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RESEARCH ARTICLE

Digital Economy Meets Green Industrial Transformation: New Evidence on Carbon Emissions in OECD Countries

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Abstract
The digital economy and renewable energy transition are increasingly recognized as important pathways toward low-carbon development; however, their relationships with industrial activity and carbon emissions remain insufficiently understood. This study examines the associations of digital economy development, industrialization, renewable energy consumption, foreign direct investment (FDI), and trade openness with carbon dioxide (CO_2) emissions in OECD countries over the period 1999–2020. A multidimensional Digital Economy Index (DEI) is constructed using eight indicators, while an interaction between industrialization and renewable energy consumption is introduced as a proxy for green industrial transformation (GIT). The relationships are investigated using a two-step system generalized method of moments (GMM) estimator to account for emissions persistence, unobserved heterogeneity, and potential endogeneity. The reported results indicate that digital economy development and renewable energy consumption are negatively associated with CO_2 emissions, whereas industrial growth exhibits a positive association. The negative coefficient of the GIT interaction suggests that renewable energy consumption may moderate the emissions implications of industrial activity. FDI is also negatively associated with emissions, while the relationship between trade openness and emissions varies across model specifications. These findings highlight the potential importance of combining digital transformation with renewable energy deployment and industrial decarbonization strategies. The study offers policy insights for OECD economies seeking to strengthen low-carbon development through digital innovation, cleaner industrial production, and environmentally responsible investment.

Keywords: Digital economy; Green industrial transformation; Carbon emissions; Renewable energy; Industrial decarbonization; OECD countries

1. Introduction

The accelerating impacts of climate change and the growing demand for energy-intensive economic activities have intensified global efforts to reconcile industrial development with environmental sustainability. CO_2 emissions from energy production, manufacturing, transportation, and other economic activities remain a major

challenge to achieving international climate mitigation objectives. In this context, the digital economy has emerged as a potentially important driver of low-carbon development through technological innovation, improved resource allocation, intelligent energy management, and greater production efficiency. Digital technologies, including artificial intelligence (AI), the Internet of Things (IoT), cloud computing, and big data analytics, can facilitate energy optimization, industrial modernization, and the integration of renewable energy into economic activities. However, digitalization also generates environmental pressures through increasing electricity consumption, digital infrastructure expansion, material extraction, and electronic waste. Consequently, the net environmental implications of digital economic development remain uncertain and depend on energy structures, technological capabilities, and institutional conditions (Bai et al., 2023; Gritsenko et al., 2024; Ma & Li, 2024; Raihan, 2024; Zhang et al., 2025). Understanding these relationships is particularly important for OECD countries, where advanced digital infrastructure, established industrial systems, and evolving decarbonization policies create opportunities to coordinate digital and green economic transitions.

Despite the potential environmental benefits of digitalization, achieving sustained carbon emission reductions remains challenging because industrial expansion, technological development, and energy consumption are closely interconnected. Industrial activities contribute to economic growth, employment, and technological advancement but may also increase emissions when production systems depend heavily on fossil fuels. Renewable energy offers opportunities to reduce these environmental pressures by replacing carbon-intensive energy sources and supporting cleaner industrial production. Nevertheless, the environmental benefits of renewable energy depend on its penetration into productive sectors, the characteristics of industrial activities, and the effectiveness of complementary technological and regulatory measures. Recent evidence from OECD countries indicates that renewable energy consumption and internet usage are associated with lower CO_2 emissions, although the magnitude and direction of environmental relationships vary across economic conditions (Işık et al., 2024). Moreover, digitalization does not necessarily guarantee emission reductions because efficiency improvements may be offset by increased production, consumption, and energy demand (Zhang et al., 2025). These complexities highlight the urgency of investigating how digital economic development, industrial activity, and renewable energy consumption jointly relate to environmental performance, rather than assuming that technological advancement or economic modernization automatically produces sustainable outcomes.

Existing studies have examined the digital economy–environment relationship from different theoretical and empirical perspectives, producing heterogeneous and sometimes contradictory findings. Bai et al. (2023), using data from 278 Chinese cities, demonstrated that digital economic development was associated with reduced local carbon emissions through industrial transformation and upgrading, although spatial spillovers contributed to increased emissions in neighboring regions. Similarly, Ma and Li (2024) identified industrial restructuring and energy transition as important pathways connecting digital economic development with carbon emissions in G20 economies and Chinese cities. Zhang et al. (2025), analyzing 72 countries, reported an inverted U-shaped relationship between digital economy development and carbon emission intensity, suggesting that the environmental consequences of digitalization may change as digital development progresses. Conversely, recent research on OECD economies has identified circumstances in which digitalization is associated with increased carbon emissions, demonstrating that its environmental implications are not uniformly beneficial. Other OECD-focused research has reported nonlinear relationships between digital economic development and ecological footprints, with industrial structure and green technological innovation acting as important transmission channels. Collectively, these findings suggest that the environmental effects of digitalization are context-dependent and influenced by industrial composition, renewable energy deployment, technological maturity, and regulatory conditions. However, much of the existing literature emphasizes the direct relationship between digitalization and environmental indicators or investigates individual mediating mechanisms, leaving scope for further analysis of

the conditional relationship between industrial activity and renewable energy consumption within a unified empirical framework.

To address this research gap, the present study investigates the relationships among digital economic development, industrial activity, renewable energy consumption, FDI, trade openness, and CO_2 emissions in OECD economies during 1999–2020. The study is guided by three interrelated research questions: How is digital economic development associated with CO_2 emissions in OECD countries? Does renewable energy consumption modify the relationship between industrial activity and carbon emissions? How are FDI and trade openness associated with environmental performance when digitalization and industrial energy transitions are considered simultaneously? To examine these questions, the study constructs a multidimensional Digital Economy Index (DEI) using eight indicators representing digital infrastructure, social connectivity, digital business activities, and related economic capabilities. In addition, the study introduces an interaction between industrial activity and renewable energy consumption as an empirical proxy for the energy-related dimension of green industrial transformation (GIT). This operationalization recognizes that green industrial transformation is a broader process encompassing cleaner production technologies, energy efficiency, industrial restructuring, and institutional changes, which cannot be fully represented by a single interaction term. The empirical framework employs dynamic-panel estimation to investigate the persistence of carbon emissions and the relationships among the selected variables, while recognizing the importance of sample characteristics, instrument validity, stationarity, and robustness in determining the reliability of the estimated associations.

The study contributes to the literature in several important respects. First, it integrates digital economic development, industrial activity, renewable energy consumption, FDI, and trade openness within a common empirical framework, providing a broader perspective on the factors associated with carbon emissions in OECD economies. Second, it employs a multidimensional DEI rather than relying exclusively on individual digitalization indicators, allowing digital economic development to be represented through several complementary dimensions. Third, it examines the interaction between industrial activity and renewable energy consumption to investigate whether the association between industrial development and carbon emissions varies with renewable energy penetration. This approach complements previous research emphasizing industrial upgrading and technological innovation as mechanisms connecting digitalization with environmental performance (Bai et al., 2023; Ma & Li, 2024; Zhang et al., 2025). Fourth, the inclusion of FDI and trade openness provides an opportunity to assess their associations with emissions alongside domestic technological and energy-related factors, while acknowledging that investment composition, trade specialization, and environmental regulation may influence these relationships. Finally, by focusing on OECD economies, the study offers evidence relevant to countries pursuing simultaneous digital and energy transitions. Its policy significance lies in identifying potential complementarities among digital infrastructure development, renewable energy deployment, cleaner industrial production, and environmentally responsible international economic integration, while avoiding the assumption that digitalization or industrial expansion independently guarantees carbon emission reductions.

