



The Effects of ICTs, Total Factor Productivity, Trade Openness, Renewable Energy and Electricity Consumption on Ecological Footprint in Türkiye

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ABSTRACT

As countries pursue growth and increased productivity within a sustainable economy, the digitalisation and energy efficiency, alongside the increased production of clean energy, are becoming increasingly important. This research evaluates the consequences of information and communication technologies (ICT), total factor productivity (TFP), trade openness, renewable energy, and electricity consumption—considered as indicators of green energy—on Türkiye's ecological footprint (EFP) during the period 1990–2022. Autoregressive distributed lag (ARDL) methodology is employed to estimate the long-run associations and short-run dynamics between these variables. According to the long-run estimation results, electricity consumption contributes significantly to environmental degradation and thus demonstrates that energy production remains dependent on carbon-intensive energy sources. In contrast, trade openness and internet usage are associated with a reductive effect on the ecological footprint, although short-term coefficients differ slightly from long-term estimates. The findings also point out that electricity consumption and TFP intensify environmental pressure, while mobile phone subscriptions aggravate ecological degradation in the short run. To summarise, this study conducted within the scope of Türkiye emphasises the necessity of policy measures that promote sustainable digitalisation and the implementation of energy-efficient technologies to reduce the environmental costs of economic and technological development.

Keywords

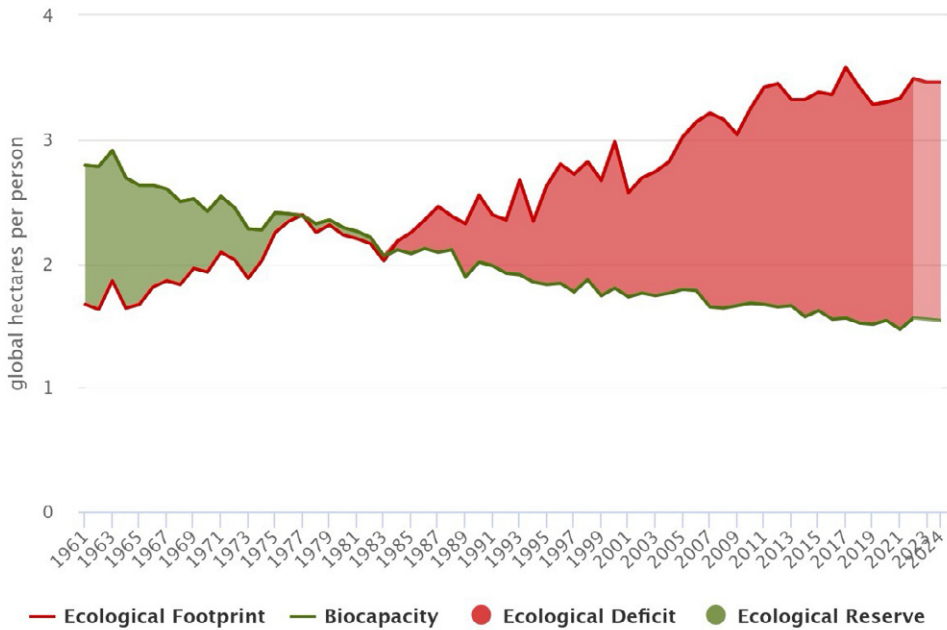
ecological footprint • information and communication technologies • trade openness • total factor productivity • renewable energy consumption



Introduction

There is an extensive literature on the economic, social, institutional impacts on environmental quality in the literature. An indicator of environmental assets level is ecological footprint and biocapacity. If ecological footprint is greater than biocapacity it is called “ecological deficit”. Ecological deficit means that the region’s demand for goods and services that environment can provide exceeds the ecosystems can regenerate. Based on Global Footprint Network’s 2024 estimates, Türkiye’s per capita ecological footprint has gone up to 3.5 gha, while its per capita biocapacity has dropped to 1.4 gha. This indicates a biocapacity deficit in Türkiye since 1984 as shown in the Figure 1 ecological footprint and biocapacity in Türkiye for the period 1961-2024.

