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THE IMPACT OF FINANCIAL INNOVATION ON ENVIRONMENTAL QUALITY, GREEN TECHNOLOGICAL INNOVATION AND RENEWABLE ENERGY PRODUCTION: EVIDENCE FROM OECD COUNTRIES

Finansal Yeniliğin Çevresel Kalite, Yeşil Teknolojik Yenilik ve Yenilenebilir Enerji Üretimine Etkisi: OECD Ülkelerinden Kanıtlar

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Keywords: Financial Innovation, Carbon Emissions, Green Technological Innovation, Renewable Energy Production.

JEL Codes: O31, Q55, Q42, Q01.

Abstract

This study examines the impact of financial innovation on environmental quality in OECD economies and investigates how this effect is transmitted through green technological innovation and renewable energy production. The analysis relies on a panel dataset constructed from annual observations for 18 countries over the period 2009–2021. In the empirical design, cross-sectional dependence and stationarity properties are assessed, and the long-run relationship among the variables is examined using a bootstrap-based cointegration approach. Long-run coefficients are estimated using the panel-corrected standard errors framework, while the direction of relationships is tested through heterogeneous panel causality analysis. The findings indicate that increases in financial innovation significantly improve environmental quality by reducing carbon dioxide emissions. Moreover, financial innovation promotes green technological innovation activities and expands renewable energy production, and these two channels reinforce the emissions-reducing effect. Causality results further suggest that financial innovation plays a leading role with respect to emissions and renewable energy, while exhibiting a bidirectional interaction with green technological innovation. Overall, the results imply that sustainable finance policies should be designed in close coordination with technology and energy transition objectives.

Anahtar Kelimeler: Finansal Yenilik, Karbon Emisyonları, Yeşil Teknolojik Yenilik, Yenilenebilir Enerji Üretimi.

JEL Kodları: O31, Q55, Q42, Q01.

Öz

Bu çalışma, finansal yeniliğin çevresel kalite üzerindeki etkisini ve bu etkinin yeşil teknolojik yenilik ile yenilenebilir enerji üretimi üzerinden nasıl iletildiğini Ekonomik İşbirliği ve Kalkınma Örgütü ülkeleri bağlamında incelemektedir. Çalışma, 2009–2021 döneminde 18 ülkeye ait yıllık verilerden oluşturulan panel veri setine dayanmaktadır. Ampirik tasarımda yatay kesit bağımlılığı ve durağanlık özellikleri değerlendirilmiş; değişkenler arasındaki uzun dönemli ilişki bootstrap destekli eşbütünleşme yaklaşımıyla araştırılmıştır. Uzun dönem katsayıları panel düzeltmeli standart hata yaklaşımıyla tahmin edilmiş; ilişkilerin yönü heterojen panel nedensellik analiziyle sınanmıştır. Bulgular, finansal yenilikteki artışın karbon dioksit emisyonlarını azaltarak çevresel kaliteyi istatistiksel olarak anlamlı biçimde iyileştirdiğini göstermektedir. Ayrıca finansal yenilik, yeşil teknolojik yenilik faaliyetlerini ve yenilenebilir enerji üretimini artırmakta; bu iki kanal emisyonlar üzerindeki azaltıcı etkiyi güçlendirmektedir. Nedensellik bulguları, finansal yeniliğin emisyonlar ve yenilenebilir enerji üzerinde öncü rol üstlendiğini, yeşil teknolojik yenilikle ise karşılıklı etkileşim bulunduğunu ortaya koymaktadır. Sonuçlar, sürdürülebilir finans politikalarının teknoloji ve enerji dönüşümüyle eşgüdüm içinde tasarlanması gerektiğine işaret etmektedir.

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1. Introduction

According to the World Economic Forum's The Global Risks Report (2023), while environmental risks are at the forefront, failure to mitigate and adapt to climate change is ranked as the most important source of global risks. Thus, the world is facing some of the most serious environmental threats, such as climate change and global warming, with carbon emissions (Dogan et al., 2020) and increased energy consumption at the heart of these problems (Jiang and Ma, 2021). The transition to carbon-neutral renewable energy is crucial for decarbonizing ecosystems, reducing CO_2 emissions, and mitigating climate change. This shift aligns with United Nations Sustainable Development Goals (SDGs) 7 and 13, promoting sustainable energy access and urgent climate action while supporting environmental resilience and socio-economic stability.

At the 2023 United Nations Climate Change Conference (COP28), a Global Stocktake (GST) was conducted for the first time to demonstrate progress on the decisions taken in the 2015 Paris Climate Agreement. Accordingly, in order to reach the 2050 target of net-zero greenhouse gas emissions worldwide, it is essential to accelerate the transition from the current system based on fossil fuels to renewable energy sources. To this end, the transformation of society should be supported, and financial and technological assistance should be provided to enable countries to realize their climate commitments (UNFCCC, 2023). This transition requires investments of USD 5 - 7 trillion per year by 2050, but currently, less than USD 2 trillion is being invested each year to make this transition (Deloitte, 2023). The main barrier to sustainable investment projects is not a lack of financing, but an inadequate and unattractive risk-return profile (Lypiridis and Kuzio, 2019). Accordingly, the acceptability of the financing of a sustainable investment project by a financial institution depends on having sufficient collateral and future cash flows to cover the bank's risk. The GST Report emphasizes the importance of reforming the multilateral financial architecture and introducing innovative sources of finance urgently in order to rapidly scale up climate change investments and achieve global climate goals. Financial innovation (FI), as defined by Khraisha and Arthur (2018), involves the creation, adoption, and integration of novel financial products, platforms, processes, or enabling technologies that transform financial activities. By enhancing efficiency and adaptability, FI addresses critical gaps in the financial landscape, driving economic progress, supporting sustainability, and meeting the evolving needs of modern economies. In this sense, FI can improve carbon emission efficiency (Dong et al., 2022) and promote environmental quality (Zeng et al., 2022) by increasing green technology innovation. In a broader context, the role of digital and financial transitions in supporting environmental goals has also been emphasized in other regional studies. For instance, Jóźwik et al. (2023) investigate the interconnected impacts of renewable energy consumption, digitalization, and financial development on environmental quality in Central European countries. While their findings highlight the mediating role of digitalization, the present study diverges by focusing instead on the innovation-driven aspects of finance in OECD economies and their direct influence on environmental quality, green technology, and renewable energy dynamics.

