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Leveraging Energy Efficiency, Digitalization, and Green Finance for Sustainable Competitiveness: Insights from OECD Economies Post-COP28

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Abstract
The COP28 summit emphasizes the importance of climate strategies to achieve net-zero carbon emissions. Following the COP28, this study explores the role of energy productivity, digitalization, and green finance for sustainable development in OECD economies from 1990 to 2022. Using the method of moments quantile regression and bootstrap quantile regression, we showed that energy productivity significantly reduces emissions, highlighting the importance of energy efficiency policies for sustainable development. Digitalization and green finance also emerge as transformative factors that facilitate low-carbon transitions. Furthermore, imports and economic growth enhance carbon emissions in OECD economies, while exports reduce emissions. These results highlight the necessity for OECD countries to integrate energy productivity, digital innovation, and green finance into their climate strategies, aligning with the COP28 decarbonization outline and promoting sustainable development.

Keywords: COP28; Green Finance; Energy Productivity; Digitalization; OECD Economies

JEL Classification: Q01, Q43, O33

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1 INTRODUCTION

The rapid rise in carbon emissions has resulted in greenhouse effects and a variety of environmental issues, which pose a substantial threat to the sustainable development of the economy and society, as well as to human health. Carbon emissions from energy use, combustion, industrial processes, and methane in the year 2021 increased by 5.7% to 39 billion tons of CO2 equivalent, as per the BP Statistical Review of World Energy (2022). The significance of reducing carbon emissions from economic activities is recognized by governments worldwide, and they have implemented measures to attain coordinated economic and environmental development. The deterioration of environmental quality and the increasing threat to sustainability necessitates substantial mitigation of carbon emissions through integrated policy frameworks and technological advancements, which is imperative for achieving climate stability and preventing irreversible ecological damage. In the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change in 2015, 200 countries signed the "Paris Agreement" committing to actively address global climate change beyond 2020 (Guo et al., 2022). However, the implementation of identical policy measures to mitigate environmental degradation across diverse economies has not been uniformly achieved, and in several instances, these approaches have proven ineffective in delivering the intended environmental outcomes (Sun, 2023). Sokolowski and Heffron (2022) argued that different factors have contributed to the failure of sustainable energy policy in different countries across the globe.

The main contributor to environmental pollution and climate change is carbon dioxide emissions, which drive global warming and its devastating impacts (EDGAR, 2019). To mitigate this, countries have signed numerous international agreements, with the most recent being COP29, the 29th United Nations Climate Change Conference in Baku, Azerbaijan. The COP29 conference brings together world leaders, negotiators, and stakeholders to advance actions that limit global temperature rise to 1.5 degrees Celsius, achieve net-zero emissions by 2050, and secure stronger climate finance commitments. The focus is on designing and placing policies to limit greenhouse gas emissions by building resilient communities and finalizing bold, implementable nationally determined contributions (NDCs) to drive the global transition away from fossil fuels (UNFCCC, 2024). Given the global commitment to reducing carbon emissions through COP conferences, digitalization and green finance can play an important role in achieving carbon neutrality.

Green finance is important in mitigating carbon emissions in OECD economies (Umar & Safi, 2023). Firms around the world and in OECD economies are investing in eco-friendly technologies and sustainable practices to achieve sustainable development goals and avoid environmental taxes and costs. Green bonds are used to finance renewable and clean energy projects, demonstrating progress toward a greener future. In today's world, along with green finance, digitalization is a significant driver of modern growth that complements green initiatives by leveraging advanced technologies like big data analytics, artificial intelligence, and the Internet of things. Digitalization of the economy helps modernize production processes, optimize energy usage, and help upgrade industrial structures. Together with green finance, digitalization enhances technological innovation, while the digital economy amplifies these efforts through its extensive reach to reduce carbon emissions and promote low-carbon development. This synergy between green finance and digital transformation can significantly help achieve carbon neutrality and a sustainable future (Zhong et al., 2024). Figure-1 shows the year-on-year percent changes in consumption-based carbon emissions, digitalization, and green finance in OECD economies. The graph reveals an inverse relationship between digitalization and carbon emissions, particularly evident post-2010, where carbon emissions demonstrate predominantly negative growth rates despite periodic fluctuations. This environmental improvement coincides with consistent positive growth in digitalization (averaging 2-3% annually with significant surges of 11.46% in 1998, 15.41% in 1999, and 13.11% in 2020), suggesting digital transformation may facilitate decarbonization through enhanced efficiency and structural economic shifts. Green finance exhibits considerable volatility throughout the observed period, oscillating between positive and negative growth rates, which indicates the evolving nature of sustainable financial mechanisms and their responsiveness to macro-economic conditions. Notably, substantial declines in carbon emissions occurred during economic downturns (-1.79% in 2009 and -1.60% in 2020), whereas digitalization demonstrated remarkable resilience, particularly during the pandemic period (13.11% in 2020).

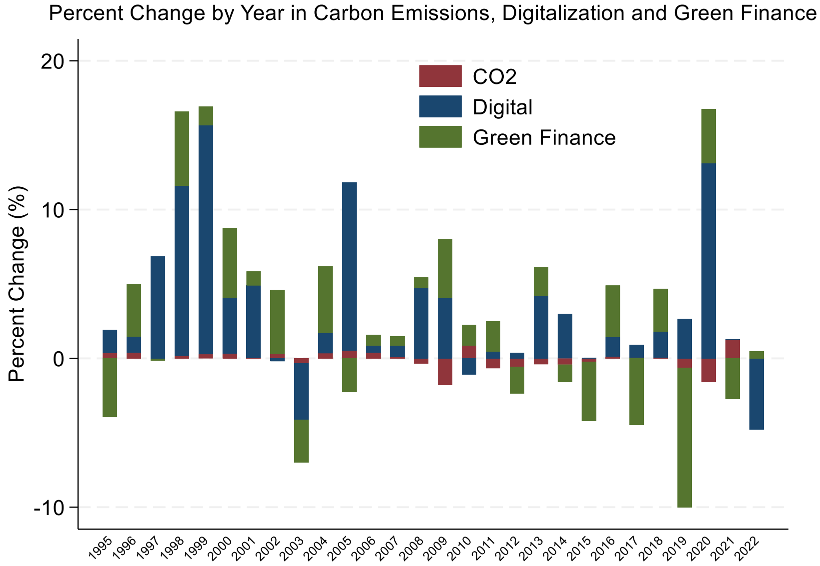

Figure 1 Percent change in CO2, Digitalization and Green Finance

Based on this discussion, this study evaluates the role of green finance, digital economy and energy productivity on consumption-based carbon emissions in OECD economies. It also considers economic growth imports and exports as control variables to have a comprehensive overview. This research fills the gap in the literature by examining how financial tools like green finance, digitalization and energy efficiency influence carbon emissions, offering a comprehensive perspective on sustainable development. We have selected the OECD economies, as these are some of the advanced countries and account for approximately 46% of global GDP and 35% of global carbon emissions from energy usage. The OECD countries show heterogeneity in environmental regulations, digitalization, and technological innovation, providing a cross-sectional variation for analysis. The OECD economies are the leaders in green finance initiatives with established regulatory frameworks and have committed to international climate agreements (i.e., Paris Accord, COP21, COP28), creating policy environments suitable for examining financial and technological interventions on the environment. Additionally, we highlight the role of green financial instruments and digital technologies together to facilitate transitions to low-carbon economies, with energy productivity serving as a key factor in decoupling economic growth from environmental degradation. By focusing on consumption-based emissions, this study includes the emissions from both domestic activities and international trade to provide a more accurate representation of their environmental impact. Furthermore, analyzing data and using the method of moment quantile regression to explore long-term trends and the effects of policies offers valuable insights for policymakers striving to balance economic growth with climate commitments in the pursuit of net zero carbon emissions.

