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Examining the growth-environment nexus in OECD countries in relation to factors that shape sustainable outcomes

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Abstract

The study aims to empirically examine the dynamic linkages among financial development, foreign direct investment (FDI) inflows, economic growth, economic complexity, energy innovation, urbanization, renewable energy consumption, and environmental degradation across 37 Organization of Economic Cooperation and Development (OECD) economies from 1990 to 2024. The pooled mean group–autoregressive distributed lag approach measures long-run homogeneity while allowing short-run heterogeneity. The empirical estimates highlight the need for OECD countries to improve environmental performance across key sectors, such as finance and urbanization. This will help mitigate degradation through eco-friendly technologies. In the short run, however, urban activities and FDI fail to meet environmental standards. Thus, OECD economies need to reduce degradation, protect biodiversity, and use resources efficiently. The study makes a significant contribution to the literature by examining key financial, economic, and environmental factors for OECD countries.

Keywords: Financial development; Environmental degradation; Economic complexity; Renewable energy; Energy innovation; Foreign direct investment

1. Introduction

The complex nexus between economic growth (EG), financial development, foreign direct investment (FDI), environmental degradation (ED), and globalization has attracted increased scholarly and policy attention worldwide in recent years. Although EG remains necessary to improve living standards, alleviate poverty, and promote social welfare, empirical studies highlight its tendency to increase environmental strain, including high carbon dioxide (CO_2) emissions and resource use, especially in developed economies such as those of the Organization of Economic Cooperation and Development (OECD).[1] This culminating tension has triggered a paradigm shift to sustainable development, which aims to find a feasible balance between sound economic development, environmental conservation, and fair social results.[2] This complicated interplay demands a detailed explanation of the mechanisms through which financial development and FDI affect the environmental quality in the specific environment of the OECD countries.[3,4] The paradigm shift to sustainable development highlights the necessity to balance economic prosperity and environmental sustainability with social equity because it emphasizes a balanced approach at the economic, societal, and environmental levels.[5] It is still an active area of international exploration, as researchers and political leaders emphasize the necessity to achieve economic sustainability and reduce environmental deterioration in the face of growing demands of growth-driven extraction of resources, pollution, and emissions[6]. The increased international focus on ED and climate change has been manifested in rising energy and infrastructure demands, which strain sustainable empirical research and reverse the knotty interrelationships between financial development, FDI, and their overall impact on CO_2 emissions and ecological well-being.[7]

The OECD countries lead the world debate on the need to balance EG and environmental sustainability, as they account for a large share of global economic production, international investment inflows, and technological innovation.[8] Such countries have enjoyed significant economic development and technological growth, but this growth has led to environmental destruction by depleting resources, polluting the environment, causing deforestation and habitat destruction, and increasing greenhouse gas emissions due to industrialization, urbanization, and energy-intensive activities.[9] As a result, it is important to understand the complex interplay between these economic variables and environmental performance within the OECD to inform policies that balance prosperity and environmental conservation. The existing literature shows that although financial development may lead to increased environmental pollution through enhanced industrialization, high-level financial markets are usually associated with cleaner environments, suggesting a complex, non-linear relationship.[10]

Moreover, the OECD has made significant progress in addressing sustainability challenges through numerous regulations and initiatives since 1961. In particular, the strategic shift of the OECD in 2000–2014 was defined by shifts in EG and energy use. The organization began focusing on renewable energy sources as alternatives to fossil fuels to reduce environmental destruction. The shift to renewable energy sources resulted in lower ED rates in OECD countries.[11] The adoption of more green technologies has contributed to reduced ED compared to non-OECD countries, due to the efforts of OECD. Efforts have reduced average death rates per 100,000 due to pollution, but some countries have experienced increases. The highest CO_2 emissions were in 2007, and they have since begun to decline; the proportion of OECD countries in the world has now fallen to 35%. Nevertheless, these activities do not eliminate the problem of ED in certain OECD countries, which creates the challenge of fully implementing green growth policies, a challenge that can be explained by the complex interplay of social and financial circumstances. This requires a careful analysis of the role of financial development in mediating the effect of technological innovation on environmental indicators across OECD countries.[12] Thus, within the framework of these sustainability actions, the OECD has prepared an extensive framework to assess the improvement of the member countries on a systematic basis, covering major dimensions, including environmental and resource productivity, natural assets, environmental quality of life, economic opportunities, and policy responses. Among the main points of Sustainable Development Goal (SDG) 12.2 is the inclusion of sustainable management and the effective use of natural resources, which aligns with broader demands for ecological conservation amid economic demands. Equally, SDG 8.4 aims to decouple EG from increased material consumption and ED, especially by increasing resource productivity. The goals emphasize that efficient natural resource management and sustainable practices cannot be achieved without advancing sustainable development goals, particularly in developed economies that must balance growth with ecological boundaries. In the case of OECD countries, which are the most sustainable globally but face challenges posed by industrialization and urbanization, this management is crucial to reducing pollution and resource exploitation. It is interesting to note that OECD material productivity has also increased significantly, with the economic value generated per kg of materials used increasing from USD 2.0 in 2006 to USD 2.9 in 2017, indicative of green growth approaches and the use of technologies that reduce environmental impacts compared to non-OECD counterparts.[13]

