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Do economic complexity and energy consumption affect environmental performance? Evidence based on the LCC hypothesis in the Türkiye economy

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Abstract

This study examines the environmental impacts of economic growth (GDP), economic complexity (ECI), and energy consumption (EU) in Türkiye for the period 1995–2023 within the framework of the Load Capacity Curve (LCC) hypothesis. Fourier ADL cointegration was used in the analyses, while FMOLS, DOLS, and CCR methods were used for long-term coefficient estimations. The findings reveal a significant and strong cointegration relationship between GDP, ECI, EU, and the load capacity factor (LCF). The long-term estimation results show a U-shaped relationship between GDP and the LCF. This means that the LCF initially decreases as income increases, but it increases above a certain income level, improving environmental quality. This confirms the validity of the LCC hypothesis in Türkiye. On the other hand, the negative impact of increasing ECI and EU on the LCF indicates that Türkiye's production structure and energy infrastructure have not yet reached a level capable of operating efficiently at full capacity. In this context, it is not enough for energy policies to focus solely on creating new production capacity; mechanisms must be developed to ensure more efficient and balanced use of existing infrastructure.

Keywords: Economic Complexity, Energy, Environment, LCC Hypothesis, Türkiye.
Jel codes: C22, O13, O44, Q56.

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1. Introduction

Fossil fuels lead to serious changes in the global climate system (Rahman, 2017). To effectively combat this environmental threat, comprehensive and structural transformations in the fundamental dynamics that shape GDP, especially the energy consumption (EU), have become inevitable (Deng et al., 2024). The traditional growth approach is built on the intensive use of natural resources and the increase in emissions that harm the environment. This has led to both the rapid depletion of resources and the serious damage to ecosystems (Dogan et al., 2022). While GDP is an important indicator of the increase in the welfare of countries and societies, it also leads to increased EU, thereby increasing environmental pressures (Adejumo, 2020). The intensive use of fossil fuels accelerates climate change, along with air pollution, and leads to the depletion of natural resources (Orubu & Omotor, 2011; Akadiri et al., 2019). A growth process based on fossil fuels jeopardizes sustainability by destroying the environment (Murshed et al., 2021). Therefore, the relationship between GDP and the environment is quite complex, and growth can often increase environmental pressures. Therefore, economic and environmental goals must be compatible and balanced with sustainability (Hassan et al., 2023; Akin & Ozgun, 2024).

ECI refers to the diversity and technological level of a country’s production structure. This concept encompasses not only the production of different goods and services, but also the advanced technologies and innovations used in the production process (Deng et al., 2024). A country's level of ECI allows us to predict the types of products that country will develop in the future. Furthermore, new products developed by a country are often based on the knowledge, skills, and production capabilities already existing in that country (Hidalgo & Hausmann, 2009). ECI has become a prominent element in discussions about environmental quality. ECI refers to the structural changes that occur as production becomes more technologically and knowledge-based, explaining differences in countries' income levels and growth dynamics (Aluko et al., 2023). A country's ECI can reflect its production structure, which relies on energy resources that can harm the environment. On the other hand, in developed countries, increasing ECI can reduce environmental pollution. As suggested by Abdi (2023), the advancement of complex economies enables greater integration of sustainable technologies, thereby enhancing environmental performance. Furthermore, increasing ECI can have an impact on the environment by enabling the adoption of more advanced and knowledge-based production processes. Furthermore, while it can increase environmental pollution by bringing about higher EU, it can also make significant contributions to environmental protection by accelerating the adoption of environmentally friendly technologies (Abdi, 2023; Hassan et al., 2023).

While carbon emissions have traditionally been used to measure environmental performance, this only reflects one aspect of environmental degradation. An alternative indicator, the ecological footprint, is considered a limited measure because it considers environmental demand while neglecting the supply dimension (Erdogan, 2024). As an alternative to indicators such as carbon emissions and ecological footprint, which are frequently used in the literature to represent the environment, the LCF was developed, based on the relationship between biocapacity, which represents the supply of productive land, and the ecological footprint (Siche et al., 2010). The LCF is calculated by dividing the biocapacity by the ecological footprint to assess the environmental carrying capacity and sustainability level of a region (Pata, 2021). An LCF value above 1 indicates environmental sustainability, while a value below 1 indicates that ecological demand exceeds biocapacity and that natural resources are consumed beyond their carrying capacity, increasing the risk of environmental degradation. The LCF offers the opportunity to analyze environmental quality more holistically by demonstrating the adequacy of existing natural resources to meet environmental pressure. The LCC hypothesis proposes a U-shaped, non-linear relationship between GDP and the LCF (Pata & Tanrıöver, 2023; Pata & Kartal, 2023).