Figure 1
Ecological Footprint and Biocapacity in Türkiye (1961-2024)



Source: Global Footprint Network (2026)

Environmental sustainability is a leading challenge of the modern world, requiring economic growth to be maintained without depleting environmental resources and in keeping with the ecosystem’s capacity for regeneration.

In this context, identifying the key determinants of environmental quality has become increasingly important for both academics and policymakers. The literature extensively

discusses the environmental implications of economic growth, technological progress, energy consumption, and economic integration. In addition to these factors, the sustainable use of environmental resources, enhanced efficiency, and the promotion of environmentally friendly scientific and technological innovations play a significant role in shaping environmental outcomes. Information and communication technologies (ICT), the green transformation of the energy sector, renewable energy deployment, efficiency improvements, and trade openness are among the prominent determinants emphasized in recent studies. However, their effects on the environment are not unidirectional, as they may either mitigate or exacerbate environmental pressure. Moreover, these impacts can differ between the short and long run. Therefore, this research evaluates the consequences of information and communication technologies (ICT), total factor productivity (TFP), trade openness, renewable energy, and electricity consumption—considered as indicators of green energy—on Türkiye's ecological footprint (EFP) during the period 1990–2022. Economic activity is represented by total factor productivity (TFP). Green energy encompasses renewable energy and electricity consumption.

Section 2 provides a brief literature review on economic activity, renewable energy, electricity consumption, information and communication technologies, trade, and environmental quality. Section 3 provides an explanation of the data and methodology. Section 4 provides an account of the empirical findings. Finally, Section 4 is the conclusions section.

Literature Review

There is a significant amount of research on the environmental effects of economic growth, ICTs, renewable energy consumption, electricity consumption and trade. In this framework the level of developments of these indicators and environmental outcomes has frequently been analysed from the perspective of Environmental Kuznets Curve (EKC) hypothesis. Short-term and long-term relationships, quartile regression methods, and dynamic models are prominent in this context.

The impact of total factor productivity (TFP) on environmental sustainability remains uncertain, depending on the country's energy mix, the nature of technological change and innovation, and the economic structure. Amri et al. (2019) reported in their study on Tunisia that TFP has an increasing effect on carbon emissions. It demonstrates that the long-term coefficient of TFP is higher than its short-term coefficient and that the increasing detrimental effect of productivity on environmental quality in the long-term leads to the rejection of the EKC hypothesis. Authors emphasise the importance of research and development activities in order to increase total factor productivity to a level where positive environmental effects may emerge. They also stress the necessity of technical developments aimed at environmental improvement. Furthermore, they note that ICTs have a negligible impact on CO₂ emissions, implying that digitalisation alone has not yet

delivered environmental benefits in Tunisia. Altinoz et al. (2021) jointly model TFP and the square of TFP in the ten most advanced emerging market economies, indicating that productivity increases are associated with emission reductions. Estimates using the panel vector autoregressive (PVAR) methodology show that, among ICT indicators, mobile phone subscriptions are associated with emission reductions, while internet usage and fixed telephone subscriptions contribute to higher carbon emissions. Furthermore, the findings reveal a double-sided causality between carbon emissions and all explanatory factors. Mukhtarov (2024), in his study on Türkiye, examines the effect of technological advancement, proxied by the number of patents, which may have a more direct impact than TFP, on carbon emissions and states that there is a negative relationship. The authors employ the ARDL methodology. The estimates reveal that renewable energy consumption and exports contribute to a fall in emission levels, while income and imports are associated with an increase in these levels. Okay-Toprak (2023) investigates the nexus between biocapacity efficiency and GDP in eight European countries exhibiting the largest biocapacity-ecological footprint deficits over the period 1970-2014, employing the Seemingly Unrelated Regression (SUR) methodology. The findings indicate a negative association between biocapacity efficiency and GDP. This suggests that economic growth contributes significantly to increased ecological pressure in these countries.

