

Article

Stock Externalities and Environmental Protection Expenditures in Türkiye: A Fourier Cointegration Analysis

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Abstract

Environmental issues such as climate change and cumulative emissions have intensified debate on the effectiveness of public environmental protection expenditure. Traditional Pigouvian taxes and subsidies mainly target instantaneous flow externalities. However, it is difficult to resolve dynamic stock externalities that accumulate over many years, such as climate change and cumulative greenhouse gas emissions, through taxation policies alone. This situation requires the government to make direct environmental protection expenditure to support the ecosystem's natural assimilation capacity and reduce the rate at which pollution accumulates. This study specifically examines the relationship between stock externalities and environmental protection expenditure within the context of the Turkish economy, which is highly industrialised and under pressure to comply with international environmental commitments such as the European Green Deal and the Paris Climate Agreement. In the study's empirical analysis phase, long-term relationships between macroeconomic variables and pollution stocks were tested using Fourier cointegration methods and econometric time series analyses. The analysis revealed a long-term co-movement (cointegration) relationship between the series, indicating that public environmental protection expenditures and industrial emissions move in the same direction over the long term. FMOLS and DOLS estimates indicate that environmental protection expenditures are positively associated with industrial emissions in the long run (FMOLS coefficient = 2.1125; DOLS coefficient = 2.0375), whereas renewable energy consumption exerts a negative effect on emissions (FMOLS coefficient = −1.4391; DOLS coefficient = −1.4967). These results suggest that environmental protection expenditure in Türkiye is not independent of current production and industrialisation dynamics, and that its emission-reducing effects are influenced by technological transformation processes.

Keywords: stock externalities; environmental protection expenditures; public economics; fiscal policy; Fourier cointegration; Türkiye



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1. Introduction

The effects of economic activities on third parties and institutions constitute market failures that indicate deviations from a perfectly competitive market and necessitate public intervention. These adverse effects, arising from production or consumption processes and not reflected in market prices, are referred to in the literature as negative externalities; the most common example is the environmental pollution caused by production activities. In the history of economic thought, the first systematic framework for addressing negative externalities through public policy was developed by Pigou [1]. Measures known as “Pigouvian” solutions to negative externalities highlight that the social costs of environmental pollution are not taken into account or internalized by the actors causing it, thereby underscoring the need for public intervention to address this issue.

Pigouvian solutions aim to achieve the optimal level of production—where marginal social costs equal marginal private costs—by incorporating external costs into the producer’s cost function. However, since Pigouvian approaches to internalizing externalities aim to eliminate current-flow externalities that arise in the moment, the following question arises: How will pollution that has accumulated over time be reduced? This situation, referred to as stock externalities, ranks among today’s most fundamental environmental problems. In the case of stock externalities, environmental damage stems not so much from the amount of pollution at any given time, but rather from the total stock level reached as pollution accumulates in the atmosphere over many years. However, it is difficult to reduce such cumulative and dynamic pollution through taxation policies alone. In this context, public environmental protection expenditures are being discussed as a fiscal policy tool with the potential to slow the accumulation rate of stock externalities and support natural assimilation capacity.

In the literature, studies by Keeler et al. [2], Smith [3], and Falk and Mendelsohn [4] treated pollution as a dynamic problem and laid the foundations for the theory of stock externalities. Bovenberg and Smulders [5], Farzin [6], and Xepapadeas [7], on the other hand, integrated this concept into macroeconomic analysis through the lens of economic growth. On the other hand, while Newell and Pizer [8], Millock et al. [9], and Zhao and Porter [10] focused on the design of optimal policy instruments and control strategies under uncertainty; Bisack and Sutinen [11], Legras [12], and Merrill and Guilfoos [13] have examined the spatial and empirical dimensions of the theory in the management of specific natural resources such as groundwater and fisheries. Studies such as Loehman and Randhir [14], Rubio and Escriche [15], López et al. [16], and Halkos and Paizanos [17], on the other hand, shifted the focus to fiscal policy, addressing the resolution of stock externalities through Pigouvian interventions, strategic taxation, and environmental public expenditures. More recently, Plinke et al. [18] argue that environmental objectives can also be achieved through complementary fiscal policy instruments alongside conventional carbon pricing, highlighting the importance of integrated policy approaches in addressing environmental externalities. Although the existing literature provides important evidence on environmental protection expenditures and environmental quality, most studies focus on conventional emission indicators rather than explicitly addressing stock externalities. Moreover, empirical evidence examining the long-run relationship between environmental protection expenditures and stock externalities in the case of Türkiye using Fourier-based cointegration techniques remains limited. Accordingly, this study examines the effectiveness of public environmental protection expenditures in reducing stock externalities in Türkiye through a Fourier cointegration framework.