The unique aspect of this study is that it examines the interaction between ECI, GDP, and EU in Türkiye, specifically within the framework of the LCC hypothesis. In the literature, environmental performance is often assessed using unidirectional indicators such as carbon emissions and ecological footprint, based on the Environmental Kuznets Curve (EKC). In this study, environmental sustainability is addressed through the LCF indicator, which reflects the capacity offered by nature and the environmental demand resulting from human activities. In this context, the relationship between the LCF and income level is examined within the framework of the LCC hypothesis, contributing to a more holistic assessment of environmental performance. Furthermore, by incorporating a structural factor such as ECI into the analysis, the study reveals its impact on environmental sustainability. Thus, the effects of the transformation in the production structure of the Türkiye economy on environmental capacity were analyzed with a more comprehensive and innovative approach.

2. Literature Review

Studies examining environmental quality appear to have focused primarily on testing the validity of the EKC hypothesis developed by Grossman & Krueger (1991). The EKC hypothesis, widely cited in the environmental economics literature, has provided a framework focusing on the relationship between GDP and environmental degradation. The hypothesis posits an inverted U-shaped relationship in which income levels initially increase environmental degradation, but environmental quality improves again after a certain income threshold is exceeded (Grossman & Krueger, 1991). Numerous studies testing the validity of the EKC hypothesis can be found in the literature (Suki et al., 2020; Jiang et al., 2021; Mehraaein et al., 2021; Tenaw & Beyene, 2021; Uche et al., 2023).

It is noteworthy that the LCF literature is developing but not yet fully mature. The LCC hypothesis shows that as income increases, the LCF, which represents environmental quality, initially decreases, but above a certain income level, the LCF increases with environmental sensitivity (Pata & Kartal, 2023). Recent studies have examined the validity of the LCC hypothesis across different countries and variables. The validity of the LCC hypothesis has been empirically supported by various studies. For example, Erdogan (2024) examined the impact of natural resources on environmental sustainability in Sub-Saharan African countries and revealed that the LCC hypothesis is valid for the region. Deng et al. (2024) confirmed the validity of the hypothesis by analyzing ECI, energy security, and renewable energy factors in selected countries such as China, Japan, and Germany. Dogan & Pata (2022) confirmed the validity of the LCC hypothesis with their studies on G-7 countries, Pata & Kartal (2023) with the example of South Korea, and Afshan & Yaqoob (2023) with their studies on China, Brazil, Mexico, India, and Türkiye. On the other hand, Yang et al. (2023) and Uçar et al. (2025) concluded that the LCC hypothesis does not support its validity in ten different countries that are successful in the tourism sector as a result of their studies in BRICS countries.

In the case of Türkiye, Güneysu (2023) established the validity of the LCC hypothesis in light of globalization, financial development, and industrialization variables. Similarly, Caglar et al. (2024) examined the impact of clean energy efficiency on environmental performance within the LCC framework, confirming its validity in the Türkiye context. Furthermore, Çamkaya (2024) demonstrated empirical support for the LCC hypothesis in Türkiye using growth and urbanization variables. While these studies demonstrate that the LCC hypothesis yields consistent results across various contexts, they also demonstrate that the number of studies in this area is still limited in the literature.

Existing literature focusing on the relationship between ECI and the environment reveals the existence of a reciprocal interaction. For example, Can & Gozgor (2017) found that carbon emissions decrease as the level of ECI increases in France. Neagu & Teodoru (2019) found that in EU countries, Boleti et al. (2021) examined the relationship between ECI and the environment in 88 developed and developing countries, proving that ECI has a significant impact on the environment. Rafique et al. (2022) concluded that ECI increases the ecological footprint in selected countries. Abdi (2023) found that ECI positively affects environmental quality in Sub-Saharan African countries. Hassan et al. (2023) identified a positive relationship between the ecological footprint and ECI in the United States. However, the existing literature falls short of providing a clear framework for the environmental impacts of ECI. Therefore, these findings suggest that ECI can contribute to environmental improvements in some cases while exacerbating environmental degradation in others.