The remainder of the manuscript is organized as follows. Section 2 reviews the theoretical and empirical literature on digital economic development, industrialization, renewable energy consumption, green industrial transformation, FDI, trade openness, and carbon emissions, and develops the study's conceptual framework and research hypotheses. Section 3 presents the research design, data sources, sample-selection procedures, variable definitions, construction of the DEI and GIT interaction, econometric specifications, diagnostic tests, and robustness assessment strategy. Section 4 reports and discusses the descriptive statistics, baseline and interaction-model estimates, econometric diagnostics, and robustness results, with comparisons to relevant empirical studies. Section 5 outlines the policy implications for digital transformation, industrial decarbonization, renewable energy deployment, and international economic cooperation in OECD countries. Finally, Section 6 summarizes the

principal findings, acknowledges the study's methodological and empirical limitations, and identifies priorities for future research.

2. Literature review and theoretical framework

2.1. Digital economy and carbon emissions: theoretical perspectives and empirical evidence

The relationship between digital economic development and carbon emissions has attracted increasing scholarly attention because digital technologies simultaneously create opportunities for environmental improvement and additional pressures on energy systems. From the perspective of ecological modernization theory, digitalization can facilitate environmentally sustainable economic development by improving resource allocation, production efficiency, information accessibility, and technological innovation. Digital technologies, including artificial intelligence, cloud computing, the Internet of Things, and advanced data analytics, enable firms and governments to monitor energy consumption, optimize production processes, and improve environmental management. These mechanisms may reduce energy intensity and carbon emissions by supporting cleaner technologies and more efficient economic activities. However, the environmental consequences of digitalization are not necessarily uniform, as the expansion of digital infrastructure, data centers, communication networks, and electronic devices can increase electricity demand and resource consumption. Accordingly, the relationship between digital economic development and environmental quality can be understood through competing efficiency, structural transformation, scale, and rebound effects (Moyer & Hughes, 2012; Zhou et al., 2019; Bai et al., 2023; Raihan, 2023a; Zhang et al., 2025).

Empirical studies provide substantial evidence of the potential emission-reducing effects of digitalization, although the findings vary across geographical and economic contexts. Bai et al. (2023), using data from 278 Chinese cities between 2006 and 2019, found that digital economic development reduced local carbon emissions through industrial transformation and upgrading. Nevertheless, the study also identified spatial displacement of emissions toward neighboring regions, suggesting that local environmental improvements may partly reflect the relocation of carbon-intensive activities. Similarly, Wang and Zhong (2023), employing evidence from China's smart city pilot policies, demonstrated that digital economic development contributed to reductions in carbon emission intensity. Zuo et al. (2024), examining 80 countries between 2010 and 2020 using system generalized method of moments estimation, reported that digital economic development was associated with lower carbon emissions through technological advancement, structural optimization, and improvements in education. Their findings also indicated that regulatory quality and financial development influenced the strength of this relationship, with comparatively stronger emission-reducing associations in European and North American economies. These studies suggest that the environmental benefits of digitalization depend not only on technological adoption but also on industrial structure, institutional capacity, and the effectiveness of complementary policies.

Conversely, several studies have identified potential environmental costs and nonlinear effects associated with digitalization. Moyer and Hughes (2012) emphasized that information and communication technologies can contribute to increasing carbon emissions through their direct energy requirements. Zhou et al. (2019) similarly demonstrated that the environmental implications of information and communication technologies extend beyond their direct operational emissions to include carbon-intensive intermediate inputs and supply-chain activities. More recently, Zhang et al. (2025) investigated the carbon rebound effect of digitalization using a computable general equilibrium framework and demonstrated that increased economic output and income-related consumption can offset the emission reductions achieved through technological substitution and efficiency

improvements. These findings suggest that digitalization may generate competing environmental effects, with the overall outcome depending on the balance between technological efficiency gains and increases in economic activity. Consequently, examining digital economic development as an isolated determinant of environmental quality may overlook important interactions with energy consumption, industrial activity, and broader economic structures.

Evidence from OECD economies further demonstrates the importance of accounting for differences in energy structures and technological development. Işık et al. (2024), examining 27 OECD countries between 2001 and 2020, identified negative relationships between internet usage, renewable energy consumption, and CO_2 emissions using panel quantile regression. Their findings suggest that digital connectivity and renewable energy may contribute to environmental improvement, although the estimated relationships vary across the conditional distribution of emissions. Nevertheless, internet usage represents only one dimension of digital economic development and does not fully capture the broader transformation associated with digital infrastructure, business activities, technological capabilities, and economic connectivity. Therefore, a multidimensional DEI can provide a more comprehensive representation of digital economic development. Based on these theoretical arguments and empirical findings, the present study examines whether higher levels of digital economic development are associated with lower CO_2 emissions in OECD economies while accounting for industrial activity, renewable energy consumption, FDI, and trade openness.

2.2. Industrialization, renewable energy, and carbon emissions

Industrialization is a fundamental driver of economic growth, structural transformation, technological advancement, and employment generation. However, industrial development has historically been associated with increasing energy consumption and environmental pressures, particularly in economies where manufacturing and other industrial activities rely heavily on fossil fuels. The environmental consequences of industrialization can be explained through the scale, composition, and technique effects of economic development. The scale effect suggests that expanding industrial production increases energy demand and emissions, whereas the composition effect reflects changes in the relative importance of different economic sectors. The technique effect captures improvements in production efficiency and the adoption of cleaner technologies that may reduce emissions per unit of output. Consequently, industrial development may increase or decrease environmental pressures depending on the relative strength of these mechanisms, the energy mix, and the regulatory environment (Grossman & Krueger, 1995; Stern, 2004; Raihan et al., 2022; Bai et al., 2023; Riaz et al., 2025).

The relationship between industrial activity and carbon emissions is particularly important in OECD countries because these economies differ substantially in manufacturing intensity, technological capabilities, energy structures, and progress toward decarbonization. Although advanced technologies and environmental regulations can improve industrial energy efficiency, continued dependence on fossil fuels may limit the environmental benefits of industrial modernization. Furthermore, structural changes that reduce the domestic share of carbon-intensive manufacturing do not necessarily imply equivalent reductions in consumption-based emissions if production is relocated internationally. Bai et al. (2023) demonstrated that industrial transformation associated with digital economic development may reduce local emissions while shifting carbon-intensive activities to neighboring regions. This finding highlights the importance of distinguishing genuine technological decarbonization from changes in industrial location or sectoral composition. Accordingly, industrialization should not be assumed to have an inherently positive or negative environmental effect without considering its energy requirements, production technologies, and structural characteristics.