Overall, ED is an important concern in OECD countries, driven by industrialization, urbanization, resource depletion, pollution, deforestation, habitat loss, and high greenhouse gas emissions. Although there have been significant improvements in green growth strategies, such as the OECD framework of green growth indicators, material productivity has increased to USD 2.9 in 2017, up from USD 2 per kg in 2006, and the global share of CO_2 emissions has decreased. This is possible with specific policies and actions, such as strict environmental policies, incentives to switch to renewable sources, investments in clean energy and transportation, and mass education, as the example of OECD shifts to renewable sources has reduced degradation compared to its non-OECD counterparts. It is important in the context of OECD countries, where advanced economies dominate global production, FDI, EG, and environmental outcomes, but struggle to balance between economic vitality and ecological preservation.[14] Nevertheless, regardless of the increasing literature in the field of environmental economics, there is still a significant research gap in the comprehensive exploration of the subtle mechanisms and dynamic interactions that mediate these influences, especially the moderating effects of economic complexity (EC) and energy innovation (EI). The EC, which is the variety and sophistication of the export basket of a nation, its sub-elements such as process, product, production, and value chain complexity, and its connection with high levels of industrial capacity and technical skills, significantly influences the formation of economic structures, innovation, and environmental processes. A more comprehensive understanding of the pattern of degradation and a further clarification of the sustainability policies may be achieved by exploring the different environmental outcomes experienced in the OECD countries with different levels of EC.[15]

The literature on environmental sustainability and EG has grown significantly; however, prior research has largely examined the impacts of factors like individual factors, such as financial development, renewable energy use, EC, FDI, and urbanization, separately, where only a handful of empirical studies explored the inclusion of these factors in a broader dynamic model. Furthermore, few studies have considered both cross-sectional dependence (CD) and the different adjustment processes across advanced OECD countries simultaneously. To address these shortcomings, the present study uses a pooled mean group (PMG)–autoregressive distributed lag (ARDL) method to examine the long- and short-run relationships among these variables, based on the latest OECD panel data. It mainly aims to investigate the causal and feedback relationships among financial development, FDI inflows, and EG on indicators of ED (CO_2 emissions as a proxy) amid ongoing crises such as industrialization, urbanization, and resource depletion. It also examines how EC, in turn representing export sophistication, industrial capacity, and value chain intricacy, and renewable EI moderate these relationships, where limited previous studies provide empirical evidence on their functions. By filling this significant research gap, particularly the understudied dynamics, the study contributes to the theoretical understanding of these dynamics and provides policymakers with evidence-based approaches to meet sustainable development targets.

2. Literature review

2.1. Economic complexity's role in environmental degradation

Environmental degradation is a complex phenomenon with a strong impact on interrelated political, social, and economic systems, extending well beyond climate change and variability. Environmental degradation requires a holistic approach that combines these dimensions to explain current and past environmental changes. Within OECD nations, factors such as intense industrialization, rapid urbanization, economic expansion, resource depletion, pollution, and overpopulation lead to degradation through increased resource extraction, ecosystem pressure, infrastructure development, and greenhouse gas emissions. These factors are dynamic and tend to increase negative trends unless mitigated by sustainable policies, and their central role in the formation of environmental paths towards or away from sustainability is clear.[16]

The ED present in OECD countries is a complex problem with the impact deeply rooted in interrelated political, social, and economic processes, such as intensive industrialization, rapid urbanization, EG, resource depletion, pollution, overpopulation, and CO_2 emissions, which go well beyond climate change. These forces encourage degradation by increasing resource extraction, straining ecosystems due to increased energy and raw materials demand, infrastructure development, and greenhouse gas emissions, which put pressure on ecosystems and contribute to pollution, deforestation, and habitat loss in developed economies. Such processes intensify during the structural shift from agrarian to industrial economies, marked by increased production of goods with high pollution levels, poor waste management, and the weakening of environmental regulations. This transition increases the use of non-renewable energy sources, increases resource extraction, increases pressure on ecosystems, and increases greenhouse gas emissions. Overpopulation also increases degradation through greater resource use, pollution, and consumer demand, further exacerbated by increased manufacturing and infrastructure development.[17]

Environmental degradation is greatly affected by EC. This idea is associated with economic frameworks. According to a few economists, EC is the key variable of EG. Innovation in technology and product composition plays a key role in determining environmental quality, including production efficiency and emission levels. The concept of EC involves process, product, production, and value chain intricacy sub-components that imply the sophistication of productive forces of a given country. Researchers believe that sustainable industrialization is impossible without positive changes in the complexity of processes, products, and value chains, and that technological changes transform production structures at various levels. The high level of EC is an indicator of strong industrial and production capacity and high technical skills, which allow resources to be used more efficiently and, potentially, alleviate the negative environmental impact in OECD countries by introducing cleaner technologies and diversified exports.[18] According to this framework, the more economically complex countries, especially those with highly sophisticated and diverse export portfolios, are more likely to exhibit environmentally conscious behaviors and adopt cleaner production technologies, which can considerably alleviate ecological constraints.

Technological innovation, EC, and financial development have become key drivers of environmental sustainability, enabling efficient resource use, cleaner technologies, and green financing. However, the existing empirical evidence on the role of EC in ED is limited, underscoring the importance of examining how it operates dynamically. The Environmental Kuznets Curve (EKC) theory assumes an inverted U-shaped pattern, in which the EG and ED are interrelated: early economic development, through resource-intensive industrialization and urbanization, increases pollution, whereas later developmental stages, through technology and regulations, lead to a decline. Unrestrained EG in developing economies tends to accelerate the depletion of natural resources, such as energy use, deforestation, and emissions, exacerbating ED. On the other hand, more developed economies, such as those in the OECD, with high EC indices indicating more advanced productive forms and export diversification, are more likely to decouple growth from degradation.[19] The recent trends in the OECD countries as the leaders in the EC index ranking emphasize their relevance in the empirical testing of the suggested relationships that would fill the knowledge gaps on the moderating role of complexity amid the current sustainability issues.