The impact of information and communication technologies (ICT) on the environment, as discussed in the literature, can vary depending on the structure of the economy and the level of development and adoption of such technologies, potentially increasing environmental costs or reducing environmental pressure. Faisal et al. (2020), in their study examining rapidly developing economies, support the view that the development of ICTs can contribute to environmental quality by increasing technological innovation and productivity gains, enhancing energy efficiency, and supporting the uptake of cleaner production technologies. The models estimated using advanced panel data methodologies reveal an inverse U-shaped association among ICT advancement and carbon emissions. Furthermore, the findings indicate that electricity usage and financial progress lead to increased CO₂ emissions, while economic growth and trade are connected to decreased emissions. Barış-Tüzemen et al. (2020) compared both ARDL and quantile regression results in their research on the linkage between ICT level and carbon emissions in Türkiye. Accordingly, while the first methodology confirmed the inverse N-shaped relationship, the second methodology identified a flat U-shaped relationship only at higher emission levels. Raheem et al. (2020) analyse the long-run and short-run effects of ICTs and financial development on carbon emissions and economic growth in G7 economies over the period 1990–2014, employing the pooled mean group (PMG) estimation technique. Their findings indicate that ICT expansion is associated with higher carbon emissions in the long run, whereas financial development exerts only a limited influence. However, it

is seen that the interaction between ICTs and financial advancement has a mitigating result on emissions, as can be understood from its negative coefficient. Huang et al. (2022) investigate how ICTs, renewable energy use, economic complexity, human capital, and financial development influence the ecological footprint in E-7 and G-7 economies over the period 1995–2018. Applying second-generation panel data techniques their findings suggest that, in E-7 countries, ICT development, economic complexity, and human capital contribute to higher environmental pressure, whereas renewable energy mitigates ecological degradation. In contrast, for G-7 economies, the majority of these variables are associated with improvements in environmental quality. The results also show a two-way causal association among ICT, human capital and ecological footprint between the two country groups. Kahouli et al. (2022) assess the effects of ICTs, green energy, and TFP on the ecological footprint in Saudi Arabia over the period 1990–2018, employing the Johansen cointegration approach and a vector error correction model (VECM). Their analysis identifies long-run linkages among green energy use, technology-related trade, TFP, and the ecological footprint, while revealing an inverse association between ICT development and environmental pressure in the short run.

Advances in renewable energy production and, consequently, increases in the share of renewable energy within total energy consumption, along with other developments in clean energy production, are expected to contribute to reducing environmental pressure. However, the environmental impact of increased electricity consumption in place of fossil fuels can be both positive and negative, depending on the energy mix used to generate that electricity. Sharif et al. (2020) examine the impact on Türkiye's ecological footprint using the Quantile ARDL framework, applying it to quarterly data from 1965 to 2017 and considering renewable and non-renewable energy consumption together in their model. According to the estimation results, renewable energy reduces the ecological footprint in all long-term quantiles, thus supporting the EKC hypothesis. Non-renewable energy use and economic growth, on the other hand, are observed to increase environmental pressure. Furthermore, the results suggest that there is reciprocal causality across the variables. Karaaslan and Çamkaya (2022) examine the long-run and causal relationships among GDP, health expenditures, renewable and non-renewable energy use, and carbon emissions in Türkiye over the period 1980–2016, employing the ARDL framework alongside the Toda–Yamamoto causality test. Their findings indicate that economic growth and reliance on non-renewable energy sources intensify carbon emissions, whereas increased health spending and renewable energy consumption contribute to emission reductions in the long run. Additionally, the results reveal unidirectional causality running from all explanatory variables toward CO₂ emissions. Zhao et al. (2024) investigate the effects of energy efficiency, natural resource utilization, and digital economy development on the ecological footprint in OECD countries over the period 2002–2020, employing the

Method of Moments Quantile Regression (MMQR) approach. Their results show that improvements in energy efficiency and natural resource management contribute to a reduction in the ecological footprint, whereas expansion of the digital economy exacerbates environmental degradation. Moreover, the authors find that renewable energy fails to offset the negative environmental impacts of digitalization, largely due to the increasing energy demand associated with digital infrastructure. Doğan et al. (2025) analyse the impact of renewable energy use, value added from agriculture, forestry, and fisheries, economic growth, and financial development on Denmark's ecological footprint over the period 1990–2020. Their findings indicate that renewable energy consumption is associated with a reduction in environmental pressure, whereas economic expansion, financial sector development, and value added from agriculture, forestry, and fisheries contribute to an increase in the ecological footprint.