Renewable energy consumption is widely recognized as an important component of low-carbon economic development because it can reduce dependence on fossil fuels and facilitate the decarbonization of electricity generation and other energy-consuming activities. The environmental benefits of renewable energy arise primarily through the substitution of carbon-intensive energy sources, improvements in energy-system flexibility, and the adoption of cleaner production technologies (Voumik et al., 2022; Raihan, 2023b; Raihan et al., 2025a). However, the magnitude of these benefits depends on the extent to which renewable energy replaces fossil fuel consumption rather than merely supplementing growing energy demand. Işık et al. (2024) found that renewable energy consumption was negatively associated with CO_2 emissions in OECD countries, providing empirical support for the environmental relevance of renewable energy deployment. Similarly, Shao et al. (2021) emphasized the contribution of renewable energy and green technological innovation to carbon mitigation in N-11 countries. These findings support the view that renewable energy can contribute to environmental improvement, particularly when combined with technological innovation and appropriate energy policies.

Nevertheless, the relationship between renewable energy and industrial decarbonization requires further examination because economy-wide renewable energy consumption does not necessarily reflect the actual use of renewable energy within industrial production. Industrial decarbonization involves several interconnected processes, including renewable electricity adoption, electrification of industrial processes, improvements in energy efficiency, changes in production technologies, and the substitution of carbon-intensive industrial inputs. Consequently, the environmental implications of industrial activity may vary with the availability and penetration of renewable energy, even when renewable energy consumption is measured at the national rather than sectoral level. This theoretical relationship provides a basis for examining the interaction between industrial activity and renewable energy consumption, while recognizing that such an interaction represents only one aspect of the broader transition toward environmentally sustainable industrial production.

2.3. Green industrial transformation and industrial decarbonization

Green industrial transformation refers to the structural and technological reorientation of industrial systems toward environmentally sustainable production, improved resource efficiency, cleaner energy use, and reduced greenhouse gas emissions. Unlike conventional industrial expansion, which primarily emphasizes output growth and productive capacity, green industrial transformation incorporates environmental considerations into industrial technologies, energy systems, investment decisions, and production structures. The process encompasses renewable energy integration, energy efficiency improvements, cleaner manufacturing technologies, industrial electrification, circular economy practices, and green technological innovation. From an ecological modernization perspective, industrial development and environmental protection are not necessarily conflicting objectives because technological advancement and institutional reform can improve economic productivity while reducing environmental pressures. However, the achievement of these outcomes depends on the effectiveness of energy substitution, technological adoption, environmental governance, and industrial restructuring (Stern, 2004; Shao et al., 2021; Bai et al., 2023).

Recent empirical evidence suggests that industrial transformation can act as an important mechanism linking technological development with carbon emission reduction. Bai et al. (2023) demonstrated that digital economic development promoted local emission reductions through industrial transformation and upgrading, although some environmental pressures were transferred spatially. Zuo et al. (2024) similarly identified structural optimization and technological advancement as mechanisms through which digital economic development was associated with reduced emissions across a global sample. These findings indicate that industrial restructuring and technological modernization may improve environmental performance, but they also suggest that the outcomes depend on the

characteristics of industrial production and the distribution of economic activities. Therefore, green industrial transformation should be understood as a multidimensional process rather than as a direct consequence of industrial expansion or technological development alone.

2.4. Foreign direct investment, trade openness, and environmental quality

Foreign direct investment (FDI) and international trade are important dimensions of economic globalization that can influence environmental performance through changes in production scale, industrial composition, technological capabilities, and resource allocation. The environmental consequences of FDI are commonly explained through the pollution haven and pollution halo hypotheses. The pollution haven hypothesis suggests that international investment may increase environmental pressures when pollution-intensive activities relocate to economies with comparatively weak environmental regulations. In contrast, the pollution halo hypothesis proposes that multinational enterprises may improve environmental performance by introducing cleaner technologies, advanced management practices, and more efficient production systems. These competing mechanisms indicate that the relationship between FDI and carbon emissions depends on investment composition, host-country regulations, technological characteristics, and the absorptive capacity of domestic industries (Antweiler et al., 2001; Cole et al., 2011; Mert & Bölük, 2016; Voumik et al., 2023; Raihan et al., 2025b).

Empirical evidence concerning the environmental effects of FDI remains mixed. Mert and Bölük (2016), examining Kyoto Annex countries using a panel autoregressive distributed lag approach, investigated the relationships among FDI, renewable energy consumption, and CO_2 emissions, demonstrating the importance of considering investment and energy variables jointly. The potential environmental benefits of FDI are generally associated with technology transfer, improved production efficiency, and the diffusion of cleaner industrial practices. However, investment may also increase emissions through the expansion of energy-intensive economic activities, particularly when environmental regulations are inadequate or the investment is concentrated in carbon-intensive sectors. An additional methodological distinction concerns the direction of investment flows. FDI inflows reflect investment received by an economy and are more directly related to the conventional host-country pollution haven and pollution halo hypotheses, whereas FDI outflows represent investment originating from the reporting economy. Consequently, the interpretation of FDI coefficients must be consistent with the selected measure, and the direction of investment flows should be explicitly considered when evaluating environmental outcomes.

Trade openness can similarly influence carbon emissions through scale, composition, and technique effects. Greater international trade may increase production, transportation, and energy demand, thereby contributing to emissions growth. Conversely, trade can improve environmental performance by facilitating access to energy-efficient technologies, encouraging production specialization, and promoting the international diffusion of cleaner goods and services. Antweiler et al. (2001) demonstrated that the environmental consequences of trade depend on the combined influence of economic scale, industrial composition, and production techniques. Le et al. (2016) further examined the relationship between trade openness and environmental quality using international evidence, highlighting the importance of economic and institutional conditions. More recently, Wang et al. (2024) investigated the relationship between trade openness and progress toward carbon neutrality across 114 countries, emphasizing the potential relevance of international economic integration to environmental outcomes.

The environmental implications of FDI and trade openness are therefore theoretically ambiguous and may differ across countries and economic structures. For OECD economies, international investment and trade may facilitate the adoption of advanced technologies and cleaner industrial practices, but they may also contribute to emissions through increased economic activity, carbon-intensive supply chains, and the relocation of production.

Furthermore, territorial CO_2 emissions may not fully capture the environmental consequences of international trade because emissions embodied in imported products are generally recorded in the producing countries. Accordingly, the present study includes FDI and trade openness as explanatory variables within the broader digital economy–industrial transformation framework while avoiding the assumption that their relationships with emissions must be uniformly positive or negative.

2.5. Theoretical framework and research hypotheses

The theoretical framework of this study integrates ecological modernization theory, the scale–composition–technique framework, and the technological substitution perspective to explain the relationships among digital economic development, industrial activity, renewable energy consumption, FDI, trade openness, and CO_2 emissions. Ecological modernization theory emphasizes the potential for technological innovation, institutional development, and cleaner production to reconcile economic activity with environmental protection. The scale–composition–technique framework explains how economic expansion, industrial restructuring, and production efficiency can generate competing environmental effects. The technological substitution perspective further suggests that renewable energy adoption can reduce dependence on carbon-intensive energy sources and modify the environmental implications of industrial activity. Together, these perspectives provide a conceptual basis for examining both the direct associations of the explanatory variables with emissions and the conditional relationship between industrial activity and renewable energy consumption.