2.2. Renewable energy consumption and environmental degradation

Energy consumption is considered one of the primary reasons for ED in numerous contexts, due to intensive economic activities that consume natural resources (e.g., minerals, forests, and water) and to large CO_2 emissions, particularly in OECD countries. This is enhanced by non-renewable sources such as coal, oil, and natural gas, which contribute to greenhouse gas emissions, air and water pollution, soil contamination, and habitat destruction, and add to the strains of industrialization and urbanization mentioned above.[20] On the other hand, the consumption of renewable energy sources, including solar, wind, and hydroelectric power, is well known to help reduce environmental degradation by decreasing reliance on fossil fuels and greenhouse gas emissions. Solar, wind, hydro, geothermal, and biomass are naturally renewable energy sources that should be promoted as the primary energy sources to achieve sustainability because fossil fuels are being depleted rapidly. They produce electricity, heat, or fuel without harmful emissions, and do not pollute the air/water, disrupt the climate, or cause general degradation. Empirical research shows an inverse relationship: in developed economies, the higher the renewable energy consumption (REC), the lower the ED, thereby mitigating climate change and aligning with the EKC. OECD nations are characterized by high EC, renewable energy adoption leverages sophisticated technologies for efficient resource use and emission decoupling. This transition not only curbs ED but also promotes sustainable development through green jobs, expanded energy access, and fossil-fuel independence.[21]

In any context, energy consumption is a primary cause of ED, specifically, the exploitation of natural resources, minerals, forests, and water, that power intensive economy and high CO_2 emissions. This is worsened by non-renewable sources of energy such as coal, oil, and natural gas, which emit greenhouse gases, cause air and water pollution, contaminate soil, and lead to habitat loss. As fossil fuel reserves are rapidly exhausted, and the consumption of this energy source grows steadily with no significant changes in demand, the need to promote renewable energy sources, i.e., naturally regenerated sources such as solar, wind, hydro, geothermal, and biomass, has become a condition of sustainability. Naturally replenished sources, including solar, wind, hydroelectric, geothermal, and biomass, produce electricity, heat, or fuel when it has a renewable supply of energy. Rather than contributing to climate disturbance and wider environmental destruction as fossil fuels do (such as coal, oil, or natural gas), renewable sources generate few harmful emissions.[22] The empirical evidence supports the opposite correlation all the time: increased use of renewable energy may decrease CO_2 emissions vastly, especially in the developed economies. This is consistent with the EKC, where renewable transitions allow OECD nations, which are highly economically complex, to decouple growth from degradation by adopting efficient technologies and diversified energy portfolios. As a result, increased reliance on renewables not only prevents degradation and climate-related effects but also promotes sustainable development through green job creation, enhanced energy access (particularly in developing countries), and reduced reliance on fossil fuels.[23] Greenhouse gas emissions are significantly reduced by replacing the combustion of fossil fuels with clean sources of power such as solar, wind, hydroelectric, and nuclear power.

2.3. Reliance of environmental degradation on financial development

Financial development has a two-sided, situational relationship with ED, as it can both accelerate and serve as a recovery factor, especially in complex OECD economies with high levels of EC. On the one hand, financial growth may accelerate degradation by facilitating access to credit for energy-intensive and polluting industries, thereby amplifying scale effects that increase CO_2 emissions through increased consumption, industrialization, air/water pollution, deforestation, and biodiversity loss. This risk has been empirically demonstrated, as liberalized finance tends to finance high-emission projects during booming EG. On the other hand, in developed OECD contexts, where financial intermediation, in terms of developed banking, insurance, stock market, and efficient mobilization of resources, is well developed. Human capital improvement and institutional quality amplify this beneficial pathway whilst enhancing low-carbon transitions. Even though they are prone to instability and shocks, properly managed financial systems in OECD countries enable green investments, regulatory compliance, and sustainable operations, reducing the effects of climate change and helping meet the EKC. Therefore, in OECD, strategic financial development, the balance between growth and green finance, is central to dealing with degradation through innovation funding and policy incentives.[24]

2.4. Urbanization and environmental degradation

The rising population density in urban centers due to improvements in transportation, technology, and communication is highly concentrated in urban areas, known as urbanization, which has a far-reaching impact on ED, especially in high EC OECD economies. On the one hand, it positively affects human wellness, EG and development, and access to basic services like education and health, supports cultural diversity, innovation, and creativity as rural residents migrate in search of improved opportunities. Nevertheless, increasing ecological pressures due to rapidly growing urbanization encompass land-use changes, increased waste, rapid resource depletion, air/water pollution, and growing carbon footprints, all of which entail habitat destruction, decreased biodiversity, soil erosion, greater air/water pollution, and increased carbon footprints.[25] These dangers are highlighted by empirical evidence: as urbanization increases and greenhouse gas emissions rise, climate change worsens, and energy demand rises exponentially. In contrast, urbanization can counter degradation in developed OECD economies, where the EC is high and compact development is enhanced, leading to lower per capita emissions. To maximize such gains, sustainable city planning involves green infrastructure, efficient resource use, and strong environmental regulations, all of which are essential for promoting ecological sustainability in developed countries. Nevertheless, they are coupled with high expenses, such as congestion, overcrowding, social inequalities, and ED.[26] The threats include the exploitation of natural resources, increased pollution, problems with waste management, and pollution of air or water. In addition, urban growth increases energy consumption and greenhouse gas emissions, thereby aggravating climate change. Further habitat destruction, soil erosion, biodiversity loss, and ecosystem disruption are brought about by infrastructure development, including buildings and roads.[27]