2 LITERATURE REVIEW

The literature review shows that energy productivity plays a key role in achieving carbon neutrality (Shah et al., 2024). In this context, Li et al. (2020) showed that energy productivity and energy prices also promote renewable energy consumption that ultimately help in reducing emissions. Cheng et al. (2021) conducted a quantile regression analysis from 1991 Q1 to 2017 Q4 to investigate the role of technical innovation and energy productivity in China's attainment of environmental sustainability. Their empirical findings indicated that the implementation and innovation of effective energy productivity could enhance environmental sustainability and decrease air pollution. Liu et al. (2023) demonstrate a causal relationship between energy productivity and carbon emissions utilizing a consistent causality methodology. The authors present comparable evidence linking economic growth to CO2 emissions. Hieu et al. (2023) investigated the interrelationships among digitalization, green technology, and green energy efficiency through the application of an extended TVP-VAR model. The results also showed that the impacts of digitalization are more significant on green energy efficiency. In contrast, Karim et al. (2022) showed that energy productivity in Malaysia increases emissions while enhancing economic growth.

Green finance facilitates environmental development, enhances resource efficiency, and also addresses climate change through green projects, carbon taxes and policies (Chin et al., 2024; Cui et al., 2020). Green finance increases the mobilization of funds for renewable energy development by attracting private investments and fostering public-private collaboration (Polzin & Sanders, 2020). A developed green financial system significantly contributes to economic stability and carbon neutrality achievements (Danish & Ulucak, 2020). Moreover, green finance and energy efficiency reduce environmental degradation through increased adoption of renewable energy sources that decrease carbon emissions (Ehsanullah et al., 2021; Li et al., 2021). Financial institutions with sufficient resources can fund environmentally friendly projects, which helps develop a sustainable financial system. Furthermore, green financial development improves the macro-environment and encourages firms to adopt eco-friendly technologies that support the green economy (He et al., 2019a; He et al., 2019b; Lee & Lee, 2022). Thus, green finance functions as an effective mechanism to mitigate climate risks and enhance environmental quality, which also reduces investment risks (Nawaz et al., 2021). Sun (2022) identified a significant correlation between GF and CO2 emissions through correlation analysis. Ahmed et al. (2022) also showed the adverse impact of green financing on CO_2 emissions within ASEAN countries. In China, green finance not only reduces provincial carbon emissions but also has spatial spillover effects on adjacent regions (Su et al., 2024). The effectiveness of green finance in reducing emissions is primarily through its influence on energy structure, energy efficiency, and industrial structure (Lin et al., 2023).

Digital economy (DE) may positively impact technical innovation, possibly boosting emissions via economic development, while reducing emissions through energy efficieny. Yi et al. (2022) contended that China's digital economy has a notable impact on reducing carbon emissions, with a more pronounced effect seen in the eastern regions of the country. Ulucak et al. (2020) performed an empirical analysis using panel data from BRIC nations from 1990 to 2015, revealing that the use of information technology substantially decreased carbon emissions. Xu et al. (2023) examined the influence of DE on the carbon performance of firms in China and determined that DE may substantially decrease carbon emissions. In contrast, Dong et al. (2022) examined the impact of digital economy development on carbon emissions and found that, while it reduces carbon emission intensity, it simultaneously increases per capita carbon emissions. The ICT sector generates substantial emissions due to its dependence on carbon-intensive inputs from non-ICT industries. Shvakov and Petrova (2020) analyzed data from the top ten economies and showed that digitalization hinders the development of green or energy-efficient economies. Similarly, Zhang et al. (2022) investigated the relationship between digital economy, energy efficiency, and carbon emissions, revealing that digital economy development increases carbon emissions. Wang et al. (2021) employed a decoupling-factor model to analyze the association between ICT investments and emission intensity, discovering that certain economies have achieved strong decoupling by reducing emission intensity while increasing ICT investments. Moreover, mature digitalization exhibits positive spillover effects by reducing emissions in neighboring regions (Zheng et al., 2023). This literature highlights the importance of different factors when evaluating the environmental impact of digitalization.

3 METHODOLOGY

This research examines the impact of green finance and digital economy on sustainable development in OECD countries through panel data analysis from 1990 to 2022. The data for this study has been taken from different sources. CO_2 is the consumption-based carbon emission expressed in metric tons per capita and is taken from the Global Carbon Atlas. Data on imports (IM) and exports (EX), represented as percentages of GDP, were obtained from the World Bank. Economic growth measured as GDP, and digitalization measuring digital economy calculated as a percent of ICT exports to GDP, was obtained from the World Bank. Energy productivity measured as energy used as GDP per unit of is obtained from the OECD database. Similarly, green finance is measured using a proxy variable RD&D of renewable energy in public, sourced from OECD databases.

In this study, we employed a robust econometric framework. We started our analysis with descriptive statistics to examine the distribution and variability of the variables. The descriptive analysis encompasses metrics including mean, standard deviation, skewness, kurtosis, and the adjusted chi-squared test for normality analysis. Subsequently, we used Pesaran's (2015) and Fan et al.'s (2015) analysis to measure cross-sectional dependency, analyzing shocks and interconnectedness among OECD economies. Slope heterogeneity was estimated using Pesaran and Yamagata's (2008) analysis methods, which indicates variability in relationships among OECD countries. We conducted panel unit root tests to examine the stationarity of the variables. The Westerlund's (2005) cointegration analysis was utilized to examine the stable long-term relationships among the variables.