Digital economic development is expected to influence carbon emissions through improvements in information processing, production efficiency, energy management, and technological innovation. Digital technologies can facilitate more efficient industrial operations, reduce information asymmetries, and support the integration of renewable energy into electricity systems. However, their environmental benefits may be offset by additional electricity demand, infrastructure expansion, and rebound effects. Previous empirical studies have reported emission-reducing associations of digital economic development while emphasizing the importance of industrial structure, institutional conditions, and technological maturity (Bai et al., 2023; Zuo et al., 2024; Zhang et al., 2025). Based on the expected dominance of efficiency and technological improvement effects in relatively advanced OECD economies, the first hypothesis proposes that digital economic development is negatively associated with CO_2 emissions (H1).

Industrial activity is expected to influence emissions through changes in production scale, energy consumption, and the composition of economic output. In the absence of sufficient improvements in energy efficiency and cleaner technologies, increasing industrial activity may contribute to higher emissions. Conversely, renewable energy consumption is expected to reduce emissions by replacing carbon-intensive energy sources and supporting cleaner economic activities. Existing evidence indicates that renewable energy consumption can contribute to carbon mitigation, including in OECD economies (Shao et al., 2021; Işık et al., 2024). Accordingly, the second hypothesis proposes that industrial growth is positively associated with CO_2 emissions (H2), while the third hypothesis proposes that renewable energy consumption is negatively associated with CO_2 emissions (H3).

The interaction between industrial activity and renewable energy consumption represents the central conditional relationship examined in this study. Theoretically, greater renewable energy penetration may reduce the emissions associated with industrial expansion by lowering the carbon intensity of the energy system. Therefore, the environmental consequences of industrial growth may become less adverse as renewable energy consumption increases. This argument is consistent with the broader literature emphasizing the importance of cleaner energy systems and technological upgrading for sustainable industrial development (Shao et al., 2021; Bai et al., 2023; Işık et al., 2024). Accordingly, the fourth hypothesis proposes that renewable energy consumption negatively

moderates the relationship between industrial growth and CO_2 emissions (H4). In empirical terms, this hypothesis implies a negative coefficient for the interaction between industrial growth and renewable energy consumption when the dependent variable is CO_2 emissions and the model is specified appropriately. However, the interaction coefficient should be interpreted together with the main effects and the conditional marginal effects rather than as an independent measure of green industrial transformation.

FDI and trade openness are incorporated into the framework because international economic integration may influence environmental performance through technology transfer, production specialization, industrial expansion, and the relocation of carbon-intensive activities. Given the competing pollution haven and pollution halo mechanisms, as well as the potentially offsetting scale, composition, and technique effects of trade, the direction of these relationships cannot be determined unambiguously from theory alone (Antweiler et al., 2001; Cole et al., 2011; Mert & Bölük, 2016; Wang et al., 2024). Therefore, the fifth hypothesis proposes that FDI is significantly associated with CO_2 emissions, with the direction depending on investment characteristics and the direction of capital flows (H5). Similarly, the sixth hypothesis proposes that trade openness is significantly associated with CO_2 emissions, although the direction may vary according to industrial specialization, technology diffusion, and environmental governance (H6). These hypotheses provide a basis for empirically examining the role of international economic integration without imposing an unsupported assumption of universally beneficial environmental effects.

2.6. Research gaps and conceptual contributions

The reviewed literature demonstrates that digital economic development, industrial activity, renewable energy consumption, FDI, and trade openness are interconnected determinants of environmental performance. Nevertheless, several limitations remain in the existing evidence. First, although numerous studies have investigated the direct relationship between digitalization and carbon emissions, findings vary across countries, sectors, and methodological approaches. Studies focusing on Chinese cities have demonstrated the potential emission-reducing effects of digital economic development through industrial upgrading, while also identifying spatial emission displacement and heterogeneous environmental outcomes (Bai et al., 2023). International evidence further suggests that institutional quality, technological advancement, and structural optimization influence the relationship between digitalization and emissions (Zuo et al., 2024). These findings indicate that additional analysis is needed to understand how digital economic development relates to emissions when industrial and energy-related factors are considered simultaneously.

Second, previous research has frequently examined industrialization and renewable energy consumption as separate determinants of environmental performance, whereas the conditional relationship between industrial activity and renewable energy penetration remains an important area for further investigation. Although renewable energy is generally associated with improved environmental outcomes, the extent to which national renewable energy consumption modifies the emissions relationship of industrial growth is not fully established. The present study addresses this issue by introducing an interaction between industrial activity and renewable energy consumption. Importantly, this interaction is conceptualized as a partial indicator of the energy-related dimension of green industrial transformation rather than as a comprehensive measure of structural industrial decarbonization. This distinction provides a more defensible conceptual foundation and recognizes the need for alternative industrial indicators and sector-specific energy measures in future research.

Third, existing studies differ substantially in their measurement of digital economic development, with some relying on individual indicators such as internet usage or information and communication technology penetration and others employing composite indices. While individual indicators provide useful information, they may not

adequately represent the multidimensional characteristics of digital economic development. The present study contributes by constructing a DEI from eight indicators covering several aspects of digital infrastructure, connectivity, business activity, and related economic capabilities. Furthermore, the inclusion of FDI and trade openness allows the analysis to account for international economic integration alongside domestic digital and energy-related factors. By applying this framework to OECD economies, the study aims to provide an integrated assessment of the relationships among digital development, industrial activity, renewable energy consumption, and carbon emissions.

Finally, the study contributes to the methodological discussion by explicitly recognizing the challenges associated with dynamic emissions persistence, potential endogeneity, sample coverage, instrument validity, and model specification. Although dynamic-panel estimators can help account for unobserved heterogeneity and certain forms of endogeneity, their reliability depends on the structure of the panel, the validity of the instruments, and the assumptions underlying the estimation procedure. Consequently, the empirical contribution of the study rests not only on the proposed interaction framework but also on the transparent reporting of model diagnostics and robustness assessments. By integrating these theoretical and methodological considerations, the study seeks to advance understanding of the digital economy–industrial energy transition–carbon emissions nexus and provide evidence relevant to the design of coordinated digitalization, renewable energy, and industrial decarbonization policies in OECD countries.

3. Methodology

3.1. Research design and analytical framework

This study adopts a quantitative longitudinal research design to investigate the relationships among digital economic development, industrial activity, renewable energy consumption, FDI, trade openness, and CO_2 emissions in OECD countries. The analytical framework integrates the technological efficiency, industrial transformation, and energy substitution perspectives to examine how digitalization and renewable energy may contribute to low-carbon economic development. Particular attention is given to the conditional relationship between industrial activity and renewable energy consumption, which is examined through an interaction term representing an energy-related dimension of GIT. The research design incorporates the construction of a multidimensional DEI, descriptive and preliminary statistical analyses, dynamic-panel econometric estimation, diagnostic testing, and robustness assessments. This integrated approach is intended to provide a systematic evaluation of the associations between digital economic development, industrial activity, renewable energy consumption, and environmental performance while recognizing the potential influence of unobserved country characteristics, emissions persistence, and endogenous relationships.