In the literature, the environmental effects of trade openness are shown to be either positive or negative, depending on factors such as the sectoral composition of the economy, the stringency of environmental regulations, and the level of technological development. Bilgili et al. (2020) examine the relationship between ecological footprint and various forms of globalization—namely economic, trade, financial, social, political, and interpersonal globalization—along with population, human capital, and capital stock in Türkiye over the period 1970–2014, employing Markov regime-switching models. Their results indicate that financial, political, trade, and interpersonal globalization, as well as human capital and capital accumulation, contribute to reducing the growth of the ecological footprint, whereas economic and social globalization are associated with increased ecological footprint growth. Magazzino et al. (2025) investigate the effects of trade openness, electricity consumption, real GDP, life expectancy, and urbanization on Türkiye's ecological footprint over the period 1960–2022, employing both econometric techniques and advanced machine learning models. Their findings indicate that electricity use, economic growth, and higher life expectancy contribute to an increase in the ecological footprint, whereas trade openness and urbanization are associated with a reduction in environmental pressure. Ersin et al. (2024) analyse the linkages between ecological footprint, environmental technology patents, high-technology exports, and economic growth in the USA, Germany, France, and China from 1988 to 2019, using Fourier ARDL and Fourier Toda–Yamamoto causality techniques. Their findings reveal that environmental technology patents reduce the ecological footprint in the USA, Germany, and France, while high-technology exports exacerbate it in these countries. Conversely, in China, high-tech exports are associated with a decline in the ecological footprint. Across all four countries, economic growth is found to negatively affect environmental quality.

This study adds to the existing literature by analysing the simultaneous impacts of ICTs, TFP, trade openness, renewable energy and electricity consumption on environmental outcomes within a single analytical framework, using the ecological footprint as the indicator of environmental quality. Furthermore, by employing ARDL approach to distinguish between short- and long-term dynamics, the study reveals that environmental outcomes can vary across time horizons. In the context of Türkiye, the analysis expands the empirical literature by jointly incorporating TFP and ICTs variables, thereby emphasizing the importance of technological factors in environmental policy outcomes.

Data and Methodology

Empirical research aims to analyse the relationship between ICTs, TFP, trade, renewable energy and electricity consumption and EFP in Türkiye for the period from 1990 to 2022. This period has been determined based on data availability and developments in ICT in Türkiye. The EFP is a dependent variable used to measure environmental quality. The EFP is compiled from Global Footprint Network. Economic activity is represented by total factor productivity at constant national prices (2021=1) (TFP). The data has been collected from the Penn World Table (PWT) version 11.0. Green energy encompasses renewable energy and electricity consumption. Renewable energy consumption (% of total final energy consumption) (REC) is obtained from the International Energy Agency (IEA). Electric power consumption (kWh per capita) (EPC) is derived from World Bank indicators database (WDI). Information and communication technologies (ICT) is expressed as two variables measured using mobile cellular subscriptions measured per 100 people and individuals using the Internet % of population. All of these are from WDI. Trade openness is defined as the sum of exports of goods and services (% of GDP) and imports of goods and services (% of GDP). The data is from WDI database. Description of the variables are given in Table 1.