We employed method of moment quantile regression (MMQR) analysis to determine the relationship between the key variables while accounting for slope heterogeneity and cross-sectional dependency. The quantile selection (25th, 50th, 75th, and 90th) provides a robust examination across the CO2 emission distribution. The 25th quantile captures low-emission economies, the median (50th) represents moderate emitters, while the 75th and 90th quantiles identify high and extremely high emitters, respectively. The general models are defined as follows:

$$CO2_{\{i,t\}} = \beta_0 + \beta_1 IM_{\{i,t\}} + \beta_2 EX_{\{i,t\}} + \beta_3 GDP_{\{i,t\}} + \beta_4 EP_{\{i,t\}} + \beta_5 Digital_{\{i,t\}} + \epsilon_{\{i,t\}} \quad (1)$$

$$CO2_{\{i,t\}} = \beta_0 + \beta_1 IM_{\{i,t\}} + \beta_2 EX_{\{i,t\}} + \beta_3 GDP_{\{i,t\}} + \beta_4 EP_{\{i,t\}} + \beta_5 Digital_{\{i,t\}} + \beta_6 GF_{\{i,t\}} + \epsilon_{\{i,t\}} \quad (2)$$

These models estimate the impact of the explanatory variables on CO2, allowing the analysis to account for variations across economies with low, medium, and high emissions. Lastly, bootstrap quantile regression (BSQR) was performed as a robustness check to validate the MMQR results.

4 Results and Discussions

Table-1 gives descriptive statistics and insights into the distribution and variability of key variables for OECD economies. CO2 (consumption-based carbon emissions) has a mean of 2.343 and a standard deviation of 0.541, indicating moderate variability, with a positively skewed distribution (skewness = 0.636). The kurtosis (2.966) is near normal, but the highly significant chi-square statistic (36.246, p = 0.000) suggests non-normality. Imports (IM) and exports (EX) have similar averages (1.531 and 1.546, respectively) and relatively low variability. Both variables exhibit slight negative skewness (-0.213 and -0.22), indicating a longer tail to the left, and their chi-square tests reveal significant deviations from normality. Gross domestic product (GDP), with a mean of 11.817, is slightly positively skewed (0.55) and has a leptokurtic distribution (kurtosis = 2.84), suggesting a few economies may have higher GDP values. The significant chi-square (30.505, p = 0.000) further confirms non-normality. Energy productivity (EP) is relatively stable (mean = 3.992, standard deviation = 0.164) and is near-normal in skewness (0.178) and kurtosis (3.084), with its chi-square result (p = 0.104) suggesting normality. Digital, representing the digital economy, shows moderate variability (mean = 0.748, standard deviation = 0.382) and a slight negative skew (-0.26). Its kurtosis (3.558) suggests a heavier tail, and the chi-square statistic (p = 0.002) points to non-normality. Lastly, green finance (GF) demonstrates the highest variability (standard deviation = 0.346, mean = 1.257) with significant negative skewness (-1.348), indicating a concentration of values on the higher end with a long tail to the left. Its kurtosis (6.742) and chi-square statistic (p = 0.000) highlight pronounced deviations from normality, reflecting substantial differences in green finance initiatives among OECD economies. These results underscore varied distributions and significant non-normality for most variables, reflecting diverse economic and environmental conditions across OECD nations.

Tab. 1 – Descriptive Analysis. Source: own research

Variables	Mean	Std. Dev.	Min	Max	Skew.	Kurt.	Adj chi2(2)	Prob>chi2
LCO2	2.343	.541	1.43	3.828	.636	2.966	36.246	0.000
IM	1.531	.212	.833	2.095	-.213	3.321	8.674	0.013
EX	1.546	.235	.945	2.137	-.22	2.96	6.372	0.041
GDP	11.817	.536	10.88	13.327	.55	2.84	30.505	0.000
EP	3.992	.164	3.611	4.628	.178	3.084	4.524	0.104
Digital ICT	.748	.382	-.438	1.764	-.26	3.558	12.590	0.002
GF	1.257	.346	-1	1.912	-1.348	6.742	151.087	0.000

Table-2 gives the results of cross-sectional dependency analysis and slope heterogeneity analysis. For cross-sectional dependency, we employed Pesaran's (2015) CD test and Fan et al.'s (2015) test, which indicate highly significant statistics across all variables, further reinforcing the presence of cross-sectional dependency. The results for the variables CO2, imports, exports, GDP, energy productivity, digitalization, and green finance are significantly influenced by shocks in the OECD countries.

Tab. 2 – Cross-sectional dependency (CD) & slope heterogeneity (SH) Analysis. Source: own research

a. CDAnalysis

	CD	**CDw+**
LCO2	35.260	991.060
	(0.000)	(0.000)
IM	62.300	1097.680
	(0.000)	(0.000)
EX	57.140	1084.360
	(0.000)	(0.000)
GDP	91.290	1519.250
	(0.000)	(0.000)
EP	88.010	1464.570

	(0.000)	(0.000)
Digital_ICT	57.110	1102.680
	(0.000)	(0.000)
GF	13.860	1148.830
	(0.000)	(0.000)
b. Slope heterogeneity Analysis		
	Delta	**adj.**
Model-1 LCO2 IM EX GDP EP Digital_ICT	17.446	20.320
	(0.000)	(0.000)
Model-2 LCO2 IM EX GDP EP Digital_ICT GF	12.828	15.684
	(0.000)	(0.000)

Table-2 also gives the results of slope heterogeneity analysis conducted using Pesaran and Yamagata's (2008) methodology. The results for Model 1 (CO2, IM EX GDP EP DIGITAL) show delta and adjusted delta statistics of 17.446 and 20.320, respectively, with significant p-values. This indicates significant slope heterogeneity, suggesting that the effects of these variables differ across OECD countries. Similarly, we further extended Model 1 and incorporated green finance in Model 2. The results of Model-2 (1 (CO2, IM EX GDP EP DIGITAL GF) give delta and adjusted delta statistics of 12.828 and 15.684, respectively, also with significant p-values. This further confirms significant heterogeneity in the coefficients.

Tab. 3 – Unit Root Analysis. Source: own research

	At level		**First Difference**	
	STAT	***P-value***	***STAT***	***P-value***
LCO2	-1.466	0.603	-5.925***	0.000
IM	-1.146	0.985	-5.078***	0.000
EX	-1.211	0.956	-5.006***	0.000
GDP	-1.034	0.999	-5.162***	0.000
EP	0.681	1.000	-6.157***	0.000
Digital_ICT	-1.356	0.877	-5.216***	0.000
GF	-2.424***	0.000		

The unit root analysis results in Table-3 indicate the stationarity properties of the variables under investigation. At the level, most variables—CO2, IM, EX, GDP, EP, and digital—fail to reject the null hypothesis of a unit root, as their test statistics are not significant and p-values are above significance thresholds. This implies that these variables are non-stationary in levels. However, when analyzed at their first differences, all these variables exhibit highly significant test statistics (e.g., CO2: -5.925, IM: -5.078, etc.) with p-values of 0.000, indicating stationarity. This suggests that these variables are integrated of order one, or I(1). An exception is green finance (GF), which is stationary at the level, as indicated by a highly significant test statistic (-2.424) and a p-value of 0.000.

