

RESEARCH ARTICLE

The relationship between environmental technologies, environmental degradation, renewable energy consumption and economic growth

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ARTICLE INFO

Article history

Received: 02 May 2025

Revised: 18 December 2025

Accepted: 23 December 2025

Key words:

Environmental technologies,
environmental degradation,
renewable energy
consumption, economic
growth

ABSTRACT

This study examines the relationships between environmental technologies, environmental degradation, renewable energy consumption, and economic growth variables in selected EU countries between 1990 and 2021 using panel data analysis. According to the results obtained from the study, a bidirectional causal relationship was identified between environmental technologies and environmental degradation. Furthermore, a unidirectional causal relationship was found from economic growth to environmental technologies and from environmental technologies to renewable energy consumption. These findings indicate that environmental technologies play an important role in reducing environmental degradation, that economic growth contributes to the development of these technologies, and that renewable energy use is effective in reducing environmental degradation.

Cite this article as: Köse Z, Tuğan Meral G. The relationship between environmental technologies, environmental degradation, renewable energy consumption and economic growth. *Environmental Research and Technology*, 2026, 9 (5), 993-1005.

INTRODUCTION

In parallel with the expanding scale of the world population and economic activities, the consumption of natural resources, energy and materials has also increased. Although environmental destruction is not caused by the deliberate actions of human beings, it has always been the natural result of wanting more. The first years of the Industrial Revolution established the idea that natural resources are unlimited and nature is a structure to be tamed with human use. The ongoing process has led to an increase in the use of fossil fuels, nuclear reactors and chemicals. While this structure carries the risk of scarcity due to limited resource capacity, it has also caused movement towards the limit of the carrying capacity of the biosphere due to reasons such as waste accumulation and concentration of pollutants. This global state of alarm has shown that traditional production methods are not sustainable in the long term, and the importance of a system in which environmental and ethical concerns are also taken into consideration from a structure that produces and wastes has been understood [1]. Therefore, this delicate balance between economic growth and environmental quality has been extremely important. International initiatives have been taken to ensure sustainable economic growth and high environmental quality simultaneously.

The European Union has drawn a road map for the green transformation process required by international agreements with the European Green Deal. Climate change

and environmental degradation have posed and continue to pose an existential threat to the European Union as well as the world. The increase in global temperatures causes extreme weather events and has devastating consequences for the vital and economic activities of the planet. The European Commission has tried to present this frightening picture with data. Firstly, global temperatures have increased by 1.22 °C between 2013 and 2023. In Europe, living areas in poor condition have reached 80 per cent. The most frightening thing is that if the use of resources continues as it is today, three more new planets will be needed by 2050 [2].

Economic impacts due to climate change are analysed under 1.5 °C, 2 °C and 3 °C temperature increase scenarios. Climate change damages the capital stock due to floods, storms, droughts, human deaths, energy supply and agricultural damages, while reducing economic output and affecting human welfare. As shown in the figure, the cost to the EU and the UK of exposing the current economy to 3 °C global warming is estimated to be at least €175 billion (1.38% of GDP). The impact of a 2 °C increase scenario on similar economies is estimated at €83 billion (0.65% of GDP) and finally the impact of 1.5 °C warming is estimated at €42 billion (0.33% of GDP) in additional welfare losses. When the total economic impacts are calculated without taking into account human deaths, 1.5°C, 2°C and 3°C global warming caused additional welfare losses of 6, 18 and 54 billion euros, respectively [3].

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Economic indicators have revealed that the changes in greenhouse gas emissions and gross domestic product have been moving in the same direction since the second half of the 20th century. In other words, economic growth leads to an increase in greenhouse gases emitted to the atmosphere. However, steps to improve energy efficiency and the use of low-carbon energy sources have allowed the link between these two phenomena to weaken [4].

As of 2023, greenhouse gas emissions from producers and households in the European Union have reached a total of 3.4 billion tonnes. In the period between 2013 and 2023, the emission level of almost all economic activities in the EU decreased. This decrease can be explained by the shift towards renewable energy sources, particularly wind and photovoltaics, instead of carbon-intensive fossil fuels such as hard coal, which are widely used in heat and electricity generation across the Union. However, the relative decline in emission levels was accompanied by the opposite trend in transport and storage. In this context, initiatives to support the green transformation process in this area are important [5].

Across the EU, intensive efforts are being made to develop solutions that support the efficient use of resources and a competitive economic structure. The European Green Deal is a package of policies that will ensure a green transformation with the goal of achieving climate neutrality by 2050. It includes regulations on energy, transport, industry, agriculture and sustainable finance. The circular economy, where waste is reduced and products are recycled; the orientation towards sustainable and clean industries in terms of energy and resources; farming practices that minimise damage to nature and support affordable food production are also addressed within this framework. In addition, the European Union aimed to reduce dependence on fossil fuels from Russia. In order to fulfil its climate targets, the European Union has put in place a series of practices such as pricing emissions, imposing a carbon tax at the border on imported products in selected sectors, increasing the use of renewable energy and saving energy, and investing in clean transport [2]. Therefore, a balanced growth linked to the economy and the environment has gained importance in order to protect ecological health and maintain stable growth in environmental factors.

While rapid urbanisation and the growing volume of economic activities cause an increasing demand above the biological carrying capacity of the ecosystem, the development of environmentally friendly technologies and a gradual transition to the use of renewable energy offer solutions that can control the increase in global emission levels [6]. At this point, green technologies have gained importance. Green technology refers to technologies that save energy, prevent pollution, recycle waste, support corporate environmental management and include green product designs. [7] emphasised that green technology innovation is the key to eliminate the vicious circle between economic development and environmental pollution. While businesses increase resource efficiency through green innovation, they also reduce environmental costs. Green product and process innovations create new market opportunities and competitive advantage as well as prevent the risk of environmental penalties [7, 8]. The continuous development process in green energy technologies offers a cost advantage in competition with a number of advances from accelerating distribution to improving performance [9].