Generally, when the existing literature is evaluated, research on the LCC hypothesis not only reveals the dynamics between GDP and environmental sustainability but also sheds light on how critical factors such as the EU, urbanization, and clean energy efficiency shape this relationship. Empirical analyses conducted in different countries and time periods indicate that the LCC hypothesis is beginning to gain a place in the literature as an environmental model. However, it is also noteworthy that the validity of the hypothesis depends largely on the economic structures, energy, and environmental policies of countries. This study, however, focuses on empirically testing environmental impacts within the context of the LCC hypothesis by considering GDP, ECI, and EU variables in Türkiye.

3. Data & Methodology

This study examines the environmental impacts of GDP, ECI, and EU in Türkiye over the period 1995–2023 using a time series analysis method within the framework of the LCC hypothesis. All variables used in the study were logarithmically transformed. The model setup was inspired by the studies developed by Pata & Kartal (2023) and Pata & Tanriover (2023) and is presented in Equation 1. In this model, the LCF, which represents environmental sustainability, is considered the dependent variable.

$$lnLCF_t = \beta_0 + \beta_1 lnGDP_t + +\beta_2 lnGDP_t^2 + \beta_3 lnECI_t + \beta_4 lnEC_t + \varepsilon_t \quad (1)$$

The variables and descriptive statistics used in the study are presented in Table 1.

Table 1. Variables and Descriptive Statistics

Variables	Abbreviation	Measurement Unit	Source
Load Capacity Factor	lnLCF	Biocapacity/ecological footprint (per capita in gha)	Global Footprint Network
Economic Growth	lnGDP	GDP per capita, constant 2015 US$	World Bank
Economic Growth Squared	$lnGDP^2$	Quadratic form of economic growth	Calculated by the authors.
Economic Complexity Index	lnECI	Index value between –2.5 and +2.5	Atlas of Economic Complexity
Energy Consumption	lnEU	Primary energy consumption per capita (kWh/person)	International Energy Agency

Descriptive Statistics

	lnLCF	**lnGDP**	**$lnGDP^2$**	**lnECI**	**lnEU**
Mean	-0.620	9.067	82.302	0.183	7.244
Median	-0.658	9.036	81.642	0.199	7.265
Maximum	-0.365	9.597	92.093	0.378	7.547
Minimum	-0.828	8.620	74.306	-0.020	6.906
Std. Dev.	0.158	0.304	5.525	0.104	0.207
Skewness	0.216	0.136	0.169	-0.259	-0.044
Kurtosis	1.481	1.689	1.708	2.273	1.572
Jarque-Bera	3.013	2.165	2.157	0.962	2.474
Probability	0.222	0.339	0.340	0.618	0.290
Observations	29	29	29	29	29

This study first investigates the stationarity properties of the time series by employing both the standard Augmented Dickey-Fuller test (Dickey & Fuller, 1979) and its Fourier-enhanced version (Enders & Lee, 2012). To assess the existence of a long-run equilibrium among the variables, the Fourier ADL cointegration approach proposed by Banerjee et al. (2017) is applied. Subsequently, the long-term coefficients are estimated using three different techniques: FMOLS (Phillips & Hansen, 1990), DOLS (Stock & Watson, 1993), and CCR (Park, 1992).

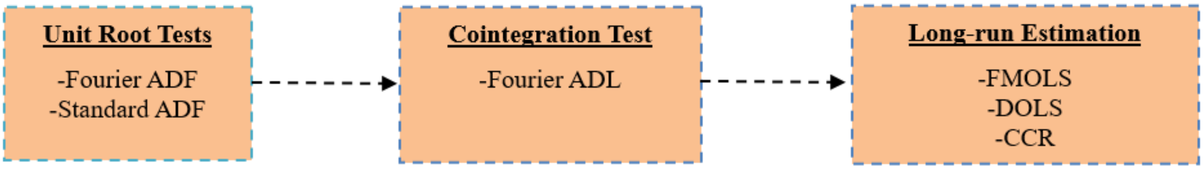

Figure 1: Empirical Analysis Diagram

The Fourier ADF test is a method used in the stationarity analysis of time series and was developed by Enders & Lee (2012). This test was structured by adding trigonometric terms to the classic ADF test of Dickey & Fuller (1979). This allows for more flexible modeling of structural breaks and periodic fluctuations. The statistical significance of the Fourier terms is first evaluated during the testing process. If these terms contribute significantly to the model, the analysis is continued with the Fourier ADF test. Otherwise, the traditional ADF test is preferred. This method helps determine the degree of integration of the series more accurately and also allows for more precise capture of structural changes and periodic effects. The equation is as follows.