Tab. 4 – Cointegration Analysis. Source: own research

Models		**STAT**	**P-value**
LCO2 IM EX GDP EP Digital_ICT	Variance Ratio	-2.397	0.008
LCO2 IM EX GDP EP Digital_ICT GF		-1.948	0.026

The results of the cointegration analysis, based on Westerlund's (2005) variance ratio test, provide evidence of long-term equilibrium relationships among the variables in both models. For the first model, which includes CO2 (carbon emissions), IM (imports), EX (exports), GDP (gross domestic product), EP (energy productivity), and digital (digital economy), the significant variance ratio statistic of -2.397 shows a stable long-term relationship. In model-2 (CO2, IM EX GDP EP DIGITAL GF), the variance ratio statistic is -1.948, confirming the existence of a long-term equilibrium relationship among the variables.

Tab. 5 – MMQR Model-1. Source: own research

VARIABLES	location	scale	Q (25)	Q (50)	Q (75)	Q (90)
IM	1.626***	-0.360***	1.942***	1.643***	1.282***	1.089***
	(0.130)	(0.0728)	(0.156)	(0.134)	(0.135)	(0.151)
EX	-1.249***	0.229***	-1.449***	-1.259***	-1.030***	-0.908***
	(0.113)	(0.0630)	(0.135)	(0.115)	(0.116)	(0.131)
GDP	0.984***	-0.0538***	1.031***	0.986***	0.932***	0.903***
	(0.0140)	(0.00782)	(0.0167)	(0.0147)	(0.0145)	(0.0161)
EP	-0.674***	0.0382**	-0.708***	-0.676***	-0.638***	-0.618***
	(0.0339)	(0.0190)	(0.0407)	(0.0342)	(0.0351)	(0.0395)
Digital_ICT	-0.205***	0.0148	-0.217***	-0.205***	-0.190***	-0.183***
	(0.0165)	(0.00922)	(0.0198)	(0.0166)	(0.0170)	(0.0192)
Constant	-7.016***	0.781***	-7.700***	-7.051***	-6.270***	-5.851***
	(0.235)	(0.132)	(0.282)	(0.244)	(0.244)	(0.272)

Table-5 gives the results from the MMQR analysis for model-1, highlighting important insights into the relationships between the variables across different quantiles. The results show that energy productivity has a negative and statistically significant impact on carbon emissions at all quantiles. This indicates that improvements in energy efficiency are effective in reducing emissions across the spectrum. The magnitude of this relationship is strongest at lower quantiles (25^{th}Q) with coefficients of -0.708 and slightly weaker at higher quantiles (90^{th}Q) with a coefficient value of -0.618. These results indicate that, while energy productivity contributes to emissions reductions in all quantiles, its relative effectiveness may diminish at higher emission levels. However, EP still remains a critical tool in OECD economies for mitigating emissions, emphasizing the importance of policies promoting energy-efficient technologies.

The role of the digital economy (digital) is also significant, with a consistently negative relationship with CO2 across all quantiles. This indicates that advancements in digital technologies contribute to reducing carbon emissions. The impact is slightly stronger in economies with lower emissions (25^{th}Q: -0.217) compared to those with higher emissions (90^{th}Q: -0.183). The negative relationship can be attributed to several mechanisms. Digital technologies enhance resource efficiency, optimize energy usage, and support less carbon-intensive economic activities, such as the transition to service-oriented and knowledge-based industries. Additionally, digital platforms enable the adoption of green technologies and renewable energy solutions, fostering sustainability. However, the slightly weaker effect at higher quantiles may reflect challenges such as the energy intensity of digital infrastructure, including data centers, or slower adoption of digital solutions in high-emission sectors.

Other variables also show significant impacts on carbon emissions. Imports (IM) have a positive relationship, suggesting that higher imports, particularly of carbon-intensive goods, contribute to increased emissions, although the effect diminishes at higher quantiles. Conversely, exports (EX) have a negative impact, potentially reflecting the adoption of greener practices in export-oriented industries. GDP positively affects emissions, highlighting the trade-off between economic activity and environmental sustainability, although the effect slightly decreases at higher quantiles, possibly due to greener growth patterns in advanced economies.

