate, although it has a small population. The United States, Australia, and Canada are the others with similar higher emission rates. This diversity among members emanates further from the wide range of emission levels, ranging from the highest for Luxembourg to the lowest for Costa Rica. The variations indicate the vast diversity in CO₂ emissions, which points towards the presence of differing factors such as industrial production, energy consumption habits, and environmental regulations accounting for the different emission capacities among countries.

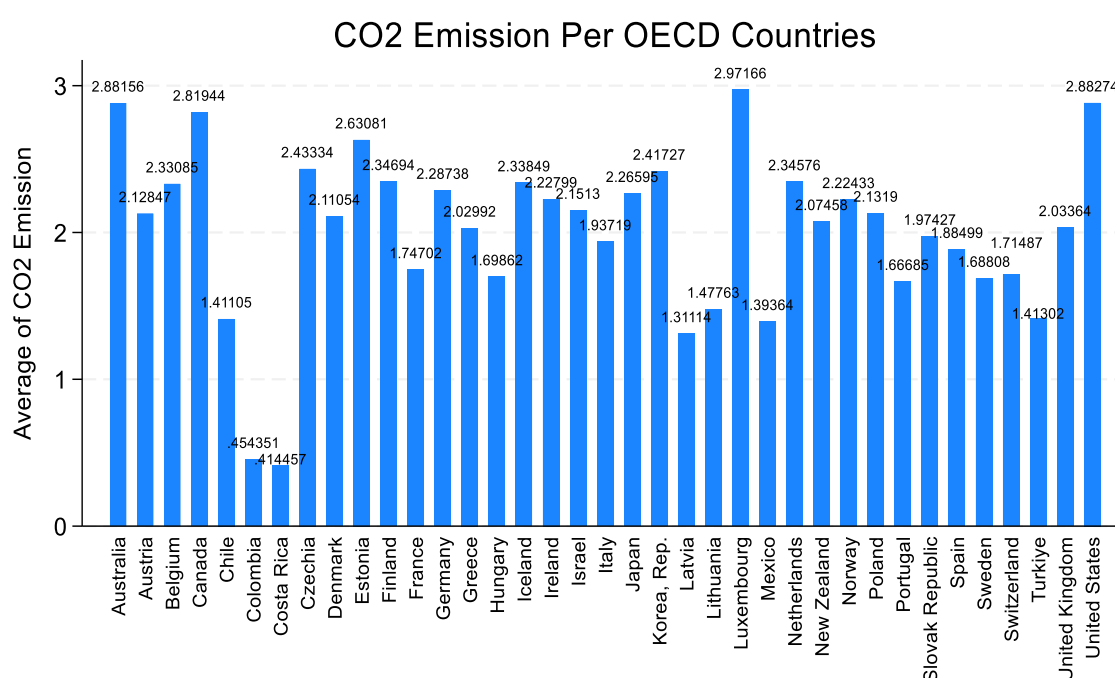


Figure 3.1. Average CO₂ Emission Rate in OECD from 1996-2021²

² This graph shows the average rate of emission of CO₂ after taking log. On average the CO₂ emission for OECD countries lies between 0.414 to 2.97. Which represents the maximum and minimum rate of emission of CO₂ higher the value means higher the emission lower the value means lower emission. The data is obtained from WDI and its time period is from 1996 to 2021.

The graph below illustrates the average of information and communication technology per OECD countries from 1996-2021. Unlike CO2 emission, ICT gives more compelling results. The graph below reveals that the average ICT is highest in Iceland compared to other OECD countries. The results also indicate that the average of ICT is lowest in Mexico. The results show that the developed countries have an ICT penetration value above the average level, and the developing countries have an ICT penetration value less than average.

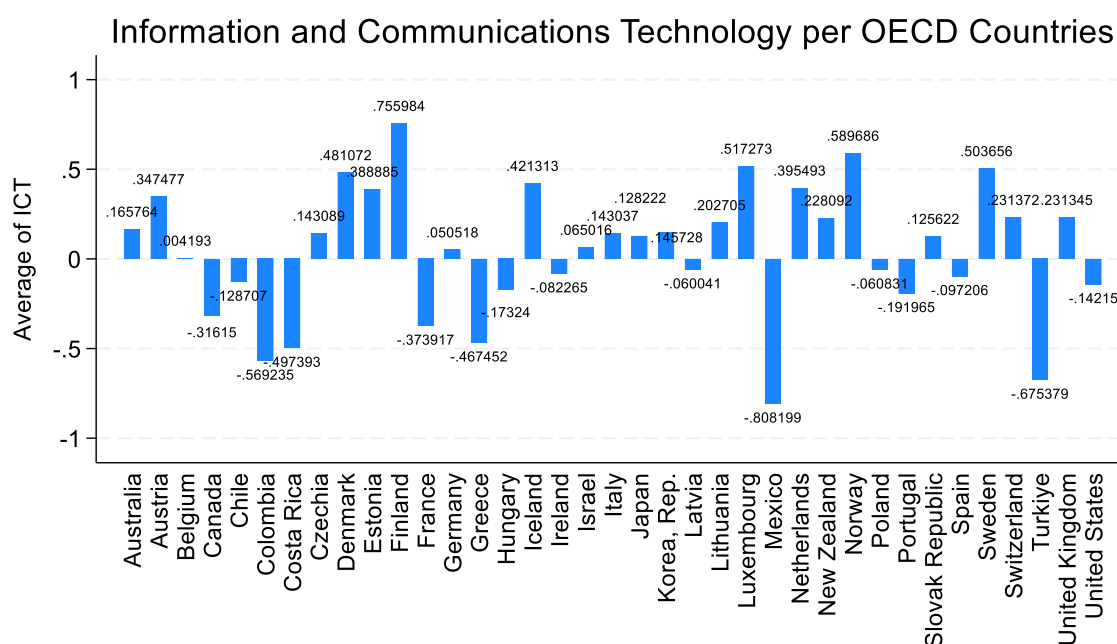


Figure 3.2. Average ICT in OECD from 1996-2021³

The graph below illustrates the average renewable energy sources per OECD countries from 1996-2021. Unlike ICT, RESS also gives more compelling results. The graph reveals that the average of renewable energy sources is highest in Norway as compared to other OECD countries. The results also indicate that the average of RESS is the lowest in the Korean Republic. These results of the average of renewable energy sources reveal that there is a considerable variation among the OECD countries in

³ Information and communication technology is index from three variables so it does not possess any unit. On average, the adoption of ICT in OECD countries is between -0.823 and 0.728. Which also represent maximum and minimum. A higher value of ICT means the adoption is higher in that country on average between 1996-2021. The negative values represent on average ICT adoption is very low.

terms of the adoption of renewable energy sources. This might be because of government policies or a lack of resources.

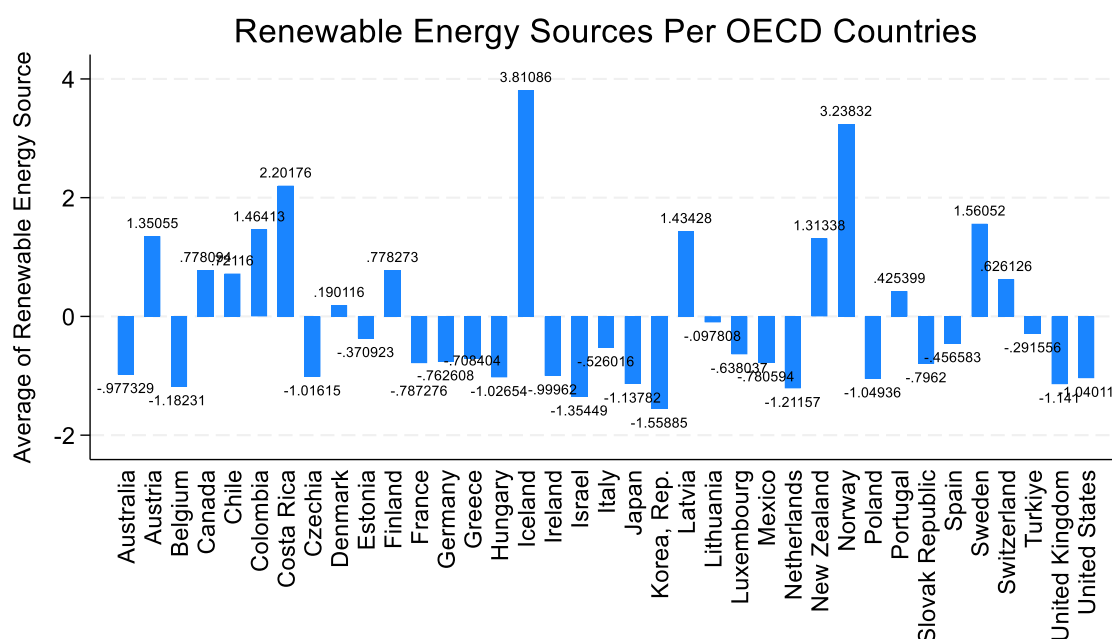


Figure 3.3. Average Renewable Energy Sources in OECD from 1996-2021⁴

The graph below illustrates the green innovation per OECD countries for the period 1996-2021. Unlike CO2 emission and ICT, it also gives more compelling results. The graph reveals that the average of green innovation is highest in Chile as compared to other OECD countries. The results also indicate that the average green innovation is lowest in Iceland. All the OECD countries, on average, have very good scores for green innovation, which is helping to reduce CO2 emissions, as we examine from existing literature.

⁴ A renewable energy source is an index made from two variables using PCA estimation. On average, the use of renewable energy sources in OECD countries is between -1.55 and 3.81. Which also represent maximum and minimum values. A higher value of RESS means the use of renewable energy is higher in that country on average between 1996-2021. The negative values represent that the average use of renewable energy is very low.

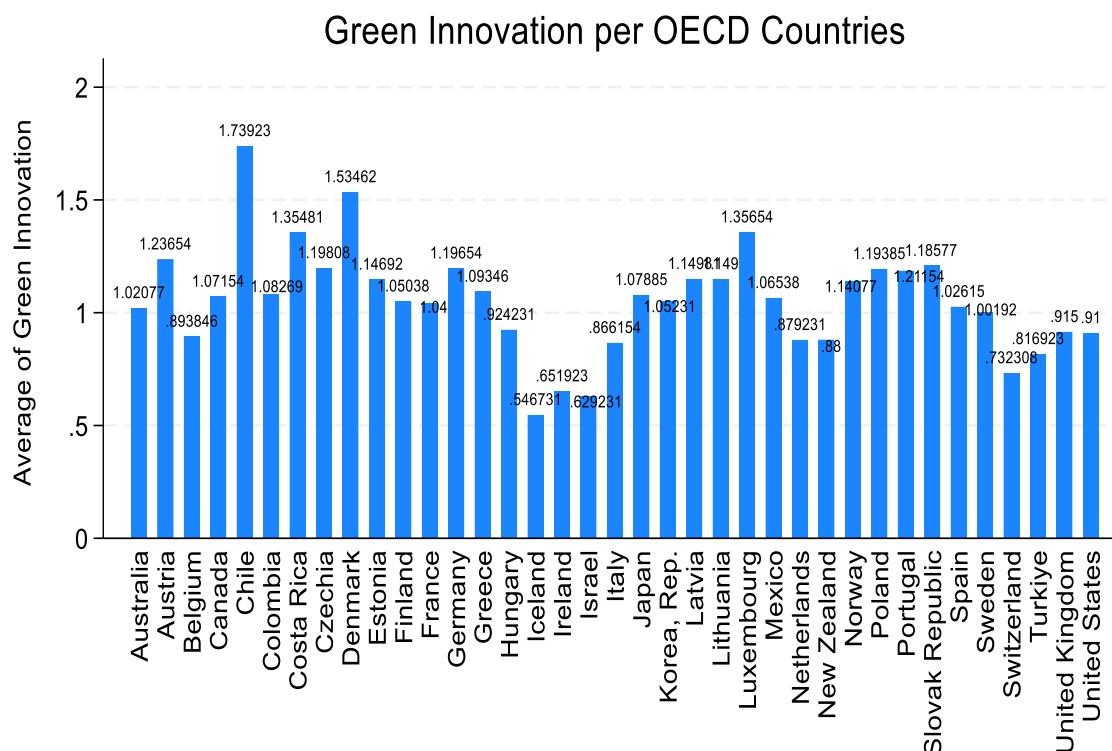


Figure 3.4. Average Green Innovation in OECD from 1996-2021⁵

The graph below illustrates the average of institutional quality per OECD countries for period 1996-2021. Unlike ICT and RESS, it also gives more compelling results. The above graph is revealing that average of institutional quality is highest in Finland as compared to other OECD countries. Denmark and Sweden are others having similar higher scores for institutional quality on average. The results also reveal that the average of institutional quality is lowest in Colombia. These results of average of institutional quality reveals that there is a considerable variation among the OECD countries in terms of institutional quality.

