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Environmental-Related Technology on Ecological Footprint: The Case of Germany

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ABSTRACT

In this study, GDP per capita (GDP), non-renewable energy consumption (NREC), renewable energy consumption (REC), and environmental-related technology (ET) on the ecological footprint (EF) were investigated by applying the Autoregressive Distribution Lag Model (ARDL) using time series data from 1990 to 2020 in Germany. According to the results, in the short-run, GDP, NREC and ET increase the EF, while REC decreases the EF. In the long-run, NREC and ET increase the EF, while GDP decreases the EF. Additionally, FMOLS and DOLS robustness tests support the ARDL results. According to these tests, NREC and ET increase the EF in the long-run. DOLS test results also show that REC and GDP will reduce the EF in the long-run. The reason why the increase in environmental technologies in Germany increases the EF is that the number of patents based on environmental technologies can have a positive impact on the environment after reaching a certain level. Accordingly, it is great importance that environmental-related technologies are designed within a framework that supports renewable energy and serves growth that excludes environmental degradation.

Keywords: Ecological Footprint, Environmental-Related Technology, Renewable Energy Consumption, ARDL, Germany
JEL Classifications: P18, Q43, Q56

1. INTRODUCTION

The formation of energy sources from fossil fuels and the uncontrolled growth approach have increased greenhouse gas emissions to excessive levels and have begun to pose a great risk to the lives of all living things. However, CO_2 emissions do not comprehensively account for multidimensional aspects of environmental quality (Ansari et al., 2020). Therefore, The Ecological Footprint (EF) is considered an indicator that better measures comprehensive environmental degradation (Ozkan et al., 2024). EF is primarily used as a tool to communicate and raise awareness about issues related to ecological sustainability. It is used by various institutions worldwide, particularly municipal and regional governments, educational institutions, corporations, and non-governmental organizations (NGOs) (Giljum et al., 2006). EF measures the impact of both CO_2 emissions and climate change, considering air pollution as well as water and soil, and assesses biodiversity ecosystem health and diversity (Ozkan et al., 2024). The EF was first developed by Rees (1992) and later by Wackernagel and Rees (1998). The authors wanted to create a planning tool that could transform the growing criticism of the sustainability of human lifestyles into collective action. They believed that human society cannot be viewed in isolation from nature, and that human life and action must be considered and analyzed within a natural context (Giljum et al., 2006).

The EF relates the environmental impact of human activities to the demand for the world's biological capacity. The demanded capacity is compared with the biosphere's current capacity to determine the extent to which the difference has changed. This trend is currently in excess due to overconsumption, meaning that the global footprint is estimated to exceed the biocapacity (Rees, 1992). The EF is considered an indicator of the deterioration in environmental quality (EQ) as a result of excessive consumption and unsustainable growth. However, renewable energy, increased institutional quality, financial development, policies that decouple economic growth from environmental degradation, and technological innovation play important roles in reducing the EF. On the other hand, since countries are interdependent in many areas such as trade, investment, tourism, and strategic partnerships, it is conceivable that environmental degradation may also converge. For this reason, sustainability targets are determined to cover all countries of the world. Therefore, issues such as the regulatory environment, international cooperation, social inclusion, and energy justice are becoming more important than ever. Global environmental sustainability requires strategic economic, social, political, and technological solutions. For this reason, sustainable development goals (SDGs) have been declared to combat climate change and countries have been provided with action plans, targets and commitments. In this context, 193-member countries of the United Nations have defined 17 goals for sustainable development by 2030 (UN, 2025). Climate change, environmental degradation and resource scarcity are increasing the need for innovative approaches to sustainable development. For the 2050 climate neutrality target, global net anthropogenic CO□ emissions must be reduced to 'net zero' within three decades (Appunn et al., 2025). Sustainable development is possible through industrial transformation, technology, and renewable energy sources that reduce dependence on fossil fuels (Wang et al., 2024). Finally, prerequisites for environmental sustainability are the reduction of subsidies for fossil fuels, technological openness and adaptability of new technologies to local contexts, as well as fair negotiation and participation processes that ensure broad societal acceptance of emerging energy fields (Feldhoff and Schneider, 2022).

