

The Role of Renewable Energy, Innovation, and Digitization on the Environmental Footprint: Empirical Evidence from National and Cross- national Studies

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ABSTRACT

In the first chapter of the thesis, detailed information regarding the focus of the thesis is provided.

In the second chapter of the thesis, the moderating role of digitalization with innovation, renewable energy, and financial development on environmental sustainability is examined. The findings from the Generalized Methods of Moments (GMM) method show that digitalization, innovation, renewable energy, and financial development are negatively correlated with environmental degradation. A key result of the study is that digitalization and its interplay with innovation, renewable energy, and financial development demonstrate footprint-mitigating effects. Considering these findings, the integration of digitalization and environmental policies may lead to more resilient outcomes and enhanced environmental quality in contrast to the implementation of a solitary policy in isolation.

In the third chapter, the impact of renewable energy sources on the displacement of fossil fuels for 36 OECD countries. The findings demonstrate a discernible trend in the replacement of fossil fuels by renewable energy sources. More specifically, an average increase of 1.4 units of renewable energy is mandated to displace one unit of fossil fuel energy. Additionally, a one-to-one displacement of fossil fuels occurs with hydropower. The results indicate that the energy transition in OECD nations is currently in progress, with renewable energy sources making significant strides towards supplanting fossil fuels.

The fourth chapter of the thesis focuses on the the determinants that influence the demand for renewable energy in the United States over the period 1987-2021. In pursuit of this objective, the factors that are industrial production, non-renewable energy prices and climate policy uncertainty are considered. The empirical results suggest that industrial production, non-renewable energy, and climate policy uncertainty have positive impact on the use of renewable energy. As a result, the findings from the study help to facilitate policymakers in formulating appropriate policies for the transition towards clean energy to combat the adverse effects of climate change.

Keywords: Digitalization, Innovation, Renewable Energy, Fossil-Fuels, Environmental Sustainability, Panel Data Analysis.

ÖZ

Tezin ilk bölümünde, çalışmanın odağı hakkında ayrıntılı bilgi sunulmuştur.

Tezin ikinci bölümünde inovasyon, yenilenebilir enerji ve finansal gelişme ile birlikte dijitalleşmenin çevresel sürdürülebilirlik üzerindeki moderator rolü incelenmektedir. Genelleştirilmiş Moment Yönteminden elde edilen bulgular, dijitalleşme, inovasyon, yenilenebilir enerji ve finansal gelişmenin çevresel bozulma ile negative ilişkili olduğunu göstermektedir. Çalışmanın önemli bir bulgusu dijitalleşmenin inovasyon, yenilenebilir enerji ve finansal gelişme ile etkileşiminin ekolojik ayak izini azaltıcı etkiler göstermesidir. Bu bulgular göz önüne alındığında, dijitalleşme ve çevre politikalarının entegrasyonu, tek başına bir politika uygulanmasına göre daha güvenilir sonuçlara ve gelişmiş çevre kalitesine yol açmaktadır.

Üçüncü bölümde, 36 OECD ülkesi için yenilenebilir enerji kaynaklarının fosil yakıtları ile yer değiştirme etkisi ele alınmıştır. Bulgular, fosil yakıtların yenilenebilir enerji kaynakları ile yer değiştirmesine dair belirgin bir eğilim olduğunu göstermektedir. Daha spesifik olarak, bir birim fosil yakıt enerjisinin yerini almak için ortalama 1,4 birim yenilenebilir enerji artışı gerekmektedir. Ek olarak, fosil yakıtların bire bir yer değiştirmesi hidroenerji ile gerçekleşir. Sonuçlar, OECD ülkelerinde enerji geçişinin şu anda devam ettiğini ve yenilenebilir enerji kaynaklarının fosil yakıtların yerini alma yolunda önemli gelişme kaydettiğini göstermektedir.

Tezin dördüncü bölümü, 1987-2021 döneminde Amerika Birleşik Devletleri'nde yenilenebilir enerji talebini etkileyen belirleyicilere odaklanmaktadır. Bu amaç doğrultusunda, sanayi üretimi, yenilenemeyen enerji fiyatları ve iklim politikası

belirsizliđi gibi faktörler ele alınmaktadır. Ampirik sonuçlar, endüstriyel üretim, yenilenemeyen enerji ve iklim politikası belirsizliđinin yenilenebilir enerji kullanımı üzerinde olumlu etkisi olduđunu göstermektedir. Sonuç olarak, çalışmadan elde edilen bulgular, politika yapıcılarının iklim deđişikliđinin olumsuz etkileriyle mücadele etmek için temiz enerjiye geçiř için uygun politikaları formüle etmelerine yardımcı olmaktadır.

Anahtar Kelimeler: Dijitalleşme, İnovasyon, Yenilenebilir Enerji, Fosil Yakıtlar, Çevresel Sürdürülebilirlik, Panel Veri Analizi.

To my family

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LIST OF ABBREVIATIONS

ADF	Augmented Dickey-Fuller
AMG	Augmented Mean Group
AR	Autoregressive
BRICS	Brazil, Russia, India, China, South Africa
CPU	Climate Policy Uncertainty
COP26	The UN Climate Change Conference in Glasgow
DIFF	Difference
DIGI	Digitalization
DOLS	Dynamic Ordinary Least Squares
ECONS	Energy Consumption
EFP	Ecological Footprint
EG	Engle and Granger
EIA	Energy Information Administration
ENDEP	Energy Dependence
EPU	Economic Policy Uncertainty
E-7	Emerging Seven
FBS	Fixed Broadband Subscriptions
FD	Financial Development
FM-OLS	Fully Modified Ordinary Least Squares
FTS	Fixed Telephone Subscriptions
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GI	Green Innovation

GMM	Generalized Method of Moments
G-7	Group of Seven
ICT	Information and Communications Technology
IEA	International Energy Agency
IMF	International Monetary Fund
INT	Internet Consumers
IoT	Internet of Things
IP	Industrial Production
IRENA	International Renewable Energy Agency
MCS	Mobile Cellular Subscriptions
NDC	Nationally Determined Contribution
OECD	Organisation for Economic Co-operation and Development
OIL	Oklahoma Crude Oil Prices
OLS	Ordinary Least Squares
PCA	Principal Component Analysis
POP	Population Density
PPI	Production Price Index
PV	Photovoltaic
RALS	Residual Augmented Least Squares
RE	Renewable Energy
REC	Renewable Energy Consumption
REN21	Renewable Energy Policy Network for the 21st Century
SDG	Sustainable Development Goals
TI	Technological Innovation
TR	Trade Openness

UNDP	United Nations Development Programme
URB	Urbanization
US	United States
WDI	World Development Indicators
VIF	Variance Inflation Factor
WIPO	World Intellectual Property Organization
WTI	West Texas Intermediate

Chapter 1

INTRODUCTION

The issue of climate change has raised concerns regarding the worsening of ecological conditions, leading to an increased focus on the concept of carbon neutrality. The continued reliance on fossil fuels to meet energy demand is the primary driver of emissions, and greenhouse gas emissions, particularly carbon dioxide, are the principal cause of climate change. Therefore, it is of the utmost importance to identify the measures and policies that can reduce emission levels to a certain extent across the global economy.

In this regard, numerous nations have instituted a range of measures in the realm of energy and environmental policy with the aim of improving environmental conditions and attaining sustainability in the environmental domain. For example, during the 26th United Nations Climate Change Conference, referred to as COP26, nearly 200 countries expressed their endorsement of the implementation of the "Climate pact." This agreement serves as a means to reiterate the responsibilities of nations in achieving decarbonization targets by the year 2050. The measures and responsibilities encompass policies pertaining to the protection of the environment via the reduction of emissions, the assurance of energy security, and the promotion of green development. Concerning these objectives, the utilization of renewable energy sources has become a pivotal environmental policy instrument for accomplishing sustainable development goals (SDG) declared by United Nations (UN). SDG-7 proposes a

practical approach to attaining energy security, energy efficiency and sustainable economic development through the generation of affordable and sustainable sources of energy. Clean energy sources minimize environmental difficulties, and achieving this goal is closely linked to SDG 13, which emphasizes the importance of focusing on climate control for a better environment. Therefore, the thesis focuses on the importance of renewable energy sources for achieving clean environment goals.

The integration of digital technologies in the energy industry, encompassing both production and consumption practices, is also an essential element of the transition towards a low-carbon economy. The implementation of digitalization in production and consumption models, as required by the SDGs, enables industries to achieve optimal and streamlined production processes by fostering innovation and shifting from traditional to renewable energy technologies. Accordingly, the second chapter of the thesis proposes the integration of digitalization with environmental policies. This is because the incorporation of digital technologies with existing technologies, clean energy systems, and financialization can fortify their mitigating impact of environmental degradation.

It is widely acknowledged that the dependence on fossil fuels for power generation is a key factor contributing to the anthropogenic release of emissions, consequently leading to climate change. Thus, the transition towards renewable energy sources holds significant potential for reducing the adverse environmental consequences linked to the utilization of fossil-fuels. In order to effectively tackle the climate crisis, it is imperative that renewable energy sources serve as a viable replacement for traditional fossil fuels. In fact, renewable energy sources have recently made significant progress in the power industry, signifying that the global shift towards renewable energy is

currently in progress. According to the report by IRENA (2022a), renewable energy (RE) capacity has grown by 130% in the last decade, surpassing the 24% increase in fossil fuel capacity. Furthermore, as of 2021, renewable energy sources constituted 81% of the total power generation capacity. From this backdrop, it can be stated that renewables are gradually replacing traditional energies worldwide. In this context, the third chapter of the thesis investigates the displacement effect of renewables on fossil-fuels for OECD countries.

The deployment of renewable energy sources in the process of decarbonizing energy systems has the potential to reduce the vulnerability of societies to climate risks. In this line, identifying the factors that affect renewable energy development is crucial for established objectives for climate change. To this end, another crucial step for effectively tackling climate change is to integrate uncertainty into climate policy frameworks. Climate policy uncertainty pertains to the fluctuations in governmental environmental policies. The implementation of policy modifications could potentially generate ambiguities that have the potential to impact investment decision-making. Furthermore, the demand for renewable energy sources may be influenced by geopolitical risks and market instability that result in fluctuations in energy prices. Given this background, in the last chapter of the thesis, the impact of climate policy uncertainty and non-renewable energy prices on the renewable energy demand for the United States is examined.

Chapter 2

DIGITALIZATION, INNOVATION, RENEWABLE ENERGY, FINANCIAL DEVELOPMENT AND ENVIRONMENTAL SUSTAINABILITY

2.1 Introduction

Over the past two decades, nations have faced severe climate-related challenges, such as biodiversity loss, escalating pollution levels, and the overexploitation of natural resources. Consequently, humanity is grappling with a novel growth paradigm that encompasses the trade-off between utilizing scarce resources and maintaining environmental sustainability. In recent times, policymakers, environmentalists, and energy economists have collectively prioritized the pursuit of sustainable, balanced, and inclusive economic growth. The 2030 Agenda for Sustainable Development outlines 17 Sustainable Development Goals (SDG 17), which have been endorsed by all United Nations Member States. Digitalization, encompassing aspects such as production and consumption patterns, energy and resource efficiency, digital infrastructure, and renewable energy, is integral to the transition towards a low-carbon economy. The adoption of digital technologies is vital for achieving environmental cleanliness and sustainable economic growth. The digital economy expedites industrial transformation by diffusing knowledge and fostering the servitization of industries, thus facilitating low-carbon economic development (Jetter *et al.*, 2009; Wang *et al.*, 2022a).

In this context, digitalization has garnered significant attention as a primary factor in mitigating pollution, prompting researchers and policymakers to examine its external influence on environmental sustainability (UNDP, 2018; Gaspar *et al.*, 2014). Qian *et al.* (2021) posited a positive correlation between digitalization and the green economy, which can contribute to the achievement of sustainable development goals. Furthermore, Chien *et al.* (2021) observed that digitalization holds the potential to act as a key enabler for the SDGs.

In line with SDG-7 (Affordable and Clean Energy), SDG-12 (Responsible Consumption and Production), and SDG-13 (Urgent Action to Combat Climate Change and its Impacts), the concepts of sustainability in production and digitalization, although seemingly distinct, exhibit a strong interconnectedness. The digitalization of production models, as mandated by the SDGs, allows firms and industries to attain effective and efficient production through the promotion of innovation, transitioning from conventional to environmentally friendly green technologies (Hosan *et al.*, 2022). As a result, digitalization modernizes the production process and enhances production efficiency by minimizing undesirable waste, including solid waste, e-waste, and agricultural and food waste (Gu *et al.*, 2017; Martynenko and Vershinina, 2018; Wen *et al.*, 2018; European Commission, 2019; Partel *et al.*, 2019). This reduction in emissions fosters a circular economy by augmenting recycling and repurposing waste materials, which directly impacts SDG-12. Consequently, the widespread integration of digital technologies into the economy is projected to contribute to a 15% decrease in global emissions (The Exponential Roadmap, 2020).

Digitalization impacts environmental sustainability through three mechanisms: use-effect, rebound effect, and substitution effect. First, the use-effect posits that the production of digital tools increases energy and resource consumption, while their installation, distribution, and utilization generate waste, leading to adverse environmental consequences (Park *et al.*, 2018; Kunkel and Tyfield, 2021). Second, the rebound effect suggests that digitalization-driven increases in production and consumption levels stimulate efficiency gains, which subsequently result in energy savings (Bartekova and Börkey, 2022). However, these digitalization-enabled efficiency improvements can lead to increased energy consumption, thereby counteracting the resources and energy saved. As a consequence, energy consumption and carbon emissions may rise (Gossart, 2015; Wang *et al.*, 2019). Third, the substitution effects of digitalization on environmental sustainability encompass dematerialization, decarbonization, and demobilization (Sui and Rejeski, 2002). Dematerialization mitigates environmental degradation by replacing traditional goods and services with virtual alternatives. For example, e-commerce, e-shopping, and e-banking can reduce outdoor activities, thus diminishing energy consumption and environmental degradation (Kouladoum *et al.* 2022). Furthermore, e-mails and e-books can decrease material consumption by curbing the demand for physical products (Sui and Rejeski, 2002; Ozcan and Apergis, 2018).

On the one hand, digitalization can lessen environmental pollution by transitioning from conventional power generation to renewable sources, such as solar and wind energy, thereby creating novel opportunities to optimize energy use and enhance the energy efficiency of innovation. This shift reduces emission intensity and generates additional cost savings (Jorisch *et al.*, 2018). Integrating digital devices like smart

meters, smart grids, battery storage, and energy storage technologies into existing renewable energy sources can also improve the efficiency of the power system, contribute to grid operation cost reduction, and support ecosystem preservation throughout the production-consumption cycle (Moyer and Hughes, 2012; Lange *et al.*, 2020; IRENA, 2021). To attain a decarbonized economy, the implementation of such smart technologies has also benefited energy systems in terms of sustainability, energy supply and demand management, safety, and productivity (Bastidas *et al.*, 2022; Hosan *et al.*, 2022). According to demobilization, digital activities such as e-commerce, teleworking, and teleconferencing can potentially reduce transportation demand, thereby decreasing transport-related emissions and air pollution (Lange *et al.*, 2020; Husaini and Lean, 2022). Despite the fact that digitalization plays a clear and active role in combating climate change, its potential environmental impact varies, as demonstrated by the preceding arguments. Therefore, it is implausible to assert that digitalization alone can protect the environment by altering production and consumption patterns, transforming the energy system, reducing resource and energy consumption, and consequently emissions. Accordingly, the impact of digitalization on the environment is contingent upon the plan for collaborating with these diverse economic actors and, consequently, their interaction with digitalization.