Accordingly, the primary aim of this study is to examine the long-run relationship between environmental protection expenditures, renewable energy consumption, and stock externalities in Türkiye using a Fourier-based cointegration framework. In doing so, the

study contributes to the existing literature from theoretical, empirical, and methodological perspectives. First, environmental degradation is addressed within the framework of the stock externalities approach rather than the flow externalities approach, focusing on the cumulative and persistent nature of environmental pressures over time. Second, the role of environmental protection expenditures in reducing stock externalities is empirically examined specifically within the Turkish economy, thereby expanding the literature on the long-term effects of environmental fiscal policies. Third, a Fourier-based cointegration approach is employed to account for the nonlinear dynamics observable in environmental indicators. Within this framework, the relationship between stock externalities, environmental public expenditures, and nonlinear environmental dynamics is evaluated within a comprehensive empirical structure.

The selection of Türkiye for this analysis can be explained as follows. First, Türkiye is among the countries with the highest rates of industrialization among emerging market economies and developing countries. As is well known, industrialization and associated industrial activities generate more pollution in developing countries than in developed countries [19,20]. Because legal and institutional regulations regarding the environment in developed countries compel firms to implement practices such as filtration systems and waste management in their production processes [21,22]. On the other hand, Türkiye is a country with candidate status for the European Union, having integrated into developed Western economies and established extensive trade relations. This model of relations that Türkiye has established with developed countries contributes to the country's growth and development on the one hand; on the other hand, it creates pressure to comply with international commitments, such as the European Green Deal (Carbon Border Adjustment Mechanism) and the Paris Climate Agreement. It is precisely because of these specific circumstances that the subject warrants examination in the context of Türkiye.

In addition, the scope and priorities of environmental protection expenditures in Türkiye have gradually evolved over time in line with national environmental policies and international commitments. During the same period, emissions have exhibited a persistent upward trend associated with industrialization and increasing energy use, reflecting the cumulative nature of environmental pressures. These characteristics make Türkiye a relevant case for examining the long-run relationship between environmental protection expenditures and stock externalities.

The first section of this study provides an introduction to the topic and presents the conceptual framework. In the second section, the relationship between the theory of stock externalities and environmental pollution will be examined within the framework of the theoretical and empirical literature. In the third section, after introducing the dataset and methodology, the empirical findings will be presented. In the conclusion, the findings will be discussed, and implications for policymakers and future research will be presented, along with an assessment of the study's limitations and potential directions for future research.

2. Theoretical Framework

Pollution, global warming and climate change, acid rain, and the loss of biodiversity, among others, are among the most serious environmental challenges facing the world today and are rooted in stock-based externalities [23]. Sustainable development is related to the ecosystem's carrying capacity, and the environment's capacity to absorb pollution is not infinite [24]. Excessive accumulation of pollution in the environment leads to intergenerational negative externalities that negatively impact the well-being of both current and future generations. The natural environment serves as a repository for waste generated throughout economic processes. At this point, the ecological threshold depends not only on

the amount of pollution but also on the rate and type of waste discharge. When the rate of pollution discharge exceeds the environment's capacity to absorb it, pollutants accumulate in the environment. The natural environment can handle biodegradable pollutants, such as sewage, food waste, and paper, relatively easily. On the other hand, if nature's capacity to absorb pollution is sufficiently high relative to the pollution release rate, pollution does not accumulate in nature at all or results in short-term, temporary effects [25]. As a result, the link between current emissions and future damage is severed. However, rendering stock pollutants harmless takes a very long time. Wastes such as plastic bottles—which the environment has limited or no capacity to break down—heavy metals that accumulate in soil (such as lead, cadmium, and mercury), and persistent organic pollutants are referred to as stock pollutants. As emissions of these pollutants continue, the total pollution stock gradually increases, and even if pollution levels are reduced to zero, the pollution stock remains at harmful levels in the environment for decades [8]. Effective allocation of stock pollutants must take into account the fact that pollutants accumulate in the environment over time and that pollution damage increases.