⁵ Green Innovation data was taken from the OECD database and was in percentage form there. This graphical representation shows that the average value of green innovation in OECD countries is between 0.54 and 1.73. Which also represents the maximum and minimum values of the percentage of innovation of technologies related to the environment.

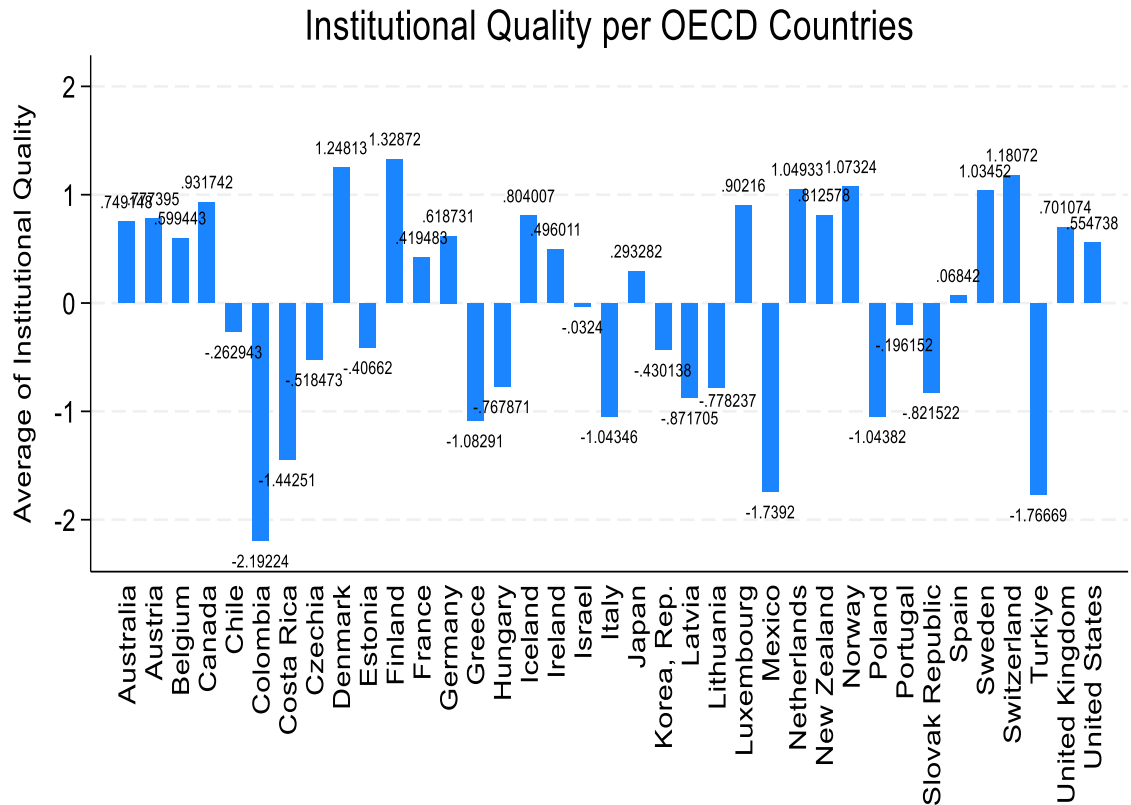


Figure 3.5. Average Institutional Quality in OECD from 1996-2021⁶

The graph below indicates that the control variable Trade Openness reveals that Luxembourg has the highest value on average than the other OECD countries. Ireland and the Slovak Republic also have similar scores for trade openness. The graph also reveals that the United States has the lowest average trade openness score.

⁶ Institutional quality is an index from six variables obtained from world governance indicators. The graph illustrates that, on average, the value of institutional quality for OECD countries lies between -2.19 to 1.32. Which also represents the maximum and minimum value of the quality of institutions. The higher value of INSQ shows that the quality of institutions is better in that country, and the lower or negative value represents that the quality of institutions is not good or effective there.

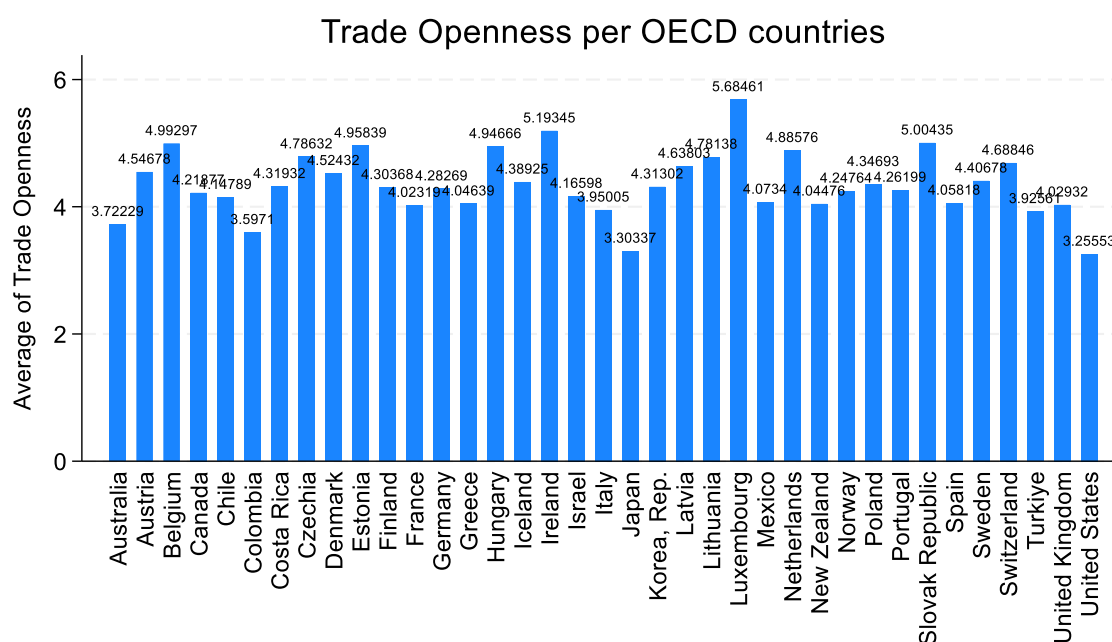


Figure 3.6. Average Trade Openness in OECD from 1996-2021⁷

The graph below shows that Luxembourg's average GDP per capita in the OECD region is the highest. Switzerland, Norway, and the United States follow the highest and have similar average GDP per capita. Colombia has the lowest GDP per capita value on average among OECD nations.

⁷ This graph shows the average rate of Trade Openness after taking a log. On average, the trade openness for OECD countries lies between 3.25 and 5.68. Which represents the maximum and minimum value of trade; the higher the value, the higher the trade; the lower the value, the lower the trade. The data is obtained from WDI and its time period is from 1996 to 2021.

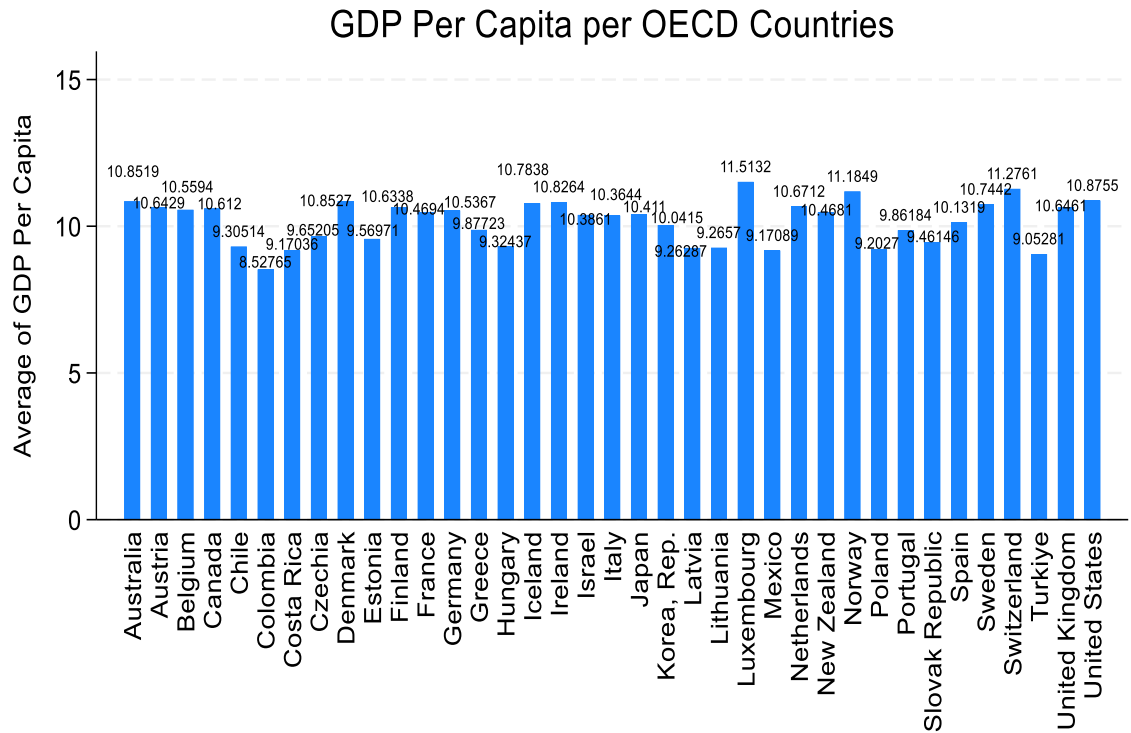


Figure 3.7. Average GDP Per Capita in OECD from 1996-2021

Overall, the Organization of Economic Cooperation and Development (OECD) has observed noteworthy disparities in the average of our dependent, independent and control variables with some demonstrating significant variations. It may be because of their demography and geography because except from some countries these countries are not close to each other.

3.8. Variable Description

Table 3.1. Variables Description and Source

No	Variable	Abbreviation	Measure	Source	Expected Result
01	Environmental Sustainability CO2 emission	ES	Metric ton per capita	WDI	
02	Information & Communication technology i- Mobile cellular telephone subscriptions per 100 inhabitants ii- Fixed telephone subscriptions per 100 inhabitants iii- Percentage of individuals using the internet	ICT	Index	ITU Database	Positive
03	Green Innovation	GINV	Index	OECD Database	Positive

Table 3.1. (cont.)

04	Renewable Energy Source i. Renewable electricity output (% of total electricity output) ii. Renewable energy consumption (% of total final energy consumption)	RESS	Index	WDI	Positive
05	Institutional Quality i. Control of Corruption ii. Political Stability iii. Government Effectiveness iv. Regulatory Quality v. Rule of Law vi. Voice and Accountability	IQ	Index	WGI Database	Positive
06	Trade Openness	TRD	% of GDP	WDI Database	Positive
07	GDP Per Capita	GDPPC	Constant 2015 US\$	WDI Database	Positive

3.9. Research Hypothesis

This research analyzes the relationship between environmental sustainability and other variables, such as information and communication technology, green innovation, renewable energy sources, and institutional quality, as well as control variables, such as trade openness and GDP per capita in the OECD region. As a result, the study intends to test three different hypotheses to determine the relationship between the dependent variable and independent variable along with the control variable. Saba et al. (2024) investigated the moderation effect of ICT on other independent variables for 51 African countries, and they found a positive relationship between the two moderators.

Here are the hypothesis of my study:

H1: Information and communication technology (ICT), Green Innovation (GINV), Renewable Energy (RESS), Institutional Quality (IQ), Trade Openness (LTRD) and GDP per capita (LGDPPC) affects environmental sustainability positively.

H2: The joint effect of ICT and RESS on environmental sustainability is positive

H3: The joint effect of ICT and GINV on environmental sustainability is positive

3.10. Selection Method for Regression

Panel data analysis provides a robust statistical methodology that allows one to examine observations both across cross-sectional units and periods. Although possessing numerous benefits, choosing the appropriate estimation technique to use in panel regression is not simple, as one needs to consider different diagnostic checks thoroughly. Failure to undergo the necessary preliminary checks and proceeding directly to model estimation will produce biased or misleading results, ultimately undermining the validity of the conclusions in the study. As stated by Baltagi (2008), panel data estimation has several advantages that make it a helpful instrument in econometric research. Firstly, it allows individual heterogeneity to be controlled through the consideration of unobservable variables that accrue to individuals but

remain constant over time. Secondly, panel data has more informative information, higher variability, less multicollinearity of the variables to be explained, higher degrees of freedom, and higher efficiency in estimates. Thirdly, it is ideally suited to analyzing the adjustment process over time. Fourthly, panel data allows effects that may not be observed in pure cross-sectional and pure time-series data to be identified and measured. Fifthly, it is used to build and empirically estimate more complex models of behavior. Sixthly, micro-level panel data based on individuals, firms, and households is likely to be measured more precisely than aggregated macro-level information and reduces aggregation bias. Finally, macro-level data primarily consists of longer time series and circumvents some unstandard distribution problems of unit root tests in time series. This is so due to the fact that panel regression produces many underlying presumptions that need to follow the characteristics of the data, as well as the goals of the study. In order to achieve the quality of findings, one needs to conduct a series of diagnostic tests before the choice of a suitable model. These tests normally involve cross-sectional dependence tests, testing of the homogeneity of slopes, testing of unit roots properties, and testing of cointegration relations. Through these preliminary steps, the best approach to estimation can be determined, and the reliability and trustworthiness of the findings can be improved accordingly. In line with this, the subsequent sections will deal with the use of diagnostic tests, which will also form the basis of the choice of the best panel data model to use in this study.

