

## Araştırma Makalesi / Research Article

## The Impact of Economic Complexity on Carbon Intensity: A Dynamic Analysis of OECD Countries

*Ekonomik Karmaşıklıkın Karbon Yoğunluğu Üzerindeki Etkisi: OECD Ülkeleri Üzerine Dinamik Bir Analiz*

Alper Aykut EKİNCİ<sup>1</sup>



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### Abstract

This study examines the effects of economic complexity on carbon intensity using dynamic panel data methods including data from 36 OECD countries over the period 1995-2023. Carbon intensity, which reflects the environmental efficiency of economic production, was used as the dependent variable, while the economic complexity index was the main explanatory variable. The analysis was conducted using the System Generalized Method of Moments to address potential endogeneity issues and account for dynamic dependence.

The results indicate that carbon intensity is highly persistent and that past emission levels strongly influence current environmental performance. The coefficient for economic complexity was positive in the short run, but the interaction term with income level ( $ECI \times \ln GDP_{per}$ ) was negative and significant. This suggests that economic complexity increases carbon intensity at low-income levels but decreases emissions at high-income levels. Additionally, trade openness is found to reduce carbon intensity, while capital formation has a positive effect.

Accordingly, the findings indicate that the environmental impact of economic complexity is conditional and varies depending on the stage of development. It is emphasized that complexity supports low-carbon production in high-income and technology-driven economies, and therefore structural transformation should play a central role in climate policies.

**Keywords:** Carbon intensity, Economic complexity, System GMM, Sustainable development.

### Öz

Bu çalışma, 1995-2023 döneminde 36 OECD ülkesinin verilerini kullanarak ekonomik karmaşıklıkın karbon yoğunluğu üzerindeki etkilerini dinamik panel veri yöntemleriyle incelemektedir. Çalışmada bağımlı değişken olarak ekonomik üretimin çevresel verimliliğini yansıtan karbon yoğunluğu kullanılmış, temel açıklayıcı değişken ise ekonomik karmaşıklık endeksi olmuştur. Analiz, olası içsellik sorunlarını gidermek ve dinamik bağımlılığı dikkate almak amacıyla Sistem Genelleştirilmiş Momentler Metodu ile gerçekleştirilmiştir.

Sonuçlar, karbon yoğunluğunun yüksek derecede kalıcı olduğunu ve geçmiş emisyon düzeylerinin mevcut çevresel performansını güçlü biçimde etkilediğini göstermektedir. Ekonomik karmaşıklık katsayısı kısa dönemde pozitif bulunmuş, ancak gelir düzeyiyle etkileşim terimi ( $ECI \times \ln GDP_{per}$ ) negatif ve anlamlı çıkmıştır. Bu durum, ekonomik karmaşıklık düşük gelir düzeylerinde karbon yoğunluğunu artırdığı, ancak yüksek gelir düzeylerinde emisyonları azalttığına işaret etmektedir. Ayrıca, ticaret açıklığı karbon yoğunluğunu düşürürken, sermaye birikiminin pozitif etkisi bulunmuştur.

Sonuç olarak, bulgular ekonomik karmaşıklıkın çevresel etkisinin koşullu olduğunu ve kalkınma aşamasına bağlı olarak değiştiğini göstermektedir. Yüksek gelirlili ve teknoloji odaklı ekonomilerde karmaşıklık düşük karbonlu

<sup>1</sup>Dr., Nevşehir Hacı Bektaş Veli University, Faculty of Economics and Administrative Sciences, Department of International Trade and Logistics. [alperaykutekinci@gmail.com](mailto:alperaykutekinci@gmail.com)

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*üretimi desteklediği, bu nedenle yapısal dönüşümün iklim politikalarında merkezi bir rol oynaması gerektiği vurgulanmaktadır.*

**Anahtar Kelimeler:** *Karbon yoğunluğu, Ekonomik karmaşıklık, Sistem GMM, Sürdürülebilir kalkınma.*

## 1. INTRODUCTION

A more integrated perspective is necessary to address global climate change than a policy which deals with the environmental impacts of economic growth by focusing on greenhouse gas emissions alone. It is a global problem that will require a total redesign of our economic systems. Carbon intensity, which measures the ratio between carbon dioxide (CO<sub>2</sub>) emissions and gross domestic product (GDP) has become an important indicator that can track environmental impact (Tudor & Sova, 2021; U.S. Energy Information Administration, 2025).

A decrease in CI indicates that less carbon input is needed to produce a certain amount of economic output and reflects higher energy efficiency and the effectiveness of clean energy utilization (Schröder & Storm, 2020). Decarbonization can only be achieved when the energy intensity of economic activity falls and low-carbon sources are deployed widely across all sectors (International Energy Agency, 2024). Consequently, the long run objective is to identify and implement climate policies based on the economic and structural factors that most effectively support CI reduction.