In light of the existing literature, this study makes several unique contributions to the current body of knowledge. First, it determines the interaction effects of digitalization—constructed based on four parameters using principal component analysis—associated with green innovation, renewable energy, and financial development on the ecological footprint. Second, although numerous scholars have investigated the direct impact of digitalization on the environment, the interactions

between the selected variables have not been previously examined in OECD countries. The choice of these variables is driven by the SDGs (7, 12, and 13). As OECD members lead the substantial process of implementing policies aligned with SDG goals, the empirical findings of this study may offer valuable insights for these governments in devising climate change policies within the context of the emerging digital economy. Third, employing emission levels as an environmental indicator may restrict the overall scope of ecological sustainability to large industrial operations while neglecting various human behaviors that jeopardize ecological sustainability. Hence, this study considers the ecological footprint as an extensive indicator of environmental degradation, as it is the sole parameter that accounts for a planet's biocapacity to support both domestic and international economic activities. Fourth, this research represents the first study on this subject to utilize a dynamic panel model estimator, specifically a two-step system Generalized Method of Moments estimator, which addresses the challenges of potential endogeneity, reverse causality, dynamic panel bias, and heterogeneity.

The findings of this study demonstrate that digitalization serves to alleviate pressure on the environment and maintain environmental quality. Furthermore, green innovation, renewable energy, and financial development significantly contribute to environmental sustainability. The empirical results also support the hypothesis that the interaction between digitalization and green innovation amplifies the ecological footprint-mitigating effect of digitalization. Additionally, renewable energy consumption exhibits a negative moderating role in the influence of digitalization on environmental sustainability, implying that renewable energy reinforces the environmental sustainability-promoting impact of digitalization. Financial

development, too, enhances the mitigating role of digitalization on the environment. These outcomes suggest that digitalization ought to be integrated with environmental policies in such a manner that the incorporation of digital technologies into existing technologies, energy power systems, and financialization fortifies their mitigating impact on environmental degradation.

The rest of the paper is ordered as follows: Section 2 presents the review of literature; Section 3 provides detailed data and model specification and is followed by empirical results and discussions in Section 4. Finally, in the last part, Section 5, consists of the conclusion and policy recommendation.

2.2 Literature Review

This section of the study provides brief reviews of the earlier studies in four sections, which focus on the impact of digitalization, innovation, renewable energy, and financial development on environmental sustainability, respectively.

2.2.1 Digitalization and Environment

Digitalization-environment nexus in the literature is gathering a pace (Godil *et al.*, 2021). Undoubtedly, digitalization is integrated into every section of the economy, helping the sustainable growth of the economy. In this regard, the effect of digitalization on the environment has been discussed, and its effect on the environment is ambiguous. The outcomes of the studies have shown that digitalization is double-edged; in other words, they have reached two viewpoints, i.e., the environmental effects of digitalization can be both improving and damaging.

One group of studies stated that digitalization plays an essential role in reducing emissions, which eventually mitigates environmental degradation. For example, a

study conducted by Matthews *et al.* (2001) utilized e-commerce as an indicator of digitalization and found that e-commerce has a significantly lower environmental impact compared to traditional retailing. In a similar vein, Al-Mulali *et al.* (2015) revealed that e-commerce leads to a reduction in emissions in developed countries. Coroama *et al.* (2012) demonstrated that teleconferences can decrease transportation-related emissions by as much as 50%. Furthermore, Monzon *et al.* (2017) indicated that digitalization contributes to the reduction of emissions in the transportation sector. Additional research by Esmaeilian *et al.* (2018), Mao *et al.* (2019), Kerdlap *et al.* (2019), and Leng *et al.* (2020) collectively established that digitalization promotes eco-friendly and sustainable production in the secondary sector, consequently mitigating environmental degradation. Danish (2019) investigated the effect of digitalization on environmental quality for 59 selected countries associated with trade and real income. The author found that digitalization abates the pollution level and helps to mitigate the emissions. Similarly, Haseeb *et al.* (2019) conducted a study focusing on BRICS countries, while Sinha *et al.* (2020) examined Next 11 (N-11) countries, both concluding that digitalization enhances environmental quality. Furthermore, Altinoz *et al.* (2021) explored the relationship between digitalization and environmental quality by considering internet usage and fixed telephone subscriptions as indicators. Their findings suggested that these factors positively contribute to environmental quality in the top ten emerging market economies. Similarly, Chien *et al.* (2021) used internet users as a proxy for digitalization and concluded that digitalization induces favorable environmental outcomes for BRICS countries. In a separate study analyzing data from G-7 and E-7 countries between 1995 and 2018, Huang *et al.* (2022) provided evidence that digitalization yields contrasting effects on the environment. Specifically, they found that digitalization contributes to environmental degradation in E-7

countries, whereas it exerts a positive impact on environmental quality in G-7 countries. In the Chinese context, Ma *et al.* (2022) also claimed that digitalization mitigates environmental deterioration. In addition, digitalization and innovation interactions significantly lead to a significant decrease in environmental degradation. A distinct group of studies has posited that the widespread adoption of digitalization could impede green growth and exacerbate environmental quality, depending on the extent of technology utilization and implementation in production processes. These studies further assert that approximately 2% of global emissions can be attributed to the digitalization sector (IEA, 2019). Reichart and Hirsch (2003) investigated the environmental impact of dematerialization and determined that printed newspapers exert a more detrimental effect on the environment compared to online news consumption. Danish *et al.* (2018) employed internet usage and mobile phone usage as proxies for digitalization and deduced that digitalization contributes to increased environmental pollution in N-11 economies. Their empirical findings also suggested that the interplay between digitalization and financial development fosters carbon emissions. This outcome aligns with the results obtained by Raheem *et al.* (2020) in their study of G-7 countries. In a related investigation, Avom *et al.* (2020) analyzed 21 Sub-Saharan African countries, using internet usage and mobile phone penetration as indicators of digitalization. Their empirical findings unveiled that digitalization has an adverse effect on environmental quality by stimulating carbon emissions.

2.2.2 Innovation, Digitalization, and Environment

Innovation plays a critical role in achieving SDGs by alleviating environmental pressures through the transformation of production models and the promotion of low-carbon technologies. Consequently, this section of the study explores the relationships

between innovation and the environment, as well as between innovation and digitalization.

First, investment in environmentally related technologies is an essential factor for mitigating adverse effects on the environment. Several prior studies have examined the impact of innovation on the environment in light of this potential. Lin and Zhu (2019) reported that, within the context of China, technological innovation has contributed positively to carbon emissions mitigation during the 2000-2015 period. Gormus and Aydın (2020) revealed that technological innovation reduces environmental degradation in the top ten innovative economies. Utilizing a bootstrap-based Autoregressive Distributed Lag (ARDL)-bound testing model, Shan *et al.* (2021) found that green technology innovation helps to decrease environmental damage in Turkey. Recently, Ahmad and Wu (2022) demonstrated that eco-innovation negatively affects the ecological footprint, indicating that it enhances environmental quality in 20 selected countries. Sun *et al.* (2022) discovered that green innovation-driven technologies foster an eco-friendly environment in the ten most polluted countries. Similarly, Suki *et al.* (2022) observed that technological innovation reduces ecological issues in Malaysia during the 1980-2018 period by mitigating both the ecological footprint and carbon emissions. In line with these findings, Wang *et al.* (2022c) presented evidence of green innovation's significant impact on emissions in 15 selected Central and Eastern European countries. Conversely, based on data from G-6, MENA, and BRICS countries from 1990 to 2016, Dauda *et al.* (2019) applied fully modified ordinary least square (FM-OLS) and dynamic OLS (DOLS) techniques, confirming that innovation increases carbon emissions in BRICS and MENA countries while reducing emissions in G-6 countries. Khattak *et al.* (2020) obtained similar

results in a sample of BRICS countries, excluding Brazil. Additionally, Demir *et al.* (2020) found that innovation was the primary cause of environmental damage in Turkey from 1971 to 2013.

Second, digitalization has the potential to promote the emergence of new industries and transform production patterns, thereby creating opportunities for the development of environmentally sustainable technological innovations. Within the digitalization-innovation context, Usai *et al.* (2021) revealed that advanced digital technologies, such as big data and robotics, directly impact innovation capabilities in European countries. In China, Xue *et al.* (2022) demonstrated that the adoption of digital technologies can enhance the progress of green innovation by alleviating financial constraints. Li *et al.* (2023) suggested that the digital economy promotes efficiency in environmentally sustainable innovation, thus contributing to the improvement of production infrastructure. Zhang *et al.* (2023) emphasized that digitalization and the implementation of the Internet of Things (IoT) strategy play a vital role in fostering innovation in energy storage systems in China.

2.2.3 Renewable Energy, Digitalization, and Environment

Renewable sources are considered to have a key role in environmental sustainability since they minimize environmental concern compared with fossil-fired based technologies, which contribute to the expansion of emissions. In this regard, renewable energy sources as clean energy sources in the energy mix of countries have a vital role in achieving SDG-7. The studies conducted on this subject matter nearly provided similar results.

Employing the augmented mean group (AMG) technique, Danish *et al.* (2019) underscored the mitigating influence of renewable energy on environmental degradation in BRICS countries. Similarly, within the context of BRICS nations, Lin and Wang (2020) demonstrated that renewable energy consumption effectively contributes to reducing the ecological footprint. Destek and Sinha (2020) found that renewable energy alternatives diminish environmental damage in 24 OECD countries, offering a sustainable solution for achieving SDGs. By analyzing data from OECD countries, Saidi and Omri (2020), Rafique *et al.* (2022), and Mujataba *et al.* (2022) disclosed that renewable energy plays a significant role in alleviating the ecological footprint and environmental degradation. In the case of E-7 countries, Bekun *et al.* (2021) found that renewable energy consumption is a significant driver of environmental sustainability. Sun *et al.* (2022) provided evidence that renewable energy is an essential component to overcome environmental issues and maintain sustainable development in the 10-most polluted countries. Hussain *et al.* (2022), verified the potential of renewables in the reduction of emissions in E-7 countries. Recently, from selected 18 Latin American and Caribbean countries, Wolde-Rufael and Mulat-Weldemeskel (2022) pointed out that renewable energy results in a decrease in environmental pollution.

With respect to the relationship between digitalization and energy, Li *et al.* (2021) posited that an energy structure dominated by coal-fired technologies exerts a detrimental impact on the environment. However, the interaction between energy structure and digitalization can jointly alleviate environmental degradation. Usman *et al.* (2021) suggested that the enhancement of the ICT sector in South Asia holds the potential to improve energy efficiency, although this may lead to an increase in energy

consumption. Shahbaz *et al.* (2022) discovered that the digital economy positively influences the transition to renewable energy and demonstrated that emphasizing the digital economy as an energy transition strategy can potentially foster the growth of renewable energy. In the context of Asian economies, Zhao *et al.* (2022) revealed that the deployment of digital technologies, such as the internet and mobile broadband, drives advancements in energy efficiency, thereby reducing the overall burden on energy usage. Zhang *et al.* (2023) noted that the internal coordination between advanced digital technologies and energy storage is anticipated to significantly expedite the progress of energy sustainability and the development of cross-regional energy systems.

2.2.4 Financial Development, Digitalization, and Environment

Many works have been performed to find out the environmental effects of financial development, and they have reached varied conclusions. For example, Shahbaz *et al.* (2018) investigated the financial development-environment link for France during 1955–2016. Their results showed that financial development is a mitigating factor for emissions. Similarly, Park *et al.* (2018) discovered that from 2001 to 2014, financial development reduced environmental degradation in selected European Union (EU) countries. In the case of Nigeria, Rafindadi (2016) reported the beneficial effect of financial development on carbon emissions. In a sample of top 10 pollutant footprint countries, Caglar *et al.* (2021) emphasized the positive influence of financial development on environmental quality. Similarly, Shobande and Ogbeifun (2021) documented the mitigating impact of financial development on the environment within the context of 24 selected OECD countries. In contrast, Cao *et al.* (2022) underscored the environmental degradation resulting from financial development in a study of 36 OECD countries. In the same line, Khan *et al.* (2022) proved the harmful impact of

financial development on environmental quality by using panel data for OECD countries. Further, in a sample of BRICS countries, Rout *et al.* (2021) reported an insignificant effect of financial development on the ecological footprint. The recent study of Huang *et al.* (2022) indicated that financial development increases environmental pollution in G-7 countries while it has an insignificant effect on the ecological footprint in E-7 countries.

Within the nexus of financial development and digitalization, Alshubiri *et al.* (2019) employed fixed broadband and internet users as proxies for ICT, concluding that a positive relationship exists between ICT and financial development. The authors further asserted that the utilization of IT technology, specifically the internet, leads to enhanced data processing and a subsequent increase in productivity for companies. Marzk and Lechman (2021) posited that the widespread adoption of the internet and the digital revolution can lay a robust foundation for the expansion of financial markets and the introduction of innovative financial instruments that rely on ICT for trading in European countries. Feng *et al.* (2022) documented that digital financial development exerts an inhibitory effect on the ecological footprint, with this impact being more pronounced in regions possessing developed network systems.

2.2.5 Literature Gaps

Following a review of the literature, preceding studies have mostly focused on determining the direct effects of digitalization on the environment using a single indicator for digitalization, i.e., the internet user. However, there are multidimensional mechanisms involved in the digitalization process. The utilization of digital technologies has the potential to improve environmental sustainability in collaboration with the promotion of green innovation, the enhancement of energy efficiency, and the

development of more effective financial systems. So far, the potential moderating role of these factors in the digitalization-ecological footprint relationship has not been explored. In addition, there is a scarcity of research on this topic for OECD countries; therefore, discussing this could be beneficial to revising the existing environmental policies in the OECD countries. To address these literature gaps, this study examines the effect of digitalization on environmental sustainability by constructing a composite index from four parameters of digitalization and the possible moderating role of green innovation, renewable energy, and financial development on the digitalization-ecological footprint nexus. The most important contribution made by this study is taking into account how digitalization can help achieve carbon neutrality in conjunction with other important factors.