3.11. Principle Component Analysis

For building composite indices for the diffusion of information and communication technology (ICT), renewable energy sources (RESS), and institutional quality (INSQ), the research uses Principal Component Analysis (PCA). PCA, conceived by Karl Pearson (1901) and later developed by Hotelling (1933), is a statistical method for dimensionality reduction that aims to capture most of the original variables' variance with a lower-dimension representation. It converts a set of potentially correlated variables into a set of linearly uncorrelated components that simplify building robust indices representing multidimensional phenomena.

In the present analysis, PCA is utilized to extract the first principal component for each category (ICT, RESS, INSQ) and use associated eigenvectors (loading coefficients) to compute the respective composite indices. Linear combinations are defined as:

$$ICT = \varphi_1.mobT + \varphi_2.FLT + \varphi_3.IAS \quad (1)$$

$$RESS = \varnothing_1.RELO + \varnothing_2.REGC \quad (2)$$

$$IQ = \beta_1.WGlc + \beta_2.WGIp + \beta_3.WGIg + \beta_4.WGIreg + \beta_5.WGIr + \beta_6.WGIv \quad (3)$$

Where $\varphi_1, \varphi_2, \varphi_3$ are the PCA-derived weights. Corresponding to ICT Indicators: Mobile cellular telephone subscriptions per 100 inhabitants(mobT), Fixed telephone subscriptions per 100 inhabitants (FLT), and Percentage of individuals using the internet (IAS).

Where $\varnothing_1$ and $\varnothing_2$ are the PCA-derived weights corresponding to renewable energy source indicators: Renewable electricity output (% of total electricity output) (RELO) and Renewable energy consumption (%of total final energy consumption) (REGC).

Here $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$ are the PCA-derived weights corresponding to institutional quality indicators: Control of Corruption (WGlc), Political Stability (WGIp), Government Effectiveness (WGIg), Regulatory Quality (WGIreg), Rule of Law (WGIr), and Voice and Accountability (WGIv).

These methods allow us to make indices of the variables that are not only statistically robust but also reflective of the underlying structure and variation in data.

3.12. Cross-Sectional Dependence Test

The cross-sectional dependence test is an important statistical technique employed to identify if there exists an interrelationship or interdependence between cross-sectional units of a dataset. It is important to identify these dependencies since cross-sectional dependence if it exists, may affect both model selection and test procedure for

econometrics. As an example, the environmental conditions of one country may not be standalone and, for instance, may be influenced by neighboring countries. Say, with respect to environmental conditions, if there is an increase in CO₂ emissions in Spain, it may have an impact, be it direct or indirect, in neighboring Europe, especially France, and similarly, an impact on France's environmental conditions may be experienced by Spain. It is, therefore, important to recognize this interrelatedness, especially since environmental and economic research are prone to spillover effects. With this, Pesaran (2004) suggested an LM-based test based on Breusch and Pagan's (1980) originally proposed LM statistic. The LM test finds application for cross-sectional dependence and is well apt for situations where N (the number of cross-sections) is constant and T (the time dimension) approaches infinity. The test statistic under this test can be computed as follows:

$$CD_{lm} = T \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij}^2$$

In the equation, $\hat{\rho}_{ij}^2$ is an estimated pairwise coefficient of residuals between units *i* and *j*. When N and T, however, are both finite, which is the most typically true for empirical analyses, the LM test will generate biased results. To overcome this potential weakness, an alternative version of the cross-sectional dependence test was proposed by Pesaran (2004), which substitutes squared correlation values with correlation coefficients and corrects for small samples. The test statistics are given by:

$$CD_{lm} = \sqrt{\frac{\sqrt{2T}}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij} \right)$$

This specification checks for cross-sectional dependence under the null hypothesis. In contrast with the initial LM test, Pesaran's approach provides improved performance for both N and T of modest size and is compatible with a range of panel data specifications, including models that have heterogeneity, unit roots, and dynamics. This research performed a cross-sectional dependency test for a panel dataset with 37

cross-sectional units and 26 periods (N=37, T=26). Breusch-Pagan's LM test and Pesaran's test were both performed to be compared.

3.13. Slope Homogeneity Test

The slope homogeneity test is a statistical process meant to assess if there is consistency in the association of variables across different cross-sectional units or groups. In panel data analysis, this test is crucial to identify if the slope coefficients estimated are equal or vary between one unit and another. The basis for this test was laid out by Swamy (1970), who provided a technique to test if slope coefficients are consistent across units within a panel, especially under cointegration models. Following Swamy's concept, an advanced version of this test was provided by Pesaran and Yamagata (2008), with both normal and adjusted statistics available for small and large samples, and the equations are shown below.

$$\tilde{\Delta} = \sqrt{N} \left(\frac{N^{-1} \tilde{S} - k}{\sqrt{2k}} \right) \sim \chi^2_k$$

$$\tilde{\Delta}_{adj} = \sqrt{N} \left(\frac{N^{-1} \tilde{s} - k}{\text{var}(T, k)} \right) \sim N(0, 1)$$

Here, N shows the number of cross-sectional units, S is the Swamy test statistics, and k is the number of regressor variables. According to the null hypothesis, slope coefficients for all units are assumed to be homogenous under this model. However, for these tests to be valid, several requirements must be met, such as no serial correlation of the residuals. Acknowledging that there is a potential weakness of the classical method, especially where heteroscedasticity or autocorrelation may exist, Blomquist and Westerlund (2013) suggested an improved alternative. T includes heteroscedasticity and autocorrelation consistent (HAC) estimators, which enables the test to be extended to situations where classical assumptions do not hold. The related tests based on HAC are expressed as:

$$\Delta_{HAC} = \sqrt{N} \left(\frac{N^{-1} \tilde{S}_{HAC} - k}{\sqrt{2k}} \right)$$

$$(\Delta_{HAC})_{adj} = \sqrt{N} \left(\frac{N^{-1} \tilde{S}_{HAC} - k}{var(T, k)} \right) \sim N(0, 1)$$

In this research, Pesaran-Yamagata and Blomquist and Westerlund's HAC-adjusted test has been used to test the homogeneity of the model slope coefficients. The results of these tests provided strong evidence against the homogeneity hypothesis, thus rejecting it, implying that the impact of the regressors varies between cross-sectional units, and hence there is heterogeneity.

3.14. Unit Root Test

After conducting cross-sectional dependence and slope homogeneity tests, which established the presence of interdependence between cross-sectional units and heterogeneity of slope coefficients throughout the dataset, it is necessary to implement a unit root test that can correct for both cross-sectional dependence and heterogeneity. Second-generation panel unit root tests were used to address this need since these tests are specifically tailored to correct for cross-sectional dependence and non-homogeneous dynamics. We employed two second-generation panel unit root tests. The first is the Fisher-type test, which relies on a test based on the cross-sectional augmented dickey-fuller (CADF) methodology proposed by Pesaran (2003). The second is the Cross-sectionally Augmented IPS (CIPS) test, proposed by Pesaran (2007), which generalizes the LM-Pesaran-Shin (IPS) framework by including cross-sectional dependence and accounting for serial correlation of error terms. CADF is represented as:

$$\Delta y_{i,t} = \alpha_i + b_i y_{i,t-1} + c_i \bar{y}_{t-1} + d_i \bar{y}_t \varepsilon_{i,t}$$

In the above equation $\Delta y_{i,t}$ is the first difference for variables i at time t , and α_i is an intercept term. The cross-sectional mean of the lagged level variable $\bar{y}_{t-1}$ and $\Delta \bar{y}_t$ is the cross-sectional dependency. The error term $\varepsilon_{i,t}$ is assumed to be randomly distributed across units. CADF test produces individual statistics for each cross-sectional unit, and the overall CIPS statistic is calculated as an average of those individual test statistics:

$$CIPS = \frac{1}{N} \sum_{i=1}^N t_i$$

Where t_i t-value for the lagged-level variable in the CADF regression for cross-sectional unit i . the application of both CADF and CIPS tests within this research showed that all the variables are stationary upon first differencing, ascertaining that they are integrated of order one $I(1)$.

3.15. Cointegration Test

In the case of panel data, the existence of unit roots requires the hypothesis of cointegration to verify the presence of a long-run equilibrium relationship among the cross-sectional units' non-stationary variables. While individual panel series can be non-stationary in a single case, their linear formation can be stationary and cointegrated. Such relationships need to be detected in order to prevent spurious regressions and valid long-run inference. In response to that need, some tests of cointegration in panels were developed by Pedroni (1999, 2004), Kao (1999), and Westerlund (2007) based on different assumptions and methods to accommodate heterogeneous panel configurations.

$$y_{it} = x'_{it}\beta_i + z'_{it}\gamma_i + c_i\bar{y}_{t-1} + \varepsilon_{it}$$

Westerlund (2005) proposed the Westerlund test, which is a residual-based methodology to examine if a panel dataset is cointegrated. The test for no cointegration under the null hypothesis is conducted based on two primary sets of statistics.

Panel Variance Ratio Statistic: This measure assesses the overall stationarity of the residuals for all cross-sectional units.

$$VR_p = \sum_{i=1}^N \sum_{t=1}^T \hat{E}^2_{it} \left(\sum_{i=1}^N \hat{R}_i \right)^{-1}$$

Group Variance Ratio Statistic (VR): It emphasizes testing for cointegration, at least for some cross-sectional units.

$$VR = \sum_{i=1}^N \sum_{t=1}^T \hat{E}_{it}^2 \hat{R}_i^{-1}$$

In these equations, $\hat{E}_{it}^2$ represents the residuals from the cointegration regression, and ε_{it} is a weighting factor related to the autocovariance of the error terms after proper normalization, both statistics converge to a standard normal distribution, enabling straightforward interpretation and hypothesis testing.

Pedroni's (1999) test is yet another residual-based technique for addressing heterogeneity between cross-sectional units. Pedroni created several different statistics, both within-dimension (panel) and between-dimension (group) test forms, which stem out of the autoregressive representation of the residuals.

$$\text{Modified } pp\ t = TN^{-1/2} \sum_{i=1}^N \left(\sum_{t=1}^T \hat{e}_{i,t-1}^2 \right)^{-1} \sum_{t=1}^T (\hat{e}_{i,t-1} \Delta \hat{e}_{i,t} - \hat{\lambda}_i)$$

$$pp\ t = N^{-1/2} \sum_{i=1}^N \left(\hat{\sigma}_i^2 \sum_{t=1}^T \hat{e}_{i,t-1}^2 \right)^{-1/2} \sum_{t=1}^T (\hat{e}_{i,t-1} \Delta \hat{e}_{i,t} - \hat{\lambda}_i)$$

$$ADF\ t = N^{-1/2} \sum_{i=1}^N \left(\sum_{t=1}^T \hat{S}_i^{*2} \hat{e}_{i,t-1}^2 \right)^{-1/2} \sum_{t=1}^T (\hat{e}_{i,t-1} \Delta \hat{e}_{i,t})$$

Here, $\hat{e}_{i,t}$ is represents the error term, which is derived from the model, and the following calculation is done:

$$\hat{\lambda}_i = \frac{1}{2} (\hat{\sigma}_i^2 - \hat{S}_i^2)$$

Here, $\hat{\sigma}^2_i$ and $\hat{S}^2_i$ are consistent estimators of the long-run and short-run variances of the residuals, respectively, as provided by the Dickey-Fuller (DF) test. Further, $\hat{S}^{*2}_i$ is an adjustment term for variance, which considers serial corrections usually made within the Augmented Dickey-Fuller (ADF) framework.