$$\Delta y_t = \rho y_{t-1} + c_1 + c_2 + c_3 sin\left(\frac{2\pi kt}{T}\right) + c_4 \, cos\left(\frac{2\pi kt}{T}\right) + e_t$$

(2)

The frequency parameter (k) in Equation (2) is generally chosen between 1 and 5 and is effective in capturing structural breaks in the series. The critical values used in the Fourier ADF test are presented in detailed tables by Enders & Lee (2012) to assess the significance of trigonometric terms and the presence of a unit root.

Following the Fourier ADF and classical ADF tests, the FADL cointegration test was applied to examine the long-term relationship between the variables. The Fourier ADL cointegration test, developed by Banerjee et al. (2017), analyzes structural breaks by integrating them into the model with trigonometric terms. In this respect, it differs from the classical cointegration test proposed by Engle & Granger (1987) in that the classical test does not consider structural breaks, and these effects are not subsequently added to the model. The basic equation for the Fourier ADL test is presented below;

$$\Delta y_{1t} = \alpha_0 + \gamma_1 sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \, cos\left(\frac{2\pi kt}{T}\right) + \delta y_{1,t-1} + \gamma' \Delta y_{2,t-1} + \varphi' \Delta y_{2t} + e_t$$

(3)

The lag number, frequency value, and lowest residual sum of squares of the variables are determined using equation (3). The test statistic is calculated from equation (3). This test statistic is shown in Equation (4);

$$t_{ADL}^{F} = \frac{\widehat{\delta_1}}{se(\hat{\delta})}$$

(4)

The test statistic is compared with the table values presented by Banerjee et al. (2017). If the calculated statistic exceeds this table value, the null hypothesis is rejected and the existence of a long-run cointegration relationship between the variables is accepted.

4. Empirical Result

Table 2 presents the outcomes of the Fourier ADF and traditional ADF unit root tests, which were applied to assess the stationarity of the variables in this study. These tests help determine whether the time series is stable over the sample period and verify the assumptions required for valid econometric analysis. Since the Fourier ADF test's F-statistic was found to be insignificant, the evaluation relied primarily on the classical ADF test results. According to these results, none of the variables (lnLCF, lnGDP, $lnGDP^2$, lnECI, lnEU) are stationary at their level values, but they all become stationary after taking the first difference. This confirms that the variables are integrated of order one, I(1), thus meeting the criteria necessary for cointegration testing.

Table 2. Fourier ADF and Standard ADF unit root test results

		FADF		ADF	
Variables	**Frequency (k)**	**FADF Test Statistic**	**F Test Statistic**	**I(0)**	**I(1)**
lnLCF	1	-1.972	1.661	1.036	-5.971
				(0.660)	(0.000)***
lnGDP	3	0.115	4.652	0.257	-4.799
				(0.971)	(0.000)***
$lnGDP^2$	3	0.549	5.114	0.398	-4.742
				(0.979)	(0.000)***
lnECI	5	-1.394	2.634	-2.045	-7.580
				(0.267)	(0.000)***
lnEU	1	-1.841	1.464	-0.962	-4.725
				(0.752)	(0.000)***

Notes: *** p<0.01, ** p<0.05, * p<0.1. Critical values for the F-statistic: 1% (10.35), 5%(7.58), 10% (6.35).

The results of the Fourier ADL (FADL) cointegration test, as shown in Table 3 (Banerjee et al., 2017), were used to investigate whether a long-run equilibrium relationship exists among the variables under study. The test results reveal a significant cointegration connection between LCF and the variables GDP, GDP^2, ECI, and EU at the 1% significance level. Specifically, the Fourier ADL test statistic of -6.137 surpasses the critical threshold values, providing strong evidence in favor of a long-term stable relationship.