Studies based on the Environmental Kuznets Curve (EKC) hypothesis, which predicts an inverted U-shaped relationship between environmental degradation and national income, are prominent in the literature (Stern, 2017; Leal and Marques, 2022). However, the EKC approach has limited validity for factors affecting the global environment (Shahbaz and Sinha, 2019; Almeida et al., 2024). Traditional approaches do not sufficiently consider the fundamental structural differences that determine countries' environmental footprints. To address this shortcoming, the Economic Complexity Index (ECI) was incorporated into the analysis. Developed by Hidalgo and Hausmann (2009), the ECI measures a country's production knowledge and the diversity and complexity of its export products. Higher ECI values indicate a more advanced economic structure and long run development potential (Hidalgo and Hausmann, 2009; Yalta and Yalta, 2021).

By including the ECI in the analysis, we consider how the economy produces rather than how much it produces. This provides a structural perspective that differs from simple income measures. This structural approach can provide a deeper understanding of the effects of economic complexity and endogenous structural factors on carbon intensity and their interactions with other macroeconomic variables (Laverde-Rojas et al., 2021). The dynamic approach used in the study takes into account the continuity of environmental impacts and demonstrates the determining role of past emissions on the current carbon load. These results contribute to the empirical literature and provide a comprehensive analytical framework for climate policy design.

The remainder of the paper is structured as follows: Section 2 provides a comprehensive review of the relevant literature. Section 3 details the data and methodology used and presents the empirical findings. Section 4 provides a detailed discussion and interpretation of the analytical results. Section 5 summarizes the key findings and presents the resulting policy recommendations.

## 2. LITERATURE REVIEW

The relationship between economic complexity and carbon intensity has become a core research topic in environmental economics, particularly as countries pursue sustainable development. Numerous studies have examined this relationship in different contexts, using different methodologies and considering various mediating factors.

Wang et al. (2024) analyzed panel data from 38 countries for the period 1995–2021 to examine how natural resource rents, geopolitical risks, and economic complexity affect carbon emissions. Using panel Autoregressive Distributed Lag (ARDL) and dynamic panel threshold regression models, they found that natural resource rents increase carbon emissions in the long run, but this relationship is nonlinear. Higher geopolitical risks strengthen the positive link between resource rents and emissions, while higher economic complexity attenuates this link, making the impact of resource rents on carbon emissions negative.

Ouerghi and Hasni (2025) investigated the effects of global value chain participation and economic complexity on environmental quality in the 10 countries with the highest emissions using data for the period 1995-2018. Using an ARDL model and Granger causality test, they found that greater participation in global value chains, economic growth, and energy consumption deteriorate environmental quality in the long run, while higher economic complexity and financial development improve it. Their results also indicate a short run causality from carbon emissions to economic complexity and from global value chains to emissions, as well as a long run bidirectional causality among carbon emissions, global value chains, economic complexity, financial development, energy consumption, and GDP.

However, there are also studies showing a negative impact of economic complexity on the environment. Sajid et al. (2024) investigated the relationship between economic complexity, institutional quality, and carbon emissions in China and Pakistan from 1996 to 2021 using the ARDL approach. Their analysis showed that economic complexity increases carbon emissions in both countries, indicating that industrial and technological advancement alone does not ensure environmental improvements. Institutional quality was found to mitigate emissions only in China, while in Pakistan its impact was insignificant due to weaker governance structures. Moreover, when institutional quality interacted with economic complexity, it amplified emissions rather than reducing them.

Ye et al. (2023) analyzed the relationship between economic complexity and carbon emissions in the logistics sector of Belt and Road countries from 1998 to 2018. They employed Granger causality tests, FMOLS and DOLS estimations using panel data within the EKC framework. The results showed that economic complexity significantly affects carbon emissions in the logistics sector. The relationship follows an inverted U-shaped pattern consistent with the EKC: in high-income countries, greater economic complexity contributes to reducing emissions, whereas in lower and middle income countries, it initially increases them. The study underscores that the effect of economic complexity on carbon intensity in industry is contingent on development level and technological capacity.

Similarly, Saqib and Dincă (2024) examined the asymmetric effects of economic complexity, foreign direct investment (FDI), environmental technology, and renewable energy on carbon emissions in leading clean-energy investment countries from 1995 to 2020. Using a Panel NARDL approach, supplemented by AMG and CCEMG estimations for robustness, they found that positive shocks in economic complexity, FDI, environmental technology, and renewable energy reduce carbon emissions, while negative shocks in economic complexity and FDI increase emissions in the long run. Short run effects mirrored these patterns with varying significance. The study indicates that enhancing economic complexity and related structural and technological factors can lower carbon intensity, but setbacks in these areas may exacerbate environmental degradation.

Adjei et al. (2022) investigated the impact of economic complexity, globalization, and other factors on carbon neutrality objectives in the ten largest African economies from 1990 to 2018. Using FMOLS, DOLS, and fixed effects models, they found that higher economic complexity and GDP increase CO<sub>2</sub> emissions, hindering carbon neutrality goals, while financial development, globalization, population growth, and renewable energy consumption help reduce emissions. Granger causality tests indicated bidirectional causality between GDP, population, and CO<sub>2</sub> emissions, and unidirectional causality from CO<sub>2</sub> to renewable energy, globalization, and economic complexity. The study suggests that managing economic complexity alongside economic growth is critical for lowering carbon intensity and achieving carbon neutrality in African economies.