Another popular test to detect cointegration with panel data is the Kao (1999) test. The Kao test is an extension of the general augmented Dickey-Fuller (ADF) and Dickey-Fuller (DF) frameworks but under the assumption of homogeneous cointegration vectors for cross-sectional units. The Kao test employs the below residual-based autoregressive equation:

$$\hat{e}_{it} = \rho \hat{e}_{i,t-1} + v_{it}$$

Several forms of this test are derived, which are given below:

$$DF\ t = \frac{t_\rho + \frac{\sqrt{6N}\hat{\sigma}_v}{2\hat{\omega}_v}}{\sqrt{\frac{\hat{\omega}_v^2}{2\hat{\sigma}_v^2} + \frac{3\hat{\sigma}_v^2}{10\hat{\omega}_v^2}}}$$

$$Modified\ DF\ t = \frac{\sqrt{N}T(\hat{\rho} - 1)\frac{3\sqrt{N}\hat{\sigma}_v}{\hat{\omega}_v^2}}{\sqrt{3 + \frac{36\hat{\sigma}_v^4}{5\hat{\omega}_v^4}}}$$

Under the specified model, $\hat{\rho}$ is an estimate of the autoregressive coefficient. ρ , $\hat{\sigma}_v^2$, and $\hat{\omega}_v^2$ are consistent estimators for long-run and short-run residual variances, respectively. t_ρ is used to test whether or not to accept the null hypothesis, which tends to assume non-cointegration between variables.

It should be noted that the Dickey-Fuller (DF) test assumes there is no serial correlation between error terms and strict homogeneity between the explanatory variables, which is necessary to make sure that the results obtained are accurate and dependable.

$$\text{Unadjusted DF } t = \sqrt{\frac{5t_\rho}{4}} + \sqrt{\frac{15N}{8}}$$

$$\text{Unadjusted modified DF } t = \frac{\sqrt{NT}(\hat{\rho} - 1) + 3\sqrt{N}}{\sqrt{\frac{51}{5}}}$$

ADF test is represented as follows:

$$\hat{e}_{it} = \rho \hat{e}_{i,t-1} + \sum_{j=1}^p \rho_j \Delta \hat{e}_{i,t-j} + v^*_{it}$$

Here, ρ is the number of lag difference terms to incorporate into the model to eliminate serial correlation through the residuals. The Augmented Dickey-Fuller (ADF) framework suggests that the test statistic is determined as follows:

$$\text{ADF } t = \frac{t_{ADF} + \frac{\sqrt{6N}\hat{\sigma}_v}{2\hat{\omega}_v}}{\sqrt{\frac{\hat{\omega}_v^2}{2\hat{\sigma}_v^2} + \frac{3\hat{\sigma}_v^2}{10\hat{\omega}_v^2}}}$$

Here, $t_{ADF} = \frac{\hat{\rho}}{SE(\hat{\rho})}$ is defined as the t-statistic based on ADF regression. Under the assumption of the null hypothesis, all test statistics will, under an asymptotic approach, reach toward the distribution $N(0,1)$.

3.16. Long Run Cointegration Test

Following the confirmation of stationarity at the first difference, the establishment of cointegration, the detection of cross-sectional dependence, and the identification of heterogeneity among the variables, the next step is to investigate the nature of the long-term relationship between dependent variables and environmental sustainability within OECD. With cointegrated panel data, simple panel OLS tends to give biased and inconsistent estimates owing to endogeneity and serial correlation. FMOLS and DOLS

overcome these problems. FMOLS removes endogeneity and serial correlation in a non-parametric adjustment process, whereas DOLS introduces leads and lags of differenced regressors to accommodate feedback effects so that long-run relationships may be estimated more reliably.

In particular, FMOLS was proposed by Phillips and Hansen (1990) to address both serial correlation and endogeneity of regressors. DOLS, which was proposed by Stock and Watson (1993), raises estimation efficiency through the inclusion of leading and lagging differences in the explanatory variables. Finally, the CCR methodology, proposed by Park (1992), performs a canonical transformation to remove potential endogeneity and serial correlation during estimation. Owing to both robustness and the ability to generate unbiased and consistent long-run estimators, these three methods have gained prominence and are used extensively in the empirical literature, especially under labor economics, development studies, and macroeconomic studies at large.

3.17. Fully Modified Ordinary Least Square

Fully Modified Ordinary Least Squares (FMOLS), which was first proposed by Phillips and Hansen (1990), was devised to enhance long-term relationship estimation for cointegrated systems. Unlike traditional methods, FMOLS employs semi-parametric adjustments that remove endogeneity effects and serial correlation, providing robust estimation of coefficients even with small sample sizes. According to Agbola (2013) and Bashier and Siam (2014), FMOLS was specifically formulated to overcome various estimation issues, such as endogeneity, autocorrelation, measurement errors, and unobserved heterogeneity of long-run relations. FMOLS aims to estimate a single cointegrating vector regardless of whether underlying variables are integrated with different orders. One major strength of FMOLS is that it adjusts not only for both series and parameter estimations due to serial correlation effects but also potential biases, a point also underscored by Park (1992). Compared to more traditional methods like Engle-Granger's two-step estimation, FMOLS not only provides better reliability of statistics but also does so with corrected t-statistics that are robust for long-term parameter testing (Amarawickrama & Hunt, 2008). Further, FMOLS is noted for asymptotic unbiasedness and efficiency, particularly for

hypothesis testing under the Wald statistic, which under that setup follows an asymptotic chi-square distribution (Adom et al., 2015).

The general equation of the FMOLS estimator is given by:

$$\hat{\mathbf{\theta}}_{FME} = \left(\sum_{t=1}^T \mathbf{Z}_t \mathbf{Z}'_t \right)^{-1} \left(\sum_{t=1}^T \mathbf{Z}_t \mathbf{Y}_t^+ - T \begin{bmatrix} \lambda_{12}^+ \\ \mathbf{0} \end{bmatrix} \right)$$

In such a framework, terms of bias correction, i.e., $\mathbf{Y}_t^+$ and λ_{12}^+ , are included to avoid endogeneity effects and effects of serial correlation, with $\mathbf{Z}_t$ being the cointegrating vector, and $\hat{\mathbf{\theta}}$ representing long-run covariance matrix.

3.18. Dynamic Ordinary Least Square

The Dynamic Ordinary Least Squares (DOLS) approach, proposed by Stock and Watson (1993), provides a parametric setup to estimate the long-run relationship between cointegrated variables, even if the individual variables are of different orders of integration. It improves the accuracy of long-run parameter estimators by adding leads and lags of the difference of the independent variables to the regression equation, relieving issues of endogeneity as well as serial correlation from the regression equation. Kurozumi and Hayakawa (2009) point out that DOLS particularly curtails small-sample distortions and simultaneity bias by adding these additional terms. Even under endogeneity conditions, estimators from DOLS are consistent and asymptotically efficient. Additionally, the method alleviates possible violations of classical regression assumptions, including non-normality or serial correlation in residuals (Stock & Watson, 1993; Herzer et al., 2006).

The general equation of the DOLS estimator is given below:

$$y_t = \alpha + bX_t + \sum_{i=-k}^{i=k} \theta_i \Delta X_{t+1} + \varepsilon_t$$

In this equation, α stands for the constant term, whereas b reflects the long-run elasticity of the endogenous variable to changes in the explanatory variable. Both lagged, and leading values of the differenced regressors are included to counteract potential endogeneity and serial correlation that could make the estimates inaccurate.

3.19. Canonical Cointegrating Regression

Canonical Cointegrating Regression (CCR), a model introduced by Park (1992), is formulated for estimating long-run equilibrium relations in models with I(1) variables. Like FMOLS, the CCR method uses transformations of the data to address the problem of endogeneity and also serial correlation. Unlike FMOLS, which transforms both the coefficients and the data, in CCR, only the data is transformed prior to estimation (Park, 1992; Adom et al., 2015). In addition, Park (1992) noted that CCR was initially developed for single-equation systems but was later generalized so that it could be applied to multivariate systems without loss of estimation efficiency.

The CCR estimator is formulated mathematically as follows:

$$\hat{\mathbf{0}}_{CCR} = \left(\sum_{t=1}^T \mathbf{Z}_t^* \mathbf{Z}_t^{*1} \right)^{-1} \sum_{t=1}^T \mathbf{Z}_t^* \mathbf{Y}_t^*$$

Here, the variables $\mathbf{Y}_t^*$ and $\mathbf{Z}_t^*$ are adjusted so that any endogeneity and autocorrelation effects are removed, and $\hat{\mathbf{0}}_{CCR}$ is the long-run covariance matrix that guarantees robust estimation.

By employing these three approaches, DOLS, FMOLS, and CCR, it was possible to estimate and examine long-run relations between selected explanatory variables and environmental sustainability measurement. Results and explanations of these estimations are depicted in detail in Chapter IV.

CHAPTER IV

RESULTS AND DISCUSSION

Before proceeding to the primary regression analysis, an extensive exploration of the descriptive statistics is needed to have a balanced view of the underlying dataset for this research. A systematic preliminary inquiry is crucial in shedding light on the data's structural characteristics and distribution attributes and thus forms a good foundation for sound econometric modeling.

This thesis seeks to evaluate how some of the most important factors, that is, Information and Communication Technology (ICT), Renewable Energy Sources (RESS), Green Innovation (GINV), Institutional Quality (INSQ), Trade Openness (TRD), and Gross Domestic Product per Capita (GDPC) influence the progress of environmental sustainability in OECD countries from the year 1996 to the year 2021. Due to the complexity of the relationships between these factors, we need to conduct a very detailed preliminary analysis to discover the dynamic relationships and possible causal links between the variables.

To realize this objective, the research will commence by providing descriptive statistics to summarize central tendencies, dispersions, and trends in all variables. Thereafter, several diagnostic tests will be utilized, including the panel cross-sectional dependence test to ascertain the existence of any dependencies between countries, the slope homogeneity test to assess possible differences in the effect of explanatory variables between panels, and panel unit root tests to check the stationarity characteristics of the dataset. Cointegration tests will also be used to investigate the long-run equilibrium relationships between the variables.

These preliminary analysis steps play an important part in determining the most proper estimation methods to develop accurate and credible results by initiating these early investigations. By anchoring the analysis in these underlying assessments, the research

aims to produce statistically sound and policy-informative findings. The findings will not only enrich the body of academic work associated with environmental sustainability but will also be of valuable input to policymakers in OECD economies. Particularly, the findings are able to inform strategic planning regarding harnessing ICT, advancing renewable energy and green innovation, and improving institutional efficiency in the quest for sustainable environmental outcomes.

4.1. Summary of Statistics

Before carrying out the primary analysis, there is a need to conduct descriptive statistics in order to summarize and learn about the research data characteristics. Summary statistics of the main variables and how to interpret them are highlighted below.

Table 4.1. Descriptive Statistics of Main Variable for OECD Countries

Descriptive Statistics					
Variables	Obs	Mean	Std. Dev.	Min	Max
LCO2	962	2.007	0.584	0.218	3.259
ICT	959	0.024	0.958	-1.782	1.343
RESS	956	0.001	0.996	-1.700	1.733
GINV	962	1.055	0.413	0.080	4.000
INSQ	962	0.024	2.285	-6.786	3.296
LTRD	962	4.353	0.522	2.897	5.974
LGDPC	962	10.167	0.749	8.282	11.63
Note: LCO2: Proxy for Environmental Sustainability, ICT: information and communication technology, RESS: Renewable Energy Sources, GINV: Green Innovation, INSQ: Institutional Quality, LTRD: Trade Openness, and LGDPC: GDP per capita					

Table 4.1 also provides a general overview of the main variables used in the present study, providing insightful information on the characteristics of their distributions in OECD economies during the 1996–2021 time frame. These descriptive statistics are preliminary and important to understand before proceeding to further econometric analysis.

The primary dependent variable, LCO₂, the natural log of CO₂ emission used as a proxy for environmental sustainability, has a mean of 2.007 and a standard deviation of 0.584. Relatively moderate variation suggests some variations in environmental achievements in OECD countries, with values differing from the minimum of 0.218 to the maximum of 3.259. ICT, representing the degree of information and communication technology usage, has a mean value of 0.024 and a standard deviation value of 0.958, suggesting high variability in ICT adoption and ICT development in the countries. Likewise, Renewable Energy Sources (RESS) have almost zero average (0.001) with balanced distributions around the average but with high variability (-1.700 to 1.733), suggesting variable rates of renewable energy usage in OECD countries. Green Innovation (GINV), with its average of 1.055 and standard deviation of 0.413, suggests relatively moderate environmental and technological progress, though with few countries with extremely high innovation activity. Institutional Quality (INSQ) is much more dispersed, with a standard deviation of 2.285 and a range of -6.786 to 3.296. This high variation highlights significant differences in institutional efficiency across the OECD countries, which is an essential consideration in light of its possible impact on policy implementation and environmental administration. There is a mean Trade Openness (LTRD) of 4.353 with a standard deviation of 0.522, indicative of greater convergence of the member countries in terms of trade integration. Finally, GDP per capita (LGDPC), a logarithmic indicator of economic progress, has a mean value of 10.167 and varies between the range of 8.282 and 11.630, indicating variations in income levels across OECD countries, though in general in the range of advanced countries.