As pollution levels increase, the marginal damage costs and control costs resulting from pollution also rise [26]. Marginal damage costs occur when the flow of pollution exceeds the environment's absorption capacity. Pollution control costs, on the other hand, are the monetary expenditures made to reduce current pollution levels. An increase in expenditures for pollution control reduces marginal damage costs [27]. Planners seeking to implement sustainable pollution policies must consider not only the direct marginal damages resulting from current pollution but also the indirect marginal damages—that is, the marginal stock externalities arising from current pollution. In this context, stock externalities represent the present value of the increase in future total social costs resulting from a marginal increase in current pollution [28]. For a long-term sustainable environmental policy, the environmental expenditure policy implemented and the selected tax level must ensure a pollution level that maximizes net social benefits.

In recent years, the Kyoto Protocol, the Sustainable Development Goals, the Paris Agreement, and the United Nations Framework Convention on Climate Change have created a “pressure mechanism” in both industrialized and developing countries, emphasizing the growing importance of green development indicators, the proper management of environmental resources, and prioritizing low-carbon development [29]. In determining a sustainable policy to combat environmental pollution, it is crucial first to establish an acceptable level of pollution and then identify measures to reduce it to that level. In this context, various public economic tools, such as environmental protection expenditures and tax policies, are utilized to achieve socially desirable sustainable development and minimize environmental degradation [30]. Environmental protection expenditures, a key component of green fiscal policy, reflect economic efforts to prevent, reduce, and eliminate pollution and other forms of environmental degradation. These efforts include waste and wastewater management, biodiversity, pollution reduction, research and development (R&D) expenditures, and remediation activities following environmental degradation [31].

There is no clear consensus in the empirical literature examining the relationship between environmental pollution and environmental protection expenditures. While some studies suggest that public expenditures have no effect on pollution or even increase total CO₂ emissions and degrade environmental quality in the long term, numerous studies have confirmed that such expenditures serve as a significant regulatory policy tool in combating industrial emissions. Akdağ et al. [32] found that environmental protection expenditures are far more effective than taxes in reducing greenhouse gas emissions; Huang [33] found that environmental protection expenditures reduced environmental pollution in China; Broniewicz [34] found that environmental protection expenditures facilitate the fight against

environmental pollution; and Bostan et al. [35] concluded that environmental protection expenditures reduce pollution. However, Ullah et al. [36] found that in selected Asian countries, except Japan, increases in government spending led to higher carbon emissions, while Barrell et al. [23] found that environmental protection expenditures do not lead to proportional improvements in environmental outcomes; Ercolano and Romano [37] found no significant positive correlation between environmental protection expenditures and environmental quality; Yalçın and Gök [38] concluded that environmental protection expenditures are ineffective in Türkiye; Halkos and Paizanos [17] found that public expenditures have no significant effect on carbon dioxide emissions; and Moshiri and Daneshmand [39] concluded that environmental protection expenditures are not significantly effective in reducing environmental pollution.

The existing literature does not provide a unanimous conclusion regarding the environmental effects of public environmental protection expenditures. These differences arise not only from variations in countries' economic and institutional structures but also from differences in the environmental indicators employed, the econometric methods adopted, and the effectiveness of environmental policies. In particular, environmental protection expenditures may be associated with higher emissions in developing economies where scale effects remain dominant, whereas they are more likely to improve environmental quality in economies that have advanced further in technological progress and the energy transition. Therefore, the environmental effects of public environmental protection expenditures should be evaluated within the specific economic and institutional context of each country.