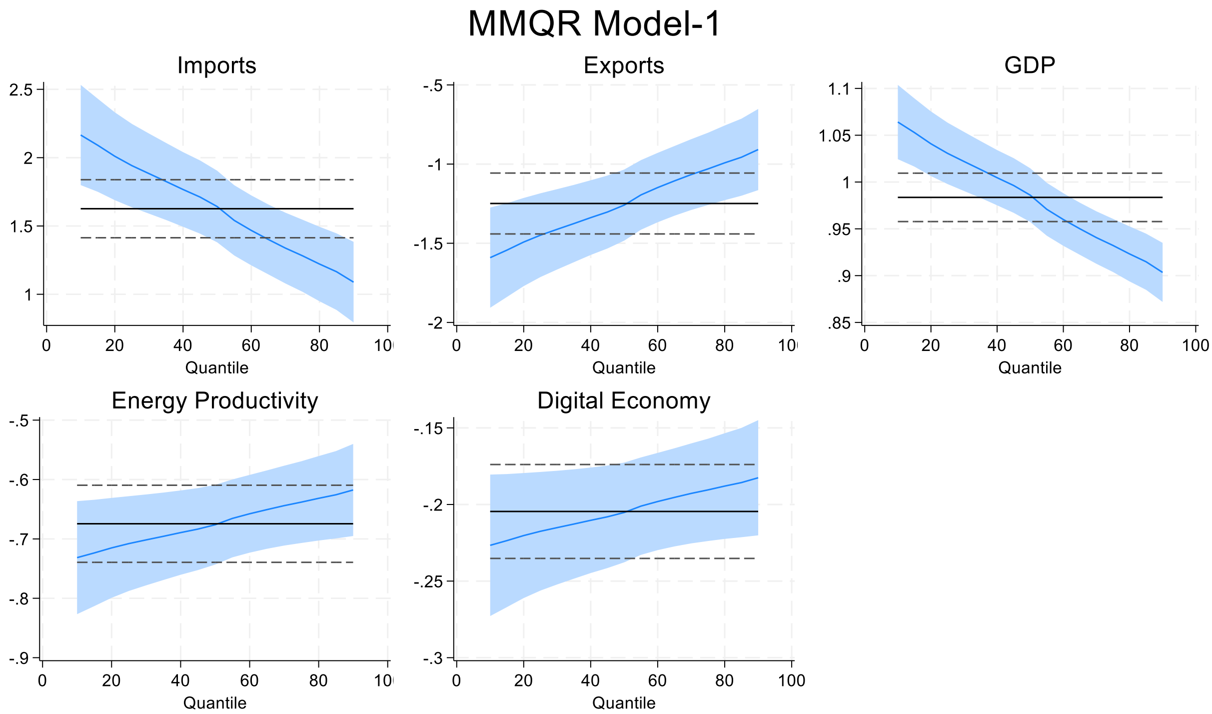

Fig. 1 – Graphical Representation. Source: own research

The results from MMQR Model-2 confirm similar relationships for IM, EX, GDP, EP, and digital, as observed in the Table-5 analysis, highlighting their consistent roles in influencing CO2 (carbon emissions). However, Table-6 includes green finance (GF) in the model and provides additional critical insights. GF exhibits a negative and statistically significant impact on carbon emissions across all quantiles, with its effect becoming stronger as emissions increase. At the lower quantile (25^{th}Q), the relationship is weaker and not statistically significant (-0.0355), but it intensifies at the higher quantiles, reaching -0.116 at the 90^{th} quantile. These findings suggest that green finance is particularly effective in mitigating emissions in economies with higher carbon footprints. Additionally, the negative scale parameter (-0.0324) highlights its role in reducing the variability of emissions, showcasing its stabilizing influence across economies. The increasing coefficients at higher quantiles are due to GF's ability to drive transformative change through funding for renewable energy projects, green infrastructure, and low-carbon technologies. These findings highlight the importance of GF policies in reducing carbon emissions and its role in promoting sustainability.

Tab. 6 – MMQR Model-2. Source: own research

VARIABLES	location	scale	Q (25)	Q (50)	Q (75)	Q (90)
IM	1.611***	-0.252***	1.825***	1.607***	1.380***	1.203***
	(0.130)	(0.0731)	(0.150)	(0.131)	(0.140)	(0.166)
EX	-1.251***	0.139**	-1.370***	-1.249***	-1.123***	-1.026***
	(0.113)	(0.0633)	(0.130)	(0.113)	(0.121)	(0.144)

GDP	0.993***	-0.0488***	1.035***	0.993***	0.949***	0.914***
	(0.0142)	(0.00798)	(0.0163)	(0.0146)	(0.0153)	(0.0182)
EP	-0.578***	0.0639***	-0.632***	-0.577***	-0.519***	-0.474***
	(0.0382)	(0.0215)	(0.0441)	(0.0384)	(0.0411)	(0.0488)
Digital_ICT	-0.171***	0.0189*	-0.187***	-0.171***	-0.154***	-0.140***
	(0.0174)	(0.00979)	(0.0201)	(0.0175)	(0.0187)	(0.0222)
GF	-0.0631***	-0.0324***	-0.0355	-0.0636***	-0.0928***	-0.116***
	(0.0211)	(0.0118)	(0.0243)	(0.0212)	(0.0227)	(0.0269)
Constant	-7.447***	0.627***	-7.981***	-7.437***	-6.872***	-6.432***
	(0.239)	(0.134)	(0.275)	(0.243)	(0.258)	(0.306)

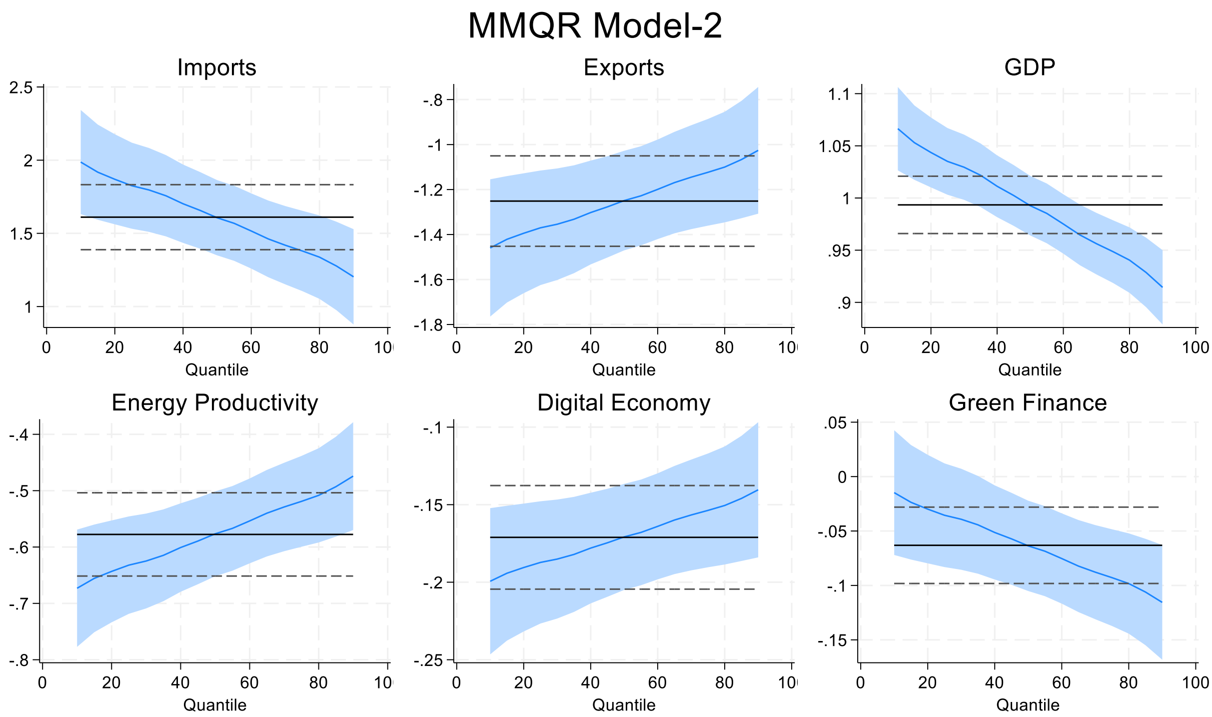

Fig. 2 – Graphical Representation. Source: own research

Table-7 gives the robustness analysis results obtained using the bootstrap quantile regression (BSQR) analysis. The results validate the MMQR analysis, showing the relationships between EP, IM, EX, GDP, DIGITAL and CO2 across quantiles. Energy productivity showed a significant negative impact on emissions, with coefficients of -0.685 and -0.517 at the 25th and 90th quantiles. Similarly, digital shows a negative influence on emissions, with coefficients of -0.217 and -0.144 at the at 25th and 90th quantiles, respectively. The control variables, such as IM, EX, and GDP, showed results similar to those of the MMQR analysis. These results closely align with the earlier MMQR analysis, confirming the reliability and robustness of the identified relationships.