This statistical overview demonstrates both the diversity and shared characteristics among OECD countries concerning the variables under study. The variation in institutional quality, renewable energy usage, and ICT adoption, in particular, signals potential explanatory power for differences in environmental sustainability outcomes. Insights into these underlying patterns are fundamental in determining proper econometric model selection and in generating relevant policy recommendations from the ensuing empirical analysis.

4.2. Correlation Analysis among the Variables

The panel correlation analysis was performed to investigate the linear relationships between the dependent variable proxy of environmental sustainability LCO2 and the chosen independent and control factors: ICT, RESS, GINV, INSQ, LTRD, and LGDPC.

Table 4.2, in revealing several statistically significant correlations, offers valuable preliminary evidence of the direction and magnitude of relationships between the variables. Of particular note is LCO2's positive and statistically significant association with LGDPC (0.635), indicating that greater GDP per capita is proving to be linked with greater emissions of carbon. This may initially seem paradoxical but may instead indicate the environmental price paid by greater industrial activity and digital infrastructure growth in richer OECD economies. On the contrary, information and communication technology (-0.210), renewable energy sources (-0.190), green innovation (-0.108), institutional quality (-0.592), and trade openness LTRD (-0.127) are all significantly and negatively associated with LCO2 emissions. These findings are intuitive that information and communication technology, renewable energy sources, green innovation, better institutional quality, and enhanced trade openness are all likely to lead to improved environmental performance through cleaner production behavior, more efficient governance, and environmentally sound trade arrangements.

Table 4.2. Pearson's Pairwise Correlation Matrix for OECD Countries

Pairwise correlations							
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) LCO2	1.000						
(2) ICT	-0.210***	1.000					
(3) RESS	-0.190***	0.111***	1.000				
(4) GINV	-0.108***	-0.160***	0.071**	1.000			
(5) INSQ	-0.592***	0.367***	0.211***	-0.017	1.000		
(6) LTRD	-0.127***	0.241***	-0.083***	0.036	0.220***	1.000	
(7) LGDPC	0.635***	0.516***	0.141***	-0.184***	0.823***	0.141***	1.000
(***), (**), and (*) represents statistical significance at 1%, 5%, and 10% levels respectively Note: LCO2: Proxy for Environmental Sustainability, ICT: information and communication technology, RESS: Renewable Energy Sources, GINV: Green Innovation, INSQ: Institutional Quality, LTRD: Trade Openness, and LGDPC: GDP per capita							

The correlation values in the matrix are mostly moderate in size, and none of the pairwise coefficients between the independent factors is close to the threshold of ± 0.8 to 0.9, which is standardly used to alert against possible multicollinearity issues. This implies that the model is free from serious multicollinearity, and therefore, the inclusion of all these factors in one regression model is statistically justified. Therefore, there is no need to run further tests immediately, such as Variance Inflation Factors (VIF).

In general, these findings highlight significant relationships between environmental performance and major factors in the economic, institutional, and technological realms in OECD economies. The correlation matrix confirms the validity of the chosen explanatory factors and recommends that these should be incorporated into further econometric modeling to assess the individual and combined impacts of these factors on environmental sustainability.

4.3. Cross-Sectional Dependence Test

In today's highly globalized and interconnected digital world, OECD countries share strong economic, technological, and environmental linkages. Consequently, economic shocks, tech developments, or policy changes in one country have the capacity to cause spillovers across others quite readily. That realization is essential in operating with macro-panel data, specifically in considering long-run determinants of environmental sustainability. Thus, performing a cross-sectional dependence (CSD) test is imperative in the first stage of empirical analysis. The CSD test assists in establishing whether there are cross-country dependencies statistically in the panel. This, in turn, determines the appropriate panel unit root and cointegration tests, as well as the general econometric approach. It is common in traditional models to assume cross-sectional independence, but that usually is unrealistic, particularly in macroeconomic analysis of OECD member countries with strong trading relationships, common environmental objectives, and institutional collaboration.

Table 4.3. Pesaran's Cross-Sectional Dependence Test Results for OECD Countries

Variable	CD-test	p-value	Corr	abs(Corr)
LCO2	41.55	0.000	0.316	0.659
ICT	123.55	0.000	0.939	0.939
RESS	3.10	0.002	0.024	0.357
GINV	2.55	0.011	0.019	0.259
INSQ	8.03	0.000	0.061	0.434
LTRD	58.26	0.000	0.443	0.619
LGDPC	109.30	0.000	0.831	0.838

Notes: Under the null hypothesis of cross-section independence, $CD \sim N(0,1)$

Table 4.3 reports the findings from Pesaran's (2004) Cross-Sectional Dependence test across all variables in the research. The findings confirm strong cross-sectional dependence in most of the variables. Precisely, ICT, INSQ, LTRD, and LGDPC have very high-test statistics and associated p-values of 0.000, proving statistically significant interdependence at the 1% level. Variables like RESS, GINV, and even the endogenous variable LCO2 also show significant cross-sectional correlation with somewhat lower test statistics, supporting the reality of systemic linkages between OECD economies.

The high correlation values in absolute terms, particularly in the cases of ICT (0.939) and LGDPC (0.838), imply that technological advancement and economic performance are in close synchronization across the countries in the sample; this aligns with the structure of the OECD economies, where the member countries often share technological platforms, policy frameworks, and economic trends, the widespread adoption of digital infrastructure and joint environmental commitments under the Paris Agreement highlights the channels through which environmental and technological development in one country affect others. Since most of the variables reject the null hypothesis of cross-sectional independence under the 1% significance level, strong interdependence must be recognized in further econometric modeling. This is evidence in favor of the application of second-generation panel unit root and cointegration analysis that is consistent with cross-sectional dependence.

4.4. Slope Homogeneity Test

Prior to proceeding with panel regression estimations, it is important to assess whether the relationship between the explanatory variables and environmental sustainability is consistent across all OECD economies. This is addressed through the slope homogeneity test, which examines whether the slope coefficients are the same homogeneous or vary heterogeneous across the panel units; assuming homogeneity when heterogeneity exists can lead to biased and inconsistent parameter estimates, misrepresenting the true nature of the underlying relationships. Given the structural, economic, and institutional differences among OECD economies despite their shared development status, testing for heterogeneity is difficult.

Table 4.4. Slope Homogeneity Test Results for OECD Countries

Test	Δ	Δ_{adj}	Δ_{HAC}	Δ_{HACadj}
Pesaran, Yamagata	23.154***	27.827***	-	-
Blomquist, Westerlund	-	-	-6.650***	-7.992***

Notes: (***), (**), and (*) represent statistical significance at 1%, 5%, and 10% levels, respectively.

Similarly, while Δ and Δ_{adj} represent the "simple" and "mean-variance bias adjusted" slope homogeneity tests, the Δ_{HAC} and Δ_{HACadj} represent the "Heteroscedasticity" and "Autocorrelation consistent" versions of "simple" and "mean-variance bias adjusted slope homogeneity tests.

Table 4.4 represents the results of the Pesaran and Yamagata (2008) and Blomquist and Westerlund (2013) slope homogeneity tests; the findings posit that the slope homogeneity's null hypothesis is rejected across cases because of statistical significance 1%, 5%, and 10% levels. This indicates that the coefficients of the slopes vary in all nations studied, suggesting heterogeneity. As a result, it is necessary to utilize panel techniques that accommodate this variation in slope coefficients. These are strong empirical results that confirm that slope heterogeneity prevails among the OECD countries under study. This implies that the effect of ICT, renewable sources

of energy, green innovation, institutional quality, trade openness, and GDP per capita on environmental sustainability is not the same across different countries.

4.5. Second Generation Unit Root Test

Gaining insights about research and conducting unit root tests is one of the key steps in panel data analysis to determine whether there are stationary variables, and this is crucial to ensure that spurious regression outcomes are avoided. Since the cross-sectional dependence test revealed strong interdependence among the variables and the slope homogeneity test revealed the country-level heterogeneity, applying second-generation unit root tests that are robust against cross-sectional dependence is methodologically appropriate. First-generation unit root tests like Levin-Lin-Chu or Im-Pesaran-Shin impose cross-sectional independence, and that is not realistic in the context of highly integrated economies in this study. This study thus uses Pesaran's (2003) Cross-sectionally Augmented Dickey-Fuller (CADF) and Pesaran's (2007) Cross-sectionally Augmented IPS (CIPS) tests. This is more appropriate to use with our macroeconomic panel data since these allow cross-sectional dependence between countries. Second-generation unit root test outcomes are presented in Tables 4.5 and 4.6.

Table 4.5. Second Generation Unit Root Test at Level for OECD Countries

Variable	CADF		CIPS	
	Constant	Constant & Trend	Constant	Constant & Trend
LCO2	-1.587	-2.506	-1.536	-2.608*
ICT	-2.172***	-2.621**	-2.181**	-2.610**
RESS	-1.960	-2.795***	-1.888	-2.837***
GINV	-3.227***	-3.432***	-3.166***	-3.473***
INSQ	-1.502	-2.343	-1.545	-2.420
LTRD	-1.799	-1.976	-1.982	-2.088
LGDPC	-1.847	-1.898	-2.046	-2.213

Notes: (***), (**), and (*) represent statistical significance at 1%, 5%, and 10% levels, respectively.

Table 4.5 shows that regardless of the test method, In level, the CADF and CIPS findings indicate that most of the variables are non-stationary because, in most instances, their test statistics are not statistically significant. Two variables, information and communication technology (ICT) and green innovation (GINV), in all instances, reject the null hypothesis of the existence of the unit root under the two 1% and 5% significance levels, indicating that they are stationary in level. LCO2 (proxy to environmental sustainability), renewable energy sources, institutional quality, trade openness, and GDP per capita mostly seem to be non-stationary in level under both testing methodologies.

Table 4.6. Second Generation Unit Root Test at First Difference for OECD Countries

Variable	CADF		CIPS	
	Constant	Constant & Trend	Constant	Constant & Trend
LCO2	-4.827***	-5.029***	-4.661***	-4.896***
ICT	-	-4.333***	-4.135***	-4.420***
RESS	-5.364***	-	-5.418***	-5.499***
GINV	-	-	-	-
INSQ	-4.622***	-4.632***	-4.597***	-4.600***
LTRD	-3.771***	-3.873***	-3.771***	-3.873***
LGDPC	-3.480***	-3.544***	-3.523***	-3.597***

Notes: (***), (**), and (*) represent statistical significance at 1%, 5%, and 10% levels, respectively.

In Table 4.6, for robustness and consistency purposes, all the variables were re-run with the first difference of each variable, irrespective of the stationarity level. All the variables have been found to be stationary in the first difference, evidenced by statistically significant values in both CADF and CIPS tests. This suggests that the variables are of order one, I(1). Therefore, this finding lends support to the existence of a long-run equilibrium relationship between ICT, renewable energy sources, green innovation, institutional quality, trade openness, GDP per capita, and environmental sustainability in OECD countries.

Thus, the next appropriate step is to have panel cointegration tests, and these tests can ascertain whether there is a long-run relationship between the variables or not. Establishing such a relationship will further offer empirical support to long-run environmental sustainability policies that combine ICT, clean energy, and innovation.

4.6. Panel Cointegration Test

Following the confirmation that all variables are integrated of order one through second-generation unit root tests, the next crucial step is to examine whether a long-run equilibrium relationship exists between the studied variables. In other words, it is essential to examine panel cointegration to determine whether variables such as information and communication technology, renewable energy sources, green innovation, institutional quality, trade openness, and GDP per capita move together over time in relation to environmental sustainability (LCO2) across OECD economies.

Three-panel cointegration tests that complement each other were conducted to guarantee strength and to reduce the weakness of single testing methods: Westerlund (2007), Pedroni (1999, 2004), and Kao (1999). These tests account for both between-group (panel-level) and within-group (individual country) cointegration behaviors.

Table 4.7. Panel Cointegration Test for OECD Countries

Tests	Methods	Statistic
Westerlund	All Panels	0.0063
	Some Panels	1.7303**
Pedroni	Modified Phillips-Perron t	5.8498***
	Phillips-Perron t	-1.4627*
	Augmented Dickey-Fuller t	-1.7469**
Kao	Modified Dickey-Fuller t	2.4793***
	Dickey-Fuller t	3.6157***
	Augmented Dickey-Fuller t	3.5700***
	Unadjusted modified Dickey-Fuller	2.0703*
	Unadjusted Dickey-Fuller t	3.1579***

Notes: (***), (**), and (*) represent statistical significance at 1%, 5%, and 10% levels, respectively.