Table 1
Description of the variables

Variables	Description	Sources
EFP (dependent)	Ecological footprint	Global Footprint Network
TFP	Total factor productivity at constant national prices (2021=1)	PWT 11.0
REC	Renewable energy consumption (% of total final energy consumption)	IEA
EPC	Electric power consumption (kWh per capita)	WDI
CELL, INT	Information and Communication Technologies. Two variables: Mobile cellular subscriptions measured per 100 people (CELL) and individuals using the Internet % of population (INT).	WDI
TO	Trade openness. Sum of exports of goods and services (% of GDP) and imports of goods and services (% of GDP)	WDI

Empirical model is presented as follows:

Model 1:

$$\ln EFP_t = \beta_0 + \beta_1 \ln TPF_t + \beta_2 \ln REC_t + \beta_3 \ln EPC_t + \beta_4 \ln CELL_t + \beta_5 \ln TO_t + u_t \quad (1)$$

Model 2:

$$\ln EFP_t = \beta_0 + \beta_1 \ln TPF_t + \beta_2 \ln REC_t + \beta_3 \ln EPC_t + \beta_4 \ln INT_t + \beta_5 \ln TO_t + u_t \quad (1)$$

Long-term relationships between variables are tested using The Autoregressive Distributed Lag (ARDL) cointegration technique and short-term coefficients are estimated using error-correction-based causality models. The ARDL cointegration technique, developed by Pesaran and Shin (1999) and Pesaran, Shin, and Smith (2001) test whether a long-term relationship exists among the variables of a model with different order of integration. This approach yields reliable and consistent results even when the sample size is limited (Baek & Kim, 2013; Panopoulou & Pittis, 2004).

Short-term using error-correction-based causality models are estimated as follows:

Model 1:

$$\Delta \ln EFP_t = \alpha_0 + \sum_{i=1}^p \alpha_1 \Delta \ln TPF_{t-i} + \sum_{i=1}^p \alpha_2 \Delta \ln REC_{t-i} + \sum_{i=1}^p \alpha_3 \Delta \ln EPC_{t-i} + \sum_{i=1}^p \alpha_4 \Delta \ln CELL_{t-i} + \sum_{i=1}^p \alpha_5 \Delta \ln TO_{t-i} + \varepsilon_t \quad (3)$$

Model 2:

$$\Delta \ln EFP_t = \alpha_0 + \sum_{i=1}^p \alpha_1 \Delta \ln TPF_{t-i} + \sum_{i=1}^p \alpha_2 \Delta \ln REC_{t-i} + \sum_{i=1}^p \alpha_3 \Delta \ln EPC_{t-i} + \sum_{i=1}^p \alpha_4 \Delta \ln INT_{t-i} + \sum_{i=1}^p \alpha_5 \Delta \ln TO_{t-i} + \varepsilon_t \quad (4)$$

Empirical Results

Prior to estimation of the ARDL models specified in equations (1) and (2) the time-series properties of the variables employed in this study are first assessed by conducting unit root tests. The results indicate that $\ln EFP$, $\ln REC$, $\ln EPC$, $\ln TFP$ and $\ln TO$ are integrated of order one $I(1)$, while $\ln CELL$, $\ln INT$ are stationary at levels $I(0)$, as reported in Table 2.

Table 2
Augmented Dickey-Fuller (ADF) unit root tests

Variable	Level		1st. difference	
	Constant	Constant and trend	Constant	Constant and trend
$\ln EFP$	-1.43(0.55)	-4.17*(0.01)	-9.12*(0.00)	-9.01*(0.00)
$\ln REC$	-1.86(0.35)	0.08(1.00)	-6.78*(0.00)	-7.42*(0.00)
$\ln EPC$	-2.13(0.23)	-1.17(0.90)	-4.63*(0.00)	-5.39*(0.00)
$\ln TFP$	-2.84(0.06)	-3.75*(0.03)	-6.89*(0.00)	-4.61*(0.01)
$\ln CELL$	-5.49*(0.00)	-6.18*(0.00)	-2.18(0.22)	-0.84(0.95)
$\ln INT$	-3.85*(0.01)	-4.33*(0.01)	-3.46*(0.02)	-1.66(0.73)
$\ln TO$	-0.58(0.86)	-3.00(0.15)	-5.83*(0.00)	-5.69*(0.00)

Notes: * denotes 5% significance level. Probability values are in parentheses.