The transformation of the German economy focuses on appropriate tools to manage the structural shift towards climate neutrality. The political management of this structural shift is fundamentally based on the CO_2 price from the European Emissions Trading System (EUETS). The sum of all existing certificates sets a maximum limit on the total amount of greenhouse gases that can be emitted by energy production and industrial enterprises. This limit is continuously being reduced (Hüther et al., 2023). The German Energy Transformation (Energiewende) proposes a strategic transformation focused on renewable energy. Germany aims to achieve a near complete substitution of non-renewable energy sources with respect to greenhouse gas reduction, renewable energy share and increased electrical efficiency (da Silva et al., 2024). Germany has made significant progress in expanding renewable energies. One of Germany's important goals is to increase the share of renewable energy in electricity consumption to 80% by 2030 (OECD, 2023). The German Sustainable Development Strategy has also been trying to achieve the global goals defined since 2016. In addition, Germany's the clear climate neutrality target is 2045 and new greenhouse gas emission reduction targets are 65% by 2030 and 88% by 2040 compared to 1990 levels (SGI, 2025). Germany also has climate targets to phase out coal storage by 2038 and achieve negative emissions after 2050 (OECD, 2023). Finally, Germany demonstrates a strong commitment to implementing innovative technologies, a developed social system and the elimination of fossil resources (da Silva et al., 2024). Despite this generally improving trend, Germany is still far from sustainable prosperity. To achieve this, beyond phasing out coal and increasing renewable energy, the German economy needs a systemic socio-ecological transformation that transcends its export-oriented growth model (Schmelzer, 2021).

Many of the studies argue that environmental-related technologies will help reduce carbon emissions and improve EQ, thus making it easier to achieve green development goals. Environmental-related technologies increase the composition, efficiency and effectiveness of renewable energy sources. As a result, factors that reduce EQ, such as carbon emissions and EF, are mitigated. Germany is also the world leader in environmental-related technologies, following China, Japan, Korea and the United States (OECD). German Greentech sector is growing significantly faster than traditional industrial sectors, is tightly integrated into global trade, and is a driver of innovation in many areas (The Greentech Atlas, 2025). The Greentech cross-industry sector brings together companies that offer environmentally and climate-friendly technologies and services, such as renewable energy production facilities or technologies for improving energy efficiency. Approximately 7.5% of Germany's workforce, 9% of Germany's gross value added, and over 8% of exports are based in the sector. Greentech's contribution to gross value added was estimated at €314 billion in 2023 (The Greentech Atlas, 2025).

Germany's leading position in green technologies and REC offers an important opportunity to examine the interconnections between growth, energy, technology and the environment (Xuan, 2025). In this respect, this paper investigates the effect of GDP per capita (GDP), non-renewable energy consumption (NREC), renewable energy consumption (REC), and environmental-related technology (ET) on EF in Germany over the period 1990–2020. For the short- and long-run analysis ARDL method and for robustness check FMOLS and DOLS methods implemented. There are few studies in the literature that address the effects of technological innovation on environmental sustainability. In addition, there is no study examined the impact of ET on the EF in only in terms of Germany. Therefore, the study will contribute to the literature on EF from this perspective.

The subsequent sections of the paper are designed as follows: The next section includes literature review. The subsections of this part include studies explaining the effect of GDP, NREC, REC and ET on EF. Section 3 presents data, model and methodology of the study. Section 4 includes results and discussion. Section 5, concludes this research and makes policy recommendations.

2. LITERATURE REVIEW

The number of studies investigating the determinants of EF has increased significantly in recent years. Many variables such as trade openness, economic growth, natural resource rents, non-renewable and renewable energy consumption, globalization, technology, etc. were used in the analyses conducted on countries or country groups. In this study, the literature section examines the EF under three subheadings relating it to GDP, NREC, REC and ET.

2.1. Ecological Footprint and Economic Growth

The pioneering study on the relationship between EQ and GDP was conducted by Grossman and Krueger (1992). The study proved that the long-term linkage between economic development and environmental degradation would be represented by an inverted U-shaped curve. Accordingly, while EQ decreases in the early stages of economic development, after a certain threshold of economic development, EQ begins to improve. This hypothesis is known as Environmental Kuznets Curve (EKC). This turning point is explained by the fact that, as a country's income increases, people become more aware, demanding a cleaner environment, and thus, the government increases its investment in renewable energy (Jun et al., 2022). In other words, developing countries often have to adopt environmentally unfriendly technologies for production in the early stages of their economic development (Wang et al., 2024). However, industrialized countries adopt environmental-related technologies and develop policies to increase the use of renewable energy. In the literature, environmental degradation is included as a proxy variable, economic growth is included in the model as linear or to investigate the EKC hypothesis. Studies supporting this hypothesis are confirmed by Ali et al. (2016) for Malaysia; Uddin et al. (2016) for 10 selected countries; Charfeddine and Mrabet (2017) for petroleum exporting countries; Destek and Sarkodie (2019) for 11 newly industrializing countries; Hassan et al. (2019) for Pakistan; Danish et al. (2020) for BRICS; Ahmad et al. (2021) for G7 countries; Nathaniel et al. (2021) for Next-11 countries; Wang et al. (2022) for 166 countries; Wang et al. (2024) for 11 most polluted countries; Xuan (2025) for Germany.