When analyzing the impact of public spending on emissions, it is necessary to consider the four arguments together. According to the income component of the Environmental Kuznets Curve Hypothesis, developed by Grossman and Krueger [19], there is an inverted U-shaped relationship between environmental pollution and per capita income. In the early stages of economic transition, the initial rise in income may increase emissions, and environmental quality may deteriorate initially. However, as the economy grows and per capita income rises, society's demand for a clean environment will increase, and higher income will create pressure to reduce pollution. Ultimately, environmental protection expenditures, subsidies provided to households, social transfers, and R&D expenditures will increase [40,41].

Lopez et al. [16] used the main arguments of scale, composition, and technical effects to explain the inverted U-shaped relationship between public spending and pollution levels. According to the scale effect, increased public spending multiplies, positively influencing economic activity. However, the resulting increase in production and GDP exacerbates environmental degradation, revealing a scale effect that supports the hypothesis of a positively sloped environmental Kuznets curve [40,42]. The Composition (structural) effect, which marks the beginning of this transformation, emphasizes that increased environmental awareness resulting from the reallocation of government expenditures will encourage a structural shift toward human capital-intensive activities—such as the service sector, which causes less environmental harm—as well as energy sources and environmentally friendly production technologies, rather than physical capital-intensive manufacturing activities. This will improve environmental quality and reduce pollution [36,43]. Meanwhile, the technical effect highlights that increased environmental protection expenditures and research and development (R&D) expenditures will lead to the development and adoption of environmentally friendly technologies, thereby reducing the pollution-to-output ratio [44,45].

On the other hand, when analyzing the search for sustainable policies to address stock externalities, it is important to consider the impact of technological advancements in pollution control. Expenditures on environmental protection create a “sustainable” impact

by encouraging long-term innovation in combating environmental stock externalities. As a result of technological advancements, the shift toward renewable resources will lead to lower prices for the inputs used to control pollution, thereby reducing the marginal damage and control costs associated with a given level of production per unit [26]. The European Green Deal demonstrates that renewable energy will play a critical role in decarbonizing the energy system, which is responsible for over 75% of the EU's greenhouse gas emissions [46]. Empirical results have shown that increased technological innovation and renewable energy help mitigate environmental degradation. For example, Zhen et al. [47] and Wang et al. [48] reported that renewable energy reduces greenhouse gas emissions in the EU. Mehta and Prajapati [49] concluded that environmental protection expenditures in the European Union encourage the private sector to increase investments in green technology, thereby reducing carbon dioxide emissions. Similarly, Tang and Yang [50] found that R&D expenditures promote green technology innovation in firms, thereby fostering sustainable development. Hossain [51] shows that in ten Canadian provinces between 1995 and 2020, government spending on environmental protection, promoting energy-efficient technologies and building improvements, reduced household energy consumption and increased energy efficiency. Akadiri et al. [52] found that renewable energy improves environmental quality, while Dziubanovska and Maslii [53] found that increasing environmental protection spending has a positive effect on economic innovation. Wang and Wang [54] analyzed provincial-level data from China between 2007 and 2018 and found that government environmental protection expenditure played a guiding and “leveraging” role, significantly promoting regional green innovation. According to Fernández et al. [55], research and development expenditures contribute to reducing CO₂ emissions, particularly in developed countries. Consistent with this perspective, He et al. [56] show that digitalization also contributes to reducing carbon emissions through technological transformation and improved production efficiency, underscoring the importance of innovation-driven environmental policies for sustainable development.

Overall, within the stock externality framework, environmental protection expenditures and renewable energy consumption can be regarded as complementary policy instruments. While environmental protection expenditures aim to mitigate existing environmental pressures through pollution control, environmental infrastructure, and support for cleaner technologies, renewable energy consumption limits the accumulation of new pollution stocks by reducing dependence on fossil fuels. Accordingly, achieving environmental sustainability depends not only on environmental protection expenditures but also on the acceleration of the energy transition. Based on this theoretical framework, this study jointly examines the long-run effects of environmental protection expenditures and renewable energy consumption on emissions.