FI triggers green technological innovation (GTI) through two mechanisms: knowledge and resource effects (Liu and Chen, 2022; Yan et al., 2024). The introduction of creative/smart financial instruments and risk strategies through the knowledge effect channel of FI enables firms to be more flexible in the maturity structure of their liabilities. Moreover, the resource effect channel of FI reduces financial constraints (Liu et al., 2022; Li et al., 2023b) by enabling a shift from guarantee-based lending to a creditworthiness-based structure (Yan et al., 2024). Developments in the information age, on the one hand, reduce information asymmetry through

more effective corporate valuation methodologies (Gomber et al., 2018; Chen et al., 2021; Kong et al., 2022); on the other hand, they enable banks to provide more accurate lending and efficient allocation of resources (Berg et al., 2022).

A GTI strategy plays a vital role in a country's ability to tackle deteriorating environmental conditions and reconcile economic development and the environment (Liu and Chen, 2022). Therefore, a relationship can be established between GTI and the transition to renewable energy sources and environmental quality. Acemoglu et al. (2012) extend the theory of technological progress to the environment and define green technology innovation as a technology that can reduce pollution and/or have a positive impact on the environment. The positive effects of green technology innovation on energy saving and emission reduction can only be possible with a well-functioning financial system (Paramati et al., 2021; Khan et al., 2022).

Current studies mainly focus on the influence of FI on CO_2 and transformation of polluting industries (Elheddad et al., 2021; Tao et al., 2022a; Yu and Yan 2022; Cheng et al., 2023; Chipangamate and Nwaila, 2024; Ullah et al., 2024), green technology innovation (Dong et al., 2022; Liu and Chen, 2022; Borah et al., 2023; Li et al., 2023a) and environmental sustainability (Hou et al. 2022; Ran and Zhang, 2023; Wang et al., 2023a). Additionally, Çetin et al. (2022) examine the role of financial development in environmental degradation across 18 upper-middle-income countries, highlighting its mitigating effect on CO_2 emissions alongside the impact of renewable energy and urbanization.

The objective of this study is to identify the effects of FI on environmental quality, GTI, and renewable energy generation. More specifically, this research aims to examine the effects of FIs on environmental quality, analyze how GTIs are supported by FIs, and identify the function of FIs in renewable energy production (RE). The study focuses on 18 OECD countries using annual data for the period 2009-2021. In this context, the study aims to present to the literature in three different dimensions. First, it addresses a notable gap in empirical research by focusing on a multi-dimensional analysis of the relationship between FI, GTI, RE, and environmental quality within the context of OECD economies, which are largely underrepresented in this area compared to studies focused on China or developing countries. Second, it introduces a novel proxy for FI, calculated as financial sector R&D expenditure intensity, in contrast to traditional proxies based on credit or market development. This approach allows for a more targeted and innovation-oriented interpretation of financial dynamics, aligning with recent theoretical developments. Third, by integrating three interrelated dimensions, environmental quality, GTI, and RE, within a single econometric framework, this study captures the complex, multi-channel transmission mechanisms through which FI operates. This holistic approach contributes to a deeper and more interconnected understanding of the sustainability finance nexus. In this context, the present study explores three interrelated research questions. First, it examines whether financial innovation enhances environmental quality in OECD countries. Second, it investigates the extent to which financial innovation supports the development of GTI. Third, it analyzes the role of financial innovation in accelerating the production and adoption of renewable energy sources. These questions guide the empirical framework of the study and aim to contribute to a deeper understanding of the multidimensional link between financial systems and environmental sustainability.

This study is structured into five sections. Following the introduction, the second section presents a review of empirical literature on the links between financial innovation, GTI, renewable

energy, and environmental quality. The third section outlines the variables, model, and methodology used in the empirical analysis. The fourth section reports the findings from econometric tests, including cointegration, long-run estimations, and causality analysis. The final section concludes with key policy implications and suggestions for future research.

2. Literature Review

2.1. Financial Innovation and Environmental Quality

The information age has fundamentally transformed the relationship between economic actors - individuals, companies, and public authorities - and the economic systems in which they operate. Natural capital consists of natural resources and can replenish itself over time. However, increasing human pressure does not allow enough time for natural capital to renew itself, which increases the risk of resource depletion. On the one hand, depleted natural capital leads to decreased food and water security, increased prices of many products, and increased competition for land and water; on the other hand, increased competition for natural capital leads to conflicts, migration problems, and triggers climate change (WWF-Turkiye, 2012).

It is generally accepted that the environmental instruments developed can be classified into two main categories: market-based instruments and regulation-based instruments (Song and Han 2022; Sun et al., 2023). Song and Han (2022), in their research on 30 provinces of China in the period 2006-2018, stated that the impact of market-based environmental regulations on carbon efficiency is greater than that of command-and-control environmental regulations. Therefore, financial development in line with market-based environmental regulations may have a boosting effect on GTI opportunities (Fang and Shao, 2022).