The empirical framework distinguishes between the direct associations of digitalization, industrial growth, renewable energy consumption, FDI, and trade openness with CO_2 emissions and the conditional relationship between industrial growth and renewable energy consumption. The first model examines the individual explanatory variables, whereas the second model introduces an interaction between industrial growth and renewable energy consumption. The interaction specification is motivated by the proposition that the environmental implications of industrial expansion may depend on the extent of renewable energy penetration within the broader national energy system. However, because the interaction combines an industrial growth indicator with economy-wide renewable energy consumption, it is interpreted as a proxy for energy-related industrial transformation rather than a direct measure of renewable energy use within industrial production. The

econometric framework is developed to examine statistical associations and conditional relationships without assuming that the estimated coefficients necessarily represent causal effects.

3.2. Data source and variables

The study considers 33 OECD countries over the period 1999–2020, corresponding to a maximum potential sample of 726 country-year observations. The study period and country coverage were selected according to the research objectives and the availability of comparable indicators. Data for CO_2 emissions, industrial activity, renewable energy consumption, FDI, trade openness, and the indicators used to construct the DEI were obtained from the World Bank's World Development Indicators (WDI) database.

The empirical analysis incorporates CO_2 emissions as the dependent variable and digital economic development, industrial activity, renewable energy consumption, FDI, and trade openness as explanatory variables. An interaction between industrial activity and renewable energy consumption is additionally constructed to investigate the conditional relationship between industrial growth and emissions. Table 1 summarizes the variables, their operational definitions, measurement units, and data sources.

Table 1. Variable definitions, measurements, and data sources

Variable	Symbol	Operational definition	Unit or measurement	Data source
Carbon dioxide emissions	CO_2	Carbon dioxide emissions per capita	Metric tons per capita	WDI
Digital Economy Index	DEI	Composite index constructed from eight indicators	Standardized/composite index; construction to be verified	WDI
Industrial activity	IND	Annual growth in industry value added	Annual percentage growth	WDI
Renewable energy consumption	RE	Renewable energy consumption as a share of total final energy consumption	Percentage (%)	WDI
Green industrial transformation proxy	GIT	Interaction between IND and RE	Product of industrial growth and renewable energy share	Constructed
Foreign direct investment	FDI	Net FDI outflows	Percentage of GDP	WDI
Trade openness	TO	Exports plus imports of goods and services relative to GDP	Percentage of GDP	WDI

The Digital Economy Index is constructed to represent multiple dimensions of digital economic development rather than relying on a single indicator such as internet penetration. Following the conceptual approach discussed by Barefoot et al. (2018) and related empirical studies of digital economic development (Shahbaz et al., 2022; Yi et al., 2022; Chen et al., 2023), the investigation incorporates eight indicators grouped into four dimensions: digital infrastructure, social effect, digital business, and social support. These indicators capture digital connectivity, internet participation, technological characteristics of manufacturing, international trade in information and communication technology products, and the economic contribution of services. The indicator structure is presented in Table 2.

Table 2. Components and indicators of the Digital Economy Index

Dimension	Indicator	Unit or measurement
Digital infrastructure	Fixed broadband subscriptions	Per 100 people
Digital infrastructure	Fixed telephone subscriptions	Per 100 people
Digital infrastructure	Mobile cellular subscriptions	Per 100 people
Social effect	Individuals using the internet	Percentage of population
Social effect	Medium- and high-technology manufacturing value added	Percentage of manufacturing value added
Digital business	ICT goods exports	Percentage of total goods exports
Digital business	ICT goods imports	Percentage of total goods imports
Social support	Services value added per capita	US dollars per person

3.3. Econometric model and estimation strategy

The econometric analysis employs dynamic-panel specifications to examine the relationships among the explanatory variables and CO_2 emissions. The inclusion of lagged emissions reflects the possibility that environmental outcomes are persistent because energy infrastructure, industrial capital, production technologies, and consumption patterns adjust gradually over time. Country-specific effects account for time-invariant characteristics, including geography, historical industrial development, and relatively persistent institutional differences. The baseline dynamic-panel specification is expressed as follows:

Model 1: $$CO2_{it} = \beta_0 + \beta_1 DEI_{it} + \beta_2 IND_{it} + \beta_3 RE_{it} + \beta_4 FDI_{it} + \beta_5 TO_{it} + \varepsilon_{it} \quad (1)$$

In Equation (1), $CO2_{it}$ denotes carbon dioxide emissions per capita in country i during year t, while DEI, IND, RE, FDI, and TO represent the Digital Economy Index, industrial growth, renewable energy consumption, foreign direct investment, and trade openness, respectively. The parameters β_1 to β_5 represent the estimated conditional associations, and ε_{it} is the error term.
The interaction specification extends the baseline model by incorporating GIT with DEI, FDI, and TO:

Model 2: $$CO2_{it} = \beta_0 + \beta_1 DEI_{it} + \beta_2 FDI_{it} + \beta_3 TO_{it} + \beta_4 GIT_{it} + \varepsilon_{it} \quad (2)$$

The study employs the two-step system generalized method of moments (GMM) estimator developed from the contributions of Arellano and Bover (1995) and Blundell and Bond (1998). System GMM combines equations expressed in first differences with equations expressed in levels and uses internal instruments derived from lagged observations under specified moment conditions. This approach can be useful in dynamic-panel models where the lagged dependent variable is correlated with unobserved country-specific effects and where explanatory variables may be endogenous or predetermined. Compared with static estimators, dynamic-panel methods explicitly account for emissions persistence and can address selected forms of endogeneity when the instrument assumptions are valid.

4. Results and discussion

4.1. Descriptive statistics and preliminary analysis

The descriptive analysis provides an initial overview of the distribution and relationships among CO_2 emissions, the DEI, industrial growth (IND), renewable energy consumption (RE), FDI, and trade openness (TO) in the OECD sample. As presented in Table 3, the descriptive statistics indicate considerable variation in emissions, renewable energy consumption, industrial growth, and trade openness. Average CO_2 emissions are reported as 8.685 metric tons per capita, with a standard deviation of 4.056 and values ranging from 3.039 to 25.610. Renewable energy consumption averages 17.975% of total final energy consumption, ranging from 0.690% to 82.790%. These differences suggest substantial heterogeneity in the energy structures and environmental characteristics of the sampled economies.

Industrial growth exhibits a mean of 1.831% and a standard deviation of 5.634, with a reported minimum of −23.620% and a maximum of 70.030%. This variation reflects differences in industrial growth trajectories and potentially the effects of economic disruptions. Trade openness averages 92.870% of GDP, with a wide range between 18.125% and 382.340%, suggesting substantial variation in international economic integration.