Nan et al. (2022) used a spatial panel model to examine the interaction between globalization and economic complexity on CO<sub>2</sub> emissions, incorporating trade and geographical distance matrices and addressing missing data via multiple imputation. Their findings indicate positive spatial spillovers of CO<sub>2</sub> emissions from neighboring countries. While globalization alone does not significantly affect local emissions, it reduces emissions in neighboring countries. Importantly, higher economic complexity mitigates the indirect negative impact of globalization on emissions, suggesting that more economically complex countries experience less reduction in neighboring countries' emissions from globalization. The study emphasizes that economic complexity and spatial spillovers are critical for understanding carbon intensity patterns across countries.

Murshed et al. (2022) investigated the environmental impacts of nuclear and renewable energy consumption, economic complexity, and economic growth in G7 countries for the period 1995–2016. The results revealed that nuclear energy reduces emissions and carbon footprints, while renewable energy consumption worsens environmental outcomes. While economic growth increases carbon intensity, economic complexity supports cleaner production processes. The study stated that supporting economic complexity alongside the energy transition is necessary to reduce carbon intensity in developed economies.

Zheng et al. (2021) examined the effects of economic complexity and renewable electricity consumption on carbon emissions in 16 major exporting countries over the period 1990 to 2019. Using AMG and DOLS estimators, the analysis found that increasing economic complexity and renewable energy use reduced CI in exporting economies.

There are also studies investigating economic complexity in terms of its impact on energy transitions. Dabbous et al. (2025) investigated the roles of economic complexity, environmental policy stringency, and FinTech financing in facilitating energy transitions in 29 countries for the period 2010-2020. They found that higher economic complexity and stricter environmental policies promote energy transitions. Wu and Hussain (2025) analyzed the impact of environmental governance, economic complexity, and geopolitical risks on energy transition in 20 OECD countries for the period 1990-2021 using a Mixed Multiple Quantile Regression model and asymmetric analysis. They found that environmental governance consistently promotes energy transition, while economic complexity has a positive effect only at certain quantiles and can become negative under high geopolitical risk. Bakhsh et al. (2024), using Westerlund cointegration and Method of Moments Quantile Regression, found that environmental governance and economic complexity increase environmental resilience by promoting sustainable energy transitions, but economic complexity can also offset stability in their study with OECD country data for the period 1990-2021.

Finally, Rana et al. (2024) examined the effects of hydropower generation, economic complexity, urbanization, technological innovation, and financial development on environmental sustainability in 13 Asian economies using data for the period 1995 to 2017. Applying Driscoll-Kraay standard errors and Dumitrescu-Hurlin panel causality tests, they found that hydropower and technological innovation improve environmental sustainability, while economic complexity initially reduces it but exhibits an inverted U-shaped effect consistent with the EKC. The study shows that economic complexity can both increase and decrease carbon intensity at higher income levels.

A general review of the literature indicates that economic complexity affects carbon intensity. This effect can vary depending on the characteristics of countries. A country's income levels, institutional structures, and managerial skills influence the direction and magnitude of this effect.

### 3. EMPIRICAL ANALYSIS

#### 3.1. Data and Methodology

This study examines the determinants of carbon intensity across 36 OECD countries over the period 1995-2023, based on data availability. The Economic Complexity Atlas produced by the Harvard Growth Lab (2025) was used as a data source for the ECI and the World Bank (2025) World Development Indicators was used for all other variables.

The dependent variable, carbon intensity (CARBON), is measured as CO<sub>2</sub> emissions per unit of GDP. The main explanatory variable is the ECI, which reflects an economy's level of development in production.

Several independent variables were included to control for other economic factors affecting carbon intensity. Trade openness (TRADE), measured as the ratio of exports and imports to GDP, gross capital formation (GCF), expressed as the ratio to GDP, the natural logarithm of GDP per capita (lnGDPper), and the inflation rate (INF) were added as control variables. Inflation is included as a macroeconomic control, as price level volatility may affect production structure, energy input costs, and demand composition, thereby influencing carbon intensity. Finally, to examine whether the effect of economic complexity on carbon intensity changes with income, the variable ECI\_GDP representing the interaction between ECI and lnGDPper was included in the analysis.

The estimated model can be specified as:

$$CARBON_{it} = \alpha_0 + \alpha_1 CARBON_{i,t-1} + \beta_1 ECI_{it} + \beta_2 \ln GDP_{per_{it}} + \beta_3 (ECI \times \ln GDP_{per})_{it} + \beta_4 TRADE_{it} + \beta_5 GCF_{it} + \beta_6 INF_{it} + \mu_i + \varepsilon_{it} \tag{1}$$

where *i* denotes the country and *t* the time period.  $\mu_i$  captures country-specific fixed effects, and  $\varepsilon_{it}$  is the idiosyncratic error term.

All variables are expressed on an annual basis. Prior to econometric estimation, all series were examined for cross-sectional dependence, slope heterogeneity, and stationarity to ensure appropriate model specification.

### 3.2. Preliminary Tests

Given the panel data, the analysis follows a three-stage empirical procedure to ensure robustness and address potential econometric issues typical in macro-panel data.