Some of the studies included the income as linear in the study. Uddin et al. (2017) concluded that GDP has a positive impact on the EF for 27 selected countries. Zeraibi et al. (2021) reached to similar conclusion for ASEAN-5; Jie et al. (2023) and Raihan (2023) for China; and Dam et al. (2024) for E-7. Some of the studies found that GDP has a negative impact on the EF. One of these studies is the study conducted by Danish and Wang (2019) for Next-11 economies. Finally, the very different conclusions reached regarding the impact of GDP on EQ imply that a decoupling may occur between GDP and environmental impacts. Identifying the divergence that occurs when environmental pressures emerge at a slower rate than economic growth is critical (Wang et al., 2022). This is because the question of whether EQ is compatible with economic growth is a matter that closely affects all economic dynamics.

2.2. Ecological Footprint and Energy Consumption

Energy consumption as an important variable is included in many models about environmental and sustainability issues. Studies in the literature confirm that NREC deteriorates EQ, while REC improves EQ. The use of EF as an environmental indicator began with the study of Al-Mulali and Ozturk (2015). According to the study examined for 14 MENA countries from 1996 to 2012, NREC increases the EF in the long-term. The studies are found that REC reduces the EF, while NREC increases the EF are Destek and Sinha (2020) for 24 OECD countries; Caglar et al. (2021) for the 10 countries; Murshed et al. (2021) for South Asia countries; Nathaniel et al. (2021) for Next-11 countries; Sharma et al. (2021) for 8 developing countries in South and Southeast Asia; and Alper et al. (2022) for Canada, China, Germany, India, Indonesia, Iran and Saudi Arabia. Shahzad and Fareed (2023) highlight the carbon footprint-reducing effect of renewable energy intensity for Canada. On the other hand, some studies have reached different results for the short and long-run. Usman et al. (2020) found that REC has a positive impact on the EF in the short-run. According to threshold panel regression model conducted by Rangrong et al. (2022) for 120 countries, REC does not always reduce the EF. As the urbanization rate increases, the EF reducing effect of REC firstly weakens and then increases.

2.3. Ecological Footprint and Technological Innovation

The number of studies has investigated the linkage between environment and technology is quite limited. Studies in the literature have generally proven that technological progress helps improve EQ. Some of these studies are as follows: Chen and Lei (2018) for the 30 countries; Ahmad et al. (2021) for G7 countries; Caglar et al. (2021) for the 10 countries; Zeraibi et al. (2021) for ASEAN-5 countries; Chu (2022) for 20 OECD countries; Hussain and Dogan (2021), Jahanger et al. (2022) and Rout et al. (2022) for BRICS; Kirikkaleli et al. (2023) for USA; Raihan (2023) for China; Dam et al. (2024) for E-7; Nketiah et al. (2024) for Ghana; Tutgun (2025) for Türkiye. In addition, Xuan (2025) reached conclusions that reinforce the role of technological advances in Germany's energy transition by showing that a 1% increase in innovation leads to a 0.35% increase in REC. Ozkan et al. (2024) showed that increasing green technologies improve environmental quality through technological innovation in Germany from 1974 to 2019.

However, there are also studies that conclude that technological development deteriorates EQ. Dauda et al. (2019) concluded that technological innovation reduced CO_2 emissions in G6 countries while increased in MENA and BRICS countries for the period 1990-2016. According to Koçak and Ulucak (2019) energy-based R&D expenditures increased CO_2 emissions in selected OECD countries period of the 2003-2015. Villanthenkodath and Mahalik (2020) studied the relationships between technological innovation and EQ in India for the period from 1980 to 2018. It was concluded that in the long-term, technological innovation and economic growth reduce EQ in India by promoting atmospheric emissions. Chunling (2021) implemented ARDL analysis for Pakistan during the period 1992-2018 and concluded that economic growth, technological innovation, and trade openness increased EF in Pakistan. Some studies have highlighted the insignificance of the impact of technological innovation on the environment. Ali et al. (2016) found that technological innovation has a negative but insignificant relationship with environmental pollution in Malaysia for the period of 1985-2012. Destek and Manga (2021) found that technological innovation is an effective way to improve EQ, but don't have a significant impact on the EF in the big emerging countries for the period of 1995-2016. Bozatli and Akca (2023) found no statistically significant effect of environmental technology on the EF in OECD countries for the period 1994-2018. On the other hand, there is also a study that finds an inverted U-shaped linkage between technological innovation and the environment. Hang and Yuan-Sheng (2011) concluded that technological innovation in China reduced carbon emissions in the early stages but increased it later. The reason for this situation is that technological innovation in the first stages of industrialization create more investments and deteriorate EQ, while in the later stages, technology improves EQ by activating alternative energy sources.