The World Intellectual Property Organization (WIPO) categorised green technology patent applications as

renewable energy technologies, alternative energy generation and nuclear power generation, energy-saving technologies and green transportation technologies. WIPO stated that innovation in environmentally friendly technologies, as measured by international patent applications, almost did not increase in 2019. While patent applications involving green technology increased by 1.3 per cent in 2019 compared to the previous year (16,940 applications), it remained behind 2016 (17,880 applications) [10]. Although the International Energy Agency (IEA) and the European Patent Office (EPO) found that inventions related to low-carbon energy technologies increased at an average annual rate of 3.3% in the period 2017-2019, the pace of development lagged behind climate targets [11]. In 2023, digital and clean technology patent applications increased by 2.9% compared to the previous year and reached 199,275. In particular, the USA, Germany, Japan and the People's Republic of China were the leading countries [12]. In summary, significant progress has been made in green technology patents. At this point, current studies analysing the impact of green technologies on environmental damage are very important for EU countries to achieve the 2030 and 2050 targets. Within the scope of this study, the impact of green technologies on environmental damage is analysed for selected EU member states, allowing the determination of medium and long-term strategic targets to achieve climate targets.

[13] stated that the number of patented innovations of low-carbon technologies in the EU is insufficient to achieve the expected climate targets. Differences in carbon taxes, R&D investments, venture capital have led to a heterogeneous distribution of green patents across the EU. In Chart 2, it is possible to see the number of patents recognised by the European Patent Office (EPO) in the field of environmental technologies in selected countries between 2014 and 2023. As stated by [13], it has been found that the patents held by EU member economies show a highly asymmetric distribution. In particular, Germany has overtaken the USA with the number of green patents in the last decade and has been in a race with Japan. Other EU member states, on the other hand, have shown a very limited development. The relatively low levels of green innovation in the EU have been associated with insufficient levels of R&D investments and venture capital [13].

[15] show that while advances in technology worldwide are promising, there has been a modest increase in innovation patents and they are still in an embryonic stage. While the European Union is also outperforming the rest of the world in utilising green innovations in clean energy production, geographical disparities are emerging. Green policies do not have the same priority for each member state and the diversity in terms of development leads to a heterogeneous distribution. This creates a need for complementary policies and initiatives. In particular, it is crucial to support the necessary green transformation through policy interventions and to promote cross-sectoral cooperation in order to achieve the sustainable development goals of affordable and clean energy (SDG-7) and climate action (SDG-13) [16, 17]. The specialisation required for environmental innovation creates a need for sectoral cooperation as well as inter-regional cooperation considering the regional inequalities in EU member economies. While the diffusion of green knowledge between regions with different innovation capacities should be supported, concentrations should be avoided [18].

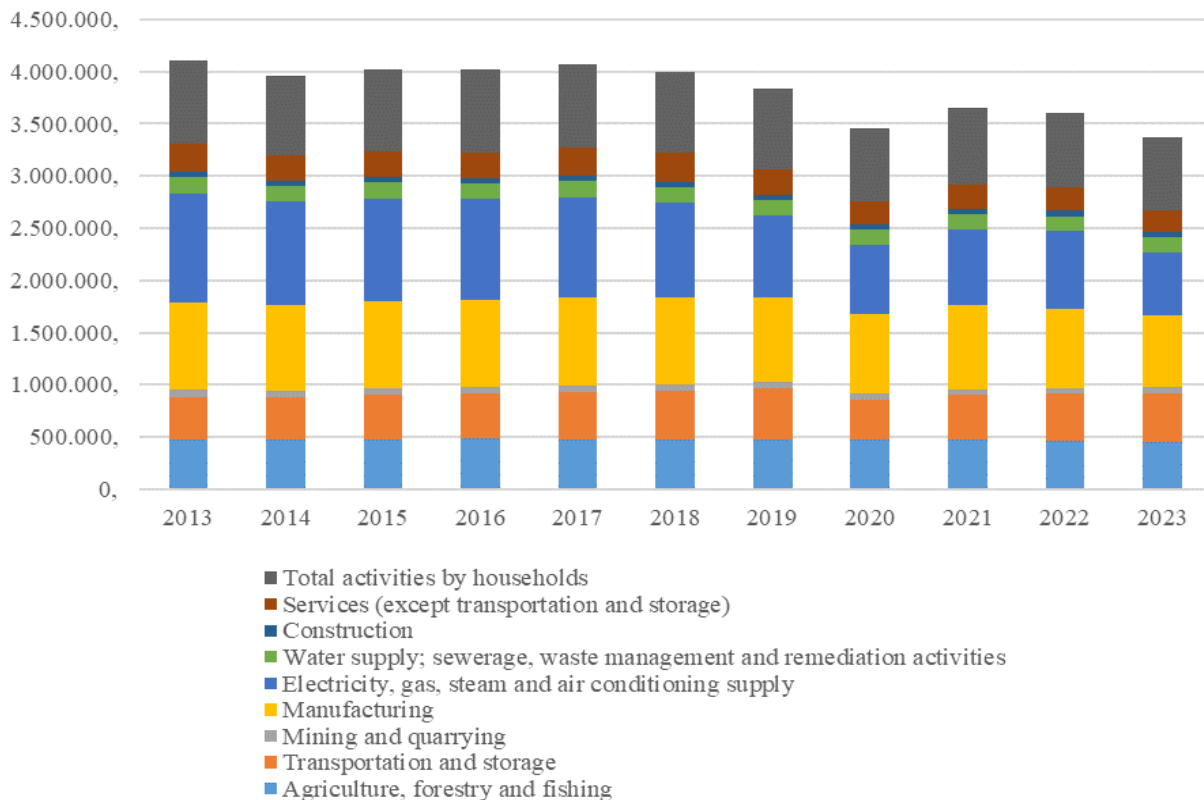


Figure 1. Greenhouse gas emissions by economic activities (thousand tonnes CO2 equivalent) [5]