Table 4.7 represents the panel cointegration test results from different tests; the Westerlund test provides statistically significant findings for both "all panels" and "some panels," with the latter statistically significant at the 5% level. This is strong evidence of cointegration among at least some OECD countries. The Pedroni test proves that conclusion, and all three of the Phillips-Perron test, Augmented Dickey-Fuller test, and Modified Dickey-Fuller test statistics are significant at both the 1% and 5% levels, further establishing cointegration among the variables. The outcome of the Kao test is more differentiated. Although the Unadjusted Dickey-Fuller test is significant at the level of 1%, and the Unadjusted Modified Dickey-Fuller test has 10% significance, the tests are comparatively less intense compared to the remaining two tests.

Taken together, the robust findings from the Westerlund and Pedroni tests produce strong evidence of long-run cointegrating between ICT, RESS, GINV, INSQ, LTRD, LGDPC, and environmental sustainability in OECD nations. The findings from the Kao tests are less uniform, but the partial support from them fails to contradict the general conclusion. These conclusions highlight those shocks in one variable (i.e., ICT or green innovation) that have long-run implications in environmental sustainability outcomes and vice versa. Hence, policymakers in the OECD nations need to consider the long-run interdependence between technological advancement, institutional quality, and economic progress while framing green environmental policies.

4.7. Panel Empirical Results

After conducting the comprehensive series of diagnostic tests that involved summary statistics, correlation analysis, cross-sectional dependence, slope homogeneity, unit root, and cointegration tests, there was a strong basis on which to estimate the association between environmental sustainability and explanatory factors in OECD countries. From the outcomes of the tests, three estimation methods were warranted to handle problems of heterogeneity, cross-sectional dependence, endogeneity, and small sample bias: Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR).

These methods have been extensively applied in macroeconomic and development studies and are very effective in studying long-run relationships. The empirical evidence from the general model, along with the other three model specifications, is shown below.

Table 4.8. Panel Regression Results for the General Model for OECD Countries

Variables	(1) Fully Modified Ordinary Least Square (FMOLS)	(2) Dynamic Ordinary Least Square (DOLS)
ICT	-0.229***	-0.361***
RESS	-0.108***	-0.170***
GINV	-0.088**	-0.074***
INSQ	-0.480***	-0.062**
LTRD	-0.012*	-0.009*
LGDPC	0.332***	0.421***
ICT*RESS	-0.191***	-0.101***
ICT*INSQ	-0.179***	-0.101***
(***) , (**) , and (*) represents statistical significance at 1% , 5% , and 10% levels respectively Note: LCO2: Proxy for Environmental Sustainability, ICT: information and communication technology, RESS: Renewable Energy Sources, GINV: Green Innovation, INSQ: Institutional Quality, LTRD: Trade Openness, and LGDPC: GDP per capita		

The estimation of the overall model of this thesis submits the rigid proof of the determinants of environmental sustainability, proxied by CO₂ emissions (LCO₂), of OECD countries. ICT's negative and significant values of both FMOLS and DOLS estimates, -0.229 and -0.361, respectively, indicate that a change in the sector of information and communications technologies plays a significant role in the reduction of CO₂ emissions and thus enhances environmental sustainability. Renewable energy sources (RESS) also have a significant negative impact on emissions (-0.108 in FMOLS and -0.170 in DOLS), which reasserts their central role in the achievement of cleaner energy transitions. Green innovation (GINV) also contributes to environmental improvement, with large negative coefficients, although slightly less in size (-0.088 and -0.074), which means innovations that are environmentally focused achieve better sustainability performance. Institutional quality (INSQ) also exhibits a large negative

coefficient in FMOLS (-0.480), which points out the importance of good governance and institutional efficiency in resolving environmental problems; although less in DOLS (-0.062), it remains significant. Trade openness (LTRD) exhibits a weak significant negative impact on emissions for both models, which means that further global market integration can trigger cleaner technologies adoption or global environmental standard compliance. While GDP per capita (LGDPC) is positively and significantly associated with emissions of CO₂ (0.332 for FMOLS and 0.421 for DOLS), economic development in OECD countries continues to be associated with higher emissions, which conforms to the initial phase of the Environmental Kuznets Curve (EKC) hypothesis. The interaction terms also concur with the integrated policy role. Both interactions of ICT and renewable energy (ICTRESS) and ICT and institutional quality (ICTINSQ) significantly lower emissions by -0.191 and -0.101, respectively, which indicates that combining digital technologies with clean energy consumption optimizes environmental performance. In a similar way, ICTINSQ also significantly lowers emissions, which reflects the importance of good governance for ICT deployment and its environmental achievements.

Table 4.9. Panel Regression Results for Model-I for OECD Countries

Variables	(1) Fully Modified Ordinary Least Square (FMOLS)	(2) Dynamic Ordinary Least Square (DOLS)	(3) Canonical Cointegrating Regression (CCR)
ICT	-0.073***	-0.040***	-0.03***
RESS	-0.177***	-0.189***	-0.17***
GINV	-0.077***	-0.058**	-0.02**
INSQ	-0.123***	-0.116***	-0.04***
LTRD	-0.099***	-0.059***	-0.13***
LGDPC	0.246***	0.229***	0.25**
(***) , (**) , and (*) represents statistical significance at 1% , 5% , and 10% levels respectively Note: LCO ₂ : Proxy for Environmental Sustainability, ICT: information and communication technology, RESS: Renewable Energy Sources, GINV: Green Innovation, INSQ: Institutional Quality, LTRD: Trade Openness, and LGDPC: GDP per capita			

Table 4.9 represents Model-I, which examines the individual effects of key macroeconomic and institutional variables on environmental sustainability used as a

proxy for carbon dioxide emission (LCO2). The results reveal that information and communication technology, renewable energy sources, green innovation, institutional quality, and trade openness all have statistically significant negative coefficients, suggesting that improvement in these areas leads to a decrease in environmental degradation, thereby enhancing environmental sustainability. Conversely, GDP per capita (LGDPC) shows a positive and significant coefficient, implying that economic growth in its current form may still be associated with increased emissions in the OECD context; these results are consistent across fully modified ordinary least square (FMOLS), dynamic ordinary least square (DOLS) and canonical cointegrating regression (CCR) reinforcing the robustness of the findings. this model lays the foundation by showing how each independent factor contributes to environmental outcomes when considered separately.

Table 4.10. Panel Regression Results for Model-II for OECD Countries

Variables	(1) Fully Modified Ordinary Least Square (FMOLS)	(2) Dynamic Ordinary Least Square (DOLS)	(3) Canonical Cointegrating Regression (CCR)
ICT	-0.070***	-0.105***	-0.27***
RESS	-0.176***	-0.178***	-0.25***
GINV	-0.065**	-0.281***	-0.05**
INSQ	-0.122***	0.183***	-0.03***
LTRD	-0.101***	-0.089*	-0.06**
LGDPC	0.246***	0.263***	0.25***
ICT*RESS	-0.012*	-0.061*	0.03
(***) , (**) , and (*) represents statistical significance at 1% , 5% , and 10% levels respectively Note: LCO2: Proxy for Environmental Sustainability, ICT: information and communication technology, RESS: Renewable Energy Sources, GINV: Green Innovation, INSQ: Institutional Quality, LTRD: Trade Openness, and LGDPC: GDP per capita			

Table 4.10 represents Model-II, which incorporates the interaction term ICT*RESS to evaluate whether the joint influence of information and communication technology and renewable energy sources offers environmental benefits. The individual coefficients for ICT and RESS remain negative and significant across all three estimators, reaffirming their standalone importance in promoting environmental

sustainability. The interaction term ICT*RESS is negative and statistically significant in FMOLS and DOLS, albeit at a 10% level. This suggests that ICT usage enhances the effectiveness of renewable energy in reducing carbon emissions. The CCR estimation provides a positive but statistically insignificant interaction term indicating some model-specific variation in joint effects. Overall, this model suggests that technological advancement and renewable energy reinforce each other, emphasizing the importance of integrated policy efforts in these areas.

Table 4.11. Panel Regression Results for Model-III for OECD Countries

Variables	(1) Fully Modified Ordinary Least Square (FMOLS)	(2) Dynamic Ordinary Least Square (DOLS)	(3) Canonical Cointegrating Regression (CCR)
ICT	-0.076***	-0.084***	-0.18***
RESS	-0.167***	-0.249***	-0.15***
GINV	-0.063**	-0.279***	0.01
INSQ	-0.118***	0.204***	-0.02***
LTRD	-0.097***	-0.051	-0.06**
LGDPC	0.246***	0.241***	0.24**
ICT*INSQ	-0.020***	0.070***	0.10***
(***) , (**) , and (*) represents statistical significance at 1% , 5% , and 10% levels respectively Note: LCO2: Proxy for Environmental Sustainability, ICT: information and communication technology, RESS: Renewable Energy Sources, GINV: Green Innovation, INSQ: Institutional Quality, LTRD: Trade Openness, and LGDPC: GDP per capita			

Table 4.11 specifies the addition of an interaction term, ICT*INSQ, in order to test for the joint impact of information and communication technology development and institutional quality strength. The individual coefficient of ICT remains negative and statistically significant in all of the above models, whereas for institutional quality (INSQ), the sign is mixed: negative in FMOLS as well as in CCR, but positive in DOLS, the interaction term ICT*INSQ is statistically significant and negative in FMOLS, but positive in both DOLS and CCR, this suggests that the effect of ICT on environmental sustainability is conditional on institutional quality, and strong institutions may enhance or moderate the environmental effectiveness of ICT infrastructure.

4.8. Discussion

Overall, all three models yield convincing evidence that governance, renewables, innovation, and ICT are key drivers for promoting environmental sustainability in OECD economies. The interactive terms shed additional light on the nature of synergy, with implications for integrated and coordinated policymaking. After conducting an in-depth analysis of the dataset through preliminary tests such as summary statistics, correlation analysis, cross-sectional dependence testing, test for slope homogeneity, test for unit roots, and cointegration test, the nature of the data and the appropriate methods of estimation were determined. The results of these diagnostic tests informed the choice of three-panel estimation techniques considered appropriate for producing reliable results consistent with the requirements of the study.

The selected estimation method is Fully modified ordinary least square FMOLS over dynamic ordinary least square DOLS and canonical cointegrating regression CCR because the results from FMOLS are more aligned with the theoretical and empirical literature, and this method is well suited for dealing with issues found in our data like cross-sectional dependence, heterogeneity, autocorrelation and endogeneity and constraints imposed by smaller sample size. They are well-established methods used in macroeconomic, environmental, and policy-driven empirical studies for estimating long-run equilibria under conditions of non-stationarity in panels. Additionally, these techniques have backing in preceding studies like those of Saba et al. (2024), Jahangir et al. (2022), and Folawewo and Yang et al. (2022), which used similar methods in investigating intricate economic relationships. In alignment with such literature, this study used results from FMOLS to investigate the influence of information and communication technology, renewable energy, green innovation, quality of institutions, and other macroeconomic variables on environmental sustainability in OECD nations.

Information and Communication Technology: The ICT coefficients in all three of these models, as well as in all estimation procedures (FMOLS, DOLS, and CCR), are negative and statistically significant, meaning that technological improvements in information and communication contribute significantly towards environmental sustainability in OECD economies, the values of the coefficients for model I are -

0.073, -0.040, and -0.03, respectively, representing a modest but persistent impact in mitigating CO₂ emissions. For Model II, ICT's negative impact is significant, (-0.07), (-0.105), and (-0.27), in FMOLS, DOLS, and CCR estimations, respectively, such that its combination with renewable resources intensifies its environmental impact. Model III maintains the same negative relationship with coefficients of (-0.076), (-0.084), and (-0.18) in FMOLS, DOLS, and CCR estimations, respectively, further establishing the positive long-run impact of ICT on environmental outcomes, these outcomes demonstrate how ICT enhances energy savings, makes smart grids available, and facilitates clean production practices, all of which work toward reducing carbon footprints in developed economies.

Renewable Energy Sources: Across the models and methods, renewable energy (RESS) exhibits a strong, negative, and statistically highly significant correlation with environmental degradation. For Model I, RESS presents strong coefficients of -0.177, -0.189, and -0.17 for FMOLS, DOLS, and CCR, respectively. The same is observed in Models II and III, affirming that an increased contribution of renewables in the energy mix directly contributes toward CO₂ reductions. These observations are in line with global decarbonization strategies promoting decarbonization, as they reveal that nations with investments in renewable energy not only diversify their energy portfolio but make firm steps towards longer-term sustainability.