Table 3. FADL Cointegration Test Results

Dep. var.	**Indep. var.**	**k**	**Min_AIC**	**Fourier ADL test statistic**
lnLCF	lnGDP, $lnGDP^2$, lnECI, lnEU	4	-4.454	-6.137***

Notes: *** p<0.01, ** p<0.05, * p<0.1. Critical values Fourier ADL: 1% (-4.75), 5% (-4.03), 10% (-3.65).

After determining the cointegration relationship, FMOLS, DOLS, and CCR methods were applied to analyze the long-term effects between the variables. According to the results in Table 4, lnGSYH has a negative effect, while $lnGSYH^2$ has a positive effect. This situation shows the validity of the LCC hypothesis for Türkiye. The negative effects of the ECI index (lnECI) and EU (lnEU) variables indicate that the complexity of the production structure and increasing energy use hinder the efficient use of existing environmental capacity. In other words, lnECI and lnEU have an increasing effect on environmental pollution. These findings indicate that Türkiye's energy system has not yet reached the efficiency threshold and is located at the lower end of the LCC curve.

Table 4. Long-Term Estimator Results

Dep. Var. : lnLCF	FMOLS	DOLS	CCR
lnGDP	-3.278 (0.002)***	-2.875 (0.030)**	-3.097 (0.014)**
$lnGDP^2$	0.177 (0.002)***	0.155 (0.024)**	0.170 (0.011)**
lnECI	-0.135 (0.004)***	-0.151 (0.011)**	-0.132 (0.020)**
lnEU	-0.838 (0.000)***	-0.824 (0.000)***	-0.914 (0.000)***
C	20.488 (0.000)***	18.559 (0.000)***	19.994 (0.000)***
SIN	0.008 (0.031)**	0.008 (0.114)	0.008 (0.057)*
COS	-0.001 (0.743)	-0.001 (0.762)	-0.001 (0.998)
ECT_{t-1}	-0.839 (0.000)***	-0.816 (0.000)***	-0.829 (0.000)***

Notes: *** p<0.01, ** p<0.05, * p<0.1.

5. Conclusion

This research investigates the long-term environmental effects of GDP, ECI, and EU in Türkiye over the period from 1995 to 2023. The study employs the Fourier ADL cointegration technique alongside FMOLS, DOLS, and CCR estimators to obtain long-run coefficient estimates. The variables analyzed include GDP, ECI, EU, and the LCF. Additionally, to test the LCC hypothesis, the squared term of real income was incorporated into the model as an explanatory factor. This approach is critical for uncovering enduring relationships among the variables.

Findings demonstrate a significant cointegration between GDP, ECI, EU, and the LCF. The long-run estimates derived from FMOLS, DOLS, and CCR methods reveal a U-shaped pattern between GDP and LCF, indicating that environmental capacity declines with increasing income at first but improves after surpassing a specific income threshold, supporting the LCC hypothesis for Türkiye. Conversely, the negative impacts of ECI and EU on environmental sustainability suggest that as production processes become more complex and energy consumption rises, maintaining efficient environmental capacity becomes increasingly challenging.

The results are also consistent with some studies in the literature. For example, Dogan & Pata (2022) demonstrated the validity of the LCC hypothesis in their study on G-7 countries, Pata & Kartal (2023) in the case of South Korea, and Çamkaya (2024) in the case of Türkiye. In contrast, Yang et al. (2023) and Uçar et al. (2025) found the validity of the LCC hypothesis in the BRICS countries, and Pata & Tanrıöver (2023) found the hypothesis not valid in ten different countries with successful tourism sectors. These differences can be attributed to factors such as countries' economic structures, energy policies, technological development levels, and environmental regulations. Furthermore, Deng et al. (2024) and Afshan & Yaqoob (2023) have similarly reported the negative impacts of ECI and EU on environmental sustainability. Consequently, the findings for Türkiye demonstrate the validity of the LCC hypothesis and point to strategic priorities that policymakers should carefully consider to ensure environmental sustainability during GDP. In this context, the use of renewable energy sources should be expanded to reduce dependence on fossil fuels, technological investments that increase energy efficiency should be encouraged, and environmentally friendly practices should be adopted in production processes. Furthermore, the transition to low-carbon and resource-efficient production systems should be considered a strategic priority to mitigate the environmental impacts of ECI. In future studies, a detailed examination of the relationships between the EU and environmental performance at the sectoral level, and an analysis of the effects of regional differences, local energy policies, and technological adoption levels will contribute to the development of more targeted and effective strategies for policymakers.

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