2.3 Data and Model Specification

2.3.1 Data Description

The purpose of this paper is to investigate the moderating effect of green innovation, renewable energy, and financial development on the relationship between digitalization and ecological footprint. In light of these considerations, a panel dataset is employed for 36 selected OECD countries, excluding Greece and Iceland due to data unavailability, spanning the period from 2000 to 2018. This study utilizes the ecological footprint proposed by Wackernagel and Rees (1997) as a proxy for the level of environmental degradation, rather than relying solely on carbon emissions. Employing emissions levels as an environmental indicator may constrain the overall focus on ecological sustainability by primarily targeting large industrial operations while neglecting various human behaviors that jeopardize ecological sustainability. In contrast, the ecological footprint encompasses the damage inflicted upon a given area's biodiversity by both economic and non-economic human activities (Sharma *et al.*,

2023). These activities are manifested in domains such as natural resource extraction, deforestation, construction, transportation, and urban development. For example, economic activities, including manufacturing and production, which are components of investment, contribute to climate change. This encompasses the use of equipment powered by fossil fuels, leading to the release of carbon emissions that are considered part of the ecological footprint (Udemba, 2020).

Table 1: Variable Information

Variables	Notations	Measurement Units	Sources
Ecological footprint	LnEFP	Global hectares per person (GHA pc)	GFW
Digitalization	DIGI	Index constructed through PCA	-
Green Innovation	GI	Development of environment-related technologies, % all technologies.	OECD
Renewable Energy Consumption	REC	% of total final energy consumption	WDI
Financial Development	FD	Country ranking on the bases of their financial market and institutional depth, access and efficiency.	IMF
GDP per capita	LnGDP	In constant 2015 US\$	WDI
Trade Openness	TR	% of GDP	WDI
Urbanization	URB	% of total population	WDI
Population Density	POP	people per sq. km of land area	WDI
Internet consumers	INT	% of population	WDI
Mobile cellular subscriptions	MCS	per 100 people	WDI
Fixed broadband subscriptions	FBS	per 100 people	WDI
Fixed telephone subscriptions	FTS	per 100 people	WDI

Note: Ln shows the natural logarithm. GFW: Global Footprint Network, WDI: World Development Indicators, IMF: International Monetary Fund.

Digitalization, a composite index that serves as the primary independent variable of central importance, comprises information pertaining to internet users, mobile cellular subscriptions, fixed broadband subscriptions, and fixed telephone subscriptions. The rationale behind the selection of these digitalization indicators lies in the fact that the establishment of digital infrastructures and the associated network connections are

fundamental to the process of digitalizing the economy. There has been consistent growth in both fixed and mobile networks in OECD countries over the past decade. On the one hand, numerous OECD nations have issued strategies in the past three years promoting the deployment of next-generation wireless networks, such as 5G, which are designed to support enhanced mobile broadband. As of June 2020, 5G technologies were available in 22 of the 38 OECD countries, and now they are available in 36, accounting for 17% of mobile broadband subscriptions. Additionally, the proportion of mobile cellular phone subscriptions in mobile broadband increased to nearly 85%, up from 31% between 2009 and 2018. Furthermore, mobile broadband penetration in OECD countries nearly tripled from 32 subscriptions per 100 inhabitants in 2009 to almost 113 subscriptions per 100 inhabitants by 2019 (OECD, 2020). On the other hand, several OECD countries have transitioned to high-capacity fixed networks. In 2019, there was a notable increase in the share of high-speed fiber in all fixed broadband subscriptions across OECD countries, reaching 27%, a significant rise from 12% in 2011. This upward trend fueled the overall surge in broadband subscriptions, with fixed broadband technologies now comprising 36% high-speed fiber (OECD, 2020). Consequently, these developments indicate that the disparities among OECD countries have gradually narrowed in terms of fixed and mobile broadband diffusion.

Green innovation, renewable energy consumption, and the financial development index are the other independent variables for OECD countries. Additionally, gross domestic product (GDP), trade openness, urbanization, and population density are considered as control variables in this study to reduce the risk of variable omission bias. Table 1 presents descriptions of the investigated variables along with their measurements and data sources.

2.3.2 Construction of Digitalization Index

Recently, in literature, there have been many studies that examine the association between information and communications technology (ICT) and environmental sustainability by taking the individual ICT parameters into account. However, in this study, digitalization is constructed as a comprehensive indicator by using four different indicators of ICT that can be listed as internet consumers, mobile cellular subscription, fixed broadband subscription, and fixed telephone subscription. This index is generated by conducting Principal Component Analysis (PCA). In this way, digitalization has general information about all ICT indicators to better examine the association between digitalization and environmental sustainability. PCA estimation results are presented in Table 2 below.

Table 2: PCA Estimation Results

Panel A. Eigenvalues			Proportion	Cumulative
Number	Value	Difference		
1	2.49156	1.43293	0.6229	0.6229
2	1.05863	0.715672	0.2647	0.8875
3	0.342957	0.236101	0.0857	0.9733
4	0.106856	-	0.0267	1.0000
Panel B. Eigenvectors (loadings):				
Variable	PC1	PC2	PC3	PC4
INT	0.6023	0.0892	-0.2955	-0.7362
MCS	0.5252	-0.3032	0.7916	0.0752
FBS	0.5954	0.0435	-0.4419	0.6696
FTS	0.0840	0.9477	0.3014	0.0626
Panel C. Correlations:				
	INT	MCS	FBS	FTS
INT	1.0000			
MCS	0.6733	1.0000		
FBS	0.8896	0.6505	1.0000	
FTS	0.1801	-0.1120	0.1270	1.0000

Source: Authors' computation

Panel A of Table 2 contains the eigenvalues of all components, where the maximum eigenvalue 2.4915 of the first eigenvalue, 1.0586 of the second factor value, 0.3429

and 0.1068 are the third factor value and the minimum eigenvalue, respectively. Also, the proportion variations of the first factor (62.29%), second factor (26.47%), third factor (8.57%) and fourth factor (2.67%) are presented in Panel A. Moreover, Panel B presents the factor loadings of all four principal components (PC1, PC2, PC3, and PC4). Digitalization is constructed with the help of first principal component (PC1) factor loadings since it covers more information than other principal components and does not contain negative values compared with other components. Lastly, Panel C represents the correlation matrix of all four sampled parameters.

2.3.3 Empirical Models

In accordance with the previous studies (Asongu *et al.*, 2018; Akinlo and Dada, 2021; Li *et al.*, 2021; Fatima *et al.*, 2021; Zaman *et al.*, 2021), a dynamic panel model estimator, which is a two-step system Generalized Method of Moments (SYS-GMM) developed by Arellano and Bover (1995) and extended by Blundell and Bond (1998), is adopted in this study. The reason why the two-step SYS-GMM method is conducted is based on several reasons. First, this method is the best owing to its highest power to overcome potential endogeneity problems in all the regressors and yields robust estimates as compared to other widely used methods, i.e., regular panel OLS, random and fixed effects models. Second, the SYS-GMM method is more effective because it can be applied to analyze cross-country studies without losing information about the differences between the countries (Blundell and Bond, 1998). Third, the SYS-GMM estimator minimizes the possible dynamic panel bias, measuring errors, and heterogeneity in the data sample, which is a serious concern with the cross-section (Blundell and Bond 1998). Fourth, this estimation is appropriate for panel structures with a large number of cross-section (N) and a small number of time span (T), which is fulfilled by the data of this study, where $N = 36$ and $T = 19$ (Arellano and Bond,

1991; Roodman, 2009). Fifth, the SYS-GMM method can report the real effects of moderating factors because it avoids problems with reverse causality and hence it is a more suitable method in the presence of moderating and instrumental variables (Fatima *et al.*, 2021). Finally, Generalized Method of Moments (GMM) estimators have been extensively utilized in ICT-related research to address the endogeneity problem arising from the absence of appropriate external instruments (Briglauer and Grajek, 2021).

Based on the aforementioned discussion, the baseline System GMM (SYS-GMM) model, which encompasses the roles of digitalization, green innovation, financial development, and renewable energy on the ecological footprint, can be formulated as follows:

$$\begin{aligned} LnEFP_{it} = & \alpha_0 + \alpha_1 LnEFP_{it-1} + \alpha_2 DIGI_{it} + \alpha_3 GI_{it} + \alpha_4 REC_{it} + \alpha_5 FD_{it} + \\ & \alpha_6 X_{it} + a_t + \varepsilon_{it} \end{aligned} \quad (2.1)$$

where α_0 is the intercept; $LnEFP_{it-1}$ represents the lagged value of the ecological footprint for country i in period t and evaluates the effect of the past ecological footprint on that in the given period. Moreover, to address the potential unit root problem, the natural logarithm of the dependent variable and the lagged dependent variable were employed. The ecological footprint only exhibited values greater than zero, and its distribution exhibited positive skewness and contained outlier values. The term X_{it} represents control variables, including GDP, population density, trade openness, and urbanization. The variable a_t denotes time-varying effects that capture all unobserved macroeconomic disturbances affecting OECD countries concurrently, while ε_{it} signifies an error term.

In the next step, to explore the moderating role of green innovation, renewable energy, and financial development in the digitalization-ecological footprint relationship, the baseline model is augmented by incorporating the moderating terms. The estimation model is set as follows:

$$\begin{aligned} LnEFP_{it} = & \alpha_0 + \alpha_1 LnEFP_{it-1} + \alpha_2 DIGI_{it} + \alpha_3 GI_{it} + \alpha_4 REC_{it} + \alpha_5 FD_{it} + \\ & \alpha_6 (DIGI_{it} \cdot GI_{it}) + \alpha_7 (DIGI_{it} \cdot REC_{it}) + \alpha_8 (DIGI_{it} \cdot FD_{it}) + \alpha_9 X_{it} + a_t + \varepsilon_{it} \end{aligned} \quad (2.2)$$

Where $DIGI_{it} \cdot GI_{it}$ donates the interaction term of digitalization and green innovation. In fact, digitalization is characterized by innovative practices that facilitate the expansion of green technology innovation. Urban areas implement enhancements to their current network infrastructure, which has implications for the development of telecommunications infrastructure. Furthermore, the collaboration of digital technologies and green innovation can improve production efficiency by altering the traditional production pattern through network spillover effects. This, in turn, may accelerate the distribution and the in-depth development of environmentally friendly technologies, impeding environmental degradation (Moyer and Hughes, 2012).

The interaction term of digitalization and renewable energy, denoted as $DIGI_{it} \cdot REC_{it}$, refers to the critical role of digital technology in realizing a zero-carbon economy. To achieve this goal, the energy structure must change to include all forms of renewable energy, necessitating digital technology to provide real-time balancing of intermittent energy. This can be accomplished by combining data, computing power, and developed networks. For instance, the variability in renewable energy generation technologies such as solar and wind requires the acquisition, processing, and transmission of large quantities of information at high speeds. In this context, the utilization of next-generation networks can potentially enhance the efficiency of

information-processing activities. Overall, the collaboration between digital technologies and the energy sector may help to lower clean energy costs, improve energy efficiency, and thus accelerate climate change mitigation (Wang *et al.*, 2022b; Wang *et al.*, 2023).

The interaction between digitalization and financial development, denoted as $DIGI_{it} \cdot FD_{it}$, indicates the potential benefits of integrating digital technologies and finance. This integration can broaden financing channels and amplify the scale of capital, thereby preventing external financing restrictions, enhancing capital allocation efficiency, and easing capital constraints. As a result, businesses may be encouraged to adopt investment-oriented and eco-friendly innovative practices. Additionally, the digitalization of financial development has the potential to efficiently direct the flow of funds and reduce transaction costs through network spillover, thereby exerting a profoundly positive impact on enhancing environmental quality (Feng *et al.*, 2022). Consequently, green innovation, renewable energy, and financial development are incorporated as essential interactions in the analysis. All other variables remain as defined earlier.

The difference generalized method of moments (DIFF-GMM) estimator, proposed by Arellano and Bond (1991), is employed for robustness checks. Both SYS-GMM and DIFF-GMM estimators have their respective advantages and disadvantages. The DIFF-GMM estimator makes use of appropriate lags of endogenous and exogenous regressors as instruments, while the SYS-GMM estimator utilizes supplementary instruments (Arellano and Bond, 1991; Arellano and Bover, 1995). The SYS-GMM estimator provides accurate parameter estimates in cases where the series are close to

random walks, whereas the DIFF-GMM estimator is prone to large finite sample biases in such situations. Furthermore, Arellano and Bover (1995) and Blundell and Bond (1998) demonstrate through Monte Carlo analysis that their SYS-GMM estimator, which employs a system of levels and first-differenced equations, exhibits a lower bias than the DIFF-GMM estimator for finite samples (Roodman, 2009; Briglauer *et al.*, 2012). In addition, the DIFF-GMM estimator displays a downward bias akin to that of the within-group estimator in cases where the instruments used are of poor quality (Blundell and Bond, 1998; Hoeffler, 2002). Due to these reasons, the SYS-GMM estimator is preferred as a baseline estimator.

To ensure the consistency of SYS-GMM and DIFF-GMM estimators, post-estimation tests such as Hansen or Sargan over-identifying restrictions tests are typically employed to verify the joint validity and appropriateness of the instrument variables utilized. To improve the reliability of the empirical results, in this study, the Hansen test is further performed since the Sargan test is not robust to handling heteroscedasticity problems (Bond *et al.*, 2001; Roodman, 2009). Moreover, the AR (2) test suggested by Arellano and Bond (1991) and Arellano and Bover (1995) is applied to check the presence of second-order serial correlation between the lagged dependent variable and the error term.

2.4 Empirical Results

2.4.1 Descriptive Statistics

Table 3, Panel A, presents the descriptive statistics of the investigated variables. During the sample period, the highest mean value is observed for the population density (POP) variable, with a value of 135.516, while the digitalization variable exhibits the lowest mean value of 0. The mean values of other variables, namely

ecological footprint, green innovation, renewable energy, financial development, logarithm of GDP, trade openness, and urbanization (URB), lie between these two extremes. Furthermore, the maximum value of POP is recorded at 528.96, while the maximum value of DIGI is 1.47. To examine the volatility level of the investigated variables and address potential econometric issues related to spurious results, standard deviations of the variables were calculated. The results indicate that financial development exhibits the lowest volatility, while population density has the highest volatility compared to the other variables. Nevertheless, based on the information obtained from the data, these values do not pose significant problems for our econometric estimations. The correlation matrix of the analyzed variables, displayed in Panel B of Table 3, reveals that all variables exhibit a positive correlation with the comprehensive indicator of environmental deterioration, with the exception of GI and POP.

Table 3: Descriptive Statistics and Correlation Coefficient Estimates.

Panel A. Descriptive Statistics									
	LnEFP	DIGI	GI	REC	FD	LnGDP	TR	URB	POP
Mean	0.67	0	10.40	17.9	0.60	11.56	93.15	75.84	135.51
Std. Dev.	0.31	1	4.37	13.62	0.21	0.66	53.97	10.97	131.07
Min	-1.08	-2.49	0	0.69	0.16	10.14	19.56	50.75	2.47
Max	1.24	1.47	33.53	61.11	1	13.29	360.13	98	528.96
Obs	684	684	684	684	684	684	684	684	684
VIF	-	2.11	1.22	2.01	3.49	3.34	1.92	1.46	1.77
1/VIF	-	0.4	0.82	0.49	0.18	0.18	0.520	0.685	0.56
Panel B. Correlation Matrix									
LnEFP	1.000								
DIGI	0.131	1.000							
GI	-0.016	0.298	1.000						
REC	0.086	0.148	0.186	1.000					
FD	0.134	0.453	-0.052	-0.257	1.000				
LnGDP	0.417	0.613	-0.018	-0.047	0.794	1.000			
TR	0.235	0.217	0.055	-0.139	-0.162	0.199	1.000		

URB	0.083	0.325	0.092	-0.061	0.481	0.410	-0.135	1.000	
POP	-0.362	0.165	-0.090	-0.564	0.336	0.212	0.133	0.312	1.000

Note: (1) Std. Dev: Standard deviation, Min: Minimum, Max: Maximum, Obs: Observation. (2) Mean VIF: 2.67.