Green Innovation: The influence of green innovation on environmental quality is predominantly negative and statistically significant, though its magnitude and uniformity change slightly from model to model. Across Model I, GINV's values are (-0.077), (-0.058), and (-0.02), FMOLS, DOLS, and CCR estimations, respectively, all of which imply that technological innovation for environmental goals reduces emissions. For Model II, DOLS indicates an especially large contribution (-0.281), while FMOLS and CCR continue in line with previous trends. Model III adds some heterogeneity while FMOLS and DOLS continue with the predicted negative association (-0.063 and -0.279). CCR turns positive slightly (0.01), though not statistically significant. Variability indicates that while green innovation overall is positive for the environment, its implications could hang in the balance depending on the way in which green innovation is implemented, supported through policies, and scaled within OECD economies.

Institutional Quality: It plays a significant role in shaping environmental outcomes, but the direction and magnitude of the coefficient are different across models. In Model-I, INSQ consistently shows a negative and significant relationship with CO₂ emission, implying that better governance, rule of law, and regulatory effectiveness contribute to environmental sustainability. In Model II, DOLS indicates a positive contribution (0.183), while FMOLS and CCR continue in line with previous trends. Model III also shows the same trend as model II as (-0.118), (0.204), and (-0.020) in FMOLS, DOLS, and CCR estimations, respectively. These mixed results suggest a more complex interaction between institutional quality and environmental performance. These findings indicate that simply improving institutions is not enough. Environmental mandates must be embedded within those frameworks to achieve sustainability goals.

Trade Openness: Across all estimation methods, nearly all the coefficients for trade openness are negative, which means that heightened openness of economies fosters decreases in CO₂ emissions in the OECD environment. LTRD has coefficients of -0.099, -0.059, and -0.13 in Model I, all of which are statistically significant. Models II and III follow suit, although the DOLS estimator for Model III no longer remains statistically significant. The results corroborate the notion that trade allows for the use of green technologies through imports, promotes technological diffusion of innovation, and exposes local firms to cleaner foreign practices. For OECD economies with relatively strict environmental policies, the openness of trade is likely to promote sustainability through access to efficient, environment-friendly inputs of production.

GDP per capita: The results consistently demonstrate a positive and statistically significant correlation between GDP per capita and CO₂ emissions for all models and estimation techniques. The coefficient ranges consistently from 0.24 to 0.26, highlighting that economic development is continuing its strain on the environment in its current manifestation. The indication is that even though OECD economies are richer and possess superior technologies, increased incomes continue to equate with rising consumption as well as emissions. This indicates favor toward the scale effect principle in environmental economics, where increased production results in increased emissions. It also highlights the necessity of green restructuring of the economy and decoupling of development from environmental degradation.

The ICT-RESS nexus investigated in Model II provides some interesting albeit mixed results. FMOLS, as well as DOLS estimators, provide negative results (-0.012 and -0.061, respectively), suggesting that the combined use of ICT, as well as renewable energy, contributes positively in an increased way toward environmental sustainability. The CCR estimation, on the other hand, presents a positive albeit statistically insignificant coefficient (0.03), which indicates that such synergy between these variables is not consistent in all estimation techniques. The results suggest that, when complemented with renewable energy systems, ICT can make such systems more efficient and optimized in terms of integration (through smart grids and demand response measures), thereby increasing the potential for reducing emissions. However, the variation in results with models demands a closer examination of the role of ICT in supporting renewable energy infrastructure.

The ICT-institutional quality interaction term (ICT*INSQ), estimated in Model III, exhibits an intriguing dynamic. FMOLS indicates negative (-0.020), whereas both DOLS and CCR estimations provide positive and statistically significant impacts (0.070 and 0.10, respectively). It infers that ICT effectiveness in promoting environmental sustainability is boosted in countries with superior institutional quality. Stronger institutions guarantee enhanced enforcement of regulation, transparency, and public investment in green digital infrastructure, enabling ICT solutions for implementation with greater efficacy and extent. The efficacy of ICT in catalyzing environmental enhancements is thereby dependent on the quality of governance and institutional mechanisms, which is a key takeaway for policymakers' intent on harnessing digital change for climate objectives.

According to the empirical results from the three-panel regression models used for OECD countries, the Fully Modified Ordinary Least Squares (FMOLS) method is the most consistent and robust method of estimation of the long-run relationship between environmental sustainability and the major macroeconomic variables of ICT, renewable energy, green innovation, quality of institutions, trade openness, and GDP per capita. Throughout the three specifications of the models Model I (baseline), Model II (interactions of ICT with renewable energy), and Model III (interactions of ICT with quality of institutions), FMOLS consistently yields statistically significant results with economically anticipated signs. For example, ICT and RESS both have

negative and statistically significant values under FMOLS in all models, reiterating their independent and combined efficacy in controlling CO₂ output. Both ICTRESS and ICTINSQ are negative under FMOLS, signifying complementarities consistent with the environmental Kuznets curve, Grossman & Krueger, (1995), as well as the Porter Hypothesis that technological progress and innovation in institutions can lead toward environmental performance in advanced economies. FMOLS handles serial correlation as well as endogeneity, for which it is well-suited for use with non-stationary panel data as well as with cointegrated relationships Pedroni, (2000). Relative to DOLS as well as CCR, which show greater sign as well as statistical significance variability, particularly with the interaction terms FMOLS generates steadier as well as policy-relevant estimates, this is consistent with previous empirical work such as Saba et al. (2024) as well as Jahanger et al. (2022), which highlights the superior performance of FMOLS in the estimating of long-term equilibrium relations in panel datasets with heterogeneous dynamics. Hence, not only is FMOLS methodologically rigorous, but it is also empirically supported as the superior estimator for testing the drivers of environmental sustainability in OECD economies.

CHAPTER V

CONCLUSIONS

Through this study, I examine the interconnection of environmental sustainability with some of the main economic, as well as policy-related, drivers such as Information and Communication Technology (ICT), Renewable Energy Sources (RESS), Green Innovation (GINV), Institutional Quality (INSQ), Trade Openness (LTRD), and GDP per capita (GDPPC) in OECD countries over the period 1996–2021. Aside from exploring the overall associations between the aforementioned variables, in this study, I assess the joint impact of ICT with renewable energy sources and institutional quality on environmental sustainability.

Based on the previous literature, the role of ICT, renewable energy, institutional quality, and other variables in determining the environmental sustainability of the OECD countries has been analyzed in various studies. There has been no previous research utilizing information and communication technology, renewable energy sources, green innovation, and institutional quality in a single study, nor did previous literature for the case of OECD countries analyze the joint impacts of ICT with renewable energy sources or ICT with institutional quality on environmental sustainability. Most previous research has utilized a few variables or focused on a specific nation group, hence the knowledge gap on the interrelation of key sustainability drivers. This study addresses these gaps through the exploration of the interrelation of environmental sustainability to these variables and the simultaneous effect of ICT, RESS, and INSQ on environmental sustainability in the case of the OECD countries employing high-tech panel estimation techniques like FMOLS and DOLS. The contribution of this research lies in providing a more integrated perspective on how technology, energy transformation, and institutional quality can collectively drive the environmental outcomes for advanced economies.

To achieve these goals, the diagnostic and pre-estimation tests were conducted in a series of steps in order to test the characteristics of the data as well as methodological suitability. These include descriptive statistics, correlation matrix, cross-sectional dependence, slope homogeneity test, and second-generation panel unit root and cointegration tests. The diagnostic checks were performed with the aim of determining suitable estimation methods and controlling for cross-sectional dependence, non-stationarity, and heterogeneity in countries. On the basis of these tests, three solid econometric methods of Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), as well as Canonical Cointegrating Regression (CCR) were utilized in examining the long-run contribution of the considered variables toward environmental sustainability in the context of OECD.

The empirical analysis yields some important results. First of all, all three models always show that ICT enhances environmental sustainability through its negative and statistically significant contribution in terms of CO₂ emissions in all estimation techniques. This indicates that increased ICT diffusion enhances efficiency, diminishes carbon-intensive activity, and facilitates the adoption of greener technologies in OECD economies. Secondly, the contribution of renewable energy sources (RESS) is found to play a key role in bringing about sustainability. For all scenarios, RESS exhibits a strong and negative impact on CO₂ emissions, thereby establishing that increasing the use of renewables in the mix helps decrease environmental degradation. These results justify policy transitions toward adopting clean energy as an environmental planning strategic pillar in developed economies. Green innovation (GINV) also proves to be a key driver of sustainability. The coefficients are always negative and statistically significant, particularly for the FMOLS and DOLS estimations, indicating that investments in eco-innovation tend to alleviate emissions and bring production activities in line with environmental standards. The sign of significance for innovation indicates direction toward the function of innovation, technological change, and favorable policy environments in addressing sustainability. Institutional quality (INSQ), capturing the effectiveness of governance, quality of regulation, and rule of law, appears to have a strong negative correlation with CO₂ emissions, highlighting the fact that effective institutions play an important role in establishing and maintaining environmental regulation. Institutional quality is positively associated with the likelihood of imposing emission caps, having

green policies in place, and efficient management of environmental externalities. There is a consistently negative correlation between trade openness (LTRD) and CO₂ emissions, suggesting that international openness is not necessarily associated with environmental degradation. Instead, in the OECD economies, international cooperation and integration can help spread green technologies and environmental standards.

On the other hand, GDP per capita (LGDP) is positively and statistically related to CO₂ emissions in all the models, suggesting that greater measures of economic development can continue to be linked with greater environmental pressure in OECD countries. The finding is consistent with the initial stages of the Environmental Kuznets Curve (EKC) hypothesis that postulates that in the absence of specific environmental measures, increased income levels can create environmental degradation. Additionally, the analysis examines interactive effects in order to provide a greater depth of insight. The ICT-RESS (ICTRESS) interaction in Model-II indicates an insignificant, weakly negative impact in the majority of estimators, with the implication being that though both RESS and ICT have positive impacts when considered separately, their joint impact is not found to have strong synergy in the current dataset. This could be an indicator of lags in implementation or inefficiencies in combining digital technologies with renewable infrastructure.

Conversely, Model III captures a substantial and adverse ICT-institutional quality interaction (ICTINSQ), predominantly in FMOLS. The results imply that environmental gains from ICT are boosted when accompanied by sound institutions. Strong enforcement of policies and governance work to amplify the positive role of information and communication technologies for the environment.

Briefly, the study reveals robust proof that ICT, green innovation, renewable energy, quality of institutions, and openness in trade have a positive impact on environmental sustainability in OECD countries, whereas increased incomes bring about expanded emissions. The analysis of interactions also indicates that the quality of institutions reinforces the impact of ICT towards increasing sustainability.

This study lays the groundwork for some of the main policy recommendations that will help improve environmental sustainability in OECD countries. Policymakers need to promote the spread of ICT technologies in areas of energy efficiency, transport, and waste management. For ICT, though, to lead to tangible environmental benefits, it needs to be accompanied by quality institutions. Administrations need, therefore, to invest in enhancing governance mechanisms, accountability, and the quality of regulation. Investments in renewable infrastructure should be increased; OECD country's governments need to continue encouraging the shift toward solar, wind, hydro, and other green sources of power in order to decouple economic growth from carbon in the atmosphere. There should be fiscal incentives, R&D subsidies, and carbon pricing mechanisms to spur green innovation. Clean technological innovation should be supported not only in the private domain but also through public-private collaboration and global cooperation. Trade openness is compatible with sustainability in the OECD, provided that environmental protection is prioritized. Free trade agreements must have binding environmental provisions in order for free trade not only not to threaten but actually to help pursue ecological goals. Policymakers should exercise care regarding the environmental costs of increased income. Mechanisms like carbon taxes, green budgeting, and sustainable urban planning should be used to contain the environmental externalities of development. Policymakers must focus on the strategic interaction of Information and Communication Technologies (ICT) with Renewable Energy Sources and Systems (RESS) to bring significant environmental dividends. The advancement of innovative grid systems, digital control structures, and data-based management systems for power can drastically improve the efficiency, coordination, and resilience of renewable power systems. The integration not only allows for the optimization of power generation and consumption but also yields an observable decrease in greenhouse gas output and the waste of resources, thus making a dramatic positive contribution towards environmental sustainability. To ensure the effectiveness of environmental policies, holistic reforms in institutions are critical. These should prioritize enhancing transparency, enforcing regulation, and enhancing governance mechanisms for environmental management. Institutional capacity development and coherence in policies can guarantee more efficient sustainability action, as well as accountability and public trust.

By implementing coherent and forward-looking strategies and policies in these areas, OECD countries and other regions can accelerate progress towards their environmental sustainability goals. Such actions not only support the alignment of economic development with ecological responsibility but also provide a replicable framework for global sustainability governance.