The ARDL bounds testing results reported in Table 3 reject the null hypothesis of no long-run association for both estimated models. Models 1 and 2 demonstrate a long-term cointegration relationship at a 1% significance level.

Table 3
ARDL Bound Test

Model 1 (with mobile cellular subscriptions)			
ARDL (1,1,2,1,1,1) F Statistic 6.12 k 5 n=31	10%	5%	1%
I(0)	2.26	2.62	3.41
I(1)	3.35	3.79	4.68
Model 2 (with individuals using the Internet)			
ARDL (1,0,2,2,0,0) F Statistic 5.40 k 5 n=30	10%	5%	1%
I(0)	2.26	2.62	3.41
I(1)	3.35	3.79	4.68

Table 4 reports the results of diagnostic checks for heteroscedasticity, serial correlation, and normality. The test statistics indicate that the null hypothesis of homoscedasticity cannot be rejected, suggesting the absence of heteroscedasticity. In addition, no evidence of serial correlation is detected in the estimated models. Moreover, the normality assumption is also not rejected.

Table 4
Heteroskedasticity (BPG), Autocorrelation (LM), Normality (JB) Tests

Model 1 (with mobile cellular subscriptions)			
Heteroskedasticity			
F statistics	0.46	Prob F(5,27)	0.81
Serial Correlation			
F statistics	0.38	Prob F(2,25)	0.69
Normality			
Test statistics	0.70		0.71
Model 2 (with individuals using the Internet)			
Heteroskedasticity			
F statistics	0.93	Prob F(5,24)	0.48
Serial Correlation			
F statistics	0.13	Prob F(2,22)	0.88
Normality			
Test statistics	1.76		0.42

Table 5 shows long-run and short-run coefficients for two models. According to the results ECT (-1) is negative and significant. In model 1 short-term shocks in the independent variables in the model bring the dependent variable to its long-term equilibrium

$((1/1.13)*12)$ 10.6 months later. For model 2 this period is slightly longer $((1/0.87)*12)$ that is 13.8 months.

The long-run coefficients indicate similar relationships to those presented in the literature above. The findings show that electric power consumption increase ecological footprint in Türkiye. The relationship is highly significant and coefficient is positive. The relationship between trade and environmental quality is negative and significant in all of the three models. Therefore, trade openness decreases ecological footprint. Only ICT indicator that is significant is the Internet usage estimated in Model 2. Internet usage decreases ecological footprint in Türkiye.

The short-run coefficients are slightly different than long-run coefficients. The findings show similarly that electric power consumption increase ecological footprint in the short-run in Türkiye. The relationship between economic activity and environmental quality is negative and significant in the short-run. The increase in total factor productivity increases ecological footprint. Only ICT indicator that is significant in the short-run is mobile cellular subscriptions measured per 100 people in model 1. Findings show that it increases ecological footprint. Therefore, ICTs can be detrimental to environment in the short-run.

Table 5
Long-run and Short-run Coefficient Estimations

Long-run			
Variables	Model 1	Variables	Model 2
lnREC	-0.25** (0.12)	lnREC	-0.10 (0.08)
lnEPC	0.33*** (0.06)	lnEPC	0.39*** (0.06)
lnTFP	-0.14 (0.25)	lnTFP	-0.30 (0.29)
lnCELL	-0.01 (0.01)	lnINT	-0.02** (0.01)
lnTO	-0.25*** (0.08)	lnTO	-0.17** (0.07)
ECT(-1)	-1.13***	ECT(-1)	-0.87***
Short-run			
Variables	Model 1	Variables	Model 2
D(lnREC)	0.16 (0.11)	D(lnEPC)	0.27 (0.21)
D(lnEPC)	-0.17 (0.28)	D(lnEPC(-1))	0.71*** (0.21)
D(lnEPC(-1))	0.58** (0.26)	D(lnTFP)	0.61*** (0.21)
D(lnTFP)	0.83*** (0.23)	D(lnTFP(-1))	-0.32* (0.18)
D(lnCELL)	0.12** (0.04)	c	-0.84* (0.48)
D(lnTO)	0.16 (0.11)		
c	0.21 (0.74)		

Notes: * denotes 10%, ** denotes 5% and *** denotes 1% significance levels. Standard errors are in parentheses.