First, the presence of cross-sectional dependence (CD) among the variables is tested using the Pesaran (2004) CD test. The existence of CD indicates interdependence across countries, which is expected for OECD economies due to trade, investment, and environmental policy linkages. The results of the Pesaran (2004) CD test in Table 1 indicate strong evidence of CD across all variables. The CD-statistics for all series are statistically significant at the 1% level. The presence of CD justifies the use of second-generation panel methods, which explicitly account for such dependence.

**Table 1.** Cross-sectional dependence (CD) test results

Variable	CD-test
CARBON	118.425 ***
ECI	8.434 ***
TRADE	65.966 ***
GCF	20.757 ***
lnGDPper	113.731 ***
INF	45.142 ***
ECI_GDP	6.504 ***

**Note:** \*\*\*, \*\*, and \* denote significance at the 1%, 5%, and 10% levels, respectively.

Second, the Pesaran and Yamagata (2008) test for slope homogeneity is employed to assess whether the coefficients differ across countries. The Pesaran and Yamagata (2008) slope homogeneity test results (Table 2) show that both the  $\Delta$  and adjusted  $\Delta$  statistics are significant at the 1% level. This indicates heterogeneous slope coefficients across cross-sections, meaning that the relationship between carbon intensity and the explanatory variables differs across countries.

**Table 2.** Slope homogeneity test results

Delta (~ $\Delta$ )	Adj.
23.741 ***	27.899 ***

**Note:** \*\*\*, \*\*, and \* denote significance at the 1%, 5%, and 10% levels, respectively.

To assess the integration properties of the variables under CD, second-generation panel unit root tests are applied, namely, the Cross-Sectionally Augmented Dickey–Fuller (CADF) and Cross-Sectionally Augmented IPS (CIPS) tests proposed by Pesaran (2007). These tests account for common factors and cross-sectional correlation, providing more reliable inference for macro-panels.

Table 3 presents second-generation panel unit root tests (the CADF and the CIPS) which account for CD. The CADF results indicate that CARBON, ECI, TRADE, GCF, and ECI\_GDP are integrated of order one,  $I(1)$ , while lnGDPper and INF are stationary at level,  $I(0)$ . The CIPS test yields mixed but broadly consistent results, showing that most variables are stationary either at level or after first differencing. Specifically, CARBON and ECI appear  $I(0)$  under CIPS but  $I(1)$  under CADF, suggesting borderline stationarity. This minor discrepancy is common, given the tests' differing sensitivities to cross-sectional dynamics. Overall, the mixed integration orders justify the application of the System

Generalized Method of Moments (System GMM), which accommodates endogenous regressors and dynamic specifications without requiring strict stationarity.

**Table 3.** Panel unit root tests results

Variable	CADF t-bar (Level)	CADF t-bar (First difference)	CIPS (Level)	CIPS (First difference)	Order of Integration
CARBON	-1.702	-2.877 ***	-2.200 **		I(1)/I(0)
ECI	-1.688	-2.978 ***	-2.155 **		I(1)/I(0)
TRADE	-1.732	-2.259 ***	-1.788	-4.003 ***	I(1)/ I(1)
GCF	-1.591	-3.013 ***	-2.050 *		I(1)/I(0)
lnGDPper	-2.140 ***		-1.937	-3.425 ***	I(0)/I(1)
INF	-2.636 ***		-3.718 ***		I(0)/ I(0)
ECI_GDP	-1.650	-2.975 ***	-2.015	-5.720 ***	I(1)/ I(1)

**Note:** \*\*\*, \*\*, and \* denote significance at the 1%, 5%, and 10% levels, respectively.

### 3.3. Regression Assessment

Given the persistence of the dependent variable and the potential endogeneity among the regressors, the study employs the System GMM estimator developed by Arellano and Bover (1995) and Blundell and Bond (1998). This estimator combines equations in levels and first differences, thereby improving estimation efficiency and addressing endogeneity through the use of internal instruments. The System GMM approach is particularly suitable for this analysis, as it controls for unobserved heterogeneity through differencing, mitigates endogeneity by employing lagged levels and differences of the variables as instruments, and captures dynamic persistence by including the lagged dependent variable in the model.

The System GMM results (Table 4) present a dynamic specification of carbon intensity (CARBON) as a function of its lagged value and the explanatory variables.

**Table 4.** The System GMM results

CARBON	Coef.	Corrected Std. Err.	t
CARBON L1	0.9198863	0.0122884	74.86 ***
ECI	0.0635647	0.0242327	2.62 **
lnGDPper	-0.0033597	0.0024215	-1.39
ECI_GDP	-0.0060463	0.0022989	-2.63 **
TRADE	-0.0000766	0.0000159	-4.81 ***
GCF	0.0003905	0.000207	1.89 *
INF	-0.000000526	0.0000473	-0.01
Cons	0.0472871	0.0262521	1.80

**Note:** \*\*\*, \*\*, and \* denote significance at the 1%, 5%, and 10% levels, respectively.

The lagged dependent variable (CARBON L1) is positive and highly significant, indicating strong persistence in carbon intensity over time. This suggests that past environmental performance exerts a substantial influence on current carbon outcomes, consistent with path dependence in energy use and industrial structures.