In addition, to check for potential multicollinearity problems between regressors, which can cause biased estimations, the variance inflation factor test (VIF) was employed. As illustrated in the lower part of Panel A, the VIF values are less than 10. This implies that the data series is free of multicollinearity problems.

2.4.2 Empirical Results and Discussion

This study employs the dynamic panel GMM method proposed by Arellano and Bover (1995). The empirical findings of the two-step SYS-GMM method for all four models are displayed in Table 4. Based on the obtained results, the parameter of the lagged ecological footprint is positive and statistically significant across all models, with values ranging from 0.354 in Model 2 to 0.872 in Model 1. This finding confirms the dynamic nature of the models and the positive persistence exhibited in the ecological footprint.

Table 4: The Result of two step SYS-GMM

Variables	Dependent Variable: LnEFP				
	Model 1	Model 2	Model 3	Model 4	Model 5
LnEFP(t-1)	0.772***	0.354***	0.678***	0.739***	0.615***
DIGI	-0.053**	0.318**	0.354***	-0.018**	-0.837***
GI	-0.025***	-0.033**	-0.046*	-0.006*	-0.025
REC	-0.007*	-0.034**	-0.066***	-0.019***	-0.030
FD	-0.742***	-2.792*	-5.367***	-0.842*	-4.560*
DIGI·GI	-	-0.065**	-	-	-0.064**
DIGI·REC	-	-	-0.071***	-	-0.062***
DIGI·FD	-	-	-	-0.145**	-0.286*
LnGDP	0.928***	4.847***	3.680*	1.591***	5.188**
TR	0.002***	0.006*	0.004	0.004**	0.002
URB	0.007**	0.035***	0.101*	0.020	0.065**
POP	-0.001***	-0.006***	-0.011***	-0.003***	-0.005***
Constant	-3.177***	-7.548***	-5.104***	-6.125***	-1.366***
Country effects	No	No	No	No	No

Year effects	Yes	Yes	Yes	Yes	Yes
# Instruments	31	32	33	31	32
# Groups	36	36	36	36	36
# Observations	648	640	640	648	648
F test	8472.29***	3179.57***	7228.14***	1573.6***	9264.87***
Hansen test					
<i>p</i> -value	0.118	0.396	0.322	0.109	0.298
AR(1) <i>p</i> -value	0.005	0.001	0.005	0.007	0.001
AR(2) <i>p</i> -value	0.106	0.145	0.160	0.126	0.101

Note: (1) “(–1)” indicates the lag of the dependent variable. (2) ***, ** and * denotes 1%, 5% and 10% levels of significance, respectively. (3) In all regressions, year effects were incorporated, while country effects were excluded due to very high collinearity with the Hausman-type instrumental variables.

For Model 1, the coefficient of digitalization is negative and statistically significant. Specifically, a one unit increase in digitalization will lead to a decline in ecological footprint by 0.053% during the study period. Digital transformation in all types of communications, interactions, technologies, economics, and business structures changes production and consumption patterns in a more environmentally sustainable way. Digitalization can increase the efficiency of production through machine learning and automation systems and reduce the waste of resources. Digitalization in this regard can be seen a powerful tool for reducing ecological footprint through dematerialization, decarbonization, and demobilization effects. This finding can be strengthened with the argument that digital activities such as e-commerce, e-banking, e-shopping, virtual meetings, and e-books can reduce material consumption and energy usage, further alleviating environmental pollution. Correspondingly, digitalization is also associated with waste management systems. Implementation of digitalization in waste management systems shows a strong development in OECD countries since 2000, and it provides great opportunities for favorable environmental impacts. Under the above arguments, this negative digitalization-environment association is consistent with the earlier findings of Li (2021), Caglar *et al.* (2021), Chen (2022), Ha *et al.* (2022) and Ma *et al.* (2022).

Moving towards the impact of green innovation on ecological footprint, the results show that a one unit increase in green innovation leads to a 0.025% reduction in ecological footprint in the long run. This result supports the fact that green innovation is an effective policy tool to minimize the negative impacts of consumption and manufacturing activities on the environment by promoting the conversion of conventional technologies into greener, energy-efficient, and cost-effective technologies. Thus, it is undoubtedly important for OECD countries to spread green innovation, which supports firms' improvement from the point of technological advancement in their production process and, accordingly, resource consumption. In this way, green innovation positively influences environmental performance by developing technologies that rely on clean energy sources. This finding is steady with the empirical contributions of Hashmi and Alam (2019), and Ahmad and Wu (2022) for OECD countries.

The empirical results further show that renewable energy consumption contributes to a reduction in ecological footprint. Given its parameter estimates, a one unit increase in the level of renewable energy consumption reduces the ecological footprint by 0.007%. In the light of this result, renewable energy is a mitigating factor of ecological footprint and renewable energy sources have integral role in transition towards clean environment by contributing to the decarbonization effect which improves environmental performance. Therefore, energy policies in OECD countries should be focused on the augmentation of renewables in their energy mix to sustainably have better environmental conditions. The negative association of renewable energy consumption with ecological footprint is in line with the empirical findings of Sharma *et al.* (2021) for Asian countries, Huang *et al.* (2022) for G7 and E7 countries, Suki *et al.* (2022) for Malaysia.

Moreover, the results also reveal a statistically significant negative effect of financial development on the ecological footprint. Precisely, a rise in the level of financial development by one unit tends to decline the ecological footprint by 0.742%. Financial development can be viewed as a positive indicator of environmental footprint reduction. The inverse nexus between financial development and ecological footprint in OECD countries might be due to financial development providing capital assistance for energy-saving technologies, which helps to reduce emissions by lowering the energy intensity or increasing energy efficiency. The present result aligns with the findings of Shobande and Ogbeifun (2021); however, it contradicts the outcomes reported by Cao *et al.* (2022).

The impact of control variables on the ecological footprint is found to be statistically significant. Ensuring the preservation of ecosystems for future generations hinges upon increasing biocapacity. Nevertheless, empirical evidence suggests that the expansion of ecological reserves results in heightened resource exploitation and a correspondingly larger ecological impact. This is corroborated by the escalating influence of GDP, trade, and urbanization on the ecological footprint. Conversely, population density exerts a negative impact on the ecological footprint. Higher population density fosters economies of scale, which in turn promotes technological progress and resource efficiency in public services and businesses, ultimately reducing environmental degradation.

For Model 2, the results reveal that the estimated coefficient of the interaction term between digitalization and green innovation (DIGI·GI) is statistically significant and negative, implying that digitalization and green innovation jointly work to diminish

the ecological footprint in OECD countries. It advocates that the integration of digitalization and green innovation policies together could be stronger for environmental quality than the individual effect of digitalization. Overall, it is observed that the moderating effect of green innovation shows a favorable impact on the digitalization-ecological footprint nexus; in other words, green innovation strengthens the mitigating impact of digitalization on environmental degradation. This empirical result coincides with the study of Ma *et al.* (2022).

Furthermore, in model 3, the estimated coefficient of the interaction term between digitalization and renewable energy consumption (DIGI·REC) is negative. The empirical results suggest that digitalization together with renewable energy has the important potential to lessen ecological footprint. Also, it is important to note that renewable energy strengthens the negative effect of digitalization on the ecological footprint. Considering this finding, digitalization of power systems leads to improve the technical performance and efficiency of energy generation, reduce the cost of renewables and it plays an essential role for decarbonization. Therefore, the interaction of digitalization and renewable energy (DIGI·REC) serves as a potential driver for environmental sustainability.

As for Model 4, the empirical results indicate that the estimated coefficient of the interaction term (DIGI·FD) between digitalization and financial development is negative and statistically significant, indicating that digitalization and financial development jointly work to reduce the ecological footprint. It can be stated that the interaction of digitalization, combined with financial development, leads to a higher mitigating effect of digitalization on the ecological footprint. This can be explained by

the fact that digital-based projects created by modern firms to promote a cleaner production process can be funded by governments or banks to let companies put into practice their creative projects. Therefore, financial development enhances the mitigation role of digitalization on the environment for OECD countries.

Finally, all the interaction terms are included in Model 5, and the estimated coefficients of DIGI·GI, DIGI·REC and DIGI·FD are statistically significant and negative. Therefore, the obtained results are consistent with the ones revealed in Models 2–4 of Table 4.

The diagnostic test results for all models are shown in the lower part of Table 4. The result of the Hansen test of over-identifying restriction verifies the overall validity of the selected instruments in all the models. Likewise, the Arellano and Bond test for serial correlation (AR(2)) indicates the insignificant p -values of AR(2) and concludes the absence of second-order autocorrelation in each model. Given that the number of instruments is less than the sample size, the two-step GMM method constitutes a valid instrument. Consequently, taking into account the results of specification tests, the two-step SYS-GMM estimator most accurately represents the empirical findings.

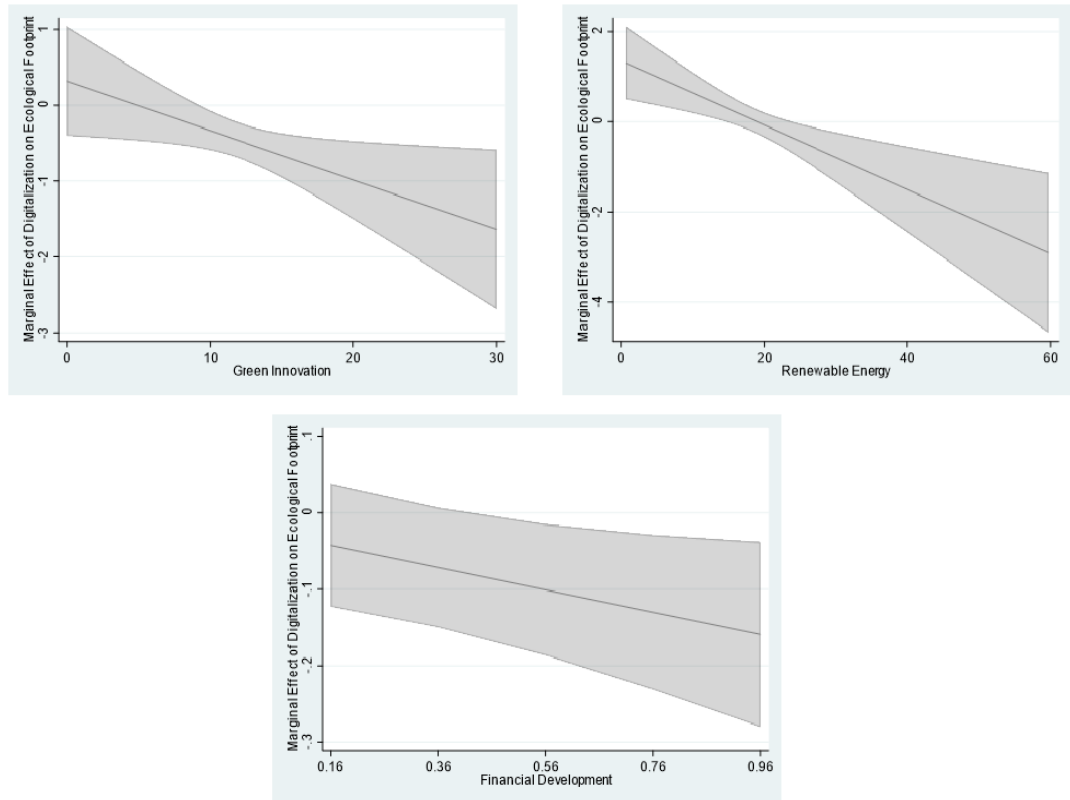


Figure 1: Average Marginal Effects of Digitalization

Figure 1 illustrates the marginal effects of digitalization on the ecological footprint, with varying values for moderating variables. As depicted in Figure 1, the marginal effect of digitalization gradually decreases as green innovation increases. This suggests that the greater the degree of green innovation, the more pronounced the mitigating impact of digitalization on the ecological footprint. The results presented in Tables 4 indicate that digitalization has a mitigating effect on the ecological footprint. Notably, the effect of digitalization is amplified as renewable energy consumption increases. Lastly, the financial development indicator exhibits a similar relationship.

2.4.3 Robustness Analysis

To assess the robustness of findings derived from the two-step SYS-GMM model, the two-step difference GMM (DIFF-GMM) estimator is employed. The empirical results from the robustness analysis, encompassing four models, are presented in Table 5. The

parameter of the lagged ecological footprint is positive and statistically significant across all models, with values ranging from 0.186 in Model 2 to 0.432 in Model 5. This observation confirms the dynamic nature of the models.

As demonstrated in the regression results, digitalization, green innovation, renewable energy consumption, and financial development exhibit negative and significant effects on the ecological footprint. With regard to control variables, the impacts of GDP and population density on the ecological footprint are statistically significant, whereas those of trade and urbanization are not. In addition, the findings regarding all the interaction variables (DIGI·GI, DIGI·REC and DIGI·FD) are consistent with the findings established in Table 4. Consequently, it is concluded that the estimation results of the robust check conducted in this study have yielded consistent and stable with those of the two-step SYS-GMM results.

Table 5: The Result of the two step Difference GMM

Variables	Dependent Variable: LnEFP				
	Model 1	Model 2	Model 3	Model 4	Model 5
LnEFP(t-1)	0.426***	0.186**	0.199***	0.382**	0.432**
DIGI	-0.075*	-0.867***	-0.857**	-0.755***	-0.836***
GI	-0.055***	-0.086***	-0.073***	-0.098***	-0.018***
REC	-0.041**	-0.103***	-0.056***	-0.014	-0.078
FD	-0.956*	-0.410	-0.247	-0.901***	-0.650
DIGI·GI	-	-0.078***	-	-	-0.140***
DIGI·REC	-	-	-0.086***	-	-0.082**
DIGI·FD	-	-	-	-0.373*	-0.470**
LnGDP	3.448***	2.970**	0.533***	1.078	3.403
TR	0.002	0.000	0.007	0.011**	0.038***
URB	0.028	0.113	0.099	0.092	0.029
POP	-0.014***	-0.030***	-0.044***	-0.012***	-0.054***
Country effects	No	No	No	No	No
Year effects	Yes	Yes	Yes	Yes	Yes
# Instruments	31	33	32	32	31
# Groups	36	36	36	36	36
# Observations	612	612	612	612	612

Hansen test					
<i>p</i> -value	0.171	0.122	0.250	0.135	0.233
AR(1) <i>p</i> -value	0.004	0.005	0.015	0.002	0.001
AR(2) <i>p</i> -value	0.112	0.164	0.143	0.111	0.260

Note: (1) “(−1)” indicates the lag of the dependent variable. (2) ***, ** and * denotes 1%, 5% and 10% levels of significance, respectively. (3) In all regressions, year effects were incorporated, while country effects were excluded due to very high collinearity with the Hausman-type instrumental variables.