3. DATA AND METHODOLOGY

3.1. Theoretical Framework and Data Descriptions

This study aims to test the impact of economic growth, energy, and technology on the environment. Green growth theory provides guidance to achieve this goal. Green Growth Theory supports economic growth while ensuring the sustainability of natural resources. In other words, according to this approach, countries can achieve economic development by reducing environmental impacts while supporting renewable energy sources and sustainable practices. Therefore, economic growth and sustainability decouples in this approach (Xuan, 2025). Green growth is shaped by human capital, renewable energy consumption, technological innovation, economic regulations and environmental standards etc. Therefore, its applicability and policy implications vary from country to country. In this context, this paper will demonstrate whether it is possible to integrate Germany's economic growth and technological innovation policies with the environmental goals promoted by the REC.

This study examined the impact of GDP per capita (GDP), nonrenewable energy consumption (NREC), renewable energy consumption (REC), and environmental-related technology (ET) on the ecological footprint (EF) in Germany. Economic growth is highly dependent on energy consumption. Therefore, NREC is highly effective in environmental degradation. Therefore, REC is great importance in improving EQ. Technological innovations have significant impacts on environmental sustainability. Accordingly, the EF model is created as follows:

$$EF = f(GDP, NREC, REC, ET) \quad (1)$$

where EF, GDP, NREC, REC, and ET are the ecological footprint, GDP per capita, non-renewable energy consumption, renewable energy consumption, and environmental-related technology respectively. The ecological footprint model with a log-linear transformation is as follows:

$$InEF_t = \alpha_0 + \alpha_1 InGDP_t + \alpha_2 InNREC_t + \alpha_3 InREC_t + \alpha_4 InET_t + \varepsilon_t \quad (2)$$

where In is natural-log, and $\varepsilon_t$shows an error term presumed to have a normal distribution. α_1 α_2, α_3 and α_4 indicate the impact of GDP, NREC, REC, and ET on EF respectively.

This study analyzed time series covering the period 1990-2020. Table 1 contains information on variables. EF data (in global hectares per capita) were obtained from the Global Footprint Network. GDP (constant 2015 US$), NREC (kWh/person) and REC (% of total final energy consumption) were gathered from the World Bank. ET data is the number of patent applications and were taken from the OECD.

Figure 1 shows the trends of the variables over time. Germany's EF has decreased over time due to the strict implementation of environmental policies. GDP has an increasing trend, except for the fluctuations during the 2008 financial crisis and the resulting European debt crisis, the 2014 Russian-Ukrainian war, and the 2020 pandemic. On the other hand, REC tends to increase while NREC tends to decrease due to increasing use of environmentally friendly energy. ET has been fluctuating, especially after 2008. Figure 2 shows the interaction between EF and the variables. Accordingly, GDP and REC have a negative effect on EF, while NREC has a positive effect in the long-run. However, ET exhibits a tendency to reduce the ecological footprint in a certain period and then increase it.

Table 1: Data description

Variables	Definition	Source
EF	Ecological Footprint (global hectares per capita)	Global Footprint Network
GDP	GDP per capita (constant 2015 US$)	World Bank (WDI)
NREC	Primary energy consumption per capita (kWh/person)	World Bank (WDI)
REC	Renewable energy consumption (% of total final energy consumption)	World Bank (WDI)
ET	Environmental-related technology (number of patents related to environment)	OECD Statistics

3.2. Methodological Framework

3.2.1. Unit root test

Recent developments in economic analysis have shown that time series are not stationary, but tend to move away from or closer to the mean over time. Series that move away from the mean over time are called non-stationary series (Nkoro and Uko, 2016). Therefore, it is important to test the stationarity of series by applying a unit root test. Unit root tests are widely used in econometric analysis to investigate whether a series is stationary, that is, contains a unit root, or follows a random walk. In this study, the stationarity of the series was investigated with the traditional unit root tests as known the extended Dickey Fuller (ADF) and Phillips-Perron (PP) unit root tests. The ADF unit root test is based on an extension of the basic Dickey-Fuller (DF) approach by including lagged differences of the variables to account for higher order serial correlation. The PP test makes the series robust to the presence of autocorrelation and heteroskedasticity in the data because it corrects for serial correlation and heteroskedasticity in the error terms without adding lagged difference terms (Afriyie et al., 2020).