The coefficient on Economic Complexity (ECI) is positive and statistically significant. This implies that, in the short run, higher economic complexity is associated with increased carbon intensity. The result aligns with the notion that more complex economies often rely on advanced manufacturing and energy-intensive production processes during early stages of industrial sophistication.

However, the interaction term (ECI\_GDP) is negative and significant, indicating that the adverse effect of complexity on carbon intensity diminishes as income levels rise. This suggests a nonlinear

relationship: while complexity may initially increase emissions, its environmental effect becomes mitigated in wealthier economies due to technological upgrading, energy efficiency improvements, and environmental regulation.

The coefficient on trade openness (TRADE) is negative and highly significant, suggesting that greater integration into global markets is associated with lower carbon intensity. This supports the hypothesis that openness facilitates the diffusion of cleaner technologies and more efficient production practices.

Inflation (INF) and lnGDPper are statistically insignificant, indicating that neither macroeconomic stability nor per capita income directly influences carbon intensity in the short run once dynamic and structural effects are controlled for.

Post-estimation diagnostics confirm the validity of the System GMM specification (Table 5). The Arellano–Bond tests indicate first-order serial correlation, as expected, but no evidence of second-order correlation. The Hansen test of overidentifying restrictions supports the overall validity of the instruments, while the Difference-in-Hansen tests confirm their exogeneity. Although the non-robust Sargan test is significant, its result is not considered reliable under heteroskedasticity. Overall, the diagnostic results suggest that the model is correctly specified and the instruments are valid.

**Table 5.** Post-estimation diagnostic tests results

Test	Statistic	p-value	Interpretation
Arellano–Bond test for AR(1)	$z = -2.04$	0.041	First-order serial correlation (expected)
Arellano–Bond test for AR(2)	$z = -1.08$	0.280	No second-order serial correlation
Sargan test of overid. restrictions	$\chi^2(2) = 24.36$	0.000	Not robust; sensitive to heteroskedasticity
Hansen test of overid. restrictions	$\chi^2(2) = 1.35$	0.508	Instruments valid (robust)
Diff-in-Hansen (exogeneity of GMM instruments)	$\chi^2(1) = 1.11$	0.292	Instrument subsets exogenous
Hansen test excluding group	$\chi^2(1) = 0.24$	0.621	Supports exogeneity of instrument set

### 3.4. Ethics Committee Approval

This research complied with ethical principles throughout the conceptual framework, application of data collection tools, data collection, analysis, and interpretation of the data. The ANKAD Editorial Board assumes no responsibility for any ethical violations encountered. All responsibility lies with the authors. I hereby declare that this work has not been submitted for evaluation to any academic publication platform other than ANKAD. All rules specified in the "Higher Education Institutions Scientific Research and Publication Ethics Directive" have been adhered to in this study. None of the actions specified in the second section of the directive, "Actions Contrary to Scientific Research and Publication Ethics," have been taken. The data used in the research was obtained from publicly available data sources such as The Economic Complexity Atlas produced by the Harvard Growth Lab (2025) and the World Bank (2025) World Development Indicators (WDI).

## 4. DISCUSSION

The results of this study reveal several key insights into the relationship between carbon intensity and economic complexity across OECD countries from 1995 to 2023. The most prominent finding is the strong persistence of carbon intensity, indicated by the highly significant coefficient of the lagged dependent variable. This suggests that the environmental performance of an economy is strongly path-dependent, shaped by historical patterns of industrial structure, energy systems, and technological adoption. Once established, carbon-intensive production pathways tend to persist over time, underscoring the inertia in transitioning toward low-carbon growth.

A second major finding concerns the dual role of economic complexity. The positive and significant coefficient of ECI implies that, in the short run, higher economic complexity is associated with increased carbon intensity. However, the negative and significant interaction between ECI and income ( $ECI \times \ln GDP_{per}$ ) indicates that this effect diminishes and eventually reverses as income levels rise. This supports the view that complexity initially intensifies emissions due to industrial upgrading and energy demand but later promotes decarbonization once technological and regulatory capacities mature. The results, therefore refine the EKC framework by showing that the greening effect of complexity is not automatic but depends on a country's stage of economic development.

When placed in the context of the existing literature, these findings align with studies reporting nonlinear or stage-dependent effects of economic complexity on environmental outcomes. Ye et al. (2023) and Rana et al. (2024) similarly identified an inverted U-shaped relationship, where complexity raises emissions at early stages but mitigates them in advanced economies through innovation and cleaner technologies. The results also support the conclusions of Zheng et al. (2021) and Saqib and Dincă (2024), who found that higher complexity reduces emissions once economies achieve a sufficient technological base and integrate renewable energy into production. Conversely, the positive short run impact of ECI observed here is consistent with the findings of Sajid et al. (2024) and Adjei et al. (2022), who documented that industrial sophistication can initially worsen environmental outcomes when institutional quality and clean technology adoption are limited.