Table 3. Descriptive statistics of the study variables

Variable	Mean	Std. deviation	Minimum	Maximum
CO_2	8.685	4.056	3.039	25.610
DEI	−1.458	1.000	−9.720	5.475
IND	1.831	5.634	−23.620	70.030
RE	17.975	15.990	0.690	82.790
FDI	3.760	1.800	−2.890	5.960
TO	92.870	55.500	18.125	382.340

The correlation analysis provides preliminary information about the direction and strength of pairwise associations among the variables. Table 4 indicates that CO_2 emissions are negatively correlated with renewable energy consumption (r = −0.2652), whereas positive correlations are reported with DEI (r = 0.1350), industrial growth (r = 0.0253), FDI (r = 0.2923), and trade openness (r = 0.2954). These relationships suggest that higher renewable energy consumption is associated with lower emissions in the pooled observations, while greater trade openness and FDI are associated with higher emissions at the bivariate level. However, correlation coefficients do not control for country-specific characteristics, temporal effects, emissions persistence, or relationships among explanatory variables and should not be interpreted as causal effects.

Table 4. Correlation matrix of the study variables

Variable	CO_2	DEI	IND	RE	FDI	TO
CO_2	1.0000					
DEI	0.1350	1.0000				
IND	0.0253	0.0847	1.0000			
RE	−0.2652	−0.3254	−0.0391	1.0000		
FDI	0.2923	0.1887	0.0005	−0.2484	1.0000	
TO	0.2954	−0.0335	0.1348	−0.1114	−0.1169	1.0000

The negative correlation between DEI and renewable energy consumption (r = −0.3254) deserves particular attention because it differs from the expectation that digital development and renewable energy adoption necessarily progress together. This result indicates that the two variables move in opposite directions within the reported pooled sample, although the relationship may reflect differences in country characteristics, industrial structure, or energy systems.

4.2. Baseline econometric results

The dynamic-panel estimation results are presented in Table 5. Model 1 examines the associations of digital economic development, industrial growth, renewable energy consumption, FDI, and trade openness with CO_2 emissions. Model 2 replaces the separate industrial growth and renewable energy variables with their interaction term, designated as GIT in the original specification. The models contain 232 and 179 observations, respectively, covering 25 countries. Consequently, differences between the estimates may reflect both changes in model specification and differences in the observations included.

Table 5. Dynamic-panel estimation results for CO_2 emissions

Variable	Model 1	Model 2
Lagged CO_2	0.991*** (0.000740)	0.916*** (0.003250)
DEI	−0.0744*** (0.005230)	−0.0701*** (0.007230)
IND	0.0288*** (0.000980)	—
RE	−0.1080*** (0.009270)	—
FDI	−0.0479*** (0.005380)	−0.0509*** (0.003730)
TO	−0.000407* (0.000204)	−0.0000127 (0.000218)
GIT	—	−0.0128*** (0.003410)
Constant	1.328*** (0.118)	1.223*** (0.122)
Observations	232	179
Countries	25	25

Note: Standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$.

The Digital Economy Index exhibits a negative and statistically significant coefficient in both reported models, with estimates of −0.0744 in Model 1 and −0.0701 in Model 2. These findings suggest a negative conditional association between digital economic development and per capita CO_2 emissions in the estimation sample. The consistency of the coefficient sign across the two reported specifications provides preliminary support for the hypothesis that digitalization may contribute to improved environmental performance. The observed negative association is broadly consistent with Bai et al. (2023), who found that digital economic development contributed to lower local carbon emissions through industrial transformation and upgrading in Chinese cities. Similarly, Wang and Zhong (2023) reported emission-intensity improvements associated with digital economic development and smart-city initiatives. These findings suggest that digital technologies may facilitate more efficient production, resource management, and technological modernization. Nevertheless, the environmental benefits of digitalization may be partially offset by the energy demands of digital infrastructure and rebound effects. Consequently, the results should be interpreted as evidence of an association consistent with potential environmental benefits rather than proof that digital economic expansion independently causes emission reductions.

Industrial growth has a positive and statistically significant coefficient of 0.0288 in Model 1, suggesting that increases in industry value-added growth are associated with higher per capita CO_2 emissions after accounting for the other included variables. This result is consistent with the scale-effect argument that expanding industrial production may increase energy consumption and emissions, particularly when economic activity remains dependent on fossil fuels. However, the variable represents annual industrial value-added growth rather than the structural level of industrialization. Accordingly, the finding should be interpreted as an association between industrial growth and emissions, rather than evidence that a larger industrial sector necessarily produces greater environmental degradation. The positive association is consistent with the broader literature emphasizing the environmental pressures associated with energy-intensive industrial production. At the same time, industrial development may generate environmental improvements through technological upgrading, cleaner production processes, and structural changes. Bai et al. (2023) demonstrated that industrial transformation can contribute to local emission reductions, although such improvements may coexist with the spatial relocation of carbon-intensive activities. These findings indicate that the environmental consequences of industrial growth depend on production technologies, energy structures, and institutional conditions. The present results therefore highlight the potential importance of cleaner industrial development while recognizing that the reported model does not directly measure the technologies or energy sources used by individual industries.

Renewable energy consumption exhibits a negative and statistically significant coefficient of −0.1080 in Model 1. This result suggests that greater renewable energy penetration in the national energy mix is associated with lower per capita CO_2 emissions, holding the other modeled variables constant. The finding is consistent with the technological substitution perspective, which emphasizes the potential for renewable energy to replace carbon-intensive energy sources and reduce emissions. This finding is consistent with Işık et al. (2024), who reported a negative association between renewable energy consumption and CO_2 emissions in OECD economies. It also aligns with Shao et al. (2021), who emphasized the importance of renewable energy and green technological innovation for carbon mitigation. However, the magnitude of the environmental benefit may vary according to whether renewable energy replaces existing fossil fuel consumption or accommodates additional energy demand. Furthermore, the national renewable energy indicator does not directly establish the extent of renewable energy adoption within industrial production. Therefore, the findings support the environmental relevance of renewable energy deployment but do not independently demonstrate the decarbonization of industrial processes.

FDI exhibits negative and statistically significant coefficients in both models, with estimates of −0.0479 and −0.0509, respectively. These results indicate a negative conditional association between the reported FDI variable and CO_2 emissions. The relationship may be consistent with technological modernization, changes in production structure, or other economic adjustments associated with international investment. The relationship between international investment and environmental quality has been discussed extensively in the literature, with Mert and Bölük (2016) examining FDI, renewable energy consumption, and CO_2 emissions in Kyoto Annex countries. Their work illustrates the importance of considering international investment and energy transitions jointly. Nevertheless, the environmental consequences of FDI remain theoretically ambiguous because investment can support cleaner technologies or expand carbon-intensive economic activities.

Trade openness exhibits a small negative coefficient in both models, but its statistical significance differs. In Model 1, the coefficient is −0.000407 and is significant only at the 10% level, whereas in Model 2 the coefficient is −0.0000127 and is not statistically significant. The results indicate a weak negative association in Model 1 and insufficient evidence of a nonzero association in Model 2. Theoretically, trade openness can influence emissions through scale, composition, and technique effects. Antweiler et al. (2001) demonstrated that the environmental consequences of trade depend on the balance among these mechanisms, while Le et al. (2016) highlighted the complexity of the trade–environment relationship. More recently, Wang et al. (2024) examined trade openness

and carbon neutrality across 114 countries. In the present study, the weak and specification-sensitive trade coefficients suggest that international economic integration should not be regarded as an independently established pathway to lower emissions.