There is an extensive literature that concludes that it is possible to effectively reduce CO_2 and thus improve environmental quality through green financing instruments (Elheddad et al., 2021; Muganyi et al., 2021; Muhammad et al., 2022; Ran and Zhang, 2023; Wang et al., 2023a; Zeng et al., 2023). Some empirical studies show that green finance has an indirect effect on reducing CO_2 by reducing financial constraints and supporting innovative green technologies (Ran and Zhang, 2023; Yan et al., 2023). The development of green finance and related green financial instruments can reduce the CO_2 of a local region and prevent the CO_2 of a wider region (Chen and Chen, 2021). Zeng et al. (2023) investigated the effect of green finance on greenhouse gas emissions and economic development in 30 Chinese provinces over the period 2008-2019. They stated that the growth of green finance reduces CO_2, which in turn promotes high-quality development, and a positive spatial spillover effect emerges. Muganyi et al. (2021) analyzed the impact of green finance policies in 290 cities in China between 2011 and 2018 and showed that financial technological developments have significantly reduced CO_2. However, Zhou et al. (2020), in their study covering 30 cities in China between 2010 and 2017, showed that the level of economic development is determinant in the relationship between green finance and environmental sustainability. In a related study, Çetin et al. (2023) examined the dynamics of environmental degradation in upper-middle-income countries and concluded that financial development and renewable energy use contribute to the reduction of CO_2 emissions. Although their analysis focuses on financial development rather than innovation, their findings reinforce the broader role of financial systems in shaping environmental quality outcomes. In a regional context, Jóźwik et al. (2023) explore the effects of renewable energy use, digitalization, and

financial development on environmental quality in Central European countries between 1995 and 2019. Their study highlights the mediating role of digitalization in the relationship between renewable energy consumption and CO_2 emissions, emphasizing how technological diffusion can amplify environmental outcomes. However, in contrast to that study, the current research employs a more innovation-specific, proxy financial sector R&D intensity within the more financially advanced context of 18 OECD countries. Furthermore, this study does not include digitalization as a mediating factor, but instead focuses on how financial innovation directly influences environmental quality, green technology innovation, and renewable energy capacity. This distinction underscores the unique methodological and conceptual framework of the present work.

Elheddad et al. (2021) considered the impact of electronic finance on CO_2 emissions in the period 2007-2016. The findings expose that electronic finance reduces CO_2 emissions and leads to a lower pollution rate in OECD countries. Muhammad et al. (2022) examined the impact of the fintech industry on environmental quality for 23 EU countries for the period 2013-2019. According to the results, the fintech industry increases environmental quality by facilitating the adaptation of green technologies to the system, thus reducing environmental pollution.

Another strand of the literature argues that the nature of the relationship between green finance and green innovation affects environmental quality. According to Huang et al. (2022), there is a strong positive correlation between green finance and green innovation, and this affects the ability of neighbouring provinces (regions) to follow green innovation. Cao et al. (2021) show that FI can improve China's energy and environmental performance through green innovation. Irfan et al. (2022) investigated the impact mechanism and policy intervention effects of inclusive green finance on green innovation using China's regional data from 2010 to 2019. The findings show that green finance contributes significantly to green innovation, and green financial innovation makes pilot regions more successful than other regions in promoting green innovation. Dong et al. (2022) showed that for 32 developed countries, green technology innovation significantly improves carbon emission efficiency, and financial development positively reduces the sensitivity of carbon emission efficiency to green technology innovation. Zheng et al. (2023) examined the impact of green finance on green energy innovation in countries with different levels of energy resources and economic development. The findings suggest that green finance positively affects renewable energy innovation, and that this effect is particularly strong in economies with relatively middle and low income levels. In a related study, Cetin et al. (2025) examine the role of technological innovation, renewable energy, and financial development in reducing ecological footprint in OECD countries, highlighting the broader importance of innovation-oriented policies for environmental sustainability. As a result, the following hypothesis was developed.

H_1: Financial innovation is a significant positive predictor of environmental quality in OECD countries.

2.2. Financial Innovation and Green Technological Innovation

According to the World Economic Forum's Global Risks Report (2023), while environmental risks are at the forefront, failure to mitigate and adapt to climate change is ranked as the most important source of global risk. Thus, the world is facing some of the most serious environmental threats, such as climate change and global warming, with carbon emissions (Dogan

et al., 2020) and increased energy consumption at the heart of these problems (Jiang and Ma, 2021).

According to the literature, it is possible to categorise the factors affecting green innovation as external and internal factors. Accordingly, green innovation is under the influence of external factors such as ensuring green productivity, which is the basis of the green economy (Wang et al., 2022), complying with the strict regulations enacted by governments (Li et al., 2022a), adapting to the demands of the stakeholders (interest groups) of the firms (Yu et al., 2022; Zameer and Yasmeen, 2022; Qu and Liu, 2022). However, internal factors such as organisational structure and culture, organisational knowledge system (Chaithanapat et al., 2022), identification and promotion of organisational capabilities, intellectual capital, infrastructure, and resources (Habib et al., 2019) are also drivers of green innovation.

Green innovation enables businesses to prioritize environmental safety and ecosystem concerns, such as waste and pollution reduction, waste recycling, and energy-efficient product design, while aligning with consumer demands (Qu and Liu, 2022). Tseng et al. (2013) classify GTI as a sub-heading of green innovation, together with definitions of management, product, and process innovation. Accordingly, GTI can be defined as the development of innovative processes, products, and technologies that minimize environmental impacts and optimize energy and raw material consumption (Braun and Wield, 1994; Guo et al., 2018).

While government and regulators play a major role in encouraging firms' green innovation activities, financing options and green finance (Ma and Wang, 2023) are also very important. Analysing the effect of financial constraints on firms' innovation performance, Zhang et al. (2019) and García-Quevedo et al. (2018) stated that limited sources of financing may cause firms to be reluctant to adopt innovative processes. Innovation processes are risky because they require large capital investments, and the level of profitability is uncertain (Tariq et al., 2017). Capital providers have concerns about providing capital for such risky projects (Cuerva et al., 2014), thus demanding higher premiums to compensate for this (Irfan et al., 2022). As a result, loans for projects that promote green technological investments are less likely to come from traditional financial institutions. The opportunities offered by FI, which Lerner and Tufano (2011) define as the creation of new financial instruments, institutions, and markets, can play an important role in overcoming these challenges.