2.5 Conclusion and Policy Recommendation

This study aims to examine the externality effect of digitalization on environmental sustainability within a comprehensive framework, focusing on its interaction with green innovation, renewable energy, and financial development. A digitalization index is created using principal component analysis, serving as a comprehensive independent variable, and encompassing information on internet users, mobile cellular subscriptions, fixed broadband subscriptions, and landline telephone subscriptions. This interaction is assessed in accordance with SDGs 7, 12, and 13, taking into account the use-effect, rebound-effect, and substitution-effect of digitalization. To this end, panel data from 36 selected OECD countries, excluding Greece and Iceland, spanning the period 2000-2018, are utilized. The ecological footprint is employed as a comprehensive proxy for the level of environmental degradation and serves as the regressand in five distinct models.

The outcomes show that digitalization, green innovation, consumption of renewable energy, and financial development exhibit negative impacts on environmental degradation. Furthermore, economic performance, trade, and urbanization demonstrate a significant and positive relationship with environmental sustainability, while population density exhibits a negative relationship. Specifically, digitalization enhances production efficiency through machine learning and automation systems, thereby reducing resource waste. Owing to its substitution effects, including

dematerialization, decarbonization, and demobilization, increased digitalization aids in mitigating environmental deterioration and sustaining environmental quality. Moreover, green innovation contributes to the environmental sustainability of OECD nations and their manufacturing activities by promoting the transformation of conventional technologies into greener, more energy-efficient, and cost-effective alternatives. Undoubtedly, fostering green innovation in economic activities is crucial for OECD countries to minimize resource waste. Furthermore, green innovation enhances the mitigating effect of digitalization on environmental degradation. Renewable energy also strengthens the environmentally sustainable impact of digitalization. In summary, the rebound impact of digitalization has been diminishing for OECD countries over time, as digitalization and its interaction with other factors exhibit footprint-mitigating effects.

In light of the findings of the study, several policy recommendations can be proposed. First, it is essential for OECD nations to integrate green innovation policies within their digitalization strategies. This necessitates fostering innovation by increasing investments in environmentally friendly technologies to restructure production patterns. Green innovation can thus gradually decrease dependence on fossil fuels while augmenting the use of renewable energy sources. These innovative solutions can be applied across all economic sectors, promoting sustainable development and contributing to the OECD's climate goals. By supporting digitalization with green innovation, the combined impact on climate change mitigation can be enhanced. To optimize the environmental benefits of digitalization, OECD nations must implement green technologies and expedite the energy transition by utilizing ICT applications.

Second, governments should monitor digital trends and assist energy companies in incorporating digital technologies within their energy systems. The adoption of digital tools in energy systems will facilitate the development of advanced technologies, such as energy storage systems and intelligent grids, in clean energy industries. Consequently, the collaboration between digital technologies and clean power-generation technologies can improve energy efficiency, reduce renewable energy costs, and encourage green production and consumption. However, these digitalization-enabled gains in energy efficiency may lead to increased energy consumption, thereby offsetting the resources and energy conserved. This heightened energy consumption due to the rebound effect can be attributed to the energy consumption inherent in the manufacturing, installation, utilization, and disposal of ICT tools, as well as the expansion of production scales in digitalization. While digitalization contributes to energy savings and enhanced efficiency, it is crucial to mitigate potential uncertainties and risks associated with the energy rebound effect that may arise from the emergence of new digital industries. By relying more on variable renewables such as wind and solar energy, digitalization can prevent further emissions and disentangle the rebound effect.

Third, financial institutions should broadly implement digital technologies in all areas of financial product development, risk management, and other related domains. The digitalization of the financial sector increases the carrying capacity of businesses and individuals, facilitating access to financial services such as banking. Moreover, digital technologies contribute to improved efficiency in financial transactions. The growing deployment of ICT, particularly in broadband networks that offer rapid and high-capacity internet connectivity, can serve as a robust foundation for the emergence and

advancement of innovative financial instruments that are technology-dependent. To ensure that the digital economy promotes sustainable development, it is also vital to encourage the use of digital infrastructure in public sector services. In summary, OECD nations must consistently regard the development of the digital economy as a critical step toward achieving carbon neutrality.

A potential limitation of the present study lies in its primary focus on the moderating influence of green innovation, renewable energy, and financial development. It is important to acknowledge that there may be additional social, economic, and environmental factors influencing the environmental effectiveness of digitalization that have not been explored in this investigation. Consequently, future research could benefit from considering other potential moderators, such as trade, globalization, environmental taxation, and institutional quality.

Chapter 3

FOSSIL FUEL DISPLACEMENT BY RENEWABLES

3.1 Introduction

It is widely known that fossil fuels for energy generation are a major cause of greenhouse gas (GHG) emissions (Greiner *et al.*, 2022). In addition to environmental considerations, the unequal distribution of fossil fuels raises concerns (Martins *et al.*, 2019). As a result, the continuous rise in GHG emissions due to global energy generation underscores the critical importance of implementing necessary actions for climate change mitigation. In this context, all UN Member States adopted the 17 Sustainable Development Goals (SDGs). Notably, SDG-7 (Affordable and Clean Energy) and SDG-13 (Urgent Action to Combat Climate Change) have attracted significant attention in response to climate change caused by pollutant emissions. Furthermore, the 2021 COP26 United Nations Climate Change Conference reached a consensus on environmental objectives, which included achieving net-zero emissions by mid-century, mobilizing financing to promote clean energy adoption, and protecting natural resources (COP26, 2021; Arora and Mishra, 2021). In this regard, integrating renewable energy (RE) sources into the energy system constitutes one of the most vital components of de-carbonization strategies (Soini *et al.*, 2020).

Recently, substantial advancements in RE sources have been observed, indicating that the process of transitioning to renewables is well underway worldwide. On one hand, there has been a significant shift in the competitive equilibrium between renewables

and fossil fuels from 2010 to 2021. The growth in RE capacities has resulted in a considerable reduction in costs associated with generating energy using RE technologies (IRENA, 2018). Since Q4 2021, fossil fuel costs have risen at a faster pace than RE costs, allowing renewables to sustain their competitive advantage (IRENA, 2022a). Consequently, RE sources have become the primary low-cost option for power generation amid the present fossil fuel crisis.

On the other hand, renewables have achieved remarkable progress in the power sector, with capacity additions reaching new highs. Over the past decade, RE capacity increased by 130%, while that of fossil fuels increased by only 24%. Moreover, global RE generation capacity has expanded nearly fourfold from 754 GW to 3064 GW between 2000 and 2021 (IRENA, 2022b). In 2021, RE sources accounted for 81% of the total power generation capacity. Solar photovoltaic (PV) installations have experienced the most rapid growth among RE sources, demonstrating a 21-fold increase from 2010 to 2021. Wind power has also shown significant growth within the same time frame as solar power, with installations increasing more than fourfold. Additionally, other forms of RE sources, such as geothermal and bioenergy, have witnessed a considerable increase over the past decade, albeit on a small scale (IRENA, 2022a; IRENA, 2022b). In summary, RE sources are progressively displacing conventional energy sources on a global scale.

Despite the notable progress achieved by renewables globally, fossil fuels continue to hold a prominent position in the energy sector of OECD countries. These nations contribute roughly 35% of global energy-related carbon emissions and produce twice the CO₂ emissions per capita (8.9 tons) compared to the global average (4.3 tons) (IEA,

2022). Given these data, addressing environmental issues, and transitioning to renewables have emerged as primary development strategies for OECD countries to maximize the advantages of renewable technologies.

Consequently, a majority of OECD nations have implemented environmental measures aimed at significantly increasing the share of RE within their energy mix. For instance, Japan has augmented its utilization of renewables and established a target of deriving 36-38% of its energy generation from renewables to attain carbon neutrality by 2050. Moreover, as of 2016, Japan had become the second-largest solar energy producer among OECD countries (IEA, 2020). In Australia, the proportion of renewables in total energy generation reached approximately 23.5% in 2021, as the country strives to sustain this progress until 2030. In Denmark, the annual share of RE sources exceeded 50% (REN21, 2022). Furthermore, RE generation in OECD Europe surpassed that of fossil fuel generation in both 2020 and 2019. These developments illustrate the rapid expansion of the RE sector across OECD-Europe, particularly in the domains of wind and solar power (IEA, 2020; IRENA, 2022a).

In summation, the present study addresses the following pivotal question: To what degree are RE sources capable of displacing fossil fuels, considering the considerable challenges they present to the decarbonization process within the energy sector of OECD countries? While existing energy literature has examined the environmental impact of RE sources or fossil fuels, the topic of energy displacement remains relatively unexplored, warranting further investigation. As such, the current study employs the system Generalized Methods of Moments (SYS-GMM) on panel data from 36 OECD countries spanning from 2000 to 2020 to provide an empirical answer

to the research question by assessing the displacement effect of renewables on fossil fuels. The study sample encompasses countries that accounted for the majority of global RE investment during the analyzed period. By offering robust evidence regarding the critical role renewables play in achieving climate change goals, this research will aid decision makers in refining environmental policies.

The remainder of this study is as follows: Section 2 offers a summary of the relevant literature. Section 3 outlines the variables and the model employed in this study, followed by a presentation of the empirical results in Section 4. Finally, Section 5 concludes the study and delineates potential policy implications.

3.2 Related Literature

The transition towards clean energy sources promises considerable benefits by diminishing the adverse ecological impacts associated with fossil fuels. To effectively address the climate crisis, RE sources must act as a substitute for fossil fuels, rather than merely facilitating a continuous expansion of energy consumption. Consequently, the first strand of the literature concentrates on the interplay between RE sources and fossil fuels.

For instance, Awerbuch and Sauter (2006) emphasized that RE investments displace fossil fuels in the United States (US) and Europe, thereby mitigating economic losses resulting from the oil-GDP effect. Marques and Fuinhas (2011) explored the factors driving RE utilization in 24 selected European countries between 1990 and 2006; their research indicated that conventional energy sources hinder the deployment of RE. Narbel (2013), utilizing panel data on electricity generation in 107 countries, asserted that fossil fuel sources impede the diffusion of renewable technology. Pfeiffer and

Mulder (2013) revealed that the abundance of fossil fuels and escalating energy consumption appear to negatively impact the quantity of non-hydro RE, concluding that non-hydro RE and fossil fuels are predominantly perceived as substitutes in numerous emerging economies. Assessing a sample of 38 countries, Aguirre and Ibikunle (2014) investigated the determinants of RE growth; their empirical findings indicated a negative correlation between RE growth and the contribution of fossil fuels to electricity production. Prehoda and Pearce (2017) emphasized that replacing coal power plants with solar power in the US yields significant environmental benefits and a clear path towards a more sustainable environment. Analogously, in the context of Portugal, Figueiredo *et al.* (2019) reported that the coal power plant phase-out results in a fivefold rise in energy imports, underscoring the critical role of renewable power capacity integration into the energy system. In this case, coal power plants could be supplanted by solar photovoltaics. In contrast, Verdolini *et al.* (2018) identified a complementary link between fossil fuels and RE technologies in 26 OECD countries. Greiner *et al.* (2022) discovered that increasing RE production effectively curtails nuclear energy production; however, renewables tend to replace fossil fuels only modestly.

The second strand of literature emphasizes the technological advancements that hold promising potential for expanding RE capacities. Popp *et al.* (2011) found that knowledge stocks exerted a small yet beneficial effect on RE capacity investments across 26 OECD countries. Verdolini and Galeotti (2011) demonstrated that augmented demand for RE technologies is positively associated with elevated levels of innovative activity. Hille and Oelker (2023) documented that innovation activity, which has contributed to significant improvements in cost efficiency, is crucial for the

sustainable success of RE. Their study's findings suggest that technological differences, particularly innovation, appear to exert a more significant influence on the development of solar capacities in comparison to wind capacities.

Conversely, within innovation research, patents are regarded as a reliable and statistically robust proxy for technological advancements and encompass an extensive body of technical knowledge (Griliches, 1990; Zheng *et al.*, 2021). In this context, Wurlod and Noailly (2018) underscored that green patenting activities are inversely related to energy intensity in OECD countries. Alexiou (2023) contended that implementing patent systems could potentially stimulate research and development efforts in the domain of RE, leading to considerable progress in advancing RE technologies. As a result, beneficial spillover effects may arise from the enhanced efficiency and cost-effectiveness of these technologies, subsequently augmenting their competitive edge relative to fossil fuel energy sources. Yang *et al.* (2022) observed that countries possessing greater green innovation capacity tend to exhibit higher efficacy in enacting renewable policies. Xin *et al.* (2023) concluded that innovation in RE promotes low-carbon development in China.

3.3 Data and Model Specification

The emphasis of this work lies in examining the displacement effect of RE sources on fossil fuels. To achieve this objective, a panel dataset encompassing 36 OECD countries, with the exclusion of Iceland and Costa Rica due to data unavailability, is utilized for the period between 2000 and 2020. Drawing on the displacement model proposed by York (2012), a displacement coefficient of renewables at -1 indicates a one-to-one basis displacement, whereby each unit of RE generated corresponds to one fewer unit of energy generated by fossil fuels. A displacement coefficient ranging

between -1 and 0 represents partial displacement. Conversely, a displacement coefficient of 0 denotes that the increase in RE exerts no displacement effect on fossil fuels.

In this regard, the dependent variable is the share of installed fossil fuel capacity ($ShareCap^{FF}$), and the main explanatory variable is the share of installed RE capacity ($ShareCap^{RE}$). As in Verdolini *et al.* (2016), the installed capacity of fossil fuel energy and RE capacity is obtained by dividing the net installed capacity by the total capacity in the country i , time t . Total capacity is used as a rescaling variable to determine the share of RE sources. Installed RE capacity and installed fossil fuel energy capacity data are obtained from the U.S. International Energy Agency (IEA). The other explanatory variable is technological innovation (TI). This variable is measured using the data on patent counts in clean energy technologies, which are (i) electrical machinery, apparatus, and energy; (ii) environmental technology; and (iii) engines, pumps, and turbines. Patents possess the benefit of serving as a reliable indicator of innovative endeavors and exhibit a strong correlation with numerous alternative metrics of innovation. Technological innovation is a crucial element that directly contributes to the expansion of RE capacities. This is expected to accelerate the displacement of fossil fuels by renewables. The data for TI comes from the WIPO statistics.