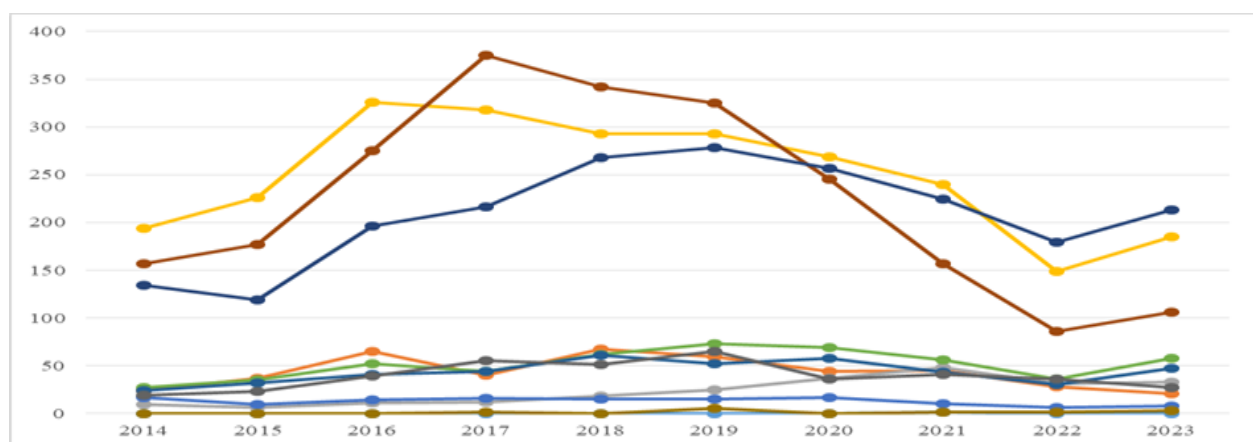


Figure 2. Number of patent acceptances in environmental technologies [14]

Within the scope of this study, the importance of environmental technologies necessary for a sustainable development for EU economies has been empirically tested. The role of environmental technologies, economic growth and renewable energy consumption on environmental degradation in EU member countries between 1990 and 2023 is analysed. In this framework, it will be very important to measure the success of Europe's green transformation strategies, to understand how environmental and economic objectives can be better integrated and to provide a roadmap for economies on the path to sustainable development. The need to accelerate progress across the EU to meet the ambitious targets set for 2030 and 2050 was emphasised. In particular, it is vital to make system changes in all sectors, to make infrastructure and innovation investments in renewable energy, and to draw a roadmap for environmentally friendly practices in terms of production

and consumption models [19]. The importance of this study emerges at this point and while emphasising the necessity of the transformation process for EU economies, it also provides a roadmap for similar economies.

In this study, a set of research questions were prepared to analyze the relationship between environmental technologies, environmental degradation, renewable energy consumption and economic growth:

1.) Is there any relationship between environmental technologies and environmental degradation?

Studies by [20, 21] concluded that environmental technologies reduce environmental damage. Accordingly, the aim is to investigate this relationship specifically in EU countries.

2.) Is there any interaction between environmental technologies and economic growth?

Studies by [22, 23] found that economic growth encourages technological innovation. In addition, environmental technologies were also found to support sustainable economic growth. [24, 25] also found in their studies that economic growth contributes to the development of environmental technologies. This study examines the relationship between environmental technologies, environmental Degradation renewable energy consumption, and economic growth in selected EU countries between 1990 and 2021, aiming to analyse the relationship between these variables.

3.) What is the relationship between renewable energy consumption and environmental degradation?

[26, 27] have determined that renewable energy consumption reduces environmental degradation. This study analyses this relationship for selected EU countries.

Previous studies have identified that environmental technologies and renewable energy consumption reduce environmental degradation and play a significant role in achieving sustainable development [28, 29]. This study analyzes the relationship between the identified variables for selected EU countries, offering important policy implications.

This study analyzes the relationship between environmental technologies, renewable energy consumption, environmental degradation, and economic growth in selected EU countries using panel data analysis. The relationship between the variables is discussed in the context of environmental sustainability and sustainable economic growth.

First, the relationship between environmental technologies and environmental degradation was examined, followed by the relationship between economic growth, environmental technology, renewable energy consumption, and environmental degradation. In this context, it was concluded that economic growth leads to technological progress, and environmental technologies encourage renewable energy consumption and reduce environmental degradation. In this respect, the study makes a unique contribution by demonstrating that environmental technologies not only reduce environmental degradation but also encourage the solution of environmental problems.

Furthermore, the relationship between environmental technologies and economic growth reveals the interaction between environmental sustainability in development and fills this gap in the literature. Based on the findings of the study, it is particularly important for policymakers to design growth strategies that encourage the development of environmental technologies [30, 31]. The findings of the study offer a significant contribution to the literature by providing a holistic perspective on the interrelationship between environmental technologies, environmental degradation, renewable energy consumption, and economic growth.

LITERATURE REVIEW

In this part of the study, studies on the relationship between environmental degradation, economic growth, environmental technologies and renewable energy consumption are given under separate headings.