3. Data, Model, and Empirical Results

3.1. Data and Variables

This study examines the long-term dynamic relationships among environmental protection expenditures, renewable energy consumption, and emissions indicators within the framework of stock externalities, using annual data from Türkiye for the period 1990–2023 and applying a Fourier-based cointegration approach. The analytical framework is based on a Fourier-extended model specification that flexibly incorporates smooth structural breaks observed in time series, rather than relying on classical linear structures. Thus, changes in political regimes, energy transition processes, and gradual structural transformations in environmental regulations can be captured parametrically. In recent years, Fourier-based unit root and cointegration tests have been widely used due to their ability to model smooth structural breaks in time series related to environmental indicators [57–59].

In particular, the fact that environmental indicators such as carbon emissions, ecological footprint, and energy transition involve nonlinear structural changes over time has led to a greater reliance on Fourier-based methods in the literature on environmental economics.

Industrial Emissions (IE) were used as the primary dependent variable in the study. IE is measured in millions of tons of CO₂ equivalent and has been included in the model as an indicator of industrial stock externalities. Although industrial emissions are measured as annual flows, persistent emission flows accumulate over time and contribute to pollution stocks. Therefore, industrial emissions are employed as a proxy for stock externalities, based on the premise that the accumulation of repeated emission flows gives rise to long-term environmental stock problems. Accordingly, IE reflects the cumulative nature of long-term environmental pressure as it manifests through industrial production processes.

To test the robustness of the analysis, Energy-Related CO₂ Emissions (EE) were used as an alternative dependent variable. EE represents the environmental pressure arising from the energy production and consumption system and enables the examination of whether stock externalities exhibit cumulative characteristics across the energy system. The primary explanatory variable is Environmental Protection Expenditures (Ln_EPE), which is included in the model in its natural logarithm. This variable represents the fiscal policy instrument used to reduce stock externalities. Renewable Energy Consumption (REC), used as a control variable, indicates the share of renewable energy (%) within total final energy consumption. The REC variable captures the energy transition process and helps isolate the effect of environmental protection expenditures from changes in the energy mix.

All variables were used on an annual basis. Descriptive statistics are presented in Table 1 to summarize the distributional properties of the variables prior to the empirical analysis.

Table 1. Descriptive Stats of Variables and Data Sources.

	IE	Ln_EPE	REC	EE
Mean	43.6732	20.6036	16.4441	5.9082
Median	38.6962	20.8557	14.2000	5.9419
Maximum	76.5427	26.1167	24.4000	6.3951
Minimum	23.0921	13.5707	11.4000	5.4312
Std. Dev.	18.2124	3.04496	4.41068	0.3023
Jarque–Bera	3.81525	0.57247	3.99583	2.6847
Probability	0.14843	0.75109	0.13562	0.2612
Data Source	TURKSTAT	TURKSTAT	World Bank	World Bank

The descriptive statistics presented in Table 1 provide preliminary information on the distribution characteristics and levels of variability of the variables. In particular, the relatively high standard deviation of the IE variable indicates that industry-sourced emissions fluctuated over the period. The REC and Ln_EPE variables, on the other hand, exhibit a more gradual upward trend over time. These patterns provide preliminary evidence of nonlinear trends and structural transformations in the series.

Figure 1 visually illustrates the trends of the variables over time. In particular, while the IE variable fluctuates throughout the period, it generally shows an upward trend. The Ln_EPE variable shows a gradual increase over time, whereas the REC variable exhibits periodic fluctuations. Overall, the graphical patterns suggest the presence of nonlinear trends and gradual structural transformations over time.

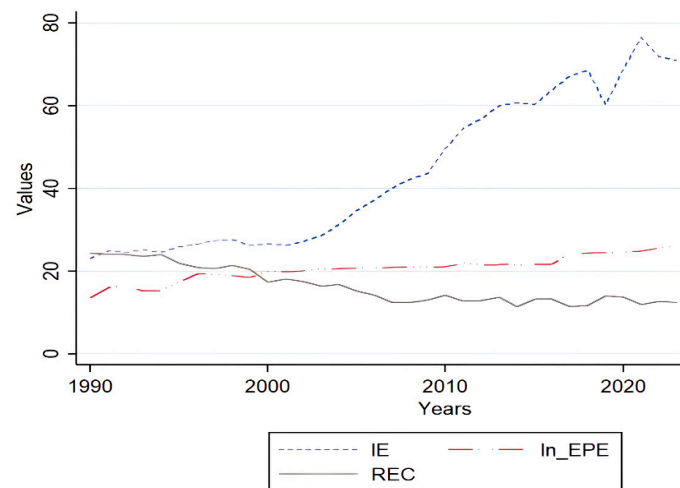


Figure 1. Time Series Plots of the Variables.