3.2.2. Autoregressive distributed lag (ARDL) test

The ARDL method is widely used in econometric analysis to detect dynamic relationships in time series data. This method developed by Pesaran et al. (2001) was used in the analysis of this study. The ARDL cointegration technique can be applied with integrated variables of different orders (I(0), I(1), or a combination of both) and provides reliable results even with a small sample size (Pesaran, 2001; Nkoro and Uko, 2016). The ARDL bounds test method does not include autocorrelation problems and the endogeneity problem is addressed by choosing an appropriate lag length (Langnel and Amegavi, 2020). In addition, ARDL models can be expressed in both level and error-correction forms. Therefore, it enables the estimation and interpretation of both short-term dynamics and long-term equilibrium relationships. The formulation of the ARDL model is as follows:

Figure 1: Trend of variables

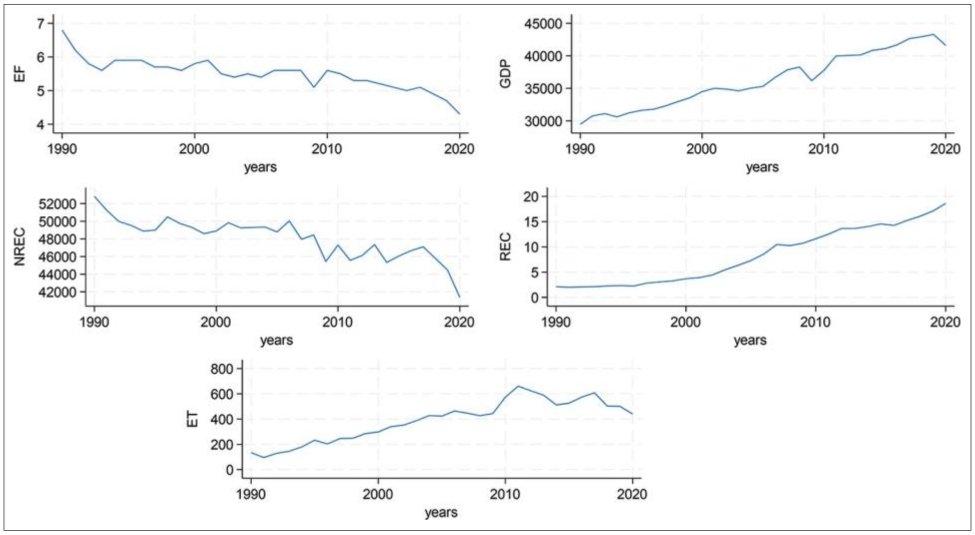
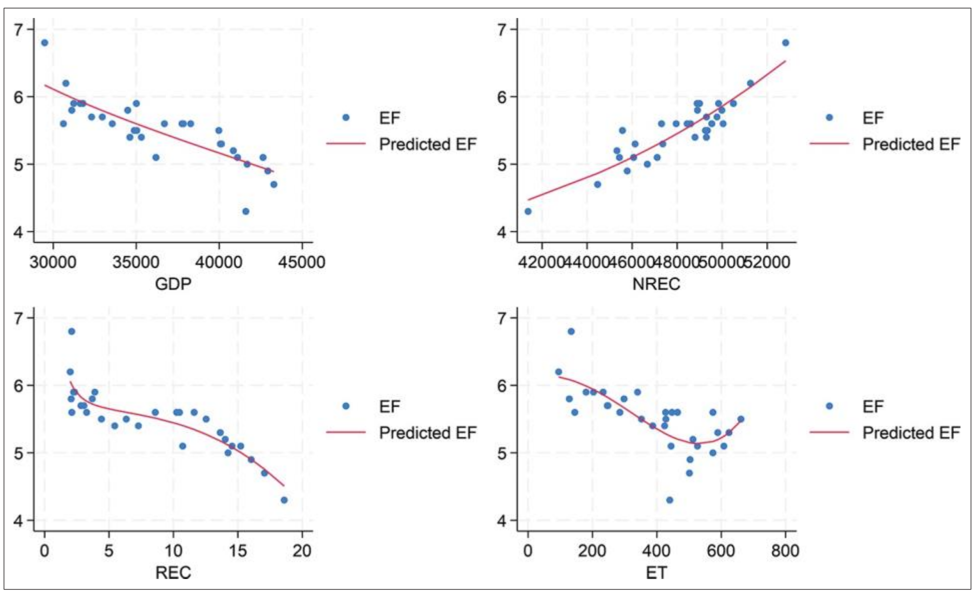