Economic Growth and Environmental Degradation

The causes of environmental degradation, due to climate change and global warming, and the identification of factors to prevent such degradation, are of intense interest at both the national and international levels. In this context, numerous studies in the literature investigate the relationship between economic growth and environmental degradation. The findings of these studies primarily suggest that economic growth causes environmental degradation. [32] investigated the relationship between economic growth and CO₂ emissions in the EU-5 countries (Germany, France, Italy, Spain, and the United Kingdom) for the period 1985-2016. The empirical results revealed that renewable electricity consumption, natural resource use, and energy innovation improve environmental quality, while trade openness and economic growth increase carbon dioxide emissions. The study highlighted the importance of increasing renewable energy resources and encouraging energy innovation in reducing the impact of fossil fuels on environmental degradation. [33] analyzed the relationship between GDP, energy consumption, and CO₂ emissions in European transition economies for the period 1990-2018. The study findings revealed that investments to increase energy efficiency will increase economic competitiveness and reduce CO₂ emissions. While economic growth creates energy demand, excessive energy consumption will create various problems in terms of efficiency. In this regard, the researchers emphasized the importance of energy infrastructures that will save energy and support emission reduction. [34] tested the relationship between carbon emissions, energy consumption, and economic growth variables in 24 EU member states for the period 1995-2018. The scope of the economic growth variable was enriched with indicators of foreign direct investment and international trade. The study findings identified a one-way relationship between economic growth and CO₂ emissions. A bidirectional causal relationship was identified between the share of low-carbon energy in consumption, carbon emissions, and GDP per capita. Long-term results showed that foreign direct investment and international trade have a positive effect on reducing carbon emissions. [35] analyzed the relationship between economic growth and CO₂ emissions in EU member states for the period 2000-2017. The study findings suggested a long-term cointegration relationship between growth and CO₂ emissions in member states, revealing that a 1% change in GDP leads to a 0.072% change in CO₂ emission levels. The existence of this relationship emphasizes the importance of designing environmental policies that reduce emissions during periods of economic growth. It emphasizes the need not to ignore climate vulnerabilities and to address the pressure from energy costs with appropriate policy tools. Additionally, some recent studies in the literature focus on sectoral effects. [36] tested the contribution of tourism sector development to economic growth and its generally negative environmental impact in 27 EU countries; [37] examined the decarbonization outcomes of industrial sectors. [38] analyzed the impact of CO₂ emissions from energy use in selected EU countries between 2000 and 2018, placing a strong emphasis on promoting low-carbon economic growth. However, the researchers also emphasized the need to include the post-2018 period, the impact of the geopolitical and economic shocks experienced by Europe during the energy crisis, and the post-coronavirus pandemic period. Accordingly, the study's dataset was expanded to accommodate data availability.

Environmental Technologies and Environmental Degradation

Clean technologies are considered one of the most effective tools currently available to achieve the goals of the Paris Climate Agreement. [6] investigated the impact of market-based ecological interventions, climate-friendly technologies, and ecological fiscal measures in selected EU countries between 2006 and 2021 to limit carbon dioxide emissions and the ecological footprint, which have become a global concern. For this purpose, they focused on the impact of carbon pricing, green technology, GDP, environmental taxes, green patents, renewable energy, and urbanization on the ecological footprint. The findings indicate that a 1% increase in GDP increases the ecological footprint by 0.02%, while carbon pricing reduces environmental constraints at higher quantile levels. While green patents cause a rapid reduction in the ecological footprint, this positive effect diminishes in the long term. Urbanization, on the other hand, is found to provide short-term ecological benefits. [39] analyzed the impact of the European Union Emissions Trading System (EU ETS) on the development of green transportation technologies. The carbon emission-reducing effect of green transportation technologies was tested using patent data covering the years 2000-2020 for 27 EU member states. The study findings revealed a significant decrease in carbon emissions in companies holding green transportation patents, and the conclusion that the environmental benefits are strengthened with the spread of new transportation technologies. [40] investigated the impact of environmental taxes, renewable energy consumption, and environmental technology on the ecological footprint of the 10 OECD countries with the highest environmental revenues between 1994 and 2018. The study findings showed that environmental taxation and renewable energy consumption play a role in reducing the ecological footprint, while environmental technology does not have a significant impact on the ecological footprint. [34] demonstrated the importance of investing in low-carbon technologies and emphasized that low-carbon infrastructure investments are a key parameter in combating environmental degradation. Therefore, the role of environmental technologies in achieving the EU's carbon neutrality target has become an important research topic in the literature, particularly in the study conducted by [6]. While the study findings largely indicate that environmental technologies have a positive impact on environmental protection, [40] concluded that environmental technologies do not necessarily provide environmental protection. Identifying this relationship is crucial for the EU in line with its carbon neutrality goals. However, while [39] analyzed this relationship through green transportation technologies, our study did not limit green technologies to a sectoral basis. In this context, our study will offer important implications for improving existing technology infrastructure and/or encouraging innovation processes.

Renewable Energy Consumption and Environmental Degradation

The use of renewable energy resources is crucial for fulfilling commitments under the Paris Climate Change Agreement and the 2030 Energy and Climate Program. The increasing share of renewable energy consumption will not only ensure environmental sustainability but also have a positive impact on economic growth through the use of wind, solar, and geothermal energy in electricity generation. This transition creates employment opportunities while reducing energy

costs and dependence on imported resources. Domestic renewable energy use is particularly important for EU member economies, which have long been dependent on energy imports [41].