3.2. Unit Root and Cointegration Analysis

The fact that environmental indicators and fiscal policy variables are influenced by processes such as energy transition, environmental regulations, and institutional policy changes suggests that the series may exhibit smooth structural breaks. These findings suggest that linear time series approaches with fixed parameters may not adequately capture structural changes. For this reason, the study adopts a Fourier-based econometric approach that can incorporate structural changes into the model. In the first stage, the stationarity properties of the series were examined using classical unit root tests as well as the Fourier KPSS and Fourier ADF tests [60,61]. The Fourier approach allows incorporating smooth structural shifts into the model without specifying a prior break date by adding sine and cosine terms to the deterministic component. The Fourier approach is preferred because it captures both smooth and multiple structural changes without requiring prior knowledge of the timing or number of structural shifts. Unlike conventional structural break tests, which generally require the number or timing of structural breaks to be specified in advance, the Fourier approach flexibly approximates gradual and nonlinear structural changes through trigonometric functions. This characteristic makes it particularly appropriate for analyzing environmental and fiscal policy variables, whose responses to policy reforms and energy transition processes typically evolve gradually rather than through a single discrete break. For the Fourier KPSS and Fourier ADF tests, the optimal frequency (k) and lag length (p) were selected according to the Akaike Information Criterion (AIC). In the second stage, long-run relationships among the variables were examined using the Fourier cointegration test, and long-run coefficients were subsequently estimated using FMOLS and DOLS estimators. While the FMOLS method addresses endogeneity and autocorrelation issues in cointegrated systems through semiparametric adjustments, the DOLS method provides efficient long-run estimates by incorporating lagged and forward-difference terms into the model [62,63]. All econometric analyses were conducted using EViews 12 and GAUSS 22.

The deterministic component of the Fourier transform is expressed as follows:

$$y_t = \delta_0 + \alpha_k \sin\left(\frac{2\pi kt}{T}\right) + \beta_k \cos\left(\frac{2\pi kt}{T}\right) + x_t' \beta + u_t \quad (1)$$

Here, k denotes the optimal frequency, t denotes the time trend, and T denotes the sample size. The sine and cosine terms enable the parametric modeling of gradual structural changes that emerge over time in the series. This approach provides a more analytically

flexible framework for evaluating long-term environmental stock dynamics and the effects of fiscal policy, accounting for time-varying transformation processes.

The results of the Fourier unit root test presented in Table 2 reveal the stationarity properties of the series within the framework of tests that account for both classical and structural breaks. When the KPSS [64] and ADF [65] tests are evaluated together, it is observed that the variables are not stationary at the level but become stationary after first differencing. The results of the Fourier KPSS (F-KPSS) [60] and Fourier ADF (F-ADF) [61] also support this finding and confirm that the series have an integration order of $I(1)$. Furthermore, the significance of the $F(k)$ statistics indicates the presence of nonlinear deterministic components and smooth structural breaks in the series. These results necessitate the application of cointegration analysis to investigate the long-term relationship among the variables.

Table 2. Unit Root Test Results.