Figure 2: Interaction between EF and the variables



$$
\begin{aligned}
\ln EF_t = {} & \omega_0 + \theta_1 \ln GDP_{t-1} + \theta_2 \ln NREC_{t-1} \\
& + \theta_3 \ln REC_{t-1} + \theta_4 \ln ET_{t-1} + \sum_{i=1}^{p} \pi_1 \Delta \ln EF_{t-i} \\
& + \sum_{j=0}^{p} \pi_2 \Delta \ln GDP_{t-i} + \sum_{j=0}^{p} \pi_3 \Delta \ln NREC_{t-i} \\
& + \sum_{j=0}^{p} \pi_4 \Delta \ln REC_{t-i} + \sum_{j=0}^{p} \pi_5 \Delta \ln ET_{t-i} + \mu_t \qquad (3)
\end{aligned}
$$

In Eq. (3) Δ is the first difference operator. The F test was used to assess cointegration. When the F statistics value falls below the critical values, the null hypothesis of no cointegration is accepted. When the F statistic exceeds the critical values, the null hypothesis of no cointegration is rejected and it is concluded that cointegration exists. After confirming cointegration, the ARDL method can be used to determine short- and long-run dynamics between variables. Then, the cumulative sum of repeated residuals (CUSUM) and cumulative sum of squared repeated residuals (CUSUMSQ) stability measures were used to assess the suitability of the ARDL model. Finally, the model's stability was confirmed with diagnostic tests.

3.2.3. Robustness checks

Fully modified OLS (FMOLS) and dynamic OLS (DOLS) methods are frequently used as an important method in determining long-run relationships in econometrics. They provide robust estimates of long-run effects among variables by correcting for endogeneity and serial correlation. Therefore, these methods are helpful in checking the consistency of the Bounds Test results. In this study, these methods were used to estimate the long-run effects of variables on the EF. FMOLS is a nonparametric technique for analyzing economic data, while DOLS is a parametric estimation method (Lin and Omoju, 2017). Therefore, using both methods in estimating long-run effects produces more robust results.

4. RESULTS AND DISCUSSION

Table 2 shows the descriptive statistics of the variables. All the variables are in logarithmic form. The variable with the highest standard deviation is REC, which has a value of 0.798. The variable with the lowest standard deviation is NREC, which has a value of 0.049. The mean, median, maximum and minimum values of GDP and NREC are quite close to each other. According to the Jarque-Bera test statistics, variables other than NREC follow a normal distribution.

In the next stage of the econometric analysis, the stationarity of the series was checked. Table 3 shows the ADF and PP unit root test results of the variables. EF, GDP, NREC and REC variables are stationary at the I(1) level according to both ADF and PP unit root test results. The ET variable was found stationary at the I(0) level according to the ADF unit root test result. Thus, it has been verified that the ARDL procedure can be applied.

ARDL bound test results are given in Table 4. Since the F test statistic is higher than the critical values, there is cointegration between the series. The long and short-term estimation results of the ARDL method are presented in Table 5. According to the long-term estimation results of ARDL, an increase in GDP per capita reduces the EF, while NREC and ET increase the EF. A 1% increase in GDP reduces the EF by 0.7465%. A 1% increase in NREC increases the EF by 0.6161%. A 1% increase in ET increases the EF by 0.1042%. According to the short-term estimation results of ARDL, GDP, NREC and ET increase the EF, while REC reduces the EF. A 1% increase in GDP increases the EF by 0.6319%. A 1% increase in NREC increases the EF by 0.4201%. A 1% increase in ET increases the EF by 0.0712%. A 1% increase in REC reduces the EF by 0.1650%. The increase in ET deteriorates the EQ of Germany to a limited extent (0.0712% in the short-term, 0.1042% in the long-term). Similar results that technology reduces EQ are confirmed by Dauda et al. (2019) for MENA and BRICS, Villanthenkodath and Mahalik (2020) for India; and Chunling et al. (2021) for Pakistan.

It has been concluded that economic growth reduces EQ in the short term and increases EQ in the long-run. This result shows the deteriorating effect of GDP on EQ, even though growth rates are low in developed economies such as Germany, as industry and technology require energy based on fossil resources. In the long-run, economic growth acts in the direction of improving EQ as long as it is provided by renewable energy sources. In addition, GDP is the variable that has the strongest effect on the EF (in the short-run 0.6319%; in the long-run −0.7465%). Wang et al. (2022); Uddin et al. (2016); Destek and Sarkodie (2019) are studies that support to EKC hypothesis. As expected, NREC increases the EF, while REC decreases. Many studies in the literature support these results. For example, Destek and Sinha (2020); Caglar et al. (2021); Rout et al. (2022) etc.

The correct and significant sign of the error correction term (CointEq(-1)) means that a certain amount of imbalance in the EF in the previous year is adjusted back to the long-run balance in the current year (Uddin et al., 2016). (CointEq(-1)) indicates the adjustment rate and is significant at the 1% level. This means that any short-term deviation from the long-run path is corrected by 68.18% each year. The R2 value of 0.86 indicates that the independent variables describe 86% of the dependent variable.