[42] investigated the role of green technology, green energy, foreign direct investment, and globalization on green economic growth in G7 countries between 1995 and 2020. The study findings revealed that green energy and foreign direct investment will positively contribute to green economic growth in both the long and short term. Green technologies, in turn, were found to enhance green economic growth in the long term. Green technology innovation will play a key role in sustainable economic growth, particularly because it will lead to an increase in green energy consumption. Considering that a green economy will reduce the burden on the environment and contribute to an improved quality of life, sustainable development for the G7 economies will be possible through green energy and green technology applications and increased foreign direct investment. Additionally, removing barriers to green energy consumption and achieving energy independence will support this process. Incentive programs, tax advantages, and investment subsidies can be listed as functional tools for this progress. [43] analyzed changes in energy efficiency for 22 European Union member states between 2011 and 2020 using variables such as GDP, environmental taxes, renewable energy use, energy pricing, population, digitalization, and green patents. The findings revealed that digitalization, green technologies, and renewable energy sources have positive contributions to energy efficiency. The impact of the environmental tax was determined to be limited and insignificant, while population, GDP, and energy prices were found to have negative effects. At this point, the importance of advanced data analytics, digital infrastructure, and green patents in energy management for a sustainable environment and economy has been demonstrated. [44] analyzed the impact of changes in the fiscal, economic, and energy indicators of 27 EU member states between 2005 and 2022 on greenhouse gas emissions and energy intensity. The study findings revealed a positive correlation between GDP growth and greenhouse gas emissions, while an inverse relationship between GDP and energy intensity emerged. In a sense, economic expansion increases environmental degradation while simultaneously promoting energy efficiency. At this point, the shift towards renewable energy sources plays a critical role in sustainable growth by limiting the environmental impacts of increased production. Studies by [34, 42, 43] have demonstrated the importance of renewable energy consumption, in addition to economic growth and environmental technologies, for a sustainable environment. The literature review has highlighted the importance of sustainable economic growth, environmental technologies, and renewable energy consumption to achieve global climate goals. Each of these studies was considered in this study design. Our study was conducted using a current dataset from economies with relatively high energy consumption and technological development capacity within the EU. While similar variables have been used in existing studies, no study has been found that examines economic growth, environmental technologies, renewable energy consumption, and environmental degradation for the economies under study using current data. [45] highlighted the highly unbalanced distribution of data across the EU region due to existing socioeconomic challenges and diverse environmental policies regarding achieving common climate goals. Therefore, the political intervention of government institutions to ensure green growth pathways is crucial. Our

study aims to reveal the impact of environmental technologies on a sustainable environment, particularly for selected EU member states. In this context, the importance of green technologies for achieving global climate goals and shaping government policies will be demonstrated for other countries, especially Turkey.

MATERIALS AND METHODS

This study investigates the relationship between environmental technology, environmental degradation, renewable energy consumption, and economic growth in selected European Union (EU) countries for the period 1990–2021, using panel data analysis. The primary reason for selecting EU countries is their role as pioneering actors in the implementation of sustainable development, environmental protection, and green transition policies. Since the 1990s, the EU has significantly increased investments in renewable energy, enacted legal regulations aimed at reducing carbon emissions, and promoted R&D activities in green technologies [46]. In this context, EU countries provide suitable case studies for examining both environmental and economic dynamics. The 1990–2021 period encompasses a timeframe in which the impacts of major international environmental agreements, such as the Kyoto Protocol (1997) and the Paris Agreement (2015), can be observed. Moreover, this period is critical for evaluating the evolution of the EU's environmentally conscious growth policies [47].

The variables employed in this study represent the environment-economy-energy nexus within the framework of sustainable development. While renewable energy consumption, environmental degradation, and environmental technology serve as indicators of efforts toward environmental sustainability, the economic growth variable is essential for assessing how economic performance is influenced throughout this process [22, 48]. Accordingly, the joint examination of these variables through panel data analysis allows for a more comprehensive understanding of the interactions between environmental sustainability and economic growth in EU countries.

The sample and variable selection for our study were determined by considering the overall purpose of the study and the variables used in previous studies. In this context, the variables identified in the study were selected from among the factors affecting sustainable development in EU countries. In previous studies, it is frequently emphasized that environmental technologies reduce environmental degradation and that economic growth encourages technological innovations [20, 22, 23] also used similar variables in their studies. In addition, the studies of [32, 33, 34, 35] have been guiding. The policy recommendations of the

EU issued in 2019 and setting the target of carbon neutrality by 2050 revealed the need to expand the scope [32]'s study in terms of data set and country examples. The research conducted by [33] has largely focused on transition economies with their economic structures based on manufacturing industry. However, the studies of leading economies in technology development such as Germany, Sweden, Finland and the Netherlands Economies with strong industrial bases, such as Italy, France, and Spain, were included in our study. This allowed us to include economies with both high potential for environmental technology development and relatively high energy consumption. Furthermore, [37] and [49] demonstrated that carbon emission levels within EU regions are affected by activities in neighboring regions, demonstrating a spatial dependence on the greenhouse gas effect. Therefore, sustainable economic growth necessitates the development of strategies to reduce CO₂ emissions not only in the target country but also in neighboring countries. Based on this approach, the selected country groups included Sweden, which, based on 2023 data, meets 66.4% of its gross final energy consumption from renewable energy sources; Finland, which follows Sweden at 50.8% with solid biofuel, wind energy, and biofuel consumption; Denmark at 44.9%; and Austria at 40%. To understand the link between environmental technologies and renewable energy consumption, the study also included the Netherlands, which ranks relatively low in terms of renewable energy share at 17.4% [5]. Therefore, based on the studies of [32, 33, 34, 35] the economic growth indicator was included in the model and tested.