Additionally, gross domestic product (GDP) is included to capture overall economic performance. This data is obtained from the World Development Indicators. Second, energy consumption (ECONS) is added to measure expectations about future demand and is obtained from IEA. Third, the model takes energy dependence (ENDEP) into

account to determine how heavily a country relies on imports from other countries to meet its energy needs. This variable is defined as net energy imports over energy consumption. Energy dependence is also linked to energy security because a country can improve its energy security by decreasing its reliance on imported energy and increasing its RE generation capacity. Consequently, the general structure of the main empirical model, which is discussed above, is as follows:

$$ShareCap_{it}^{FF} = \alpha_0 + \alpha_1 ShareCap_{it-1}^{FF} + \alpha_2 ShareCap_{it}^{RE} + \alpha_3 TI_{it} + X_{it}\beta' + \varepsilon_{it} \quad (3.1)$$

where $ShareCap_{it}^{FF}$ and $ShareCap_{it}^{RE}$ stand for installed fossil fuel capacity and installed RE capacity, respectively. $DIGI_{it}$ presents technological innovation and X_{it} is the set of control variables including GDP, ECONS and ENDEP with β denoting the vector of coefficients relating to X_{it} . α_2 is the displacement coefficient, and ε_{it} is the error term.

In the main model, the various definitions of RE sources are employed separately for robustness checks. However, specifically variable RE sources, such as solar and wind power, are considered in Equation (2). Even though their output varies depending on meteorological conditions, they are the most promising technologies among RE sources. More importantly, due to the rapid decline in their costs, they have become the primary option for new capacity additions on a global scale, challenging prevalent power systems like fossil fuel technologies. The empirical model can be rewritten as follows:

$$ShareCap_{it}^{FF} = \alpha_0 + \alpha_1 ShareCap_{it-1}^{FF} + \alpha_2 ShareCap_{it}^{VRE} + \alpha_3 TI_{it} + X_{it}\beta' + \varepsilon_{it} \quad (3.2)$$

where $ShareCap_{it}^{VRE}$ denotes the installed variable RE capacity. Other variables remain as defined earlier. The assessment of Equation 2 has been carried out utilizing data from 23 OECD¹ countries, considering the availability of data for variable RE sources across the research period of the study.

In the above empirical models, the system GMM method introduced by Arellano and Bover (1995) and extended by Blundell and Bond (1998) is conducted. Firstly, RE and fossil fuel investments can be affected by unobservable time-varying shocks because these investments are the results of decisions by power producers. Therefore, the GMM method is chosen due to its power to reduce endogeneity and solve reverse causality problems. Second, the flexibility of the SYS-GMM method is particularly advantageous for mitigating bias in estimating the effect of the installed capacity of RE on fossil fuel capacity. Third, the GMM method outperforms other commonly used methods because it does not lose information about country differences (Blundell and Bond, 1998).

3.4 Empirical Results

Table 6 illustrates descriptive statistics for the whole sample in Panel A and for the inclusive sample in Panel B. According to Panel A of Table 6, the installed capacity of fossil fuels surpasses that of RE sources. Specifically, the installed capacity of hydropower and biomass in total accounts for roughly two-thirds of the total installed capacity of RE on average. The installed capacity of RE ranges from 0 up to 95%, and the maximum installed capacity of fossil fuels is about the same as renewables (99%). The installed capacity distribution of RE sources exhibits a greater degree of leftward

¹ The sample includes Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Italy, Japan, Luxembourg, Mexico, Netherlands, Norway, Portugal, Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom, the United States.

skewness in comparison to that of fossil fuel capacity. Descriptive statistics from Panel B of Table 6 show that the mean value of the installed capacity of fossil fuels is 0.476, while the installed capacity of variable renewables exhibits a lower mean, with a value of 0.103. The maximum installed capacity of fossil fuels is higher than the installed capacity of variable renewables.

Table 6: Descriptive Statistics

Panel A. Whole sample (N=36)					
Variables	Observation	Mean	Standard Deviation	Min	Max
ShareCap ^{FF}	756	0.517	0.248	0.004	0.999
ShareCap ^{RE}	756	0.318	0.225	0.001	0.959
ShareCap ^{RE} (excl. hydro)	756	0.115	0.114	0	0.548
ShareCap ^{RE} (excl. hydro, waste, and biomass)	756	0.089	0.101	0	0.469
Additional control variables					
ShareCap ^{HYDRO}	756	0.203	0.226	0	0.95
ShareCap ^{BIOMASS}	756	0.027	0.031	0	0.142
LTI	756	6.134	2.221	0	11.181
LGDP	756	10.202	0.719	8.284	11.63
LECONS	756	6.389	1.43	3.616	10.206
ENDEP	756	0.006	0.029	-0.001	0.153
Panel B. Inclusive sample (N=23)					
ShareCap ^{FF}	483	0.476	0.247	0.004	0.928
ShareCap ^{VRE}	483	0.103	0.111	0.001	0.467
ShareCap ^{SOLAR}	483	0.033	0.053	0	0.235
ShareCap ^{WIND}	483	0.071	0.08	0	0.360
Additional control variables					
LTI	483	6.79	2.026	2.197	11.181
LGDP	483	10.376	0.655	8.712	11.63
LECONS	483	6.751	1.494	3.616	10.206
ENDEP	483	0.008	0.032	-0.074	0.153

Table 7 summarizes the main findings of the system GMM estimates using the above-mentioned Equation (1) variations. Model 1 provides a specification that includes the

installed capacity of RE sources. Model 1 presents that there is a statistically significant and good displacement of fossil-fuel capacity by RE capacity.

Table 7: System GMM Results for whole Sample.

Variables	Dependent variable: $ShareCap^{FF}$		
	Model 1	Model 2	Model 3
$ShareCap^{FF}(-1)$	0.178**	0.192***	0.118*
$ShareCap^{RE}$	-0.693***	-	-
$ShareCap^{RE}$ (excl. hydro)	-	-0.762***	-
$ShareCap^{RE}$ (excl. hydro, waste, and biomass)	-	-	-0.808***
$ShareCap^{HYDRO}$	-	-0.990***	-0.989***
$ShareCap^{BIOMASS}$	-	-	-0.830***
LTI	-0.015***	-0.007***	-0.011***
LGDP	-0.061***	-0.037***	-0.031***
ENDEP	0.637***	0.582***	0.504***
LECONS	0.087***	0.031***	0.015***
CONSTANT	0.629***	0.872***	0.935***
# Observations.	648	684	684
# Instrument	26	22	25
# Groups	35	35	35
F-test	3012.49***	2457.78***	2442.94***
Sargan test p value	0.217	0.168	0.113
AR (1) p value	0.003	0.005	0.008
AR (2) p value	0.173	0.129	0.150

Notes: ***, ** and * denote 1%, 5% and 10% levels of significance, respectively.

Model 2 uses the installed capacity of RE sources excluding hydropower and includes the installed capacity of hydropower in the estimation. As stated by Popp *et al.* (2011), hydropower is a fast-responding dispatchable technology. It is therefore distinct from the other forms of RE technologies in terms of its limitations and characteristics. When excluding hydropower from the definition of RE capacity, the outcomes indicate a significant and slightly higher displacement than in Model 1. In other words, a one-unit increase in non-hydro renewable capacity is related to a 0.76-unit decrease in fossil fuel capacity. On the other hand, the findings further show that hydropower strongly displaces fossil fuels. The displacement coefficient of hydropower is -0.99,

which indicates that a nearly one-to-one displacement of fossil fuel capacity by hydropower has occurred. This might be because hydropower is the largest energy source among renewables by generation and capacity (IEA, 2022a).

Model 3 considers the installed capacity of RE sources excluding hydro, waste, and biomass and includes the installed hydropower capacity and the installed biomass capacity. Biomass can be stored and burned when it is needed, making it a dispatchable fuel source. It is possible to co-fire biomass by combining it with natural gas and coal, and biomass can be fed into a variety of burners that are also capable of burning fossil fuels (Verdolini *et al.* 2018). Accordingly, the findings of Model 3 reveal that the displacement coefficient of renewable capacity excluding hydro and biomass (-0.80) is statistically significant and different from “-1”, implying that non hydro-biomass renewables substantially displace fossil fuels. A one-unit augment in non-hydro-biomass renewable capacity leads to a reduction in fossil fuel capacity of 0.80 units. In addition, biomass has a good displacement effect on fossil fuels, with a coefficient of -0.83. A one-unit augment in the capacity of biomass results in a reduction in fossil fuel capacity of 0.83 units. This might be since biomass is more competitive with fossil fuels due to its lower cost compared to other RE technologies.

Overall, the findings obtained from Models 1 to 3 show that the displacement coefficients are significantly different from -1. Furthermore, the displacement coefficients for the different definitions of renewable capacity significantly differ from each other in Models 1 to 3. This indicates that renewables are moving in the direction of displacing fossil fuel sources on a one-to-one basis. It is observed that hydropower is more effective in competition with fossil fuels, therefore increasing their harmful

impact on the environment. RE capacity has an impact on fossil fuel capacity, and displacement can be achieved by renewables in OECD countries. It reveals that RE technologies are essential for reducing fossil fuel consumption and transitioning to a low-carbon energy system. Moreover, the capacity additions of RE have served to decarbonize the energy sector and limit the environmental damage caused by fossil fuels.

Table 8 summarizes the findings of the system GMM estimates using the above-mentioned Equation (2) variations. In this context, Model 1 provides a specification that includes the installed capacity of variable energy sources. In addition, Model 2 and Model 3 include installed capacity for solar power and wind power, respectively. The findings of Table 3 show that variable energy capacity is negatively associated with fossil fuel capacity, indicating the partial displacement of fossil fuels by variable energy sources. Moreover, solar energy capacity adversely affects fossil fuel capacity, with a displacement coefficient of -0.724. In the case of wind power capacity, the displacement coefficient is negative (-0.58), and it is slightly lower than solar energy capacity. Therefore, solar power seems to displace more fossil fuels than wind power does. In the OECD countries, solar power grew at a rate of 33.2% between 2010 and 2018, and wind power exhibited a similar pattern, with a growth rate of 13.5%. Accordingly, these results indicate that there is a significant pathway that still needs to be taken for OECD countries to attain one-to-one displacement of fossil fuels with variable renewables.

The coefficients associated with technological innovation show that technological innovation in clean energy technologies negatively affects the increase in fossil fuel

capacity. The energy sector is entering a new era of innovation that will drive actions on energy transition and, consequently, climate change. The energy transition will be facilitated by technological innovation, particularly in the RE sector. In this manner, innovation in RE technologies promises a path toward resilient, flexible, and sustainable energy systems. This can be attributed to rapidly declining costs and the rising competitiveness of renewables against fossil fuels. Consequently, it can be said that technological innovation is the backbone of RE technologies.

Table 8: System GMM Results for Inclusive Sample

Dependent variable: $ShareCap^{FF}$			
	Model 1	Model 2	Model 3
ShareCap ^{FF} (-1)	0.182 ^{**}	0.564 ^{***}	0.865 ^{***}
ShareCap ^{VRE}	-0.522 ^{***}	-	-
ShareCap ^{SOLAR}	-	-0.580 ^{***}	-
ShareCap ^{WIND}	-	-	-0.344 ^{***}
LTI	-0.025 ^{***}	-0.012 ^{***}	-0.014 ^{***}
LGDP	-0.106 ^{***}	-0.075 ^{***}	-0.003
ENDEP	0.113	0.778 [*]	0.789 ^{***}
LECONS	0.176 ^{***}	0.064 ^{***}	0.031 ^{***}
CONSTANT	0.191 [*]	0.642 ^{***}	0.068 [*]
# Observations	460	437	437
# Instruments	16	11	10
# Groups	23	23	23
F-test	1844.40 ^{***}	5093.62 ^{***}	2965.25 ^{***}
Sargan test p value	0.572	0.456	0.193
AR (1) p value	0.061	0.013	0.002
AR (2) p value	0.149	0.309	0.320

Notes: See the notes for Table 2.

The effect of GDP is negative and significant, thereby playing a role in the reduction in fossil fuel capacity. This outcome can be supported by the fact that nations with higher incomes tend to rely more heavily on RE in their energy mix. This result is in line with Narbel (2013). With respect to energy dependence, it is positively correlated with fossil fuel capacity. This result suggests that countries that rely significantly on imported energy also exhibit a substantial proportion of fossil-fuel-based energy

generation capacity. Moreover, it can be argued that fossil fuel technologies are inadequate for fulfilling the energy requirements of sample countries. Given that the advancement of RE technologies is outpacing that of fossil fuels, the adoption of renewables has the potential to substantially diminish the necessity for imported energy. In conclusion, the matter of RE is not solely an environmental concern but also a matter of energy security. The result also indicates that energy consumption is one of the drivers of fossil fuel technologies. The demand for energy leads to a greater need for installed energy-generating capacity for fossil fuels.

The lower sections of Tables 7 and 8 display the diagnostic test outcomes for all models. The Sargan test approves the validity of the chosen instruments across all models. In addition, the results of the Arellano and Bond test reveal that the p-values of AR(2) are insignificant, concluding that second-order autocorrelation is absent in all models. As evidenced in the lower sections of Tables 7 and 8, the number of instruments is less than the sample size. Therefore, this finding supports the conclusion that the SYS-GMM method serves as a valid instrument. Consequently, it can be inferred that the SYS-GMM method provides the empirical outcomes in the most accurate way.

3.5 Conclusion

This work investigates the displacement influence of RE sources on fossil fuels by utilizing panel data for 36 OECD countries spanning from 2000 to 2020, with the objective of evaluating the current state of the global energy transition. In this regard, the SYS-GMM method is implemented. The findings illustrate that RE has a significant effect on the displacement of fossil fuels. Specifically, an average increase of 1.4 units of RE is mandated to displace one unit of fossil fuel energy in OECD

countries. This observation remains consistent across a range of rigorous tests, which include varying interpretations of RE capacity. Exclusion of hydropower, biomass, and waste from the RE mix leads to an enhanced displacement effect. On average, a displacement of one unit of fossil fuel necessitates 1.2 units of RE under this scenario. More precisely, a one-to-one displacement of fossil fuels occurs with hydropower. Further examination focusing on variable RE, utilizing panel data from 23 OECD countries, reveals that an average increase of 1.9 units of variable RE is required to displace one unit of fossil fuel energy.

In conclusion, this work adds to the literature by illustrating that the energy transition in OECD countries is well underway, with RE sources progressing towards effectively displacing fossil fuels. The research underscores the potential of RE sources, particularly hydropower, in supplanting fossil fuels. The findings indicate that the capacity of renewables to displace fossil fuels can be partially attributed to their implementation in nations that have adopted measures aiming to combat climate change.

Given the current unavailability of cost-effective technologies, the deployment of RE sources has emerged as a crucial aspect of the contemporary energy system, as these resources present the most competitive alternatives to fossil fuels. Effectively transitioning from fossil fuels to RE sources not only necessitates the advancement of RE technologies but also requires coordinated economic and political efforts for the successful execution of innovative energy production techniques derived from renewables. Market-based mechanisms, such as fuel taxes and incentives, can promote the adoption of alternative energy sources while concurrently mitigating the rebound

effect linked with fossil fuel consumption. Carbon and fuel tax implementation can generate revenue that can support the subsidization of RE sources as a viable replacement for fossil fuels.