The resource imbalance between financial institutions and the real economy can be addressed through FI (Huang et al., 2023). FI can encourage green technology innovation by justifying the allocation of credit resources, moderating short-term financing for long-term investment (Yan et al., 2024), indirectly by reducing financial constraints through improved personalised products/services (Kong et al., 2022; Liu et al., 2022), reducing the information asymmetry problem in traditional financial transactions (Liu et al., 2022; Ma and Wang, 2023). As a mode of FI, digital finance (Liu et al., 2022) increases green R&D investments by reducing financing constraints, thereby realizing green transformation and GTI in the long run (Li et al., 2023a). Hence, digital finance is a resource-conserving and environmentally sensitive financial service (Ding et al., 2023) and has enriched the financial market with numerous new financial products. For example, the green bond is an innovative financing instrument that provides the necessary financing for innovative green processes, engages private investors in green projects, and reduces the risks associated with development (Bhutta et al., 2022). Liu and Chen (2022) conducted an empirical analysis of the factors driving the effect of FI on green innovation,

focusing on the resource and knowledge effect. Their findings indicate that digital finance significantly enhances both the quantity and quality of green innovation by alleviating financial constraints faced by enterprises. Furthermore, they emphasize that digital finance leverages both internal and external knowledge effects, thereby fostering a more robust environment for sustainable innovation.

Li et al. (2023b) evaluated the impact of digital finance on green technology innovation in terms of production, consumption, financial institutions, and sustainability. Digital finance strengthens green investments and increases green production efficiency by supporting the resource needs for GTI and energy transition (Feng et al., 2022a; Feng et al., 2022b; Yu and Yan, 2022). The consumption dimension of digital finance is realized through increased demand for green products (Flores and Jansson 2022), which, together with increased consumer awareness of green innovation or sustainability, incentivizes firms to improve products and services and innovate green technology. Digital finance increases financial depth by diversifying the tools offered by financial institutions in traditional finance and provides financial instruments to support firms' GTI (Ding et al., 2023). Firms comply with stringent environmental regulations (Hou et al., 2022), but also turn to green innovation to ensure environmental quality and competitive advantage (Ding et al., 2023). In this sense, green digital finance provides financing to enterprises with SDGs. As a result, the following hypothesis was developed.

H_2: Financial innovation is a significant positive predictor of green technological innovation in OECD countries.

2.3. Financial Innovation and Renewable Energy

According to Lund (2007), technological innovation in the energy sector for the realisation of sustainable development has three sides: energy conservation on the demand side, increasing energy production efficiency on the production side, and finally, substitution of fossil fuels with various renewable energy sources on the conversion side. Energy transition refers to the shift from fossil fuels to low-carbon energy sources (An et al., 2022). The installation cost of renewable energy projects is relatively high compared to fossil fuels (Kösedağlı et al., 2021; Olabi and Abdelkareem, 2022; Li et al., 2022b; Wang et al., 2023b), and the amount of energy obtained is not constant (Li et al., 2022b). Despite these challenges, the main goals of renewable energy development are to reduce carbon emissions and oil price volatility, and to address concerns about energy security. The transition to renewable energy is critical for environmental sustainability, consistent with the United Nations Development Programme's (UNDP) SDGs 7, 8, 11, 12, and 13.

The impact of financial development on energy use can occur through four channels (Sadorsky, 2011; Çoban and Topcu, 2013; Croutzet and Dabbous, 2021): The development of the financial sector facilitates consumers' access to durable goods and increases energy consumption, which is referred to as a 'direct effect'. The 'commercial effect' is that financial development enables new enterprises to enter the market, grow, and directly affects energy demand by increasing production. If financial development increases confidence, it may increase economic activities that support energy demand, which is the 'wealth effect'. Finally, in the 'substitution effect' defined by Croutzet and Dabbous (2021), financial development facilitates access to finance for innovative technology projects and/or activities that can reduce energy demand or

save energy. In this context, financial development affects renewable energy sources in two main ways: First, for the owners or operators of renewable energy assets; and second, for companies that produce or manufacture renewable energy technologies (OECD, 2020). Therefore, FIs influence consumption, saving, and investment decisions in the renewable energy sector (Croutzet and Dabbous, 2021). It is important to offer new financing options/products to renewable energy investors through FIs (Chen et al., 2017; Li et al., 2022c). In this context, Hussain and Papastathopoulos (2022) emphasize the importance of conducting a comprehensive analysis that integrates multiple dimensions, including customer expectations, technical requirements, financial service delivery processes, and the capabilities of FI. They highlight that a holistic approach to these interrelated factors is crucial for understanding and optimizing the role of FI in addressing evolving market demands and fostering sustainable financial practices.

There is extensive literature on the effects of FIs on companies producing or manufacturing renewable energy technologies. For example, part of the literature has focused on the effect of financial improvement on energy usage and found positive findings (Shahbaz et al., 2016; Raza et al., 2020; Croutzet and Dabbous, 2021; Khan et al., 2020; Wang et al., 2021). Croutzet and Dabbous (2021) examined the relationship between FinTech developments and renewable energy consumption in 21 OECD countries in the period 2005-2018 and showed that there is a positive relationship between these two variables. On the other hand, Assi et al. (2021) concluded that financial improvement does not affect renewable energy consumption in their study of ASEAN+3 countries.

Another body of research in the literature addresses the link between FI and energy transition. While there is a mature market for conventional energy, technological limitations and financial barriers emerge as important constraints in renewable energy (Peimani, 2018). Traditional financial institutions are driven by profit maximization and a risk-return basis for their transactions. The large amount of initial investments and relatively long payback periods of energy transition initiatives make it difficult for these initiatives to find financing (Tao et al., 2022b). Therefore, the role of the financial system (institutions and instruments) is of considerable importance in shaping the dynamics and pace of development of the energy transition (Appiah-Otoo et al., 2023; Chipangamate and Nwaila, 2024). In this sense, green financial instruments (Wang et al., 2023c), an innovative financial instrument related to environmental protection, can provide financing for energy transition initiatives (Rasoulinezhad and Taghizadeh-Hesary, 2022). Ainou et al. (2023) propose the development of Morocco's energy transition through increasing the use of renewable energy and efficient technologies, which can be achieved through the implementation of green investment projects.