In this study, which applied panel data analysis, a cross-sectional dependence test was first used. The presence of cross-sectional dependence provides information about the application of new-generation tests. Therefore, the stationarity level of the variables was determined using the CADF-CIPS new-generation unit root test. As a result of the unit root test, all variables were found to be stationary at level, and therefore, a panel regression analysis was conducted. Finally, a panel causality test was applied to determine the causal relationship between the variables.

Throughout the study, cross-sectional dependence among the variables was first tested using the cross-sectional dependence test. Subsequently, the presence of homogeneity was examined using the delta test. The stationarity of the variables was assessed by employing the CADF-CIPS panel unit root test. Finally, based on the results of the unit root test, the regression relationship between the variables was analyzed using panel regression analysis. The variables used in the study, along with their forms of use and sources, are presented in the table below.

Table 1. Variables and data sources

Variable(s)	Transformation	Description	Source
Environmental technology	<i>lnenvi</i>	Environment-related technology	World Bank
Environmental degradation	<i>lnCO₂</i>	Carbon dioxide (CO ₂) emissions (total), excluding LULUCF (Mt CO ₂ e)	World Bank
Economic growth	<i>lnGDP</i>	GDP (constant 2015 US\$)	World Bank
Renewable energy consumption	<i>lnrew</i>	Renewable energy consumption (% of total final energy consumption)	World Bank

The natural logarithm of the variables used in the study has been taken, and the resulting model is specified as follows:

$$\ln CO_{2it} = \beta_0 + \beta_1 \ln GDP_{it} - \beta_2 \ln env_{it} - \beta_3 \ln renew_{it} + u_{it} \quad (1)$$

The selection of variables in this study was guided by previous literature. Specifically, environmental technology were adopted based on the works of [50] and [51]. Economic growth was included following the framework established by [22]. Renewable energy consumption was considered in line with the studies of [48, 52, 53]. Finally, carbon dioxide (CO₂) emissions were used as a proxy for environmental degradation, as supported by the findings of [54] and [55].

RESULTS AND DISCUSSION

Cross-Sectional Dependence Test

Determining the presence or absence of cross-sectional dependence among the series in the dataset is crucial for ensuring the reliability of the results. Therefore, before proceeding with the analysis, a cross-sectional dependence test is conducted [56, 57]. If the time dimension in the panel is greater than the cross-sectional dimension ($T > N$), the Lagrange Multiplier (LM) test developed by [56] is applied. Conversely, if the number of cross-sectional units exceeds the

time dimension ($N > T$), the Cross-Section Dependence (CD) test proposed by [57] is employed.

The table presents the results of the cross-sectional dependence tests. In this analysis, The Breusch-Pagan LM Test, The Pesaran LM CD test, and The Pesaran, Ullah, and Yamagata adjusted LM (LMadj) test were employed [56, 57, 58]. Since the dataset used in the study satisfies the condition $T > N$ ($N = 9$, $T = 32$), the Cross-Section Dependence (CD) test developed by [57] was utilized. Based on the test results, it was concluded that cross-sectional dependence is present.

Slope Homogeneity Test (Delta Test)

Following the assessment of cross-sectional dependence, it is necessary to perform a homogeneity test before analyzing any potential long-run relationship. In this context, the homogeneity of slope parameters is tested using the Delta (Δ) test developed by [59]. This test evaluates whether the slope coefficients are homogeneous across panel units. For large sample groups, the Delta test is employed, while for smaller samples, the adjusted version Delta Adj is used [59].

An examination of the table presenting the results of the slope homogeneity test indicates that, due to the insignificance of the probability value, the slope coefficients are determined to be heterogeneous.

Table 2. Results of the cross-sectional dependence test

	Breusch- Pagan LM	Pesaran LM	LM	Pesaran CD
lnenvi	259,1232 (0,0000)	26,29532 (0,0000)	26,15016 (0,0000)	8,496407 (0,0000)
lnCO2	575,9656 (0,0000)	636,63555 (0,0000)	63,49039 (0,0000)	21,89654 (0,0000)
lnGDP	1032,981 (0,0000)	117,4953 (0,0000)	117,3501 (0,0000)	32,05538 (0,0000)
lnrew	970,7147 (0,0000)	110,1572 (0,0000)	110,0120 (0,0000)	31,10720 (0,0000)

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

Table 3. Results of the cross-sectional dependence test

	t ist.	value
Delta	-0,912	0,819
Delta adj.	-0,990	0,839

CADF-CIPS Unit Root Test

First-generation unit root tests assume that the cross-sectional units within the panel are independent from one another and that all units are equally affected by any external shock. However, in real-world scenarios, it is highly unlikely that all units would respond identically to a shock. Therefore, second-generation tests, which account for cross-sectional dependence, are required. The MADF (Multivariate Augmented Dickey-Fuller) test was developed by [60], the SURADF (Seemingly Unrelated Regression Augmented Dickey-Fuller) test by [61] and the CADF (Cross-sectional Augmented Dickey-Fuller) test by [62].

Considering the results of the cross-sectional dependence and delta tests together, it was deemed appropriate to apply second-generation unit root tests. In this study, the CADF-CIPS unit root test, one of the second-generation panel unit root tests, was employed. The unit root test results are presented in the table below.

In this study, the CADF-CIPS unit root test was applied, and the results indicate that the variables are stationary at level. Given the stationarity of the variables at level, panel regression analysis was conducted.