Moreover, cost savings resulting from efficiency improvements can make government interventions focused on reducing energy demand and encouraging RE sources more economically viable, thus enhancing the probability of their effective execution. In summary, fostering the deployment of RE sources, coupled with the establishment of climate mitigation strategies, can expedite the transition of OECD countries towards a low-carbon economy.

Chapter 4

THE DETERMINANTS OF RENEWABLE ENERGY

4.1 Introduction

Climate policy is designed to address climate-related issues and has been shown to introduce significant risk to economic growth. The emergence of serious environmental issues and their possible implications for economic progress have elicited worldwide concerns (Li *et al.* 2023). Hence, the transition from conventional fuels to sustainable and eco-friendly renewable energy is a crucial policy instrument for facilitating the transition of economies towards a low-carbon option (Shang *et al.* 2022). In this perspective, the growing global efforts to mitigate and adapt to climate change have led to a surge in attention towards RE. The utilization of RE sources for decarbonizing energy systems can potentially mitigate the susceptibility and fragility of societies towards climate risks and impacts, while concurrently augmenting their social and economic functionality (Sarma and Zabaniotou, 2021; Kim and Park, 2023). Various measures aimed at addressing the potential hazards of climate change are currently being implemented at the global and national levels. In recent decades, numerous developed and developing countries have made significant progress in transitioning from non-renewable to clean energy. In this context, there are several aspects to the transition to clean energy sources. One of the critical aspects of this transition is the implementation of supportive environmental policies by governmental bodies, such as tax incentives and green financing for investments in renewables (Shang *et al.*, 2022). Carfora and Scandurra (2019) reported that GHG emissions are

reduced in response to financial incentives provided by climate funds, indicating that transitioning away from fossil fuels in favor of RE is environmentally preferable. The second critical aspect is the climate crisis. Given that fossil fuels are the primary drivers of GHGs, promoting the RE utilization and enhancing energy-efficient technologies reduces GHGs and the adverse impacts of climate change. Finally, interest in RE sources has risen lately due to the fluctuation in the price of non-RE, such as crude oil, caused by geopolitical risks and market instability (Sadorsky, 2009). Moreover, the escalation of oil prices and heightened volatility, coupled with their detrimental impact on the environment, expedite the replacement of crude oil with alternative energy sources (Cao *et al.* 2020).

In light of the aforementioned context, this paper focuses on the United States (U.S.), which is presently responsible for emitting 11% of the total annual global GhG emissions, ranking second to China. Fig. 2 represents the shares of primary energy sources consumed in the U.S. in 2022. Despite being the foremost investor in clean energy globally, the U.S. economy continues to be predominantly reliant on non-RE sources. Fossil fuel sources are a substantial contributor to total energy consumption, and they constituted approximately 79% of the overall primary energy consumption in 2022. RE sources comprised 13% of the overall energy consumption, while nuclear energy held an 8% share. Specifically, biomass accounted for a significant proportion of RE sources, comprising approximately 37% of the total. It is followed by wind and hydropower.

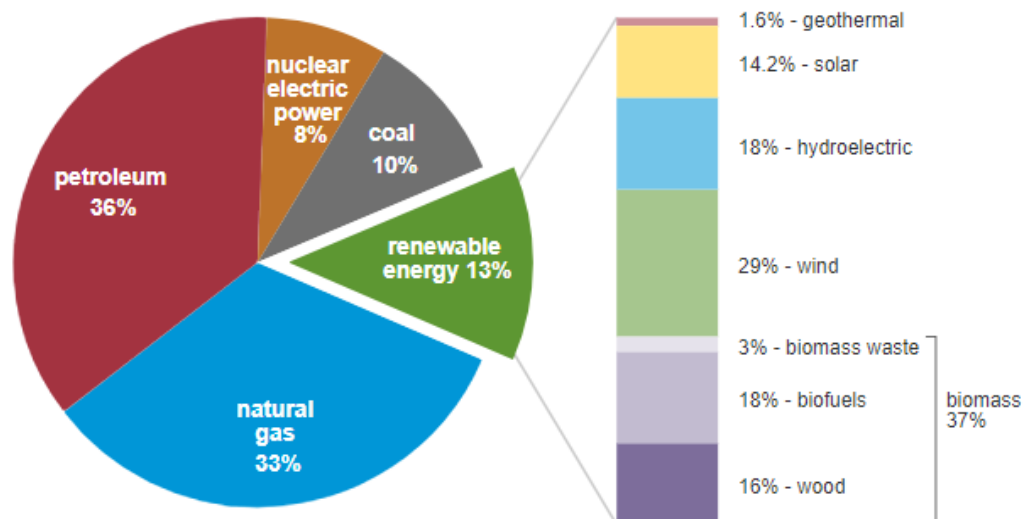


Figure 2: The US primary energy consumption by energy source in 2022.

Source: U.S. Energy Information Administration.

<https://www.eia.gov/energyexplained/us-energy-facts>

The reduction of GHG has the capacity to effectively alleviate the detrimental influences of climate change within the U.S. Accordingly, the U.S. government has reiterated its commitment to accomplishing climate change goals, primarily through the implementation of a forceful new nationally determined contribution (NDC). Additionally, the country has set a goal of achieving 100% clean energy by 2035 and the composition of fossil fuel sources utilized for power generation is currently undergoing a significant transformation. Renewable electricity has experienced a swift expansion due to a combination of declining costs and supportive policies from governmental entities (IEA, 2023). Advancements in technology, coupled with a reduction in cost and an enhancement in performance, have contributed to the growing popularity and competitiveness of solar and wind energy in comparison to other forms of energy (Sahu *et al.*, 2022). Recently, the country has allocated a substantial portion of its tax revenue towards the development of infrastructure for solar and other renewables. According to the IRENA, it is projected that the proportion of RE in the

U.S. may experience an upsurge to 27% by the year 2030. Overall, RE has been steadily advancing in the United States.

Given this background, this paper examines the determinants that contribute to the increased interest in RE in the United States, which being one of the developed nations, holds the position of being the foremost energy consumer and the second-largest contributor to pollution globally. Thus, the empirical findings can offer valuable policy recommendations for relevant authorities to implement sustainable energy measures. The first contribution of this paper is to employ the climate policy uncertainty index as a novel metric to evaluate the influence of ecological policy or regulation on the demand for RE. Second, non-RE prices are employed as a broad measure of energy costs. The advantage of this factor lies in its ability to function as a comprehensive indicator of the prices associated with all goods that rely on non-RE sources. Overall, the main contribution is to explore the influence of uncertainty in climate policy and non-RE prices on the use of RE sources. To achieve this aim, the study employs the RALS methodology and incorporates monthly data spanning from 1985 to 2021, representing the most current intersectional data available for all variables under consideration within this context.

The paper is organized as follows: Section 2 presents an overview of the earlier literature regarding the determinants of RE. Section 3 discusses the detailed data and methodology. Section 4 provides the empirical results, followed by Section 5, which concludes the study.

4.2 Literature Review

This section of the study provides a review of literature pertaining to RE forms and their determinants, including policy uncertainties, energy prices, and industrial production. Therefore, the literature is categorized into three different parts: policy uncertainties and renewables, energy prices and renewables, and economic growth and renewables.

4.2.1 Policy Uncertainties and Renewables

The presence of policy uncertainty has an adverse impact on the allocation of resources towards RE investments. For example, Balcilar *et al.* (2019) indicated that economic policy uncertainty (EPU) is negatively related to macroeconomic conditions that impede investment and consequently affect the expansion of RE. They also emphasized the importance of mitigating energy market uncertainty as a crucial factor for the achievement of a successful transition towards clean energy in Europe. Liu *et al.* (2020) discovered that the presence of EPU has a notable influence on impeding investment by conventional energy companies. However, this inhibitory effect is not found to be statistically significant for RE companies. Shafiullah *et al.* (2021) found that EPU has the potential to disrupt the progress of RE and impede its development in the U.S. Khan and Su (2022) found that the presence of economic uncertainty poses a significant disadvantage for the production of RE in G7 countries. Zeng and Yue (2022) showed that the rise in EPU hindered the adoption of RE in BRICS countries by promoting the use of non-RE. Yi *et al.* (2023) revealed that heightened EPU specifically an unstable policy regime in the U.S., resulted in a decrease in the utilization of RE sources. Li *et al.* (2023a) revealed that EPU has a positive short-term impact on the clean energy index but an increasingly adverse medium- to long-term

effect. They also stated that the resilience of clean energy markets to external uncertainties is comparatively lower.

Conversely, there is limited research indicating that EPU may have a favorable influence on the RE sector. Feng and Zheng (2022) documented that innovation in RE technologies is boosted by EPU in countries with high institutional quality. Focusing on China, Lei *et al.* (2022) indicated that the mitigation of EPU has a favorable influence on the reduction of reliance on traditional energy sources, while simultaneously promoting innovation and growth in the RE sector.

To effectively address anomalous climate change, Drouet *et al.* (2015) stated that it is crucial to quantify and incorporate uncertainty into policy frameworks. This motivated Gavriilidis (2021) to create a CPU indicator, a novel way to quantify the risk associated with climate policy. Afterwards, climate policies became a prominent topic in literature. For example, Ren *et al.* (2022) showed that CPU is associated with a decrease in investment expenditure among energy-related firms in China. Shang *et al.* (2022) highlighted that CPU has a beneficial influence on RE sources in the U.S. In other words, uncertainty regarding climate policy upsurges RE use. Li *et al.* (2023) noted a mixed pattern of negative and positive causality between RE and climate change policy uncertainty, which may be largely attributable to the stance taken by authorities in the U.S. towards climate change. Sarker *et al.* (2023) highlighted that the heightened level of CPU serves as a driving force for investors to allocate their resources towards environmentally friendly investments. Accordingly, increased investment in clean energy may result in higher demand. Zhou *et al.* (2023) concluded

that CPU increases short-term usage of hydro power and wind energy. In addition, they discovered that CPU reduces the utilization of solar and geothermal energy.

4.2.2 Energy Prices and Renewables

The influence of oil prices on RE sources remains a topic of debate among scholars, as it is contingent upon the degree to which fluctuations in oil prices incentivize RE investment. A group of scholars emphasized the favorable influence of energy prices on RE sources. Chang *et al.* (2009) demonstrated that countries that experience strong growth can effectively respond to elevated energy prices by increasing their utilization of RE sources. Shah *et al.* (2018) discovered that oil prices have a positive influence on the RE industry, particularly in the U.S. Yang *et al.* (2019) documented that increasing energy prices can result in higher costs for energy consumption. Guo *et al.* (2021) indicated that rising oil prices stimulate RE investment and infrastructure, resulting in an increase in its overall consumption in the U.S., Italy, and Canada. Sahu *et al.* (2022) showed that an augment in crude oil prices is positively associated with a rise in the utilization of RE in the U.S. Atems *et al.* (2023) demonstrated that after a positive price shock in the non-RE sector, RE consumption increases across the board, whereas reactions to negative price shocks are negligible.

Another group of scholars has emphasized the adverse influence of energy prices on the use of RE resources. Using the Generalized Methods of Moments (GMM) method, Cao *et al.* (2020) revealed that the fluctuation in crude oil prices has a negative influence on RE investment in China. They also stated that the variability in oil prices may also strengthen the association between risk and investment prospects. Mukhtarov *et al.* (2020) found that a rise in oil prices has an adverse effect on the utilization of RE sources in Azerbaijan. In the case of Russia, Karacan *et al.* (2021) revealed that

the increase in oil prices impeded the progress of the shift from conventional energy sources to RE alternatives. Shang *et al.* (2022) stated that a rise in oil prices decreases demand for RE and a corresponding rise in reliance on oil in the U.S. In the case of China, Yu *et al.* (2023) highlighted the negative link between crude oil imports and RE consumption. In other words, the consumption of RE sources has a diminishing effect on crude oil imports. They noted that the actions taken to achieve carbon neutrality have raised a heightened focus on the utilization of RE sources while reducing reliance on non-renewable alternatives.

4.2.3 Economic Growth and Renewable Energy

In the case of the G7 countries, Sadorsky (2009) indicated that income is the primary driver of RE utilization. Ohler and Fetters (2014) noted a positive correlation between various forms of RE such as hydroelectricity, wind, biomass, and waste energy. Bamati and Raoofi (2020) highlighted that economic growth have a larger impact on RE growth in industrialized nations than in less developed ones. Tudor and Sova (2021) concluded a positive link between income and RE use. Apergis and Danuleti (2014) found that RE investment is positively correlated with economic growth. Dogan *et al.* (2023) concluded that the utilization of RE is positively impacted by economic growth in 25 selected EU countries. Using GMM method, Kilinc-Ata and Dolmatov (2023) obtained the same results for the BRICS and 34 OECD countries.

There are few studies that used industrial production as a measure of economic growth. For instance, Sari *et al.* (2008) demonstrated that industrial production is the primary driver of RE sources. In addition, they also stated that the production of industrial goods results in a decrease in the demand for both natural gas and solar energy. Employing continuous wavelet transform analyses, Bilgili (2015) reported a positive

correlation between renewables and industrial production in the U.S. Marques *et al.* (2016) documented that as industrial production expands, there is a corresponding rise in the utilization of non-RE sources. Hoang *et al.* (2020) revealed a positive correlation between industrial production and RE.

4.3 Data and model

This study focuses on the effects of CPU and the production price index (PPI) on the RE consumption of the U.S. economy during the period 1987M4-2021M8. RE consumption is obtained from the U.S. Energy Information Administration (EIA). The core explanatory variable is the CPU index, which was proposed by Gavriilidis (2021). In accordance with Baker *et al.* (2016), this variable was constructed through the identification of specific terms in eight leading U.S. newspapers. These terms include "climate risk", "global warming", "CO₂ emissions", "GHG emissions", "green energy", "climate change", "RE", and "environmental", as well as their respective variants such as "regulatory", "uncertainties", and "policies". Industrial production (IP) as a measure of gross domestic product is included to capture the income effect on energy demand. The PPI for Processed Fuels and Lubricants is utilized as a broad measure of non-RE prices. The rationale for utilizing PPI as a primary measurement is the inadequacy of crude oil prices in accurately reflecting non-RE prices. The U.S. held the position of the world's foremost oil producer in 2021. Rising oil prices may result in cost-effectiveness favoring investment in RE sources, thereby incentivizing the country to increase production of such sources. Therefore, to ensure the reliability of the PPI, the West Texas Intermediate (WTI)-Cushing, and Oklahoma crude oil prices (OIL) are also utilized. The data for IP, PPI, and OIL are gathered from the Federal Reserve Economic Database (FRED). According to the study variables, the empirical model can be expressed as follows:

$$\ln REC_t = \beta_1 + \beta_2 \ln IP_t + \beta_3 \ln PPI_t + \beta_4 \ln CPU_t + \varepsilon_t \quad (4.1)$$

where β_1 is the constant, $\beta_{2,3,4}$ are the long-run coefficients, $\ln$ is logarithm form and ε_t is the error term. REC_t stands for RE consumption; $\ln IP_t$ denotes the industrial production; $\ln PPI_t$ represents non-RE prices; $\ln CPU_t$ is the CPU index. In order to facilitate the computation of elasticities, a logarithmic transformation is applied to all variables in the model.