Variable	KPSS	F-KPSS $\tau(k)$	k	5% CV	ADF	F-ADF $\tau(k)$	k	p	5% CV	$F_\tau(k)$	Order
IE	0.1566	0.059	1	0.055	−2.2735	−3.197	1	5	−4.350	57.490 *	I(1)
ΔIE	0.1280 **	0.020	1	0.055	−5.9444 *	−7.346	1	1			
$\ln_EPE$	0.7635	0.095	1	0.055	−3.4912	−3.591	1	5	−4.350	17.7052 *	I(1)
$\Delta \ln_EPE$	0.2281 **	0.026	1	0.055	−5.8157 *	−7.541	1	2			
REC	0.1931	0.082	1	0.055	−1.7103	−3.086	1	5	−4.350	57.2415 *	I(1)
ΔREC	0.1069 **	0.015	1	0.05	−6.8540 *	−7.275	1	1			
EE	0.6770	0.059	1	0.055	−3.0151	−3.931	1	5	−4.350	30.8153 *	I(1)
ΔEE	0.1465 **	0.026	1	0.055	−6.2887 *	−6.041	1	0			

Note: F-KPSS tests the null hypothesis of stationarity, while F-ADF tests the null hypothesis of a unit root. The reported $\tau(k)$ statistics correspond to the Fourier-based specifications allowing for smooth structural breaks. The optimal frequency (k) and lag length (p) are selected based on the Akaike Information Criterion (AIC). The $F(k)$ values denote the joint significance of the trigonometric (sin and cos) terms. The critical values for the Fourier KPSS test are taken from Becker, Enders, and Lee [60], whereas those for the Fourier ADF test are based on Enders and Lee [61]. * and ** indicate significance levels of 1% and 5%, respectively.

Accordingly, the long-run relationships among the variables were examined using the Fourier cointegration test, and the long-run coefficients were then estimated using FMOLS and DOLS estimators. This approach ensures consistent estimation of long-run parameters by addressing endogeneity and serial correlation. Accordingly, the long-run models are specified as follows:

Model 1 (Industrial Emissions Model):

$$IE_t = \alpha_0 + \alpha_1 \ln_EPE_t + \alpha_2 REC_t + \alpha_3 \sin\left(\frac{2\pi kt}{T}\right) + \alpha_4 \cos\left(\frac{2\pi kt}{T}\right) + \varepsilon_t \quad (2)$$

In this model, IE is treated as an industry-level indicator of stock externalities, and the long-term effects of environmental protection expenditures and renewable energy consumption are examined. Trigonometric terms account for smooth structural breaks in the time series.

Model 2 (Alternative Emissions Model):

$$EE_t = \beta_0 + \beta_1 \ln_EPE_t + \beta_2 REC_t + \beta_3 \sin\left(\frac{2\pi kt}{T}\right) + \beta_4 \cos\left(\frac{2\pi kt}{T}\right) + u_t \quad (3)$$

In this model, energy-related CO₂ emissions (EE) have been used as an alternative proxy for stock externalities. This enables the robustness of the findings to be evaluated under an alternative emissions specification.

The results presented in Table 3 are obtained using the Fourier cointegration test developed by Tsong et al. [66]. Unlike classical cointegration approaches, this test in-

incorporates smooth structural breaks in the series via sine and cosine terms and tests for nonlinear long-run relationships. From this perspective, it is methodologically consistent with the assumption that policy changes and structural transformations may influence environmental indicators.

Table 3. Results of the Fourier Cointegration Test.

Model	$F_{\mu}(k)$	k	CI_f^m	Critical Values		
				%1	%5	%10
Model 1	31.106 *	2	0.008 *	0.127	0.081	0.052
Model 2	45.520 *	3	0.011 *	0.143	0.094	0.075

Note: * indicates statistical significance at the 1% level. CI_f^m shows the test statistic calculated for the Fourier-Tsong cointegration test. The critical values were obtained from the work of Tsong et al. [66]. Additionally, the $F_{\mu}(k)$ statistics test the significance of the trigonometric terms in the model; the criterion values for the constant, trend, and Fourier component ($m = 1$) models at the 1%, 5%, and 10% significance levels are 5.860, 4.019, and 3.306, respectively.

In Model 1 (with IE as the dependent variable), the Fourier cointegration test statistic exceeds the critical thresholds. This result indicates the existence of a long-run equilibrium relationship among industrial emissions, environmental protection expenditures, and renewable energy consumption. Furthermore, the significance of the $F(k)$ statistic, indicating the common significance of the trigonometric terms, suggests that the relationship is shaped by a process involving smooth structural breaks rather than a linear structure. This result is consistent with the Fourier-based environmental economics literature, which emphasizes the importance of accounting for nonlinear transformations and smooth structural breaks in time series of environmental indicators [59,67–69].