Panel Regression Analysis

Based on the results of the Hausman test, the Fixed Effects Model was determined to be the appropriate model for the panel regression analysis. As a result of the regression conducted using the Fixed Effects Model, the following equation was established:

$$\ln CO_{2it} = -6,131 + 0,42 \ln GDP_{it} - 0,10 \ln env_{it} - 0,02 \ln renew_{it} \quad (2)$$

Table 4. Result of CADF- CIPS unit root test

Countries	Statistic Constant	Statistic Constant+Trend
Germany	-3,73	-4,321
Austria	-3,71	-4,004
Denmark	-4,19	-4,565
Finland	-3,55	-3,737
France	-3,29	-4,026
Netherland	-2,44	-2,686
Spain	3,31	-4,612
Sweden	-3,67	-5,381
Italy	-4,61	-5,889
CIPS	-3,61	-4,358
Germany	-4,075	-4,284
Austria	-4,579	-4,551
Denmark	-3,699	-4,804
Finland	-3,565	-4,668
France	-4,412	-4,660
Netherland	-3,717	-4,344
Spain	-3,369	-4,111
Sweden	-3,986	-4,666
Italy	-4,778	-4,511
CIPS	-4,020	-4,511
Germany	-4,433	-4,639
Austria	-4,657	-4,650
Denmark	-3,465	-4,259
Finland	-2,948	-4,164
France	-4,605	-4,488
Netherland	-3,687	-4,927
Spain	-3,577	-4,697
Sweden	-4,393	-5,262
Italy	-4,835	-4,636
CIPS	-4,067	-4,636
Germany	-4,160	-4,081
Austria	-3,549	-3,817
Denmark	-3,696	-4,373
Finland	-3,604	-3,859
France	-3,264	-3,653
Netherland	-3,685	-4,550
Spain	-4,169	-4,520
Sweden	-4,495	-5,275
Italy	-3,859	-3,804
CIPS	-3,891	-4,215

Note1: According to Table IIb of Pesaran (2007), at the 90% confidence level (since $t:32, n:9$), the critical value for the model with a constant is -2.21, and for the model with a constant+trend, according to Table IIc Pesaran (2007). The decision was made based on the critical value of 2.73. In addition, * represents stationarity at level $I(0)$.

According to the results of the regression analysis, a 1% increase in economic growth leads to a 0.42% rise in environmental degradation. This finding can be explained by the increased emissions resulting from the use of fossil fuels to meet the energy demand required for production. It aligns with the literature emphasizing the environmental costs of energy-intensive growth processes. [55], in his study on France, found that economic growth increases energy consumption, which directly leads to higher CO₂ emissions. [54] also found a positive and significant relationship between growth and CO₂ emissions in the case of Pakistan, highlighting the environmental impacts of fossil fuel dependency. In this context, the findings of the present study underscore the critical role of energy sources in the sustainability of economic growth and emphasize the necessity of transitioning to clean energy in order to mitigate environmental degradation.

Furthermore, a 1% increase in environment-friendly technologies results in a 0.10% decrease in environmental degradation. This outcome can be attributed to the mitigating effect of eco-friendly technologies on environmental harm. The result is consistent with the literature emphasizing the positive role of environmental technology in reducing emissions. For example, [63] found that environmental patents and the diffusion of low-carbon technologies significantly reduced CO₂ emissions in OECD countries. Additionally, [51] showed that green technological innovations help reduce environmental degradation, particularly by promoting the use of renewable energy. [50], in their study on China, demonstrated that environmental R&D investments lowered carbon intensity, thereby fostering a more balanced relationship between economic growth and environmental quality. These findings confirm that the widespread adoption of eco-friendly technologies not only contributes to reducing environmental problems but also serves as a fundamental component of long-term sustainable development strategies.

A 1% increase in renewable energy consumption leads to a 0.02% reduction in environmental degradation. This result can be explained by the role of renewable energy consumption in reducing environmental pollution. It is consistent with previous literature that supports the

significant role of renewable energy use in mitigating environmental deterioration. [48] emphasized that renewable energy consumption reduces CO₂ emissions and promotes environmental sustainability, particularly in G7 countries. Similarly, [52] demonstrated that renewable energy consumption serves as a key factor in balancing economic growth and environmental sustainability, and contributes to reducing environmental degradation in OECD countries. [54] also found that renewable energy consumption in Pakistan helps decrease environmental degradation and improves the relationship between economic growth and environmental quality. The findings of this study thus confirm that renewable energy consumption is a critical tool for achieving environmental sustainability, and that reducing dependence on fossil fuels can significantly lower environmental pollution.

Dumitrescu–Hurlin Causality Test

In panel datasets characterized by time-invariant structure and heterogeneity, the Dumitrescu–Hurlin Causality Test is employed to examine causality relationships between variables. The DH causality test is an advanced version of the Granger Causality Test [64].

According to the results of the causality analysis, a bidirectional causal relationship was found between environmental technologies and environmental degradation. In addition, a unidirectional causal relationship from economic growth to environmental technologies was identified. A unidirectional causal relationship from both economic growth and environmental technologies to renewable energy consumption was also identified. Furthermore, it was concluded that there is a reciprocal causal relationship between renewable energy consumption and environmental degradation. [52] showed that environmental technologies encourage renewable energy use and play an effective role in reducing environmental degradation. The causal relationship between environmental technologies and economic growth is consistent with the study by [50], which emphasises that environmental technologies can support economic growth while also protecting the environment.