Tab. 7 – Bootstrap Quantile Regression Analysis (BSQR) Model-1. Source: own research

	Q (25)	Q (50)	Q (75)	Q (90)
IM	1.849***	1.499***	1.078***	0.668***
	(0.213)	(0.262)	(0.0920)	(0.195)
EX	-1.328***	-1.080***	-0.890***	-0.635***
	(0.177)	(0.201)	(0.0921)	(0.176)

GDP	1.055***	0.983***	0.904***	0.840***
	(0.0143)	(0.0267)	(0.0152)	(0.0164)
EP	-0.685***	-0.729***	-0.607***	-0.517***
	(0.0513)	(0.0571)	(0.0355)	(0.0434)
Digital_ICT	-0.217***	-0.215***	-0.183***	-0.144***
	(0.0150)	(0.0345)	(0.0123)	(0.0231)
Constant	-8.127***	-6.844***	-5.965***	-5.288***
	(0.229)	(0.464)	(0.204)	(0.199)

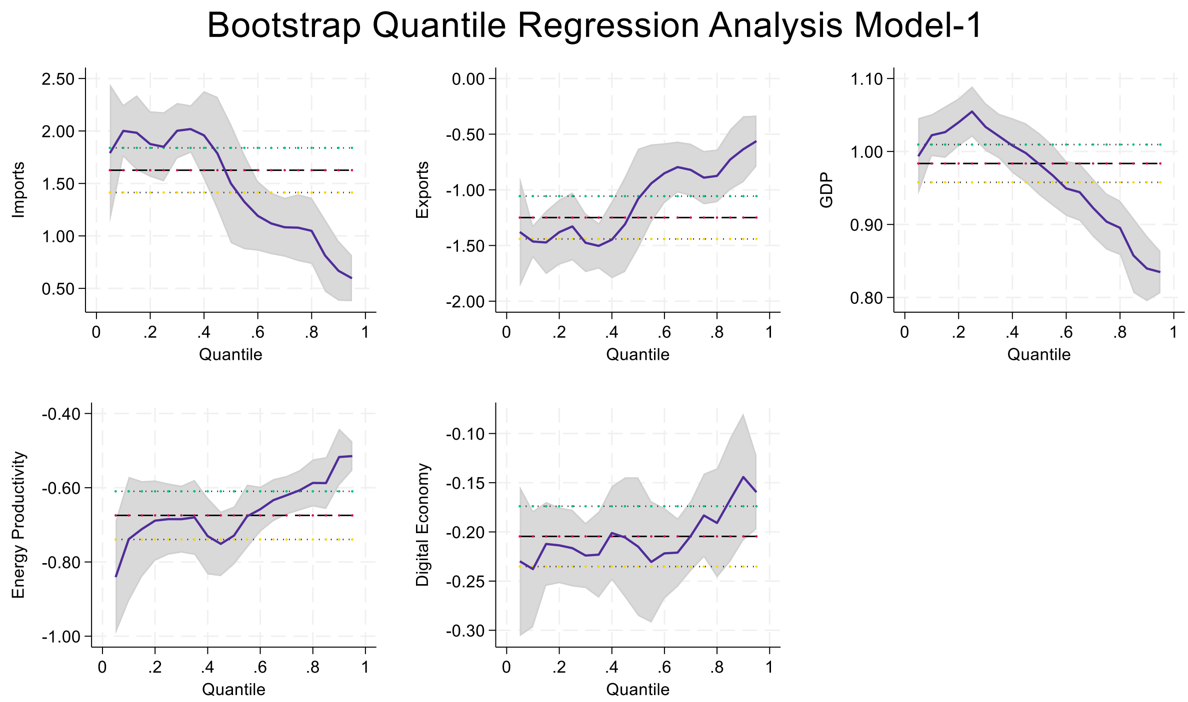

Fig. 3 – Graphical Representation. Source: own research

The BSQR analysis for Model-2 in Table-8 confirms the robustness of earlier findings. EP shows an adverse effect on emissions, ranging from -0.621(25th quantile) to -0.487 (90th quantile), while digital also maintains a significant negative effect, from -0.206 (25th quantile) to -0.159 (90th quantile). Green finance (GF) has a significant negative impact at 50thQ (-0.0817) and 75thQ (-0.0952), but is not significant at 25th and 90th quantiles, suggesting its varying influence across emissions levels. Other variables, such as IM, EX, and GDP, retain their consistent relationships, confirming the reliability of the earlier results.

Tab. 8 – Bootstrap Quantile Regression (BSQR) Analysis Model-2. Source: own research

	Q (25)	Q (50)	Q (75)	Q (90)
IM	1.760***	1.459***	1.197***	0.758***
	(0.166)	(0.435)	(0.168)	(0.160)
EX	-1.285***	-1.062***	-0.986***	-0.674***
	(0.116)	(0.355)	(0.150)	(0.148)
GDP	1.050***	1.031***	0.929***	0.857***
	(0.0148)	(0.0291)	(0.0215)	(0.0156)
EP	-0.621***	-0.576***	-0.521***	-0.487***
	(0.0494)	(0.0473)	(0.0653)	(0.0594)

Digital_ICT	-0.206***	-0.167***	-0.146***	-0.159***
	(0.0230)	(0.0290)	(0.0238)	(0.0392)
GF	-0.0351	-0.0817***	-0.0952**	-0.0218
	(0.0318)	(0.0277)	(0.0421)	(0.0213)
Constant	-8.226***	-7.937***	-6.563***	-5.656***
	(0.264)	(0.512)	(0.306)	(0.277)