Conclusion

Turkiye has experienced a persistent a biocapacity deficit since 1984 and the level of this deficit increasing at an accelerating pace. According to 2024 estimates, the ecological footprint for Türkiye reaches approximately to 3.5 gha per person, while its biocapacity is 1.4 gha per person, implying that the country would require the equivalent of 2.34 Turkiyes to meet its demand for goods and services provided by the ecosystem. Against this background, this study investigates the short-term and long-term effects of information and communication technologies (ICTs), TFP, trade openness, renewable energy and electricity consumption (considered as green energy indicators) on environmental pressure, measured by the ecological footprint (EFP) over the period between 1990-2022. Economic activity is proxied by total factor productivity, while green energy is captured through renewable energy use and electricity consumption. The empirical analysis is conducted using the autoregressive distributed lag (ARDL) approach to identify both long-run equilibrium relationships and short-run dynamics.

According to the long-run results electric power consumption significantly increases ecological footprint in Türkiye, suggesting a continued reliance on carbon-intensive energy sources. Whereas, trade openness and internet usage contribute to a reduction in environmental pressure. In contrast, the short-run estimates reveal that electric power consumption and total factor productivity exacerbate the ecological footprint. Mobile cellular subscriptions also intensify environmental degradation in the short-run. These findings imply that although certain dimensions of digitalization may support environmental improvement in the long run, rapid expansion of digital infrastructure can generate adverse environmental effects in the short run due to increased energy demand.

From a policy perspective, the results highlight the urgent need for Türkiye to accelerate the decarbonization of its electricity sector by expanding renewable energy capacity and improving energy efficiency, particularly in digitally intensive activities. Policies aimed at promoting digitalization and productivity growth should be carefully coordinated with green innovation strategies and supported by clean energy investments to mitigate adverse environmental impacts. This is particularly important given that efficiency gains from ICT adoption and productivity improvements can increase energy demand and electricity consumption, while scale effects associated with higher economic expansion can further exacerbate environmental pressure. In summary, promoting environmental sustainability in Türkiye requires policies that integrate clean energy development, digital transformation, and enhanced productivity. At the same time, the increase in the use of mobile phones and other devices, and the frequent advancement of their technological capabilities, is making the search for a sustainable policy for the management of technological waste increasingly important.

Finansman Beyanı	Bu araştırma; kamu, ticari veya kâr amacı gütmeyen sektörler kuruluşlarından herhangi bir hibe almamıştır.
Çıkar Çatışması Beyanı	Yazar; bu makalenin araştırılması, yazarlığı ve/veya yayımlanmasıyla ilgili olarak herhangi bir muhtemel çıkar çatışması bulunmadığını beyan eder.
Yazar Katkıları	Bu makale tek yazarlıdır. Kavramlaştırma, metodoloji, araştırma, yazım ve düzenleme süreçlerinin tamamı yazar tarafından gerçekleştirilmiştir.
Etik Kurul Onayı	Bu çalışma, birincil veri toplama (anket, görüşme, deney vb.) içermediğinden etik kurul onayı gerektirmemektedir.
Yapay Zekâ Kullanım Beyanı	Bu makalenin hazırlanmasında yapay zekâ destekli araçlar kullanılmamıştır.
Funding Statement	This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.
Declaration of Interests	The author declares that there is no conflict of interest regarding the research, authorship, and/or publication of this article.
Author Contributions	This is a single-authored article. Conceptualization, methodology, investigation, writing, and editing were all carried out by the author.
Ethics Approval	This study did not involve primary data collection (surveys, interviews, experiments, etc.) and therefore did not require ethics committee approval.
Artificial Intelligence Usage Statement	No artificial intelligence-assisted tools were used in the preparation of this article.

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