On the other hand, the relationship between FI and energy transition can also be influenced by factors such as the functioning of the financial system and public policies/legislation (Wang and Zhi, 2016; Nguyen et al., 2021; Meo and Karim, 2022). Hou et al. (2023) demonstrated that the impact of green finance on renewable energy development is more pronounced in economically advanced countries characterized by well-established green finance frameworks and stringent environmental regulations. Conversely, in less economically developed nations with weaker green finance infrastructure and lax environmental policies, the impact of green finance on energy transition is comparatively weak. Olaniyi et al. (2023) also stated that the effectiveness of the financial system in supporting and delivering the significant financial impacts required by the transition to renewable energy depends on the quality of the institutional framework. As a result, the following hypothesis was developed.

H_3: Financial innovation is a significant positive predictor of renewable energy production in OECD countries.

3. Methodology

3.1. Data Collection and Models

The primary purpose of this study is to investigate the impact of FI on environmental quality, GTI, and RE. In the study, 18 OECD countries (Canada, Estonia, Finland, Germany, Israel, Italy, Japan, Korea, Lithuania, Netherlands, Norway, Portugal, Slovenia, Spain, Turkey, United States, Denmark, Belgium, Czechia) were studied. Annual data for the period 2009-2021 are used. Based on the studies of Beck et al. (2016), Bernier and Plouffe (2019), and Ullah et al. (2024), FI is measured by taking into account research and development (R&D) expenditures in the financial sector and the value added by these expenditures to the sector. The relevant data are obtained from the Analytical Business Enterprise Research and Development (ANBERD) database, which allows for detailed monitoring of the innovative activities of the financial sector at the global level. This database allows us to examine the economic impact of FI and its innovative contributions to the sector more comprehensively. In this context, the dependent and independent variables used in the research are given in Table 1.

The selection of the period 2009–2021 is based on both theoretical relevance and data availability. First, 2009 marks a turning point in global financial regulation and innovation, following the 2008 global financial crisis, which triggered substantial reforms and the emergence of new financial instruments aimed at increasing resilience and sustainability. Simultaneously, the OECD and its member countries began to intensify their commitments to environmental policies and green innovation in the aftermath of the crisis. Second, the starting year aligns with the availability of consistent and comparable FI-related R&D data from the ANBERD database across selected OECD countries. The year 2021 was chosen as the endpoint due to the most recent and complete dataset coverage across all variables and countries during the preparation of this study. This period thus captures a full post-crisis cycle, overlapping with significant climate policy initiatives and financial innovation trajectories, making it both analytically meaningful and empirically robust.

Table 1. Data Description

Variable(s)	Symbol	Measurement Units	Data Source
Financial innovation	FI	Financial sector R&D expenditures intensity (% of value added).	ANBERD
Carbon emissions	CO_2	CO_2 emissions (metric tons per capita).	WDI
Green technological innovation	GTI	Development of environment-related technologies, % inventions worldwide.	WDI
Renewable energy production	RE	Renewable electricity output (% of total electricity output).	IEA
Income	GDP	GDP per capita (constant 2015 US$).	WDI

Note: ANBERD is now indicated as Analytical Business Enterprise Research and Development https://www.oecd.org/
WDI is now indicated as World Development Indicators (World Bank) https://databank.worldbank.org/source/world-development-indicators
IEA is now indicated as International Energy Agency https://www.iea.org/

Table 1 shows the dependent and independent variables used and Figure 1 shows the research model.

$$CO_{2i,t} = \beta_0 + \beta_1 FI_{i,t} + \beta_2 GTI_{i,t} + \beta_3 RE + \beta_4 GDP + \varepsilon_{i,t} \quad (1)$$

$$GTI = \beta_0 + \beta_1 FI_{i,t} + \beta_2 RE_{i,t} + \beta_3 GDP + \varepsilon_{i,t} \quad (2)$$

$$RE_{i,t} = \beta_0 + \beta_1 FI_{i,t} + \beta_2 GTI_{i,t} + \beta_3 GDP_{i,t} + \varepsilon_{i,t} \quad (3)$$

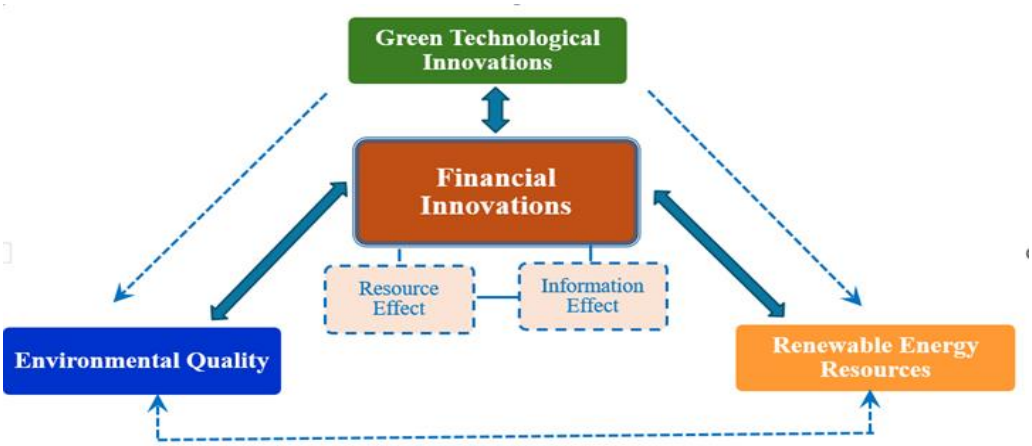

Figure 1. Research Model

3.2. Empirical Procedure

In the first stage of the study, cross-section dependence (CSD) tests are conducted using the Breusch-Pagan LM test (Breusch and Pagan, 1980), Pesaran's scaled LM (CD_{LM}) and CD tests (Pesaran, 2004), and the Bias-Corrected Scaled LM (LMadj) test (Pesaran et al., 2008), as outlined in equations 4 to 7.

$$LM = T \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij}{}^2 \quad (4)$$

$$CD_{LM} = \sqrt{\frac{1}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left(T\hat{\rho}_{ij}{}^2 - 1\right) \quad (5)$$

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

$$LM_{adj} = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left[\hat{\rho}_{ij}^2 . \frac{(T-K-1)\hat{\rho}_{ij} - \hat{\mu}_{Tij}}{v_{Tij}} \right] \sim N(0,1) \quad (7)$$