Furthermore, the diagnostic tests serial correlation, heteroscedasticity, and Ramsey RESET test results show that the model does not have serial correlation, is correctly specified, and the variability (or spread) of the dependent variable is constant across the range of values of the independent variable. In other words, the Breusch-Godfrey Lagrange multiplier test and the heteroskedasticity test indicate that the null hypothesis of no serial correlation and no evidence of heteroskedasticity cannot be rejected. The Ramsey RESET test is a method developed to test whether model fit will improve if higher order terms or interactions are included in the model. The result of test reveals that the model is correctly specified. The Ramsey RESET algorithm achieved a goodness of fit 81% for the model, indicating that GDP, NREC, REC, and ET variables can explain 81% of the EF.

CUSUM and CUSUMSQ graphs an effective analysis tool used to determine the stability of models over time estimated by ARDL models. Figure 3 show that the models are stable over time (ie. In both figures, the blue curve remains between the boundary curves). Table 6 includes the robustness check. According to the

Table 2: Descriptive statistics

Statistics	lnEF	lnGDP	lnNREC	lnREC	lnET
Mean	1.701233	10.49352	10.77928	1.839394	5.845558
Median	1.722767	10.47193	10.79535	1.985131	6.056784
Maximum	1.916923	10.67574	10.87472	2.923162	6.493754
Minimum	1.458615	10.29166	10.6305	0.688134	4.553877
Standard deviation	0.085679	0.116565	0.048839	0.798049	0.528278
Variance	0.007341	0.013587	0.002385	0.636882	0.279078
Skewness	−0.397532	−0.003067	−0.838713	−0.189175	−0.875537
Kurtosis	4.398847	1.734686	4.142887	1.426379	2.732805
Jarque-Bera	3.344	2.068	5.322	3.383	4.053
Probability	0.1879	0.3556	0.0699	0.1842	0.1318
Observations	31	31	31	31	31

Figure 3: CUSUM and CUSUM of squares

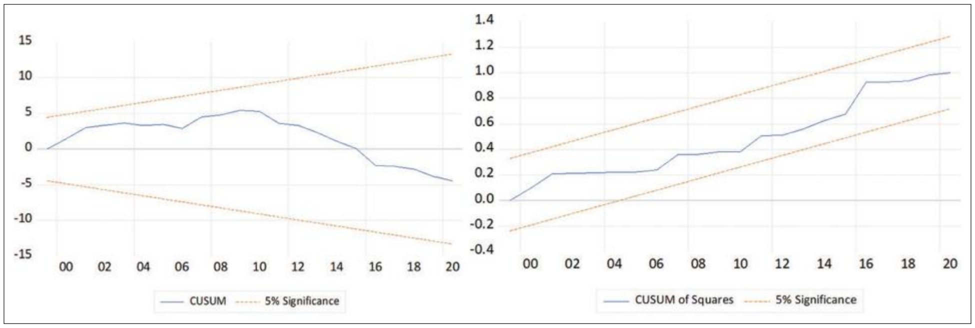


Table 3: ADF and PP unit root test results

Variables	ADF		PP	
	Level	First difference	Level	First difference
lnEF	−0.135	−4.532***	−1.163	−5.741***
lnGDP	−0.865	−5.615***	−1.296	−4.967***
lnNREC	0.129	−2.854***	−0.314	−6.675***
lnREC	−0.865	−2.930***	−0.312	−4.335***
lnET	−4.009***	−2.803*	−1.891	−6.233***

(i) *P<0.1, **P<0.05, ***P<0.01. (ii) lags (1) in unit root tests

Table 4: Results of ARDL bound test approach

Estimated model	Lag selection	F-value	Remarks
EF=f (GDP, NREC, REC, ET)	1,1,1,0,0	16.825***	Conclusive
Critical value bounds			
Significance	I0 bound	I1 bound	
10%	2.45	3.52	
5%	2.86	4.01	
2.50%	3.25	4.49	
1%	3.74	5.06	

***P<0.01

Table 5: Results of ARDL estimation

Regressor	Coefficient	Standard error	P-value
Long-run estimate			
lnGDP	−0.7465***	0.2126	0.002
lnNREC	0.6161***	0.2194	0.010
lnREC	−0.0009	0.0332	0.979
lnET	0.1042***	0.0344	0.006
C	1.5500	2.4252	0.529
Short-run estimate			
lnGDP	0.6319***	0.1867	0.003
lnNREC	0.4201**	0.1572	0.014
lnREC	−0.1650**	0.0604	0.012
lnET	0.0712***	0.0196	0.001
CointEq(-1)	−0.6818***	0.0944	0.000
R2	0.86		
DW Stat	1.798		
Breusch–Godfrey serial			
Correlation LM test	0.401		0.5266
Heteroskedasticity	1.46		0.2263
Ramsey RESET test	0.81		0.5045

*P<0.1, **P<0.05, ***P<0.01

FMOLS and DOLS test results, NREC and ET increase the EF in the long-run. DOLS test results also show that REC and GDP will reduce the EF in the long-run. These results support the long-run results of ARDL test.