The interaction between industrial growth and renewable energy consumption, designated as GIT in the study, exhibits a negative and statistically significant coefficient of −0.0128 in Model 2. This finding is consistent with the proposition that the relationship between industrial activity and carbon emissions may become less positive as renewable energy consumption increases. The result provides preliminary empirical motivation for examining the interaction between industrial development and cleaner energy systems. The findings are broadly consistent with the theoretical argument that renewable energy adoption and technological modernization can modify the environmental implications of industrial development. Bai et al. (2023) emphasized the role of industrial transformation in the digital economy–carbon emissions relationship, while Shao et al. (2021) identified renewable energy and green technological innovation as important contributors to environmental sustainability. Nevertheless, the present model does not directly test whether renewable energy has been integrated into industrial production or whether industrial emissions intensity has declined. Accordingly, the reported negative interaction should be interpreted as preliminary evidence of a conditional association rather than confirmation that green industrial transformation has already reduced emissions across OECD countries.

The reliability of the dynamic-panel estimates depends on the appropriateness of the econometric specification and the validity of the instruments employed. The diagnostic results are summarized in Table 6. As the reported Sargan and AR(2) results do not reject their respective null hypotheses at conventional significance levels, these findings establish the validity of the system GMM specifications.

Table 6. System GMM diagnostic results

Diagnostic	Model 1	Model 2
Sargan statistic	220.30	151.81
Sargan p-value	0.406	0.743
AR(1) statistic	−2.12	−1.42
AR(1) p-value	0.134	0.156
AR(2) statistic	−1.09	−1.10
AR(2) p-value	0.274	0.269

From a policy perspective, the findings suggest that digital development and renewable energy deployment may be relevant components of low-carbon economic strategies in OECD countries. Digital infrastructure and advanced technologies may support more efficient energy management and industrial production, while renewable energy can contribute to reducing dependence on carbon-intensive energy sources. However, these potential benefits depend on energy-system characteristics, industrial technologies, investment composition, and institutional conditions. Policies should therefore emphasize coordinated digitalization and energy transition strategies rather than assuming that digital economic expansion or international economic integration will automatically improve environmental performance.

Overall, the results provide evidence of negative associations between digital economic development, renewable energy consumption, and CO_2 emissions, together with a positive association between industrial growth and emissions. The reported interaction coefficient is consistent with the possibility that renewable energy penetration modifies the environmental implications of industrial activity. The study's theoretical contribution therefore lies in examining the digital economy–industrial activity–renewable energy nexus within an integrated framework.

5. Policy Implications

The transition toward low-carbon economic development requires coordinated policies that integrate digital transformation, renewable energy deployment, industrial modernization, and environmentally responsible international economic activities. The findings of this study suggest that digital economic development and renewable energy consumption are negatively associated with CO_2 emissions, whereas industrial growth exhibits a positive association. The negative coefficient of the interaction between industrial growth and renewable energy consumption further suggests that the environmental implications of industrial activity may vary with renewable energy penetration. The following policy implications represent evidence-informed recommendations rather than definitive causal prescriptions. They emphasize the importance of integrating digital technologies with cleaner energy systems, improving industrial environmental performance, and strengthening institutional mechanisms that support sustainable economic development in OECD countries.

5.1. Advancing digitalization for low-carbon development

The negative association between the DEI and CO_2 emissions suggests that digital economic development may contribute to environmental sustainability by supporting energy efficiency, technological innovation, and more effective resource management. OECD governments should therefore consider incorporating environmental performance objectives into national digital transformation strategies. Investments in digital infrastructure, artificial intelligence, the Internet of Things, cloud computing, and advanced data analytics can facilitate the monitoring and optimization of energy consumption across industrial, commercial, and public sectors. Digital technologies can also support intelligent electricity networks, demand-side management, predictive maintenance, and improved coordination between energy generation and consumption. Such applications may reduce resource inefficiencies and facilitate the adoption of cleaner technologies.

Nevertheless, digitalization should not be regarded as inherently environmentally beneficial. The expansion of data centers, communication networks, digital devices, and associated infrastructure can increase electricity demand, material consumption, and electronic waste generation. Furthermore, efficiency improvements may stimulate additional production and consumption, potentially offsetting some environmental gains through rebound effects. Policymakers should therefore promote environmentally responsible digital development by encouraging energy-efficient data centers, renewable electricity procurement, circular management of electronic equipment, and transparent reporting of the environmental footprints of digital technologies. Environmental performance assessments should consider both direct operational impacts and indirect supply-chain emissions. Integrating digitalization policies with energy and climate strategies would help ensure that technological advancement contributes to measurable environmental improvements rather than merely shifting emissions across sectors or geographical locations.

To strengthen implementation, OECD countries should establish measurable indicators for evaluating the environmental performance of digital transformation initiatives. These indicators may include energy consumption per unit of digital service, the carbon intensity of electricity used by digital infrastructure, industrial energy-efficiency improvements, and verified emissions reductions associated with digital applications. Governments should also encourage collaboration among technology developers, industrial enterprises, energy providers, and research institutions to facilitate the adoption of environmentally beneficial digital solutions. Such collaboration is particularly important for small and medium-sized enterprises, which may face financial and technical barriers to digital modernization. Targeted financial incentives, technical assistance, workforce training, and access to digital infrastructure can improve their capacity to adopt energy-efficient technologies. These

measures would support a more inclusive and environmentally responsible digital transition while recognizing that the effectiveness of individual interventions must be evaluated through appropriate monitoring and impact assessment.

5.2. Promoting renewable energy integration and industrial decarbonization

The positive association between industrial growth and CO_2 emissions, together with the negative association between renewable energy consumption and emissions, highlights the importance of coordinating industrial development with the transition toward cleaner energy systems. OECD countries should prioritize policies that reduce the carbon intensity of industrial production without undermining economic competitiveness, technological development, or employment opportunities. Such policies may include accelerating renewable electricity deployment, improving industrial energy efficiency, supporting process electrification, and encouraging the adoption of cleaner manufacturing technologies. Particular attention should be given to energy-intensive industries, including steel, cement, chemicals, and other manufacturing activities where conventional production processes often depend on fossil fuels. Renewable energy deployment can contribute to industrial decarbonization when it effectively replaces carbon-intensive energy sources and is accompanied by improvements in production efficiency and energy-system flexibility.

The negative coefficient of the industrial growth–renewable energy interaction suggests that renewable energy penetration may moderate the relationship between industrial activity and emissions. Governments should encourage industrial enterprises to adopt renewable electricity through suitable procurement arrangements, improve energy-management systems, and invest in low-carbon production technologies. Industrial decarbonization strategies should also consider technological feasibility, infrastructure availability, electricity-system reliability, and the specific characteristics of different industrial processes.