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APPENDIX

APPENDIX A

SUPPORTING ESTIMATIONS

Table A.1. Panel Cointegration Test at First Difference for OECD Countries

Tests	Methods	Statistic
WesterLund	All Panels	0.0828
	Some Panels	3.0918***
Pedroni	Modified Phillips-Perron t	1.4881*
	Phillips-Perron t	-16.388***
	Augmented Dickey-Fuller t	-15.938***
Kao	Modified Dickey-Fuller t	-38.517***
	Dickey-Fuller t	-27.087***
	Augmented Dickey-Fuller t	-18.443***
	Unadjusted modified Dickey-Fuller	-41.817***
	Unadjusted Dickey-Fuller t	-27.229***

Notes: (***), (**) and (*) represents statistical significance at 1%, 5% and 10% levels, respectively.

Table A.2. PCA for Information and Communication Technology

Principal Component Results					
Component	Value	Difference	Proportion	Value	Proportion
Component 1	1.870	0.887	0.623	1.870	0.623
Component 2	0.983	0.836	0.328	2.853	0.951
Component 3	0.147		0.049	3.000	1.000

Table A.3. Principal Components Eigenvectors for ICT

Principal Components Eigenvectors			
Variable	Component 1	Component 2	Component 3
Internet Access	0.692	0.186	-0.698
Mobile-Telephones	0.703	0.050	0.710
Fixed Telephones	-0.167	0.981	0.096

Table A.4. Correlation Matrix Results for ICT

Correlation Matrix Results			
Variable	i	ii	iii
(i) Internet Access	1.000		
(ii) Mobile-Telephones	0.845	1.000	
(iii) Fixed Telephones	-0.046	-0.161	1.000

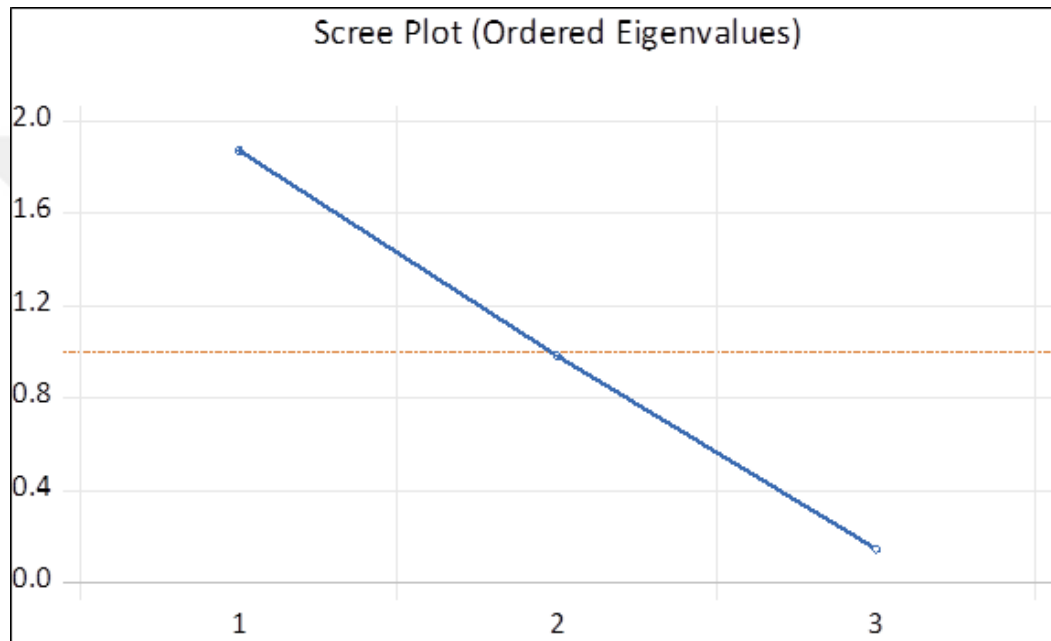


Figure A.1. Plot of Eigenvalues After PCA for ICT

Table A.5. PCA for Renewable Energy Sources

Principal Component Results					
Component	Value	Difference	Proportion	Value	Proportion
Component 1	1.856	1.711	0.928	1.856	0.928
Component 2	0.144		0.072	2.000	1.000

Table A.6. Principal Components Eigenvectors for RESS

Principal Components Eigenvectors		
Variable	Component 1	Component 2
RELO	0.707106781	-0.707106781
REGC	0.707106781	0.707106781

Table A.7. Correlation Matrix Results for RESS

Correlation Matrix Results		
Variable	i	ii
(i) RELO	1.00	
(ii) REGC	0.86	1.00

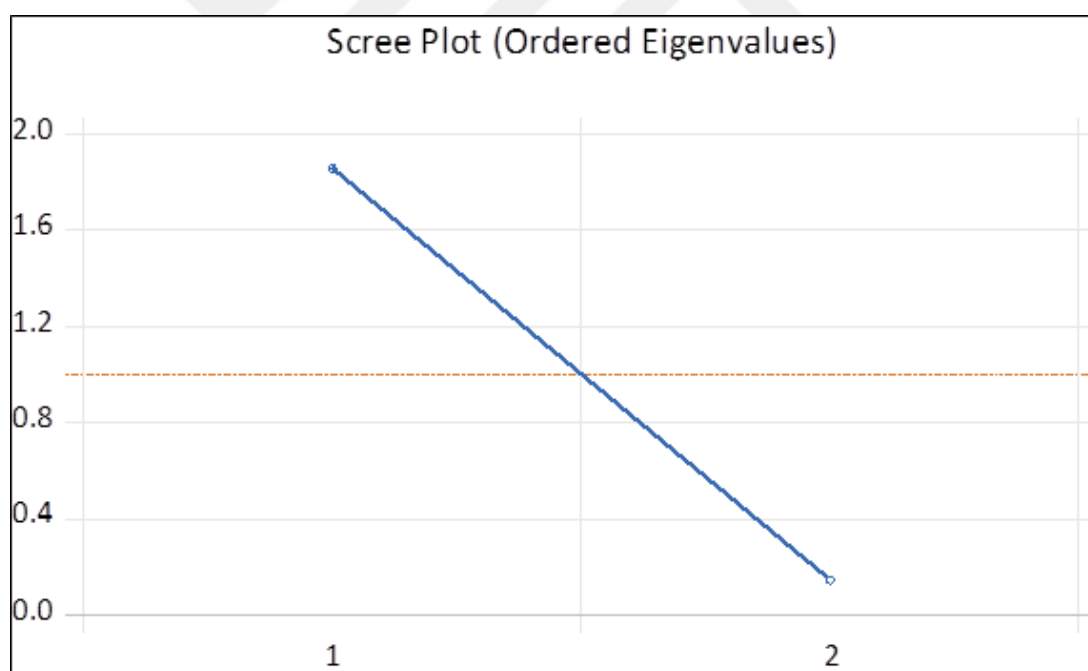


Figure A.2. Scree Plot of Eigenvalues After PCA for RESS

Table A.8. PCA for Institutional Quality

Principal Component Results					
Component	Value	Difference	Proportion	Value	Proportion
Component 1	5.192	4.703	0.865	5.192	0.865
Component 2	0.489	0.371	0.081	5.681	0.947
Component 3	0.118	0.013	0.020	5.799	0.966
Component 4	0.105	0.045	0.017	5.903	0.984
Component 5	0.060	0.023	0.010	5.963	0.994
Component 6	0.037		0.006	6.000	1.000

Table A.9. Principal Components Eigenvectors for INSQ

Principal Components Eigenvectors						
Variable	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6
WGIc	0.419	-0.275	0.295	-0.180	0.749	0.261
WGIg	0.417	-0.293	0.437	0.240	-0.588	0.381
WGIp	0.351	0.836	0.138	0.373	0.125	0.059
WGIreg	0.413	-0.231	-0.783	0.386	0.050	0.102
WGIreg	0.429	-0.150	0.167	0.027	-0.051	-0.873
WGIv	0.415	0.251	-0.248	-0.788	-0.269	0.105

Table A.10. Correlation Matrix Results for INSQ

Correlation Matrix Results						
Variable	i	ii	iii	iv	v	vi
(i) WGIc	1.000					
(ii) WGIg	0.936	1.000				
(iii) WGIp	0.656	0.654	1.000			
(iv) WGIreg	0.899	0.896	0.661	1.000		
(v) WGIreg	0.950	0.951	0.723	0.920	1.000	
(vi) WGIv	0.864	0.840	0.822	0.851	0.896	1.000

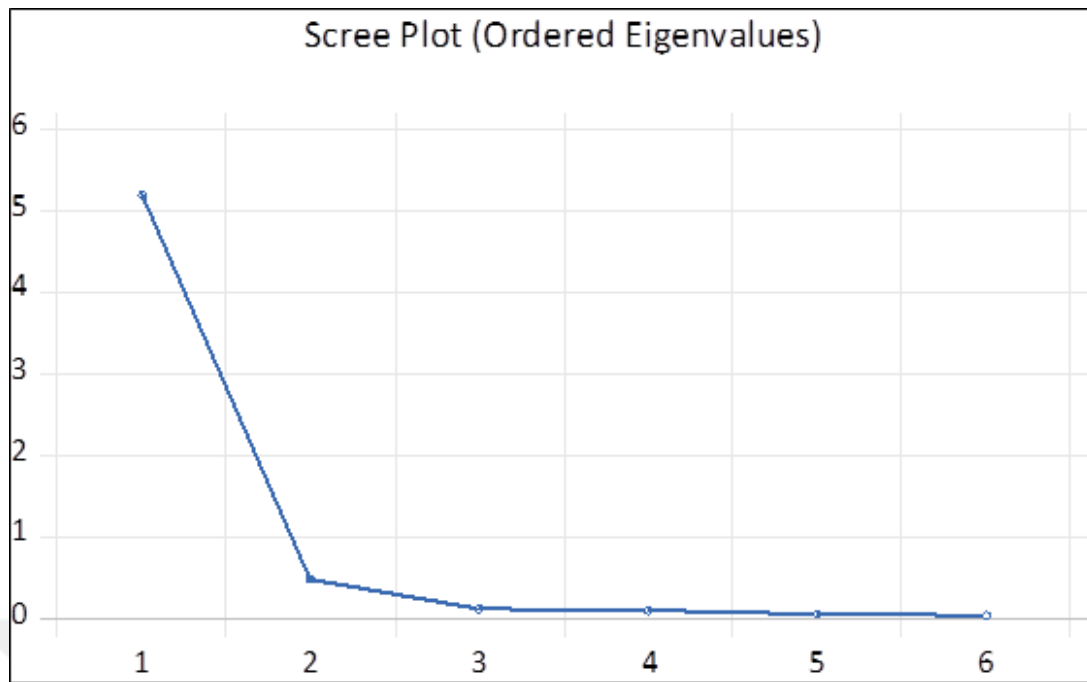


Figure A.3. Scree Plot of Eigenvalues After PCA for INSQ

Table A.11. Panel Casual Relationship among the Variables

Model	Null hypothesis	W-Stat	Zbar-Stat	p-value	Direction of relationship observed	Conclusion
1	$lco2 \nrightarrow ict$	4.5521	15.2782	0.00	$lco2 \leftrightarrow ict$	bidirectional
	$ict \nrightarrow lco2$	1.835	3.5917	0.00		
2	$lco2 \nrightarrow res$	1.8553	3.6788	0.00	$lco2 \leftrightarrow res$	bidirectional
	$res \nrightarrow lco2$	3.557	10.9981	0.00		
3	$lco2 \nrightarrow ginv$	1.1731	0.7446	0.46	$ginv \rightarrow lco2$	unidirectional
	$ginv \nrightarrow lco2$	2.2645	5.4389	0.00		
4	$lco2 \nrightarrow insq$	2.7706	7.6158	0.00	$lco2 \leftrightarrow insq$	bidirectional
	$insq \nrightarrow lco2$	3.09	8.9895	0.00		
5	$lco2 \nrightarrow ltrd$	3.4818	10.6745	0.00	$lco2 \leftrightarrow ltrd$	bidirectional
	$ltrd \nrightarrow lco2$	2.7916	7.7061	0.00		
6	$lco2 \nrightarrow lgdpc$	5.7366	20.373	0.00	$lco2 \leftrightarrow lgdpc$	bidirectional
	$lgdpc \nrightarrow lco2$	1.8778	3.7754	0.00		

Table A.12. Summary of Causality

	Summary of Causality	
lco2	bidirectional	ict
	↔	
lco2	bidirectional	ress
	↔	
ginv	unidirectional	lco2
	→	
lco2	bidirectional	insq
	↔	
lco2	bidirectional	ltrd
	↔	
lco2	bidirectional	lgdpc
	↔	

Table A.13. Fixed Effect

Fixed Effect			
LCO2	Coefficient	Std. err.	p - value
ICT	-0.095	0.009	0.000
RESS	-0.020	0.006	0.000
GINV	-0.023	0.011	0.046
INSQ	0.101	0.014	0.000
LTRD	-0.139	0.034	0.000
LGDP	0.354	0.043	0.000
ICT*RESS	-0.009	0.004	0.040
ICT*INSQ	-0.023	0.453	0.000

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