2.5. Environmental issues and energy innovation

The phenomenon of energy consumption is one of the major driving forces of ED in any situation, especially the depletion of natural resources, which, under their influence, lead to intensive economic activity and significant CO_2 emissions. Exacerbators of this include non-renewable resources such as coal, oil, and natural gas, which lead to greenhouse gas emissions, air and water pollution, soil pollution, and habitat destruction. As fossil fuels are rapidly depleting and the demand is growing, the shift to renewable energy sources, which are naturally replenished, such as solar, wind, hydro, geothermal, and biomass, has become the only solution to achieving sustainability, as such sources have long been found to help reduce renewable energy, which is a form of electricity, heat, or fuel produced with the help of naturally replenished sources, which include solar power, wind power, hydroelectric power, geothermal power or biomass power, does not drain finite resources. Compared to non-renewable fossil fuels such as coal, oil, and natural gas, which have contributed to the causes of climate disruption and wider environment destruction through greenhouse emissions, air and water pollution, soil contamination, and destruction of habitats, renewable sources It has always been empirically proved that the used renewable sources and their increased use can negatively affect ED: the greater the adoption, the smaller the CO_2 emissions, especially in developed economies. This corresponds to the EKC, in which renewable energy sources facilitate decoupling of growth and degradation in OECD countries with high EC by enabling efficient technologies and diversified energy sources. This means that renewable-based growth will not only reduce degradation and climate change but also support sustainable development by creating green jobs, improving access to energy, particularly in developing markets, and reducing reliance on fossil fuels. Greenhouse gas emissions are significantly reduced by replacing combustion of fossil fuels with clean sources such as solar, wind, hydroelectric, and nuclear power.[28]

Largely due to the rapid growth and continual development of transportation, communication, and other technologies, urbanization has a strong, twofold impact on environmental degradation, especially in high-EC OECD economies. On the one hand, it improves human life and increases the level of EG and development, extends access to necessary services, including education and health, and fosters cultural diversity, innovation, and creativity as rural residents migrate in search of a better life. Yet, urbanization leads to increased ecological impacts due to high rates of resource use, waste production, land-use changes, and infrastructure development, which destroy habitats, decimate biodiversity, increase soil erosion, and contribute to air and water pollution and carbon footprints. It can be stated with great impact that EI further affects ED, specifically in the highly complex economies of the OECD. At the sustainable level, two major trends are common: improving energy efficiency and using renewable resources. On the one hand, unregulated EI may indirectly contribute to degradation through scale effects, i.e., efficiency increases result in rebound consumption, or high-resource-intensive research and development (R&D) increases material needs and mining.[29] There are transition risks that are magnified in less developed economies, but they are lower than in OECD environments.

In developed OECD economies with developed R&D sectors and policy drivers, on the other hand, EI alleviates degradation through investing in clean technologies, lowering greenhouse gas emissions, improving air quality, and limiting resource loss. For example, renewable technologies such as solar and wind reduce the dependence on fossil fuels, whereas efficiency initiatives reduce the energy loss. These positives are supported by studies indicating that innovation is decoupling from growth. In this way, strategic EI, enhanced by the incentives and cooperation of governments, companies, and the academic world, is critical to supporting low-carbon transitions and the sustainability of OECD countries.[30] Sustainable EI involves the development of new technologies, processes, and systems capable of improving energy efficiency, reliability, and sustainability, e.g., the development of renewable sources of energy (e.g., solar, wind), energy storage technologies, and energy efficiency, including the use of LED lamps or smart appliances, especially in economies with high EC (e.g., OECD economies). Such developments reduce energy use, lower greenhouse gas emissions, enhance air quality, and prevent resource depletion, with minimal impact on EG and consistent with the EKC, due to technique effects that decouple growth from CO_2 emissions. EI is successful when interventions by governments (funding R&D and regulation), the private sector (investing in clean technology), and academia (facilitating breakthroughs) are guided by environmental imperatives, economic competitiveness, energy security, and policy orientations, as illustrated by examples from advanced OECD ecosystems. More importantly, it solves climate change by shifting to fossil fuels, which reduce emissions and encourage low-carbon systems, as well as creating economic opportunities such as new sectors, jobs, and resilient communities.[31]

Energy innovation is linked to several forms of environmental degradation. EI implementation can avert ED by introducing new, cleaner, and sustainable energy sources. As an illustration, it is possible to minimize greenhouse gas emissions and enhance air quality by reducing fossil fuel consumption through the development of renewable energy technologies, such as solar, wind, and geothermal power. Also, innovation in energy can aid in reducing resource waste by fostering energy efficiency. With improvements in the performance of energy production and consumption processes, less energy is wasted, reducing the demand for resources. By encouraging EI, there is potential to develop new technologies and systems that can help curb the adverse economic impacts associated with ED. Nonetheless, unregulated EI may also indirectly cause degradation through scale effects, where efficiency improvements cause rebound consumption, i.e., reduction of costs and an increase in total energy consumption, or resource-intensive R&D increases material demands and mining pollution.[32]

2.6. Latent relationship of environment with economic growth

Over the past few years, the correlation between EG and ED has become the focus of much debate and empirical research, especially regarding the ways in which degradation negatively affects EG in the short and long term. In the short term, it generates immediate economic costs, such as crop failures, biodiversity loss, and high healthcare costs due to pollution-related diseases, that undermine productivity and raise operational costs for businesses and households. Degradation, in the long term, has a devastating effect on natural capital needed to maintain economic activity; e.g., overfishing reduces fish stocks, affecting the livelihoods of fishermen and disrupting seafood processing industries, and deforestation reduces timber supplies, which can support industries that rely on forestry. These problems are aggravated by climate change, including infrastructure destruction, decreased agricultural productivity, and altered water supply, all of which suffocate sectoral productivity and sustainability in the long run. Therefore, the significant effects of ED are multifaceted and far-reaching, impacting all economic operations and thus requiring proactive measures to mitigate resilient growth. This theory assumes that, in the initial stages of an economy's development, it focuses on industrialization and resource extraction, becoming increasingly polluted; however, at some point, higher incomes and technological development will enable investment in cleaner technologies and environmental policies. Moreover, social and political instability triggered by the ED has worsened the economy. Degradation causes resource shortages that frequently lead to disputes over water, land, fisheries, and forests, provoking population displacement, social disturbances, and increased healthcare costs due to pollution-related diseases. Long-term economic operations require principles of sustainable agriculture, biodiversity conservation, and greenhouse gas reduction to address climate change. These do not merely prevent the waste of resources, but they also enhance sector feasibility.[33] For example, deforestation and overfishing destroy industries by degrading biodiversity, disrupting ecosystems, damaging agriculture, harming infrastructure, and undermining water availability.