Then, the Δ tests calculated by Pesaran et al. (2008) are used. Blomquist and Westerlund (2013) Δ tests are used since there is serial correlation and variance in regression error terms and are shown in equations 8, 9, 10 and 11:

$$\Delta_{HAC} = \sqrt{N}\left(\frac{N^{-1}S_{HAC} - k}{\sqrt{2k}}\right) \tag{8}$$

$$S_{HAC} = \sum_{i=1}^{N} T\left(\hat{\beta}_i - \hat{\beta}\right)'\left(\hat{O}_{iT}\hat{V}_{iT}^{-1}\hat{O}_{iT}\right)\left(\hat{\beta}_i - \hat{\beta}\right) \tag{9}$$

$$\hat{\beta} = \left(\sum_{i=1}^{N} T\hat{O}_{iT}\hat{V}_{iT}^{-1}\hat{O}_{iT}\right)^{-1}\sum_{i=1}^{N}\hat{O}_{iT}\hat{V}_{iT}^{-1}X_i'M_T y_i \tag{10}$$

$$\hat{V}_{iT} = \hat{\Gamma}_i(0) + \sum_{j=1}^{T-1} K\left(\frac{j}{M_{iT}}\right)\left[\hat{\Gamma}_i(j) + \hat{\Gamma}_i(j)'\right] \tag{11}$$

Then, the stationarity analysis of the series is performed using Pesaran (2007) cross-sectionally augmented ADF (CADF-Cross Sectionally Augmented Dickey Fuller) and CIPS (cross-sectionally augmented IPS) tests and equations 12, 13, 14, 15 and 16 are shown below:

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + u_{it} \tag{12}$$

$$u_{it} = \gamma f_t + \varepsilon_{it} \tag{13}$$

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t-1} + d_0\bar{y}_{t-1} + d_1\Delta\bar{y}_t + \varepsilon_{it} \tag{14}$$

$$\Delta y_{i,t} = \alpha_i + \rho_i y_{i,t-1} + c_i\bar{y}_{t-1} + \sum_{j=0}^{p} d_{i,j}\,\Delta\bar{y}_{t-j} + \sum_{j=0}^{p}\beta_{i,j}\,\Delta y_{i,t-j} + \mu_{i,t} \tag{15}$$

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i \tag{16}$$

In the next stage, the long-run cointegration relationship between the variables is analyzed with Westerlund and Edgerton (2007) Panel Lagrange Multiplier (LM) tests. Westerlund and Edgerton (2007) cointegration test using the Langrange test multiplier (McCoskey and Kao, 1998) and is shown in equations 17, 18 and 19.

$$\gamma_{it} = \alpha_i + x_{it}'\,\beta_{it} + Z_{it} \tag{17}$$

$$Z_{it} = \mu_{it} + V_{it}\; V_{it} = \sum_{J=1}^{t}\eta_{ij} \tag{18}$$

$$LM_N^{+} = \frac{1}{NT^2}\sum_{i=1}^{N}\sum_{t=1}^{T}\widehat{\omega}_i^{-2}\,S_{it}^2 \tag{19}$$

The panel corrected standard error (PCSE) (Beck and Katz, 1995) approach is used because it is robust to heteroskedastic, autocorrelation and CDS problems and valid for T<N (Baltagi, 2008). The PCSE model is shown in equations 20, 21, and 22.

$$y_{it} = x_{it}\beta + \varepsilon_{it} \tag{20}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} \beta + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_m \end{bmatrix} \quad (21)$$

$$\sum[\varepsilon\varepsilon'] = \Omega = \begin{bmatrix} \sigma_{11}I_{11} & \sigma_{12}I_{12} & \cdots & \sigma_{1m}I_{1m} \\ \sigma_{21}I_{21} & \sigma_{22}I_{22} & \cdots & \sigma_{2m}I_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{m1}I_{m1} & \sigma_{m2}I_{m2} & \cdots & \sigma_{mm}I_{mm} \end{bmatrix} \quad (22)$$

Finally, Dumitrescu and Hurlin (2012) causality test can be used in the case of heterogeneous panels, N>T or T>N and horizontal CSD (Dumitrecu and Hurlin 2012). The linear model testing the causality relationship between variables X and Y is shown in equation 23

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \beta_{ik}\, y_{i,t-k} + \sum_{k=1}^{K} \gamma_{i,k}\, X_{i,t-k} + \varepsilon_{it} \quad (23)$$

4. Findings

In this section, empirical findings on the impact of FI on environmental quality, GTI, and RE are presented. The summary statistics in Table 2 reveal that variables such as carbon emissions (CO_2), financial innovation (FI), GTI, renewable energy generation (RE), and income (GDP) show significant differences across countries. Indicators such as CO_2 and FI have a high variance across countries, which may be largely due to differences in the level of economic development and differences across sectors. GTI and renewable energy generation similarly show a wide dispersion in line with countries' environmental policy priorities and investments in technology. Income level, with its high variance, reflects economic inequality across countries. These findings suggest that environmental and economic factors are shaped interactively rather than independently and that sustainability strategies differ across countries.

Table 2. Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
FI	234	491.9723	1484.635	0.83	12896.17
CO	234	8.498241	3.44152	3.7	17.43
GTI	234	3105.619	5463.64	4.67	18452.13
RE	234	19.9287	13.7495	1.2	60.9
GDP	234	37098.51	18508.81	8638.74	103553.8

The correlation analysis in Table 3 reveals the relationships between the variables. There is a negative relationship between FI and CO_2, indicating that CO_2 may tend to decrease as FI increases. There is a positive relationship between FI and GTI, and renewable energy consumption.

Table 3. Correlation Analysis

	FI	CO	GTI	RE	GDP
FI	1.0000				
CO	-0.3941	1.0000			
GTI	0.4837	-0.5234	1.0000		
RE	0.1473	-0.2395	0.4811	1.0000	
GDP	0.2967	0.2825	0.1663	0.4195	1.0000

The cross-sectional dependence tests in Table 4 show that statistically significant results are obtained for all variables. The results of the Breush-Pagan LM, Pesaran scaled LM, Bias-corrected scaled LM, and Pesaran CD tests reveal that each variable (CO_2, FI, GTI, RE, and GDP) shows horizontal CSD. In other words, the null hypothesis H0 "there is no horizontal CSD" is rejected, and it is concluded that there is horizontal CSD for all series.