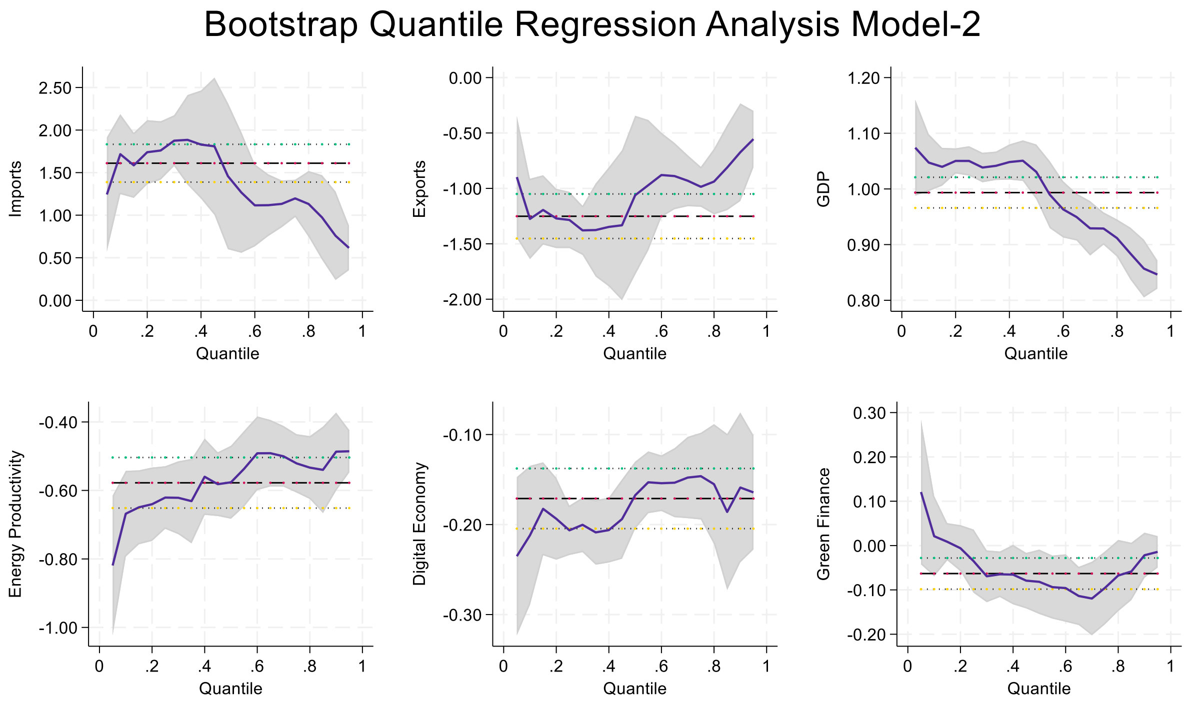

Fig. 4 – Graphical Representation. Source: own research

5. CONCLUSION

This study examines the determinants of carbon emissions in OECD economies by analyzing key drivers, including trade, economic growth, energy productivity, digitalization, and green finance from 1990 to 2022. The results show that energy productivity reduces carbon emissions, highlighting the importance of energy efficiency initiatives in transitioning to a low-carbon economy. Energy productivity shows negative coefficients across all quantiles (-0.632, -0.577, -0.519, and -0.474 at the 25^{th}, $50^{th,}$ 75^{th} and 90^{th} quantiles, respectively) with slightly reduced coefficients at higher quantiles. Similarly, digital economy also has a negative impact on emissions, indicating the transformative potential of digital technologies to optimize resource use, enhance energy efficiency, and foster greener economic activities. Moreover, green finance results show a negative effect on emissions, indicating that it also plays an important role in reducing carbon emissions and facilitates low-carbon transitions in OECD economies. The results also showed that imports and economic growth increase environmental pollution, whereas exports reduce emissions, highlighting the adoption of eco-friendly technologies in export-driven sectors.

Based on the findings of this study, the achievement of climate objectives established in COP29 necessitates a comprehensive strategy. Energy productivity exhibits a significant negative association with carbon emissions, emphasizing the fundamental importance of enhancing energy efficiency across economic sectors. Policymakers and regulatory authorities should substantially increase financial allocations for energy-efficient technological innovations, particularly targeting energy-intensive industries, to optimize the emissions-mitigating impact of improved energy productivity. Furthermore, implementing fiscal incentives and regulatory frameworks that encourage firms to adopt advanced energy management systems would accelerate the transition toward more sustainable energy consumption patterns and contribute significantly to environmental quality improvement. Similarly, the digitalization of the economy also plays a transformative role in reducing emissions. Therefore, governments should promote digital solutions, such as smart grids and digital monitoring systems, while ensuring that the infrastructure powering digital technologies is low-carbon. Based on the results of our study, green finance emerges as a vital tool for funding renewable energy projects, green technologies, and carbon-neutral infrastructure. Policymakers and regulators should issue more green bonds and create incentives for sustainable investments for firms to further mobilize private capital toward climate goals. Moreover, imports exhibit a positive relationship with carbon emissions, suggesting that trade policies should incentivize environmentally friendly production processes in exporting economies and implement more stringent environmental criteria for imported products. By integrating these strategies, OECD economies can effectively advance decarbonization efforts, aligning economic growth with environmental sustainability.

OECD countries can integrate these findings into their next climate strategy cycles and nationally determined contributions (NDCs) through various practical mechanisms. Member states should revise their NDCs to incorporate quantifiable energy productivity targets with sector-specific benchmarks that directly correlate with the emission reductions identified in our study. A well-established digital transformation framework with explicit carbon reduction metrics should be developed as a core component of climate commitments, as digitalization significantly reduces consumption-based carbon emissions. Financial regulatory frameworks require modification to mandate climate risk disclosure and establish green finance portfolio requirements for financial institutions, creating a direct link between financial flows and NDC objectives. Moreover, OECD economies should adopt consumption-based carbon accounting mechanisms to address emissions embedded in imports, potentially implementing carbon border adjustment measures to encourage trading partners to adopt environmentally friendly production processes. Additionally, standardized monitoring systems should be established to track the emission impact of green finance, digitalization, and energy productivity improvements, ensuring these measures deliver the expected climate benefits. By methodically incorporating these evidence-based approaches into their climate commitments, OECD countries can enhance the effectiveness of their NDC submission cycles.

REFERENCES

Ahmed, N., Areche, F. O., Sheikh, A. A., & Lahiani, A. (2022). Green finance and green energy nexus in ASEAN countries: A bootstrap panel causality test. *Energies*, *15*(14), article 14. https://doi.org/10.3390/en15145068

BP Statistical Review of World Energy. (2022). *Statistical review of world energy 2022*. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf

Cheng, G., et al. (2021). Does energy productivity and public-private investment in energy achieve carbon neutrality target of China? *Journal of Environmental Management*, *298*, 113464. https://doi.org/10.1016/j.jenvman.2021.113464

Chin, M.-Y., Ong, S.-L., Ooi, D. B.-Y., & Puah, C.-H. (2024). The impact of green finance on environmental degradation in BRI region. *Environment, Development and Sustainability*, *26*(1), 303–318. https://doi.org/10.1007/s10668-022-02709-5

Cui, H., Wang, R., & Wang, H. (2020). An evolutionary analysis of green finance sustainability based on multi-agent game. *Journal of Cleaner Production*, *269*, 121799. https://doi.org/10.1016/j.jclepro.2020.121799

Danish, & Ulucak, R. (2020). How do environmental technologies affect green growth? Evidence from BRICS economies. *Science of The Total Environment*, *712*, 136504. https://doi.org/10.1016/j.scitotenv.2020.136504

Dong, F., et al. (2022). How does digital economy affect carbon emissions? Evidence from global 60 countries. *Science of The Total Environment*, *852*, 158401. https://doi.org/10.1016/j.scitotenv.2022.158401

EDGAR. (2019). *Fossil CO2 and GHG emissions of all world countries. Luxembourg: Emission database for global atmospheric research.* https://edgar.jrc.ec.europa.eu/overview.php?v=booklet2019

Ehsanullah, S., et al. (2021). How energy insecurity leads to energy poverty? Do environmental consideration and climate change concerns matters. *Environmental Science and Pollution Research*, *28*(39), 55041–55052. https://doi.org/10.1007/s11356-021-14415-2

Guo, L., et al. (2022). Green finance, chemical fertilizer use and carbon emissions from agricultural production. *Agriculture*, *12*(3), Article 3. https://doi.org/10.3390/agriculture12030313

He, L., et al. (2019a). Can green financial development promote renewable energy investment efficiency? A consideration of bank credit. *Renewable Energy*, *143*, 974–984. https://doi.org/10.1016/j.renene.2019.05.059