The interdependence between EG and ED is a reciprocal phenomenon, with empirical studies showing that EG usually has a more pronounced impact, especially in developing economies. This paper assumes that EG is a leading cause of ED, with increased economic activity promoting resource use, energy use, and industrial production, which in turn increase pollution and ecological pressure, i.e., scale effects such that GDP growth is strongly linked to deforestation, loss of habitat, and greenhouse gases. On the other hand, economic development can be slowed down by ED, which can lead to short-term costs, such as failures of crops, biodiversity loss, and healthcare expenses associated with pollution, or long-term costs, such as overfishing and deforestation.[34]

2.7. Impact of foreign investment inflows on the environment

The FDI, also known as capital inflows from one country into another to set up or acquire business activities, has been the subject of numerous studies, especially regarding its environmental impacts.[35] There is empirical evidence that ED has a deleterious effect on FDI inflows, with the most significant effects being reduced profitability, increased risk, and undermined long-term feasibility, driving out investors and hampering EG. In the short run, degradation increases operational expenses on businesses, including meeting strict environmental requirements, cleaning up pollution, and compensating for environmental damage, thereby reducing investment profitability and deterring FDI. Examples include pollution-related healthcare costs and biodiversity loss, which add to business costs and reflect trends seen in resource-mining industries.[36] Besides, natural disasters induced by climate, such as floods and droughts, increase risks by damaging infrastructure and disrupting supply chains, and the lack of resources contributes to conflicts over water, land, and fisheries, leading to political instability and expropriation risks. These are contributing to a perpetual cycle of lower capital inflows, which are needed to innovate, employ, and upgrade infrastructure, thereby increasing perceived investment uncertainty, especially in developing contexts.[37,38]

In the long run, degradation wipes out natural capital that is vital in industries relying on FDI. The overexploitation of resource-intensive industries (agriculture, forestry, tourism), disruption of ecosystems, and obsolescence of high-emission industries (fossil fuels) are experiencing the effects of global decarbonization. This aligns with the dynamics of the EKC, as uncontrolled degradation is an obstacle to the use of cleaner technologies after the income threshold.[39] Green innovation, shift to renewable energy, protection of biodiversity, and strict regulations not only reduce costs and risks, but also increase sectoral resilience and returns in the long term.[40] Host countries can use FDI to develop sustainably by avoiding the degradation-growth trap, as identified in empirical studies, by preserving natural capital.[41] On the other hand, other studies indicate that FDI may drive ED, especially in developing nations, and this is because of lax environmental regulations where the strategy to attract foreign capital is being disregarded, a phenomenon commonly known as the pollution haven hypothesis.[42,43]

3. Methodology

To empirically examine the presence of a long-run relationship and the short-run dynamics among the variables, our study used the PMG estimator within an ARDL framework for a heterogeneous panel of 37 OECD countries.[44] This complex method is especially appropriate to panels that have CD, slope heterogeneity, and cointegration, which have been validated by prerequisite tests: second-generation unit root tests identifying stationarity at first differences, Pesaran's CD test identifying CD, the delta tilde test in Pesaran–Yamagata identifying heterogeneity, and robust cointegration tests identifying long-run equilibrium.[45] The PMG estimator is an effective method for aggregating long-run coefficients across a group, but it allows for short-run heterogeneity and therefore yields consistent and efficient estimates where other methods, such as mean-group or dynamic fixed effects, fail to do so. Cointegration implies causality exists, but the PMG–ARDL estimator is not meant to determine causal directions. Although causality is plausible and usual for panel data, such as bi-directional feedback between EG and ED, or reverse causality between financial development and CO_2 emissions.[46] However, the approach adopted for the study captured the interconnectedness among ED, FDI, and EG and accounts for both short- and long-term shocks in the economic environment across a diversity of contexts.

3.1. Data source and variable description

The study used annual panel data from 37 OECD countries from 1990 to 2024 to examine the short- and long-run dynamic linkages among the selected variables. Costa Rica became an OECD member in 2021; hence, previous data were not available, and the country is therefore excluded. Variables included in the analysis were extracted from different sources. For instance, data on FDI, EG, REC, urbanization, and economic degradation (carbon emissions) were obtained from the World Development Indicator (WDI). The data on the remaining variables were obtained from diverse sources, as depicted in Table 1 along with the variable description.

The OECD consists of 38 member countries, including Australia, Austria, Belgium, Canada, Chile, Colombia, Costa Rica, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Republic of Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerl, Türkiye, United Kingdom, United States; however, our study considered only 37 countries as Costa Rica became part of OECD in 2021.

3.2. Unit root testing

To assess stationarity properties and avert spurious regressions in a heterogeneous panel of 37 OECD countries, this study applies the second-generation Pesaran's CD and

Table 1. Data and variables description

No.	Variable	Description	Measurement	Source
1	Economic degradation/CO_2	CO_2 emissions	Metric tons per capita	WDI
2	Economic growth	Gross domestic product is the sum of the market value of all final goods and services generated within a nation's territory during a defined time frame, usually calculated quarterly or annually	Annual growth rate of GDP	WDI
3	REC	REC is the share of renewable energy in total final energy consumption	Percentage of total energy	WDI
4	Urbanization	The proportion of a country's population living in urban areas, reflecting the level of urban development	Percentage of the total population residing in urban areas	WDI
5	FDI	Involves a resident entity of one country committing resources to a business located in another country, with the purpose of exerting meaningful control or influence over its operations and decision-making processes	Annual inflows and outflows of FDI	WDI
6	EC	The sophistication of a country's productive structure is measured by its EC	EC index	The Atlas of EC
7	Energy innovation	Research and development expenditures in energy sector	Research and development expenditure	WDI
8	Financial development	The financial development is measured with total sum of domestic credit provided by the financial sector (% of GDP), domestic credit to private sector (% of GDP), and domestic credit to the private sector by banks (% of GDP)	Financial development index (domestic credit to private sector [% of GDP])	IMF

Abbreviations: CO_2: Carbon dioxide; EC: Economic complexity; FDI: Foreign direct investment; GDP: Gross domestic product; IMF: International Monetary Fund; REC: Renewable energy consumption; WDI: World Development Indicator.