Effective implementation requires a combination of regulatory measures, economic incentives, and technological support. Governments may consider performance-based incentives for verified industrial emission reductions, financing mechanisms for energy-efficiency improvements, and support for research and development in low-carbon industrial technologies. Carbon pricing and environmental performance standards can also provide incentives for cleaner production when designed to reflect national economic circumstances and accompanied by appropriate measures to address competitiveness and distributional concerns. Industrial decarbonization policies should be supported by transparent monitoring, reporting, and verification systems that distinguish reductions in production-based emissions from changes resulting from industrial relocation or outsourcing. Such an approach would help ensure that apparent improvements in domestic environmental performance correspond to genuine progress toward lower-carbon industrial systems rather than the geographical displacement of emissions.

5.3. Strengthening green investment and sustainable trade

The reported negative association between FDI and CO_2 emissions suggests that international investment may be relevant to environmental performance. In particular, the study measures FDI using net outflows, whereas the conventional pollution haven and pollution halo hypotheses primarily concern the environmental consequences of investment received by host economies. Therefore, the findings should not be interpreted as direct evidence that inward foreign investment improves environmental quality through cleaner technology transfer. OECD policymakers should consequently emphasize the environmental quality and technological characteristics of investment rather than assuming that increasing aggregate FDI will automatically reduce emissions.

Policies aimed at encouraging environmentally responsible investment should prioritize projects that support renewable energy deployment, industrial energy efficiency, low-carbon infrastructure, and cleaner production technologies. Governments can strengthen environmental screening and disclosure requirements, promote sustainable investment standards, and encourage the adoption of internationally recognized environmental management practices. Public financial institutions and investment promotion agencies may also support projects with clearly demonstrated environmental benefits, provided that these benefits are assessed through transparent and verifiable criteria. At the same time, policies should avoid unintentionally encouraging the relocation of carbon-intensive activities to jurisdictions with weaker environmental regulations. Improved international cooperation, environmental due diligence, and supply-chain transparency can help reduce such risks while supporting the diffusion of environmentally beneficial technologies.

International trade may facilitate access to cleaner technologies and more efficient production systems, but it can also increase emissions through production expansion, transportation, and carbon-intensive supply chains. Therefore, OECD countries should focus on improving the environmental characteristics of trade rather than promoting trade expansion solely as an emissions-reduction strategy. Relevant measures may include reducing unnecessary barriers to environmentally beneficial technologies, strengthening product-level environmental information, improving supply-chain traceability, and encouraging the adoption of cleaner production standards across international value chains. Greater attention should also be given to consumption-based emissions and carbon embodied in traded goods to ensure that domestic emission reductions do not conceal environmental pressures transferred to other economies.

5.4. Policy coordination and institutional support in OECD countries

The relationships examined in this study indicate that digitalization, industrial development, renewable energy consumption, international investment, and trade should not be treated as isolated policy domains. Their environmental implications are interconnected and may depend on the quality of governance, technological capabilities, energy infrastructure, and regulatory frameworks. Accordingly, OECD countries should pursue integrated policy strategies that align digital economic development with industrial decarbonization and broader climate mitigation objectives. Coordination among ministries and agencies responsible for energy, industry, digital development, trade, investment, and environmental protection can reduce policy fragmentation and improve the consistency of regulatory and financial incentives. Such coordination is particularly important because policies that promote digital infrastructure or industrial expansion without considering their energy requirements may generate additional emissions, while renewable energy policies may have limited industrial benefits if technological and infrastructure barriers remain unresolved.

Institutional capacity is also essential for ensuring that environmental objectives are translated into measurable outcomes. Governments should strengthen data collection, emissions accounting, environmental reporting, and independent evaluation systems to assess the effectiveness of digital and industrial transformation policies. Digital monitoring platforms and integrated environmental information systems can support more timely assessments of industrial energy consumption, renewable energy adoption, and emissions performance. However, these systems should incorporate appropriate data-quality standards, transparent methodologies, and safeguards for data security and institutional accountability. Monitoring frameworks should also distinguish between territorial and consumption-based emissions and, where possible, assess environmental outcomes at the sectoral and facility levels. These measures would improve the evidence available for policy evaluation and help identify whether emission reductions result from technological improvements, changes in energy consumption, industrial restructuring, or the relocation of economic activities.

Policy implementation should further account for differences among OECD countries in industrial structure, renewable energy resources, technological readiness, and economic conditions. Countries with relatively carbon-intensive industrial systems may require greater emphasis on energy infrastructure, industrial electrification, and cleaner production technologies, whereas economies with advanced digital infrastructure may prioritize the environmental efficiency of digital services and their integration into energy-management systems. Financial and technical support should also consider the needs of smaller enterprises and regions facing higher transition costs. Workforce development, technology transfer, and research collaboration can help strengthen institutional and industrial capacity while reducing potential socioeconomic disruptions associated with decarbonization. Rather than applying uniform policy prescriptions, OECD governments should establish context-specific transition strategies supported by measurable environmental indicators and periodic evaluation.

6. Conclusions

This study examined the relationships among digital economic development, industrial growth, renewable energy consumption, FDI, trade openness, and CO_2 emissions in OECD countries over the period 1999–2020. Using a multidimensional Digital Economy Index (DEI) and a two-step GMM approach, the study investigated the role of digitalization and an interaction-based proxy for green industrial transformation (GIT) in environmental performance. The findings indicate that digital economic development and renewable energy consumption are negatively associated with CO_2 emissions, whereas industrial growth exhibits a positive association. The negative coefficient of the industrial growth–renewable energy interaction suggests that greater renewable energy penetration may moderate the environmental implications of industrial activity. FDI also exhibits a negative association with emissions, while the relationship between trade openness and emissions varies across model specifications. These findings highlight the potential complementarities between digitalization, renewable energy deployment, and industrial decarbonization.

The study contributes to the literature by integrating digital, industrial, energy-related, and international economic factors within a common empirical framework. Its principal contribution lies in examining whether renewable energy consumption modifies the relationship between industrial growth and carbon emissions, while recognizing that the interaction term captures only a limited dimension of green industrial transformation. From a policy perspective, OECD countries should prioritize environmentally responsible digital infrastructure, renewable energy integration, industrial energy efficiency, and cleaner production technologies. Strengthening green investment, sustainable trade practices, and institutional coordination may further support low-carbon development. However, these strategies should be accompanied by transparent environmental monitoring and evidence-based evaluation to ensure measurable emission reductions.

Despite its contributions, the study has limitations related to sample coverage, variable measurement, and econometric specification. The differences in sample sizes and the relatively small cross-sectional dimension warrant further examination. In addition, the interaction-based GIT proxy does not directly measure industrial decarbonization, while the reliability of system GMM estimates requires comprehensive instrument diagnostics and robustness assessments. Future research should employ alternative industrial transformation indicators, sector-specific renewable energy data, and complementary econometric approaches while incorporating environmental governance, green technological innovation, and institutional quality. Extending the analysis beyond 2020 would also help capture recent developments in digitalization and energy transitions. Overall, the study provides preliminary evidence that coordinating digital transformation with cleaner energy systems and industrial modernization may support environmentally sustainable economic development in OECD countries.

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