Table 9 represents descriptive statistics. On average, non-RE prices exhibit the highest value, whereas RE consumption demonstrates the lowest value. The median value of non-RE price is the highest median value, followed by industrial production. All variables exhibit a right-skewed distribution, with the exception of industrial production. Furthermore, the variables $\ln REC$, $\ln IP$, $\ln PPI$, $\ln OIL$ and $\ln CPU$ are indicative of a normal distribution, as evidenced by their skewness values approaching 0 and kurtosis values approaching 2.

Table 9: Descriptive Statistics

	lnREC	lnIP	lnPPI	lnOIL	lnCPU
Mean	-0.4745	4.4500	4.8507	3.6429	4.4873
Median	-0.5758	4.5214	4.8892	3.6458	4.4696
Maximum	0.1287	4.6459	5.7748	4.8793	5.9323
Minimum	-0.9074	4.0500	4.2184	2.4725	3.4251
Std. Dev.	0.2672	0.1838	0.3947	0.6441	0.4645
Skewness	0.5911	-0.8681	0.0783	0.0995	0.5422
Kurtosis	2.0122	2.2191	1.5531	1.6304	3.2374

Note: Std. Dev denotes standard deviation.

4.3.1 Econometric Methodology

The present study examines the stationarity of the variables of concern by using the Augmented Dickey-Fuller (ADF) (Dickey and Fuller, 1981) and the Residual Augmented Least Squares ADF (RALS-ADF) (Im *et al.* 2014) unit root examinations.

Following the establishment of the stationary characteristics of the variables, the identification of long-term associations is conducted through the utilization of Engle and Granger (EG) (Engle and Granger, 1987) and RALS-EG (Lee *et al.* 2015).

The EG test is conducted using a two-step cointegration approach, which was selected based on the residuals framework and standard t-statistics. After determining the stationarity level of integration in the first step of the test, the next step involves estimating the regression using the ordinary least squares (OLS) method.

$$y_t = \beta z_t + \varepsilon_t \quad (4.2)$$

Subsequently, the residuals, denoted as $(\hat{u}_t)$, are subjected to decomposition from the model, and an ADF test is utilized to assess their degree of integration.

$$\Delta \hat{u}_t = \varphi_0 + \varphi_1 \hat{u}_{t-1} + \sum_{i=1}^p \varphi_{i+1} \Delta \hat{u}_{t-1} + e_t \quad (4.3)$$

The RALS applied by Im and Schmidt (2008) enables the utilization of supplementary high-order moment information. The RALS technique has the potential to yield more robust outcomes in cases where the error term conforms to a non-normal distribution. As an extension of the EG cointegration test, Lee *et al.* (2015) implemented the RALS cointegration test, which is formulated by incorporating a novel term that is derived from the second and third moments of the residuals obtained from conventional tests. In order to implement the RALS methodology, the equation (4.3) was expanded by the inclusion of the subsequent term.

$$\hat{w}_t = p(\hat{e}_t) - \hat{K} - \hat{e}_t \hat{D}_t, \quad t = 1, 2, 3, 4, \dots, T,$$

The residuals obtained from Equation (3) are represented by $\hat{e}_t$ and $p(\hat{e}_t) = [\hat{e}_t^2 \hat{e}_t^3]$, $\hat{K} = \frac{1}{T} \sum_{i=1}^T p(\hat{e}_t)$, $\hat{D}_t = \frac{1}{T} \sum_{i=1}^T p'(\hat{e}_t)$. Additionally, the subsequent equation illustrates the RALS definition formulated by Meng *et al.* (2017):

$$\hat{w}_t = [\hat{e}_t^2 - m_2, \hat{e}_t^3 - m_3 - 3m_2 \hat{e}_t] \quad (4.4)$$

where $m_j = T^{-1} \sum_{i=1}^T \hat{e}_t^j$. The RALS cointegration regression model is derived by incorporating the variable $\hat{w}_t$ into Equation (4.3).

$$\Delta \hat{u}_t = \varphi_1 \hat{u}_{t-1} + \sum_{i=1}^p \varphi_{i+1} \Delta \hat{u}_{t-1} + \hat{w}_t \gamma + v_t \quad (4.5)$$

The standard t-statistics are utilized to test the null hypothesis ($\alpha_1 = 0$) in Equation (4.5). Using the following equation, one can find the asymptotic distribution of the test statistic, which is based on the assumption that there is no cointegration:

$$t^* \rightarrow \rho \cdot t + \sqrt{1 - \rho^2} \cdot Z \quad (4.6)$$

where t^* represents the RALS-EG statistics, while t is used to denote the EG test statistics. The variable denoted as Z in the equation shows the standard normal random variable, whereas ρ signifies the long-term correlations of the error terms.

Finally, long-run coefficients are obtained by the fully modified least squares (FMOLS) (Philips and Hansen, 1990) and dynamic least squares (DOLS) methods (Stock and Watson, 1993).

4.4 Empirical Results

The initial stage of empirical analysis involves conducting unit root tests to check the spuriousness of the dataset being used.

Based on the ADF and RALS-ADF assessments outlined in Table 10, it can be inferred that all variables have demonstrated stationarity subsequent to the implementation of first-order differences. These results allow for the investigation of the cointegration association among the variables.

Table 10: Unit Root Test Results

Variables	ADF	RALS ADF	
	test-stat	test-stat	ρ^2
Level			
lnREC	-0.085 (3)	-0.205 (3)	0.995
lnIP	-1.109 (2)	-1.263 (2)	0.736
lnPPI	-0.671 (1)	-0.511 (1)	0.899
lnOIL	-1.934 (1)	-1.381 (1)	0.867
lnCPU	-2.106 (5)	-2.172 (1)	0.991
First differences			
Δ lnREC	-16.847* (2)	-16.968* (2)	0.995
Δ lnIP	-14.944* (1)	-18.461* (1)	0.736
Δ lnPPI	-14.921* (0)	-16.106* (0)	0.896
Δ lnOIL	-13.880* (1)	-12.897* (1)	0.866
Δ lnCPU	-13.278* (5)	-13.086* (5)	0.991

Notes: The optimal lag length, ascertained through recursive t-statistics, is indicated by the numbers in parentheses.

Conducting a test for long-term association is a prerequisite for assessing the impact of industrial production, non-RE prices, and uncertainty in climate policy on RE. Therefore, to ascertain the presence of the linkage, the EG and RALS-EG cointegration tests are utilized prior to estimation. The results of the cointegration tests are shown in Table 11. The calculated test statistics for EG (-5.609) and RALS-EG (-5.033) are statistically significant, signifying the existence of a cointegration linkage among the variables under consideration.

Table 11: Cointegration Results

Method	k	Test Stat	ρ^2
EG	0	-5.609***	-
RALS-EG	0	-5.033***	0.939

Notes: (1) *, ** and *** represent the significance level at 10%, 5% and 1%.

The FMOLS technique is utilized in the final stage to ascertain the long-term effects. Table 12 shows that industrial production is positively correlated with RE

consumption. A 1% increase in industrial production increases RE consumption by 0.12%.

The coefficient regarding non-RE prices is significant and positive, suggesting that a 1% upsurge in non-RE prices leads to a corresponding 0.327% rise in RE consumption. This implies that the escalation of non-RE prices has prompted the government to promote the increased utilization of RE sources. Therefore, it can be said that the consideration of non-RE prices is crucial when formulating RE policies. In Model 2, oil prices are utilized to evaluate the robustness of the long-run effect of non-RE prices. It can be said that as the cost of oil increases, the feasibility of investing in and manufacturing RE becomes more economically advantageous. The outcomes are in accordance with expectations, as the rise in oil prices incentivizes the U.S. to adopt more cost-effective energy substitutes, such as RE. Moreover, the aforementioned findings contribute to attaining cost-effective, modern, and sustainable energy. This finding aligns with Guo *et al.* (2021) and Sahu *et al.* (2022), which revealed that oil prices are one of the main determinants of RE utilization.

Table 12: Long-Run Coefficients

	FMOLS		DOLS	
Variables	Model 1	Model 2	Model 1	Model 2
lnIP	0.124* (0.785)	0.409*** (2.794)	0.141* (0.932)	0.407*** (2.931)
lnPPI	0.327*** (4.073)	-	0.303*** (3.774)	-
lnOIL	-	0.086* (2.017)	-	0.081* (1.961)
lnCPU	0.291*** (7.037)	0.361*** (8.791)	0.318*** (6.423)	0.379*** (8.064)
Constant	-3.929*** (-8.302)	-4.239*** (-7.612)	-4.013*** (-8.602)	-3.293*** (-7.993)

Note: (1) *, ** and *** represent the significance level at 10%, 5% and 1%. (2) () shows the t-stats.

Climate change policy uncertainty is positively associated with RE consumption. Specifically, a rise of 1% in the level of uncertainty pertaining to climate policy is associated with a corresponding increase of 0.29% in the utilization of RE sources. The outcomes indicate that the consumption of RE will increase as the degree of uncertainty over climate policy increases. This could be because the rise of ambiguity surrounding climate policies in recent times has had a favorable influence on the utilization of RE. In addition, tax policies, which are one of the objectives in the U.S. climate action plan, support the implementation of GhG-abating technologies, i.e., clean energy technologies. This, in turn, discourages investment in fossil-fuel technologies. The outcome supports the work of Shang *et al.* (2022) for the U.S.

To assess the reliability of the FMOLS estimation outcomes, the DOLS method is also employed, and the corresponding findings are displayed in Table 4. According to the DOLS, industrial production, non-RE prices, and CPU exhibit positive and significant effects on RE consumption. Consequently, it can be inferred that the findings of the robust check conducted in this research have yielded conclusions that are consistent and dependable with those of the FMOLS results.

4.5 Conclusion

Climate issues have been a concern for the international community, prompting nations to take action towards achieving a net-zero economy. This endeavor has led to numerous modifications and advancements in climate policy. In this regard, RE has been extensively documented as playing a significant role in mitigating GHGs and addressing the environmental crisis. Accordingly, the determinants that influence the utilization of RE sources have been a crucial topic in the pursuit of ecological sustainability, given the present circumstances of global warming. Therefore, this

paper investigates the determinants that contribute to the increased interest in RE in the United States. To this end, monthly data on industrial production, non-RE prices, CPU, and RE consumption from April 1987 to August 2021 were utilized. The EG and RALS-EG are applied for the purpose of assessing cointegration, while the FMOLS and DOLS methods are conducted to estimate elasticities.

The study has the following outcomes. First, there is a positive link between industrial production and RE consumption. The utilization of industrial production has a favorable influence on the surge in demand for RE in the U.S. Second, higher costs for non-RE sources incentivize the utilization of RE alternatives. In other words, in response to escalating non-RE prices, the United States augments its demand for RE and reduces its reliance on fossil fuel-based sources. Therefore, it can be concluded that non-RE prices are a significant driver of RE utilization. Likewise, crude oil prices increase RE use. Third, CPU has a positive influence on the utilization of RE sources. This finding suggests that an upsurge in CPU is positively linked with a rise in demand for RE sources. The imposition of pollution taxes by the United States government on firms that contribute to environmental degradation may serve as a motivating factor for producers to decrease their reliance on fossil fuels.

Finally, this study has some limitations. One potential limitation is the lack of consideration for the various forms of RE sources. Expanding the framework to include these different forms may provide a more comprehensive understanding of the association between CPU and RE consumption. The other limitation of the paper is that it solely examines the influence of uncertainty pertaining to climate policy, while disregarding the other types of policy uncertainty, such as those related to energy

markets and trade policies. Overall, the framework of the study can be further enhanced by incorporating these variables into future research.

Chapter 5

CONCLUSION

In the first chapter of the thesis, the impact of digitalization and its interaction with diverse factors on environmental sustainability in OECD countries are examined. The primary findings of the SYS-GMM method indicated that digitalization has the capacity to mitigate environmental degradation through various substitution effects, such as dematerialization, decarbonization, and demobilization. In addition, green innovation, renewable energy usage, and financial development have a mitigating effect on environmental deterioration. Furthermore, the association among digitalization, innovation, renewable energy utilization, and financial development amplifies the ecological footprint-reducing impact of digitalization. The empirical findings of this study provide valuable insights for OECD members in developing climate change policies within the context of the digital economy, as they lead the process of implementing SDG-aligned policies. In order to maximize the environmental advantages of digitalization, it is imperative for OECD nations to carefully deliberate the role of digitalization in restructuring production patterns. Additionally, they should prioritize leveraging digital tools to accelerate the energy transition by promoting energy efficiency. Furthermore, it is crucial to aim the implementation of environmentally sustainable and innovative financial instruments in this context. As a result, it is necessary for OECD nations to consistently prioritize the advancement of the digital economy as a crucial tool in attaining carbon neutrality.

In the second chapter, the displacement effect of renewables on fossil fuels is explored for 36 OECD countries. To conduct reliability testing, various definitions of renewable energy sources are used. To achieve this objective, this study employed the SYS-GMM method, which allows the consideration of endogeneity and reverse causality problems. The results demonstrated that a prerequisite for the replacement of one unit of energy obtained from fossil fuels is an average increase of 1.4 units of RE. In addition to this, the exclusion of hydropower, biomass, and waste from renewable energy results in an intensified displacement effect. On average, the utilization of one unit of fossil fuel requires an accompanying 1.2 units of renewable energy. Moreover, the findings indicate that a rise of 1.9 units in the variable RE is necessary to substitute one unit of energy derived from fossil fuels. Specifically, hydropower is the only renewable energy source that directly substitutes fossil fuels on a one-to-one basis. The study highlights the considerable potential of renewable energy sources, with a specific emphasis on hydropower, as a viable alternative to fossil fuels. Based on the study findings, it can be posited that the capacity additions of renewable energy have served to decarbonize the energy sector and limit the environmental damage caused by fossil fuels. Hence, the promotion of renewable energy sources, along with the implementation of climate change mitigation measures, has the potential to accelerate the shift of OECD nations towards a low-carbon economic model. As a policy framework, it can be said that the implementation of market-based mechanisms can facilitate the adoption of alternative energy sources and simultaneously alleviate the rebound effect associated with the consumption of fossil fuels.

Finally, the last chapter investigated the determinants of renewable energy consumption in the U.S. during the period 1987–2021. The United States holds the

position of being the primary consumer of energy and is ranked as the second most significant contributor to worldwide pollution. Therefore, the outcomes possess the capability to offer noteworthy recommendations for relevant authorities to implement sustainable energy programs. The findings from FMOLS and DOLS methods revealed that industrial production, non-RE prices, and CPU are important drivers of RE consumption. Considering the increasing prices of non-renewable energy, the U.S. is taking steps to address this issue by increasing its demand for renewable energy and decreasing its dependence on fossil fuel-based sources. Additionally, the presence of CPU in the U.S. contributes to enhanced energy security by promoting the adoption of renewable energy sources, consequently leading to improvements in environmental quality. Consequently, in formulating renewable energy policies, it is essential to consider non-RE prices and the uncertainty of climate policies.

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