Augmented Dickey–Fuller unit root tests. These tests are robust to prevalent CD—arising from global factors like synchronized trade, energy prices, and policies in OECD contexts—unlike first-generation tests (e.g., Breitung, Im–Pesaran–Shin, Levin–Lin–Chu) that assume independence and yield unreliable inferences under such conditions.[47] The cross-sectionally augmented Dickey–Fuller test (CADF) equation for the unit i augments the standard Dickey–Fuller regression with cross-sectional averages (**Equation 1**):

$$\Delta X_{it} = A_i + B_i X_{i,t-1} + C_i \overline{X}_{t-1} + \in_{it} \tag{1}$$

The cross-sectionally augmented Im–Perasan–Shin (CIPS) statistics average the individual CADF t -ratios across units. Results in Table 2–4 confirm all variables (CO_2 emissions, energy complexity index, renewable energy, financial development, urbanization, EI, EG, FDI) are non-stationary at levels (I) but stationary at first differences (I), validating the subsequent cointegration framework. This mixed order of integration (I(1) and I(0)) further justifies the application of the PMG–ARDL model, which is specifically designed to handle variables with different integration orders. By employing the PMG–ARDL approach, the study mitigates prevalent econometric concerns—including endogeneity, heteroscedasticity, and multicollinearity—strengthening the credibility and reliability of the empirical results.

3.3. Cross-sectional dependence

Following the unit root tests confirming stationarity at first differences, this study proceeds to examine CD in the heterogeneous panel dataset of 37 OECD countries to select robust subsequent econometric methods, such as second-generation cointegration tests. CSD often arises from global factors, such as synchronized trade cycles, energy prices, and common policies, across advanced economies. Accordingly, Pesaran's CD test is applied (**Equation 2**). These tests are essential, as first-generation alternatives assume cross-sectional independence and yield biased results under prevalent CSD conditions.[48]

$$CD_p = \sqrt{\left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{r_{ij}^2}\right)} \tag{2}$$

3.4. Panel cointegration tests

Following the confirmation of CD, slope heterogeneity, and stationarity at first differences in the heterogeneous panel of 37 OECD countries, this study employs robust second-generation cointegration tests—including the Pedroni, Kao, and Westerlund tests—to investigate long-run equilibrium relationships among the variables. These tests are particularly suitable for panels with CD and heterogeneity, unlike first-generation alternatives that assume cross-sectional independence. The Westerlund test is error-correction based and generates four statistics: panel statistics P_a and P_t, alongside group-mean statistics G_a and G_t, providing comprehensive evidence of co-integration even under prevalent OECD-wide common shocks. Results reject the null hypothesis of no co-integration across these tests, validating the subsequent PMG–ARDL framework.[49]

3.5. Estimation of long-run coefficients

Following the panel co-integration tests confirming long-run equilibrium relationships among the variables in the heterogeneous panel of 37 OECD countries, this study estimates the short-run dynamics and long-run coefficients using the PMG estimator embedded within the ARDL framework.[50] The PMG estimator employs a two-step procedure: in the first step, country-specific ARDL(p_i, q_i) regressions are estimated via maximum likelihood; in the second step, the long-run coefficients are pooled across groups (imposing homogeneity $\theta_i = \theta$), while short-run coefficients and error variances remain heterogeneous across units.[51] The optimal lag length was determined using the Akaike Information Criterion (AIC) by estimating the model across a set of lag structures.

This approach is particularly robust for panels exhibiting CD, slope heterogeneity, and mixed orders of integration (I(0)/I(1)), as previously established, delivering consistent and efficient estimates superior to the Mean Group estimator (which allows full heterogeneity but sacrifices efficiency) and dynamic fixed effects estimator (which imposes homogeneity in both short- and long-run dynamics). The underlying error-correction form of the PMG–ARDL model is specified as **Equations 3** and **4**:

$$\Delta y_{i,t} = \phi\psi\Delta y_{i,t} + \sum_{j=0}^{q-1} \Delta X_{i,t-1}\beta_{i,t} + \sum_{j=1}^{p-1} \lambda_{i,y} * \Delta y_{i,t-j} + \varepsilon_{i,t} \tag{3}$$

$$EC_{i,t} = y_{i,t-1} - X_{i,t}\theta \tag{4}$$

4. Results and discussion

This paper examines an equal panel of 1,220 observations in 37 member countries in the OECD across 1990–2024 with an aim of robustly estimating the effect of seven key determinants, namely, energy complexity index, REC, financial development, urbanization, EI, EG, and FDI, on the CO_2 emissions as an indicator of ED. **Table 2** shows the descriptive statistics of the balanced panel data set of 1,220 observations of 37 OECD countries between 1990 and 2024 of CO_2 emission, which is used in this study as a proxy of ED, as well as core explanatory variables: energy complexity index, REC, financial development, urbanization, EI, EG, and FDI.

Such statistics indicate that the variables exhibit significant cross-country and time variation, making it essential to use heterogeneous panel techniques to capture their underlying dynamics and heterogeneity. Table 3 shows the correlation matrix of the variables.