Table 5. Dumitrescu–Hurlin causality test results

Variable(s)	Statistic	Probability
lnGDP–lnenvi	9,24046	0,0000*
lnenvi–lnGDP	2,27736	0,3052
lnCO2–lnenvi	2,28732	0,0228**
lnenvi–lnCO2	1,63637	0,1018***
lnren–lnenvi	1,24986	0,2114
lnenvi–lnren	2,48793	0,0128**
lnCO2–lnGDP	0,76776	0,4426
lnGDP–lnCO2	9,54375	0,0000***
lnren–lnGDP	0,54558	0,5854
lnGDP–lnren	6,56453	0,0005*
lnren–lnCO2	13,6644	0,0000*
lnCO2–lnren	4,0335	0,0005*

Note: *p<0.01, **p<0.05, ***p<0.10

The bidirectional relationship between environmental degradation and renewable energy consumption is consistent with the findings of [48, 54]. Finally, the unidirectional causal relationships from environmental technologies to renewable energy consumption and from economic growth to environmental technologies are consistent with the findings of [51], which conclude that environmental innovations increase energy efficiency and economic growth can increase demand for environmental technologies.

The findings obtained from the causality test are summarized as follows:

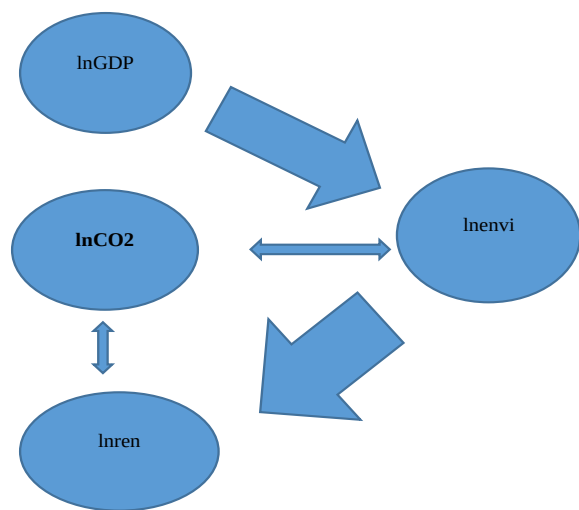


Figure 1. An overview of causal relationships

CONCLUSION AND SUGGESTIONS

This study examined the bidirectional causality between environmental technologies and environmental degradation while analyzing the impact of factors such as economic growth and renewable energy consumption on this relationship. The causality tests revealed a mutual interaction between environmental technologies and environmental degradation. This finding indicates that environmental technologies not only help mitigate environmental degradation but that their development can also be influenced by the extent of environmental degradation. The result that renewable energy consumption reduces environmental degradation is also supported by previous studies, including those by [48, 52, 65, 66]

Moreover, a bidirectional relationship was identified between environmental technologies and economic growth, suggesting that while environmental technologies stimulate growth, economic growth in turn contributes to the advancement of such technologies. Additionally, the study found a bidirectional relationship between environmental degradation and renewable energy consumption, indicating that growing environmental issues may trigger increased demand for renewable energy. Finally, a unidirectional causality was detected from environmental technologies to renewable energy consumption and from economic growth to environmental technologies. These findings highlight that environmental innovations promote renewable energy use by increasing energy efficiency and that economic growth can enhance investment in environmental technologies.

This study clearly demonstrates the critical role of environmental technologies and renewable energy usage in

reducing environmental degradation. Based on these findings, several policy recommendations can be made to ensure environmental sustainability and prevent further environmental degradation:

Promoting Environmental Technologies: Increasing investments in environmental technologies and supporting innovation in this field can form an effective strategy to reduce environmental degradation. In particular, the development of environmental technology holds the potential to limit environmental harm by reducing reliance on fossil fuel-based energy production.

Boosting Investments in Renewable Energy: Expanding investments in renewable energy sources can significantly reduce environmental degradation. This step is crucial not only for achieving environmental sustainability but also for ensuring long-term energy security. Accordingly, environmental degradation can be reduced by implementing policies that will increase the use of renewable energy (subsidies, energy certificates, clean energy infrastructure investments).

Developing Sustainable Growth Strategies: In order to balance economic growth with environmental protection, it is necessary to adopt sustainable growth strategies. Such strategies can increase investment in environmental technologies, prevent environmental degradation, and enable the establishment of a greener model of economic development in the long run.

Policy and Regulatory Measures: Economic tools such as tax incentives, subsidies, and grants can be used to encourage the adoption of innovative technologies aimed at reducing environmental degradation. Furthermore, the development of energy efficiency standards and regulations can facilitate the faster and broader adoption of environmental technologies.

This study examines the relationship between environmental technologies, renewable energy consumption, economic growth, and environmental degradation in selected EU countries using panel data analysis. The study has certain limitations in terms of the variables included in the model. The exclusion of certain demographic indicators such as population, migration, urbanisation, and education, as well as policy instruments shaping environmental innovation such as carbon taxes, renewable energy investments, and R&D support, limits the comprehensiveness of the findings. Furthermore, the fact that the study covers EU countries and spans the period from 1990 to 2021 reduces the generalisability of the results to both geographical contexts and longer periods.

Future researchers may develop this methodology and scope further to overcome the limitations mentioned above. Accordingly, using different techniques (such as Panel VECM and Panel cointegration) to analyse the short- and long-term relationship between variables and expanding the sample to include developing countries or different regional integration groups will lead to more comprehensive and general results. Furthermore, including public policy instruments, which play an important role in the development and diffusion of environmental technologies, in the analysis will contribute to the analysis of policy effects. Finally, sectoral analyses using microdata at the firm level will allow for a more detailed examination of the effects of environmental technologies on efficiency, competitiveness, and sustainability.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest with any individual, institution, or organization in the preparation, evaluation, or publication of this study.

USE OF AI FOR WRITING ASSISTANCE

Grammar and proof editing were refined using QuillBot and Grammarly in accordance with ethical writing standards.

ETHICS

There are no ethical issues with the publication of this manuscript.

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