He, L., et al. (2019b). Green credit, renewable energy investment and green economy development: Empirical analysis based on 150 listed companies of China. *Journal of Cleaner Production*, *208*, 363–372. https://doi.org/10.1016/j.jclepro.2018.10.119

Hieu, N. T., Le Thanh, H., & Minh Anh, B. T. (2023). Scrutinizing time-varying interlinkages between digitalization, green technologies, CO2 emission, and energy productivity in Vietnam. *Journal of Cleaner Production*, *415*, 137581. https://doi.org/10.1016/j.jclepro.2023.137581

Karim, M. Z., Gee, C. S., Ismail, N. H., & Sharif, A. (2022). Does energy productivity lead to economic efficiency and lower Co2 emission in Malaysia? Evidence From bootstrapped ARDL approach. *Journal of Sustainability Science and Management*, *17*(3), 32–50. https://doi.org/10.46754/jssm.2022.03.004

Lee, C.-C., & Lee, C.-C. (2022). How does green finance affect green total factor productivity? Evidence from China. *Energy Economics*, *107*, 105863. https://doi.org/10.1016/j.eneco.2022.105863

Li, J., Zhang, X., Ali, S., & Khan, Z. (2020). Eco-innovation and energy productivity: New determinants of renewable energy consumption. *Journal of Environmental Management*, *271*, 111028. https://doi.org/10.1016/j.jenvman.2020.111028

Li, Z.-Z., et al. (2021). Determinants of carbon emission in China: How good is green investment? *Sustainable Production and Consumption*, *27*, 392–401. https://doi.org/10.1016/j.spc.2020.11.008

Lin, Z., Wang, H., Li, W., & Chen, M. (2023). Impact of green finance on carbon emissions based on a two-stage LMDI decomposition method. *Sustainability*, *15*(17), article 17. https://doi.org/10.3390/su151712808

Liu, M., et al. (2023). The dynamic impact of energy productivity and economic growth on environmental sustainability in South European countries. *Gondwana Research*, *115*, 116–127. https://doi.org/10.1016/j.gr.2022.11.012

Luo, C., & Wu, D. (2016). Environment and economic risk: An analysis of carbon emission market and portfolio management. *Environmental Research*, *149*, 297–301. https://doi.org/10.1016/j.envres.2016.02.007

Ma, Z., et al. (2025). Study on how the digital economy affects urban carbon emissions. *Renewable and Sustainable Energy Reviews*, *207*, 114910. https://doi.org/10.1016/j.rser.2024.114910

Nawaz, M. A., et al. (2021). Nexus between green finance and climate change mitigation in N-11 and BRICS countries: Empirical estimation through difference in differences (DID) approach. *Environmental Science and Pollution Research*, *28*(6), 6504–6519. https://doi.org/10.1007/s11356-020-10920-y

Polzin, F., & Sanders, M. (2020). How to finance the transition to low-carbon energy in Europe? *Energy Policy*, *147*, 111863. https://doi.org/10.1016/j.enpol.2020.111863

Raberto, M., et al. (2019). From financial instability to green finance: The role of banking and credit market regulation in the Eurace model. *Journal of Evolutionary Economics*, *29*(1), 429–465. https://doi.org/10.1007/s00191-018-0568-2

Saeed Meo, M., & Karim, M. Z. A. (2022). The role of green finance in reducing CO2 emissions: An empirical analysis. *Borsa Istanbul Review*, *22*(1), 169–178. https://doi.org/10.1016/j.bir.2021.03.002

Shah, W. U. H., et al. (2024). Role of renewable, non-renewable energy consumption and carbon emission in energy efficiency and productivity change: Evidence from G20 economies. *Geoscience Frontiers*, *15*(4), 101631. https://doi.org/10.1016/j.gsf.2023.101631

Shvakov, E. E., & Petrova, E. A. (2020). Newest trends and future scenarios for a sustainable digital economy development. In E. G. Popkova & B. S. Sergi (Eds.), *Scientific and technical revolution: Yesterday, today and tomorrow* (pp. 1378–1385). Springer International. https://doi.org/10.1007/978-3-030-47945-9_150

Sokołowski, M. M., & Heffron, R. J. (2022). Defining and conceptualising energy policy failure: The when, where, why, and how. *Energy Policy*, *161*, 112745. https://doi.org/10.1016/j.enpol.2021.112745

Su, X., Qiao, R., & Xu, S. (2024). Impact of green finance on carbon emissions and spatial spillover effects: Empirical evidence from China. *Journal of Cleaner Production*, *457*, 142362. https://doi.org/10.1016/j.jclepro.2024.142362

Sun, C. (2022). The correlation between green finance and carbon emissions based on improved neural network. *Neural Computing and Applications*, *34*(15), 12399–12413. https://doi.org/10.1007/s00521-021-06514-5

Sun, C. (2023). How are green finance, carbon emissions, and energy resources related in Asian sub-regions? *Resources Policy*, *83*, 103648. https://doi.org/10.1016/j.resourpol.2023.103648

Ulucak, R., Danish, & Khan, S. U.-D. (2020). Does information and communication technology affect CO2 mitigation under the pathway of sustainable development during the mode of globalization? *Sustainable Development*, *28*(4), 857–867. https://doi.org/10.1002/sd.2041

Umar, M., & Safi, A. (2023). Do green finance and innovation matter for environmental protection? A case of OECD economies. *Energy Economics*, *119*, 106560. https://doi.org/10.1016/j.eneco.2023.106560

Wang, J., Jiang, Q., Dong, X., & Dong, K. (2021). Decoupling and decomposition analysis of investments and CO2 emissions in information and communication technology sector. *Applied Energy*, *302*, 117618. https://doi.org/10.1016/j.apenergy.2021.117618

Xu, Q., Li, X., & Guo, F. (2023). Digital transformation and environmental performance: Evidence from Chinese resource-based enterprises. *Corporate Social Responsibility and Environmental Management*, *30*(4), 1816–1840. https://doi.org/10.1002/csr.2457

Yi, M., Liu, Y., Sheng, M. S., & Wen, L. (2022). Effects of digital economy on carbon emission reduction: New evidence from China. *Energy Policy*, *171*, 113271. https://doi.org/10.1016/j.enpol.2022.113271

Zhang, L., et al. (2022). Digital economy, energy efficiency, and carbon emissions: Evidence from provincial panel data in China. *Science of The Total Environment*, *852*, 158403. https://doi.org/10.1016/j.scitotenv.2022.158403

Zheng, R., et al. (2023). How does digitalization drive carbon emissions? The inverted U-shaped effect in China. *Environmental Impact Assessment Review*, *102*, 107203. https://doi.org/10.1016/j.eiar.2023.107203

Zhong, M., Umar, M., Mirza, N., & Safi, A. (2024). Mineral resource optimization: The nexus of sustainability, digital transformation, and green finance in OECD economies. *Resources Policy*, *90*, 104829. https://doi.org/10.1016/j.resourpol.2024.104829

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