The Pearson correlation table (Table 3) depicts the presence of statistical significance in the relations between the variables ($p < 0.01$) in a balanced panel dataset. Interestingly, CO_2 emissions show strong positive relationships with the index of energy complexity and EG, consistent with EKC behavior in developed nations.[52] On the other hand, financial development shows a significant negative correlation with CO_2 emissions, suggesting its potential for green investments. Renewable energy has a moderate positive correlation with the energy complexity index and a significant positive association with EI. There is a strong positivity between financial development and EI. Urbanization shows a positive but low relationship with financial development and EI, and a weak negative relationship with FDI. There is a negativity between EG and FDI. Importantly, none of the pairwise correlations is below 0.80 in absolute value, indicating no serious multicollinearity in the study and justifying further multivariate analyses.[53] Table 4 shows the results of panel unit root tests for stationarity.

The CIPS and CADF unit root test results for OECD countries show that some of the variables are non-stationary at the level and become stationary after first difference. CO_2 emissions, EG, and FDI are non-stationary at the level and become stationary at 1st difference. The findings presented in Table 4 reject the null hypothesis of

Table 2. Descriptive statistics

Variables	Mean	Standard deviation
Carbon dioxide emission	8.514	0.983
Economic complexity index	2.231	1.310
Renewable energy	1.625	1.559
Financial development	5.071	0.995
Urbanization	3.945	0.584
Energy innovation	2.375	1.509
Economic growth	6.823	2.638
Foreign direct investment	4.892	1.039
Total observations = 1,220		

Table 3. Correlation matrix

Variables	CO_2	ECI	REC	FD	Ub	EI	EG	FDI
CO_2	1.000	–	–	–	–	–	–	–
ECI	0.724	1.000	–	–	–	–	–	–
REC	−0.513	0.499	1.000	–	–	–	–	–
FD	−0.763	0.623	0.247	1.000	–	–	–	–
Ub	0.317	0.353	−0.460	0.352	1.000	–	–	–
EI	−0.420	0.219	0.716	0.974	0.571	1.000	–	–
EG	0.846	0.181	0.159	0.178	0.361	−0.173	1.000	–
FDI	−0.464	0.641	0.168	0.184	−0.094	0.064	−0.403	1.000

Abbreviations: CO_2: Carbon dioxide emission; ECI: Economic complexity index; EG: Economic growth; EI: Energy innovation; FD: Financial development; FDI: Foreign direct investment; REC: Renewable energy consumption; Ub: Urbanization.

Table 4. Panel unit root tests (stationarity testing)

Variables	CIPS unit root test		CADF unit root test	
	Level	1st difference	Level	1st difference
CO_2	−2.234	−4.648***	−1.104	−4.034***
ECI	−2.046*	−5.198***	−1.157	−3.093***
REC	−2.392**	−5.052***	−1.400	−4.427***
FD	−1.906*	−4.235***	1.395	−2.175**
Ub	−1.156*	−3.038***	2.613	1.738*
EI	−1.497	−4.526***	−1.412	−3.448**
EG	1.281	3.038***	−1.940	−4.892***
FDI	2.962	2.729**	2.539	−3.916***

Notes: Intercept and trend variables are included in the CIPS and CADF tests; $^*p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
Abbreviations: CADF: Cross-sectionally augmented Dickey–Fuller test; CIPS: Cross-sectionally augmented Im–Perasan–Shin; CO_2: Carbon dioxide emission; ECI: Economic complexity index; EG: Economic growth; EI: Energy innovation; FD: Financial development; FDI: Foreign direct investment; REC: Renewable energy consumption; Ub: Urbanization.

a unit root at all levels and at first differences, confirming the order of integration and the appropriateness of cointegration analysis. The significance of this finding is that it is the essential precondition of using cointegration methods to examine the long-run relationships between the variables. The values are depicted in Table 5.

The panel time-series data were used to test for the presence of CD using Pesaran's CD test.[54] The findings in Table 3 reject the null hypothesis of cross-sectional insensitivity of every variable ($p < 0.01$), which proves that prevalent CSD is likely to be caused by common OECD-wide shocks. In this case, the results of first-generation unit root tests are biased[55]; therefore, the second-generation CIPS and CADF tests are used in this study because they are free of CSD and heterogeneity of slope. Table 6 presents the panel cointegration test results.

This study employs the Pedroni, Westerlund[56], and Kao[57]panel cointegration tests to ascertain the existence of long-run relationships.[58] The Westerlund test, robust to CD, alongside the Pedroni and Kao tests, rejects the null hypothesis of no cointegration across specifications, as shown in Table 6. These results, confirming cointegration, validate the application of the PMG–ARDL estimator for heterogeneous panels with prevalent CSD.

Table 5. Cross-sectional dependence test

Variable	CD-test	*p*-value
CO_2	33.6440	<0.001
ECI	3.2320	0.024
REC	6.5810	<0.001
FD	10.7260	<0.001
Ub	24.6770	<0.001
EI	14.7630	<0.001
EG	5.8236	<0.001
FDI	4.1098	<0.001

Abbreviations: CD: Cross-sectional dependence; CO_2: Carbon dioxide emission; ECI: Economic complexity index; EG: Economic growth; EI: Energy innovation; FD: Financial development; FDI: Foreign direct investment; REC: Renewable energy consumption; Ub: Urbanization.

Table 6. Panel cointegration test results

Tests	Test statistic	*p*-value
Kao test for cointegration		
Modified Dickey–Fuller *t*	−5.8051	<0.0001
Dickey–Fuller *t*	−4.2942	<0.0001
Augmented Dickey–Fuller *t*	−3.1772	0.0007
Unadjusted modified Dickey–Fuller *t*	−6.8252	<0.0001
Unadjusted Dickey–Fuller *t*	−4.5656	<0.0001
Modified Phillips–Perron *t*	1.7299	0.0418
Phillips–Perron *t*	−2.4737	0.0067
Augmented Dickey–Fuller *t*	−2.6575	0.0039
Westerlund test for cointegration		
Variance ratio	−2.2718	0.0115
Kao test for cointegration		

The PMG–ARDL estimation results in Table 7 confirm the statistical significance of all variables at the 1% level in both the long and short runs, with a valid error-correction term indicating cointegration and adjustment toward equilibrium. EI and FDI are significant in the long run, with *p*-values of 0.0126 and 0.0174, respectively, whereas in the short run, these variables are highly significant at 0.004 and <0.0001, respectively. The effect of renewable energy, measured in the long run, was negative ($\beta = -1.8324$) on CO_2 emissions at the 1% significance level. The coefficient suggests that renewable energy use will lead to a 1.83% decline in ED, thereby reinforcing the importance of renewable energy for OECD economies. Similarly, EI also has a significant impact on CO_2 emissions ($\beta = -2.4382$, $p = 0.0126$), indicating that technological advancements in cleaner energy systems play a significant role in reducing CO_2 emissions.