Table 6: Results of robustness checks (FMOLS and DOLS)

Variables	FMOLS	DOLS
lnGDP	−0.0875	−0.8124***
	[0.1529]	[0.0565]
	(0.5670)	(0.0000)
lnNREC	1.1009***	1.0198***
	[0.1600]	[0.1218]
	(0.0000)	(0.0000)
lnREC	−0.0365	−0.0410***
	[0.0269]	[0.0102]
	(0.1740)	(0.0000)
lnET	0.0409*	0.2079***
	[0.0213]	[0.0144]
	(0.0550)	(0.0000)
Constant	−9.4235***	−1.8835
	[2.4352]	[1.7382]
	0.0000	0.2790

(i) *P<0.1, **P<0.05, ***P<0.01. (ii) () contains *P* values (iii) [] contains standard error

5. CONCLUSIONS AND POLICY SUGGESTIONS

Ecological footprint is frequently used as an important variable in measuring environmental quality. In this context, the ecological footprint tends to increase in developing countries due to factors such as dependence on fossil energy sources, rapid population growth, high growth rate targets, and flexible environmental policies. In developed countries, it tends to decrease due to factors such as the accelerating transition to renewable energy sources, lower population growth, strict environmental policies, and effective socio-political commitment to environmental issues. However, universal agreements on environmental issues force all countries of the world to take decisive steps regarding the environment. Germany is a global leader in renewable energy, environmental sustainability and environmental-related technologies. Germany has a strategic policy called the German Energy Transformation (Energiewende), which includes technological innovation in energy and refers to the transition from fossil fuels to low-carbon energy sources. It aims to contribute to sustainable development by ensuring energy efficiency and energy security. Germany has climate targets aiming to achieve climate neutrality by 2045 and negative emissions after 2050. For this, there is a need to grow renewable energy sources faster (OECD, 2025).

The number of studies examining the ecological footprint and other economic variables specifically for Germany is quite limited.

In this respect, it is examined the impact of GDP, NREC, REC, and ET on the EF of Germany using ARDL, FMOLS and DOLS estimation methods. Thus, it is the first study to address the impact of environmental technology on the EF in Germany. According to results of this study, in the short term, GDP, NREC and ET variables increase the EF, while the REC variable decreases the EF. In the long-run, NREC and ET variables increase the EF, while the GDP variable decreases the EF. As expected, NREC causes environmental degradation, while REC increases EQ. GDP per capita increases environmental degradation in the short-run while improving EQ in the long-run. Contrary to expectations, environment- related technologies increase environmental degradation in the short and long-run. Similarly, for MENA and BRICS countries Dauda et al. (2019); for India Villanthenkodath and Mahalik (2020), and for Pakistan Chunling et al. (2021) have also concluded that technology increase the EF. The reason why the increase in environmental technologies in Germany increases the EF is that the number of patents based on environmental technologies can have a positive impact on the environment after reaching a certain level. On the other hand, the analysis results report that renewable energy consumption will reduce the EF. Therefore, it is of great importance that environmental technologies are designed specifically to increase renewable energy consumption and serves growth that excludes environmental degradation. In addition, according to ARDL results, the positive impact of ET on the EF is 0.0712% and 0.1042% in the short and long-run, respectively. Besides, according to FMOLS and DOLS results, 0.0409% and 0.2079% in the long-run, respectively. These results remain at low levels when compared to GDP, which increases the EF in the short-run, and NREC, which increases it in the short and long-run. Finally, these results indicates that environmental sustainability can be compatible with economic growth in the long-run. Hovewer, technological development increases the ecological footprint implies that the factors that accelerate technological development should also be investigated. As a result, the separation of economic growth and environmental impacts contained in green growth theory has been confirmed for Germany in the long-run. However, the source of the positive effect of GDP on environmental quality can be associated with different variations of technological innovations.

Future studies can be extended to different countries or country groups by adding variables that include different sources of technological development. In addition, panel data analysis including Germany may be useful for comparing results. More evidence is needed on the impact of ET on the EF. The importance of investigating the linkage between technology, growth, and the environment is increasing.

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