Table 4. CDS Test

Variable(s)	**FI**	**CO**	**GTI**	**RE**	**GDP**
Breush-Pagan LM	758.54*	527.54*	485.05*	928.21*	574.85*
Pesaran scaled LM	31.85*	21.37*	18.71*	65.59*	20.18*
Bias-corrected scaled LM	23.28*	20.18*	17.55*	48.95*	15.86*
Pesaran CD	10.79*	8.59*	6.89*	29.92*	11.85*

Note: * denotes significance at 1% level.

The results of the slope homogeneity test are presented in Table 5. The findings of the test developed by Blomquist and Westerlund (2013) reveal that there is no slope homogeneity in the models used in the study, and the hypothesis H_0 is rejected. In other words, these results suggest that the slopes in the analyzed models are heterogeneous, i.e., there are different trends and relationships across countries or observations.

Table 5. Slope Homogeneity

Models	**Statistics**
$\tilde{\Delta}$	14.68*
$\tilde{\Delta}$adj	9.85*

Note: * denotes significance at 1% level.

The CIPS and CADF unit root test results in Table 6 examine the stationarity of the variables used in the study. CADF and CIPS tests are second-generation panel unit root tests used in cases of cross-sectional dependence (CSD) and provide more accurate results. The test results show that variables are stationary when first differences are taken. This finding indicates that the null hypothesis H_0 (the hypothesis that the series are unit-rooted) is rejected, i.e., they are stationary. This result shows the validity of the model and provides a more reliable analysis of the dynamics of the variables used.

Table 6. Unit Root Test

Variable	**CIPS and CADF test statistic for constant**	
	first difference	**first difference**
FI	-6.75*	-3.86*
CO	-5.64*	-3.31*
GTI	-5.25*	-3.24*
RE	-6.79*	-3.95*
GDP	-7.85*	-4.62*

Note: * denotes significance at 1% level.

In Table 7, the Westerlund-Edgerton LM Bootstrap (2007) test is applied to determine the long-run cointegration relationship between the variables. According to the test results, it is observed that the Bootstrap p-value is greater than 0.10 in all models. In this case, the null hypothesis H_0 is accepted. This indicates that there is a long-run cointegration relationship between the variables. In other words, the variables used in all models move together in the long run and exhibit a cointegrated relationship with each other.

Table 7. LM Bootstrap Cointegration Test

Models	Test	LM Statistics	Asymptotic-p	Boostrap-p
Model 1	LMN^T	11.28	0.0001	0.652
Model 2	LMN^T	14.85	0.0000	0.727
Model 3	LMN^T	16.53	0.0000	0.808

Note: The number of bootstrap iterations is 1000.

The long-run estimator results in Table 8 reveal the effects of the independent variables used in three different models on the dependent variables. In Model 1, CO_2 carbon emission is utilized as the dependent variable. According to the results, the impact of FI on CO_2 is negative and significant ($p < 0.05$). This indicates that FI has an effect on reducing CO_2. That is, innovative practices of the financial sector can reduce CO_2 by enabling the financing of environmentally friendly projects. The findings are consistent with those of Cao et al. (2021) and Ullah et al. (2024). In addition, GTI and RE variables also have negative effects on CO_2, suggesting that green technologies and RE support environmental sustainability and have the potential to reduce CO_2. The positive effect of the GDP variable on CO_2 indicates that economic growth may increase CO_2. This result can be attributed to the fact that growing economies impose environmental costs, especially the use of high-carbon-emitting resources such as fossil fuels.

Table 8. Panel Estimator Results

	Model 1	Model 2	Model 3
Variables	**CO_2**	**GTI**	**RE**
FI	-1.99**	5.64***	3.78***
	(-0.03)	(1.30)	(0.26)
GTI	-4.44***	-	-2.14**
	(-0.02)		(-0.05)
RE	-2.14**	9.90***	-
	(-0.04)	(25.34)	
GDP	3.64***	5.28***	14.39***
	(0.04)	(0.09)	(0.25)
Constant	14.12***	5.73***	-5.04***
	(6.74)	(36.12)	(-4.83)
chi2	111.49	3955.27	234.80
R-squared	0.3404	0.4735	0.5598
p	0.0000	0.0000	0.0000

Note: Values in parentheses represent standard errors. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

In Model 2, the dependent variable is GTI. The findings of the model show that FI and GDP variables have positive and significant effects on GTI. It reveals that FI encourages GTI and thus contributes to the development of environmentally friendly technologies. These findings are

consistent with the findings of authors such as Kong et al. (2022); Liu et al. (2022); Ma and Wang (2023), and Yan et al. (2024). In Model 3, RE is used as the dependent variable, and in this model, the effect of the FI variable on RE is analyzed. The findings indicate that the FI variable has a significant and positive effect on RE. This suggests that FIs have the potential to encourage investments in environmentally friendly technologies, especially in renewable energy. These findings are in line with those of Meo and Karim (2022); Ainou et al. (2023); Wang et al. (2023). It also reveals the strong positive effect of GDP and GTI variables on RE. This shows the significant relationship between economic growth and RE and that growing economies tend to generate more renewable energy. The effect of GTI on RE is also quite high, with GTIs accelerating developments in RE.