The significant and negative coefficient of trade openness indicates that greater integration into global markets tends to reduce carbon intensity, likely by facilitating technology diffusion, increasing competitive pressures for efficiency, and encouraging compliance with international environmental standards. This aligns with Ouerghi and Hasni (2025) and Wang et al. (2024), who observed that openness and economic complexity jointly promote environmental improvement through learning and innovation spillovers. But the result also shows that the environmental benefits of openness depend on participation in cleaner global production networks.

In contrast, GDP per capita and inflation exert no statistically significant effect on carbon intensity once structural and dynamic factors are controlled for. The insignificance of GDP per capita implies that income alone is not a reliable determinant of environmental performance in advanced economies, consistent with the growing critique of the traditional EKC hypothesis (Stern, 2017; Shahbaz and Sinha, 2019). Likewise, the weak role of inflation suggests that short run macroeconomic fluctuations have limited bearing on structural environmental outcomes.

An unexpected but noteworthy finding is the weakly positive coefficient of gross capital formation, suggesting that higher investment may slightly increase carbon intensity. This may reflect that a portion of investment in OECD economies still targets infrastructure and capital goods with relatively high embodied carbon content. Although the effect is small, it highlights the importance of steering investment toward low-carbon technologies and energy-efficient capital formation.

## 5. CONCLUSION

This study examines the relationship between economic complexity and carbon intensity using data for 36 OECD countries for the period 1995-2023. The study's findings reveal that carbon intensity is persistent and that carbon reduction efforts yield slow results. Furthermore, while economic complexity increases carbon intensity at low-income levels, it reduces it at higher income levels. This result extends the Environmental Kuznets Curve approach by indicating that the environmental impacts of economic complexity depend not only on income levels but also on structural transformation.

The findings emphasize that focusing solely on income levels is insufficient in explaining environmental performance; economic structural characteristics should also be considered. Economic complexity is a key factor in explaining carbon efficiency differences across countries. The results demonstrate its influential role in sustainable development.

The study has some limitations. Because the analysis covers only OECD countries, it is not possible to argue that the findings have the same implications for all economies. Furthermore, because macro-level data is used, it may not fully reflect the effects of differences across sectors. Future research should include other country groups and factors such as institutional quality and energy transition, and conduct

sectoral analyses to provide a more detailed understanding of the environmental impact of economic complexity.

The study provides empirical guidance for policymakers. It demonstrates that economic complexity alone is not sufficient to achieve carbon reduction. First, it emphasizes the need to design industrial policies in line with green innovation and clean energy investments. Second, trade openness and international technology diffusion should be encouraged, as integration into cleaner global production networks can accelerate the transition to low-carbon production. Finally, implementing long run, consistent, and innovation-oriented climate policies is crucial to mitigate the persistence of carbon-intensive production structures.

Consequently, while economic complexity may lead to increased emissions in the short run, it becomes a key element of sustainable development in the long run. When supported by appropriate innovative and environmentally friendly policies, complex, knowledge-based economic structures will support low-carbon growth.

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*Araştırma Makalesi / Research Article*

**The Impact of Economic Complexity on Carbon Intensity: A Dynamic Analysis of OECD Countries**

*Ekonomik Karmaşıklıkın Karbon Yoğunluğu Üzerindeki Etkisi: OECD Ülkeleri Üzerine Dinamik Bir Analiz*

**Alper Aykut EKİNCİ**



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**GENİŞLETİLMİŞ ÖZET**

**GİRİŞ**

Küresel iklim değişikliği, yalnızca çevresel değil aynı zamanda ekonomik bir dönüşüm sorununa işaret etmektedir. Bu nedenle, ekonomik büyümenin çevresel etkilerini yalnızca sera gazı emisyonları üzerinden değerlendiren yaklaşımlar yetersiz kalmaktadır. İklim değişikliği, üretim sistemlerinin yapısal biçimde yeniden tasarlanmasını gerektiren küresel bir sorun haline gelmiştir. Bu bağlamda, CO<sub>2</sub> emisyonları ile gayri safi yurtiçi hasıla (GSYİH) arasındaki oranı ölçen karbon yoğunluğu, çevresel etkinin ölçülmesinde temel bir gösterge olarak kullanılmaktadır (Tudor ve Sova, 2021; U.S. Energy Information Administration, 2025). Karbon yoğunluğunun azalması, belirli bir üretim düzeyine ulaşmak için daha az karbon girdisi gerektiğini, bu sebeple enerji verimliliğinin ve temiz enerji kullanımının arttığını göstermektedir (Schröder ve Storm, 2020).

Karbon yoğunluğunun düşürülmesi, yalnızca enerji verimliliğini artırmakla değil, aynı zamanda ekonomik yapıların dönüşümüyle mümkün olabilmektedir. Bu anlamda, Ekonomik Karmaşıklık Endeksi (ECI), bir ülkenin üretim yapısındaki bilgi derinliğini, teknoloji yoğunluğunu ve ihracat çeşitliliğini ölçen önemli bir değişken olarak öne çıkmaktadır (Hidalgo ve Hausmann, 2009). Geleneksel Çevresel Kuznets Eğrisi (EKC) yaklaşımı, çevresel bozulma ile gelir arasında ters-U şeklinde bir ilişki öngörmektedir (Leal ve Marques, 2022; Stern, 2017). Ancak bu model, ülkelerin üretim teknolojilerindeki farklılıkları, enerji karışımını ve yapısal dönüşüm dinamiklerini yeterince yansıtamamaktadır.