Table 8 confirms the robustness of the estimated model. The Hausman test indicates that the PMG estimator is appropriate, the normality test indicates that residuals are normally distributed, and the Ramsey regression equation specification error test shows no evidence for the misspecification of the functional form. However, financial development, urbanization, EC index, FDI, and EG positively affect CO_2 emissions in the long run, indicating

Table 7. Pool mean group estimation

Variables	Coefficient	Standard error	*Z*	*p-value*
Long-run results				
REC	−1.8324	0.0820	−22.3463	<0.0001
FD	0.5460	0.0445	12.2697	<0.0001
Ub	3.9731	0.9928	4.0019	0.0004
ECI	1.2991	0.2644	4.9134	<0.0001
EI	−2.4382	0.9206	−2.6485	0.0126
EG	0.9241	0.0481	19.2121	<0.0001
FDI	5.2098	2.0743	2.51159	0.0174

(*Cont'd...*)

Table 7. (*Contuined*)

Variables	Coefficient	Standard error	*Z*	*p-value*
Short-run results				
REC	−2.1660	0.5970	−3.6281	0.0010
FD	−0.2910	0.0355	−8.1972	<0.0001
Ub	2.7479	0.2288	12.0101	<0.0001
ECI	−1.0081	0.4060	−2.4830	0.0186
EI	−2.6300	0.6600	−3.9848	0.0004
EG	0.8239	0.193	4.26891	0.0002
FDI	2.2391	0.4321	5.1819	<0.0001
Constant	2.3578	0.7250	3.2500	0.0010

Abbreviations: ECI: Economic complexity index; EG: Economic growth; EI: Energy innovation; FD: Financial development; FDI: Foreign direct investment; REC: Renewable energy consumption; Ub: Urbanization.

a strong positive impact on ED, consistent with OECD observations that structural factors reinforce emissions without green transitions. The short-run estimates show several important dynamic differences as compared to the long-run estimates. Urbanization, EG, and FDI indicate a positive impact on ED (CO_2); however, the estimates show a lesser magnitude as compared to the long-run estimate (reported in Table 7).

In short, the PMG–ARDL results provide strong empirical evidence that REC and EI significantly improve environmental quality in sampled OECD countries, whereas urbanization, EG, financial development, EC, and FDI lead to ED, particularly in the long run. The distinction between short-run and long-run coefficients further underscores the importance of using the PMG–ARDL framework, which captures heterogeneous adjustments across OECD economies.

Table 8. Diagnostic tests

Diagnostic tests	Test statistics	*p*-values
Hausman	3.48	0.81
Normality test	0.86	0.73
Ramsey RESET	1.49	0.67

Abbreviation: RESET: Regression equation specification error test.

5. Conclusion

The relationship between financial development, urbanization, EI, REC, energy complexity, EG, FDI, and CO_2 emissions was examined for OECD countries from 1990 to 2024, accounting for the dynamic nature of these relationships. The empirical analysis shows a clear difference between the effects of long-run and short-run drivers, providing helpful insights into how each influences ED.

In the long run, REC and EI play a significant role in reducing ED by replacing carbon-intensive fossil fuels and by reducing the carbon intensity of production and consumption systems. Furthermore, EI optimizes the use of technology across production processes and reduces reliance on carbon-intensive technologies. On the other hand, financial development, urbanization, energy complexity index, EG, and FDI positively impact the ED. Strong financial systems, rapid urban expansion, industrial and EG, and foreign investment collectively impact CO_2 emissions by increasing energy-intensive production, accelerating consumption and infrastructure demand, and reinforcing the concentration of pollution-laden activities in less regulated or structurally carbon-dependent sectors.

From a policy perspective, the findings emphasize that OECD countries need to pursue multifaceted policies to meet the Sustainable Development Goals, to achieve the long-term elimination of carbon emissions, and to strengthen EI to enhance the financial instruments for green investments. There is a need for mechanism-driven interventions rather than broad sustainability commitments, which can be achieved by improving the quality of foreign investment, enhancing carbon disclosure, and incentivizing low-carbon and green technology inflows. Similarly, aligning financial development with climate goals through green credit allocation and climate-risk disclosure will help reduce ED. Economies need to have accelerated investment in renewable energy and EI through public–private partnerships and R&D support. The role of the governing bodies of the OECD is indispensable for achieving policy objectives; therefore, future studies may extend the framework by incorporating institutional and regulatory quality and governance effectiveness to examine how better governance moderates the impact of financial development, FDI, and urbanization on CO_2 emissions in OECD countries. The study assumes long-run homogeneity across OECD economies, given that member states share broad institutional and policy characteristics, although they differ in terms of income levels, industrial structures, and environmental regulations. However, long-run homogeneity may hide cross-country heterogeneity in the growth–environment nexus; therefore, future research can address this by employing fully heterogeneous panel estimators to evaluate and compare cross-country contexts. Furthermore, to enhance methodological rigor, the advanced diagnostic techniques may provide deeper insights into CD, heterogeneity, and endogeneity across panel datasets as well as a heterogeneous non-causality test.

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Conflict of interest

The authors declare they have no competing interests.

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Availability of data

Data are available from the corresponding author upon reasonable request.

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