Table 9. Panel Causality Test

	W bar	Z bar	p
$CO \nrightarrow FI$	0.785	0.554	0.751
$FI \nrightarrow CO$	3.875	2.954	**0.011**
$GTI \nrightarrow FI$	4.453	3.646	**0.000**
$FI \nrightarrow GTI$	5.452	4.632	**0.000**
$RE \nrightarrow FI$	0.544	0.458	0.854
$FI \nrightarrow RE$	3.857	3.058	**0.003**
$CO \nrightarrow GTI$	0.875	0.658	0.524
$GTI \nrightarrow CO$	4.780	3.289	**0.000**
$CO \nrightarrow RE$	1.105	0.928	0.195
$RE \nrightarrow CO$	5.297	4.278	**0.000**
$CO \nrightarrow GDP$	0.895	0.596	0.562
$GDP \nrightarrow CO$	5.582	3.954	**0.000**
$GTI \nrightarrow RE$	4.528	3.962	**0.000**
$RE \nrightarrow GTI$	5.198	3.864	**0.000**
$GTI \nrightarrow GDP$	3.985	2.985	**0.023**
$GDP \nrightarrow GTI$	4.472	3.582	**0.000**

Note: The maximum lag length is set as 1.

Table 9 presents the results of the Dumitrescu–Hurlin panel causality test conducted to examine the direction and existence of causal relationships among the variables. The findings reveal several key insights. First, a bidirectional Granger causality exists between FI and GTI, as well as between GTI and RE, and between GTI and GDP, indicating strong mutual interdependence. Second, unidirectional Granger causality is observed from FI to CO_2, FI to RE, GTI to CO_2, RE to CO_2, and GDP to CO_2, implying that changes in FI, GTI, RE, and economic growth significantly Granger-cause variations in carbon emissions, but not vice versa. These results suggest that financial innovation not only drives improvements in environmental quality but also promotes technological and energy transitions. Moreover, the bidirectional causality between FI and GTI underscores a potential endogeneity concern, highlighting the dynamic and reinforcing nature of financial innovation and green technology. It is important to note that all causality interpretations are made in the Granger sense and do not imply direct structural causation.

5. Results and Discussion

In this paper, the effect of FI on ecological quality, GTI, and RE is investigated using annual data of 18 OECD countries for the period 2009-2021. As a result of the analysis, it was found that FI improves environmental quality. This finding shows that FI is an important tool to promote environmental sustainability. By supporting the financing of investments in green technologies and renewable energy projects, FI can reduce the use of environmentally damaging traditional energy sources. In this context, FIs can accelerate an economic transformation to reduce carbon emissions and increase environmentally friendly investments. Moreover, the adoption of incentive policies by financial institutions that increase resource allocation for environmentally friendly projects will contribute to the reduction of CO_2 and the growth of the green economy. In line with these findings, policymakers and financial institutions are recommended to develop strategies to strengthen financial mechanisms that promote sustainable growth and reduce environmental impacts.

It is also found that FI positively affects GTIs. This finding suggests that FIs encourage investments in the development and implementation of environmentally friendly technologies. GTIs offer great potential for advances in areas including the development of low-carbon production processes, energy-efficient solutions, and the use of environmentally friendly materials. FIs contribute to faster deployment of green technologies by increasing the financing of such projects, especially through instruments such as green bonds, environmentally friendly loans, and sustainable investment funds. To this end, it is important to structure financial markets to support investments in green technologies. Governments and financial institutions can develop incentive policies such as tax incentives, low-interest loans, and government-backed funds for companies investing in green technologies. Moreover, the resources provided by FIs will enable more green technology startups to emerge and ensure environmental sustainability. In this context, regulators in the financial sector need to put in place appropriate regulations to support the diffusion of green technologies and increase the accessibility of green investment instruments.

Another important finding of the study is that FI positively affects RE. These results emphasize the importance of increased investment and financing opportunities for sustainable energy solutions. Innovative financial instruments, especially green bonds, green credit mechanisms, and financial products based on environmental risks, play a critical role in financing renewable energy projects. These instruments facilitate the channeling of investors into this sector, allowing for increased RE and reduced dependence on fossil fuels. The impact of FIs in this area can not only ensure environmental sustainability but also strengthen energy security and economic development. Moreover, increased financial resources for renewable energy projects can help to realize them more efficiently and sustainably. Dedicated funding for renewable energy projects by governments and international financial institutions would allow these projects to grow rapidly and enable more innovative solutions in energy production. Thus, FIs can not only contribute to the sustainability of energy production, but also to economic development, environmental protection, and strengthening the security of energy supply.

As a result, FIs positively affect environmental quality, GTIs, and RE. The findings suggest that FIs encourage investments in environmentally friendly projects, accelerate the development of green Technologies, and reduce dependence on fossil fuels by increasing RE. These results suggest that the financial sector and innovation play a critical role in achieving environmental goals. In future studies, research on the environmental impacts of FIs can be expanded to cover a

wider time period and more countries. In addition, in-depth analysis on a sectoral basis would allow for more specific identification of the impacts on the financing of green technologies and renewable energy projects.

In light of the findings, several concrete policy implications can be drawn. First, governments should establish targeted green financial frameworks that facilitate the issuance and regulation of green bonds, ensuring transparency, traceability, and alignment with international sustainability standards (e.g., EU Green Bond Standard, ICMA Principles). These frameworks can enhance investor confidence and scale up financing for environmentally sustainable projects. Second, central banks and financial regulatory authorities should incorporate climate-related risks into financial supervision practices, such as climate stress testing and mandatory ESG reporting, thereby incentivizing banks to prioritize low-carbon investments in their portfolios. Third, tax-based incentives such as deductions or exemptions can be provided for private firms engaging in financial R&D focused on sustainability or for issuing green financial products. Similarly, subsidized credit programs or guarantee mechanisms can reduce the perceived risk of investing in early-stage green technologies and renewable energy startups. Fourth, public–private partnerships (PPPs) can be leveraged to scale RE infrastructure, especially in countries with high transition costs. Public investment in green technology incubators and innovation clusters can accelerate the commercialization of GTI. Finally, OECD-level coordination should be promoted to harmonize green finance taxonomies and reporting systems across member states. This will reduce regulatory fragmentation and facilitate cross-border investment flows into green sectors.

Declaration of Research and Publication Ethics
This study which does not require ethics committee approval and/or legal/specific permission complies with the research and publication ethics.

Researcher's Contribution Rate Statement
I am a single author of this paper. My contribution is 100%.

Declaration of Researcher's Conflict of Interest
There is no potential conflicts of interest in this study.

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