Bu çalışma, karbon yoğunluğu ile ekonomik karmaşıklık arasındaki ilişkiyi yapısal bir bakış açısından 36 OECD ülkesine ait 1995-2023 dönemi verileriyle analiz etmektedir. Araştırma ayrıca ekonomik karmaşıklığın çevresel performans üzerindeki etkisinin gelir düzeyine göre değişip değişmediğini de test etmektedir. Bu doğrultuda, ECI ile kişi başına düşen gayri safi yurtiçi hasıla (lnGDPper) arasındaki etkileşim terimi analizde kullanılmıştır. Ayrıca modelin dinamik yapısı, geçmiş dönem karbon yoğunluğunun mevcut değer üzerindeki etkisini dikkate alarak analiz gerçekleştirmiştir. Bu yaklaşım, karbon yoğunluğunu sadece enerji veya gelir düzeyiyle değil, üretim yapısının karmaşıklığı ve teknolojik derinliğiyle ilişkilendirerek literatüre yapısal bir katkı sağlamaktadır.

**YÖNTEM VE ANALİZ**

Çalışma, 36 OECD ülkesi için 1995-2023 dönemine ait panel verileri kullanmaktadır. Ekonomik Karmaşıklık Endeksi (ECI) verileri Harvard Growth Lab (2025)'ten, diğer değişkenler Dünya Bankası (2025) Dünya Kalkınma Göstergeleri'nden alınmıştır.

Bağımlı değişken, CO<sub>2</sub> emisyonlarının GSYH'ye oranı olan karbon yoğunluğu (CARBON) olarak tanımlanmıştır. Temel açıklayıcı değişken ekonomik karmaşıklık endeksi (ECI)'dir. Kontrol

değişkenleri olarak ticari açıklık (TRADE), sabit sermaye oluşumu (GCF), kişi başına düşen gayri safi yurtiçi hasıla (lnGDPper) ve enflasyon oranı (INF) analize eklenmiştir. Ayrıca, ekonomik karmaşıklığın gelir düzeyine bağlı etkisini ölçmek için  $ECI \times \ln GDPper$  etkileşim terimi ( $ECI\_GDPper$ ) analize dahil edilmiştir.

Tahmin edilen dinamik panel modeli aşağıdaki şekildedir:

$$CARBON_{it} = \alpha_0 + \alpha_1 CARBON_{i,t-1} + \beta_1 ECI_{it} + \beta_2 \ln GDPper_{it} + \beta_3 (ECI \times \ln GDPper)_{it} + \beta_4 TRADE_{it} + \beta_5 GCF_{it} + \beta_6 INF_{it} + \mu_i + \varepsilon_{it}$$

Burada  $i$  ülkeyi,  $t$  ise zaman dilimini ifade etmektedir.  $\mu_i$  ülkeye özgü sabit etkileri,  $\varepsilon_{it}$  ise hata terimini ifade etmektedir.

Modelde dinamik yapı ve olası içsellik sorunları bulunduğundan Sistem Genelleştirilmiş Momentler Yöntemi (Sistem GMM) kullanılmıştır (Arellano ve Bover, 1995; Blundell ve Bond, 1998). Bu yöntem, değişkenlerin gecikmeli değerlerini araç değişken olarak kullanarak içsellik sorunlarını azaltmakta ve ülkeler arası heterojenliği kontrol etmektedir.

Analiz öncesinde serilerin kesit bağımlılığı (Pesaran, 2004) ve eğim heterojenliği (Pesaran ve Yamagata, 2008) test edilmiştir. Her iki testin sonuçları, OECD ülkeleri arasında güçlü karşılıklı bağımlılık ve heterojenlik bulunduğunu göstermiştir. Bu nedenle ikinci nesil panel birim kök testleri olan CADF ve CIPS (Pesaran, 2007) testleri uygulanmıştır. Bulgular, serilerin karışık bütünleşme derecelerine sahip olduğunu göstermiş, bu da Sistem GMM yaklaşımının geçerliliğini desteklemektedir. Model tanı testleri tahminlerin güvenilir olduğunu doğrulamaktadır.

Sistem GMM tahmin sonuçları, karbon yoğunluğunun yüksek derecede süreklilik gösterdiğini ortaya koymaktadır. Bu sonuç, karbon emisyonlarının geçmiş düzeylerinin bugünkü emisyon performansını belirlediğini göstermekte ve çevresel performansta yol bağımlılığını teyit etmektedir.

Ekonomik karmaşıklık (ECI) katsayısı pozitif ve anlamlı bulunmuştur. Bu sonuç, kısa vadede üretim yapısındaki karmaşıklığın artmasının enerji ve emisyon yoğunluğunu artırdığını ortaya koymaktadır. Ancak  $ECI \times \ln GDPper$  etkileşim katsayısının negatif ve anlamlı olması, gelir düzeyinde meydana gelen artışın karmaşıklığın karbon yoğunluğu üzerindeki olumsuz etkisini azalttığını ve belirli bir eşik sonrasında tersine döndürdüğünü göstermektedir.

Ticari açıklık (TRADE) değişkeni negatif ve anlamlı bulunmuş, dışa açıklığın karbon yoğunluğunu azalttığı tespit edilmiştir. Bu bulgu, küresel üretim zincirlerine entegrasyonun temiz teknoloji yayılımını hızlandırdığı görüşünü destekler niteliktedir.

Sabit sermaye oluşumu (GCF) istatistiksel olarak düşük anlamlılık göstermekle birlikte pozitif olarak bulunmuştur. GCF karbon yoğunluğunu artırmaktadır. Bu sonuç, yatırım faaliyetlerinin hâlâ enerji yoğun sektörlerde yoğunlaştığını işaret etmektedir. Kişi başına düşen gayri safi yurtiçi hasıla (lnGDPper) ve enflasyon (INF) katsayıları ise istatistiksel olarak anlamlı olarak bulunmamıştır.

## TARTIŞMA ve SONUÇ

Bu çalışma, 1995-2023 döneminde OECD ülkelerinde ekonomik karmaşıklık ile karbon yoğunluğu arasındaki ilişkiyi inceleyerek çevresel sürdürülebilirliğin yapısal belirleyicilerine dair önemli bulgular ortaya koymaktadır. Bulgular, öncelikle karbon yoğunluğunun güçlü bir süreklilik gösterdiğini, yani çevresel performansın geçmiş üretim ve enerji yapılarından güçlü biçimde etkilendiğini göstermektedir. Bu durum, düşük karbonlu büyümeye geçişin yapısal bir durağanlıkla karşı karşıya olduğunu ve politika müdahalelerinin kısa vadede sınırlı etkiler yapabileceğini göstermektedir.

Çalışmanın önemli sonuçlarından biri, ekonomik karmaşıklığın çevresel etkisinin gelir düzeyine bağlı olarak değiştiğini ortaya koymasındır. Düşük gelir düzeylerinde karmaşıklık, daha fazla sanayi çeşitliliği ve enerji talebiyle karbon yoğunluğunu artırmakta; yüksek gelir düzeylerinde ise teknolojik yenilikler, enerji verimliliği ve çevre politikaları sayesinde emisyonları azaltmaktadır. Bu sonuç, ekonomik gelişmişlik düzeyine bağlı koşullu bir çevresel fayda mekanizmasının varlığını desteklemektedir. Böylece çalışma, çevresel Kuznets eğrisi yaklaşımını genişleterek, çevresel iyileşmenin yalnızca gelir artışıyla değil, aynı zamanda ekonomik yapının bilgi yoğunluğu ve yenilik kapasitesiyle de ilişkili olduğunu savunmaktadır.

Ticari açıklığın negatif ve anlamlı katsayısı, küresel piyasalara entegrasyonun karbon yoğunluğunu azalttığını ortaya koymaktadır. Bu bulgu, teknoloji yayılımı, verimlilik baskısı ve uluslararası çevre standartlarına uyum mekanizmaları üzerinden açıklanabilir. Ancak bu etkinin yönü ve gücü, ülkelerin temiz üretim ağlarına entegrasyon derecesine bağlıdır. Bu durum, ticaretin tek başına değil, yeşil üretim zincirleriyle bütünleştiğinde çevresel kazanımlar sağladığını göstermektedir.

Kişi başına gelir ve enflasyonun karbon yoğunluğu üzerinde anlamlı bir etkisinin bulunmaması, çevresel performansın yalnızca makroekonomik büyüklüklerle açıklanamayacağını göstermektedir. Bu bulgu, gelir düzeyinin çevresel sürdürülebilirliğin belirleyicisi olarak yetersiz kaldığını savunan güncel literatürle uyumludur. Sermaye oluşumunun pozitif ancak zayıf katsayısı ise OECD ülkelerinde yapılan yatırımların bir kısmının hâlen karbon yoğun sektörlerde yoğunlaştığını göstermekte, yatırımın yönünün yeşil teknolojilere kaydırılmasının önemini vurgulamaktadır.

Politika açısından üç temel sonuç öne çıkmaktadır. İlk olarak, ekonomik karmaşıklığın çevresel faydaya dönüşebilmesi için, yüksek teknoloji üretimi temiz enerjiyle desteklenmelidir. İkinci olarak, dışa açıklığın olumlu etkilerinin sürdürülmesi için, temiz üretim standartlarına dayalı uluslararası işbirlikleri teşvik edilmelidir. Son olarak, karbon yoğun sektörlerin dönüşümü için sürdürülebilir, yenilikçi ve istikrarlı politika çerçeveleri oluşturulmalıdır.

Sonuç olarak, ekonomik karmaşıklık kısa vadede karbon yoğunluğunu artırsa da uzun vadede sürdürülebilir kalkınmanın önemli bir unsuru hâline gelmektedir. Uygun politika çerçeveleriyle desteklendiğinde karmaşık ve bilgi temelli üretim yapıları, düşük karbonlu büyüme sürecinin en etkili araçlarından biri olarak işlev görecektir.