In Model 2 (with EE as the dependent variable), a long-run cointegration relationship was also identified between energy-related carbon emissions and the explanatory variables. The fact that the test statistic exceeds the critical values indicates that energy-based emissions move systematically with environmental protection expenditures and renewable energy consumption in the long run. This finding supports the notion that stock externalities have a cumulative character not only through industry-based factors but also through the structure of energy production and consumption.

3.3. Long-Run Coefficient Estimates

To determine the direction and magnitude of the relationship identified by the Fourier cointegration test, we proceeded to estimate the long-run coefficient. The detection of cointegration enables the application of FMOLS (Fully Modified Ordinary Least Squares) and DOLS (Dynamic Ordinary Least Squares) methods to ensure consistent parameter estimation. These methods correct for endogeneity and serial correlation issues that may arise in cointegrated series, ensuring unbiased and efficient estimation of long-run coefficients. Furthermore, the combined use of FMOLS and DOLS estimates enhances the robustness of the findings, thereby strengthening the statistical reliability of the long-run relationship.

The FMOLS and DOLS estimation results presented in Table 4a show that the $\ln_EPE$ variable, representing environmental protection expenditures, is positive and statistically significant in both estimation methods. According to the FMOLS estimates, a 1% increase in environmental protection expenditures is associated with an approximately 2.11-unit increase in industrial emissions in the long run. Similarly, the DOLS estimate of 2.04 indicates that this relationship remains robust across alternative long-run estimation methods. The results are consistent with the Environmental Kuznets Curve framework, which highlights the nonlinear relationship between environmental public expenditures and pollution [16,19], and suggest that in early stages of development, where scale effects dominate in economies

like Türkiye, an increase in public expenditures may be associated with the expansion of economic activity and higher emission levels. This finding is also consistent with studies showing that public expenditures in developing economies can increase emissions by expanding economic activity through scale effects [42,48,70]. Similarly, Adewuyi [40] demonstrates that while environmental public expenditures may reduce emissions in the short term, they may increase total emissions in the long term due to indirect scale effects.

Table 4. FMOLS and DOLS Long-Run Coefficient Estimator Results.

(a)							
Model 1 FMOLS				Model 1 DOLS			
Dependent Variable IE	Coefficient	St. Error	p Value	Dependent Variable IE	Coefficient	St. Error	Statistic Value
ln_EPE	2.1125 *	0.7282	0.007	ln_EPE	2.0375 *	0.7239	0.009
REC	−1.4391 ***	0.7067	0.051	REC	−1.4967 ***	0.7366	0.051
Sin	−10.2245 *	1.7696	0.000	Sin	−10.1568 *	1.8763	0.000
cos	7.7668 *	1.7504	0.000	cos	7.7472 *	1.7944	0.000
Const.	23.8796	26.2132	0.370	Const.	26.3058	26.3058	0.332
(b)							
Model 2 FMOLS				Model 2 DOLS			
Dependent Variable EE	Coefficient	St. Error	p Value	Dependent Variable EE	Coefficient	St. Error	Statistic Value
ln_EPE	0.040947 *	0.008536	0.0000	ln_EPE	0.039542 *	0.008594	0.0001
REC	−0.032446 *	0.008283	0.0005	REC	−0.032524 *	0.008744	0.0009
Sin	−0.093858 *	0.020742	0.0001	Sin	−0.097059 *	0.022276	0.0002
cos	0.076486 *	0.020517	0.0009	cos	0.074837 *	0.021303	0.0015
Const.	5.598714 *	0.307262	0.0000	Const.	5.628343 *	0.316273	0.0000

Note: * and *** indicate statistical significance at the 1%, and 10% levels, respectively.

Nevertheless, the dominance of the scale effect should not be regarded as the only possible explanation for the positive relationship identified in this study. The effectiveness of environmental protection expenditures may also depend on the composition of public spending, the efficiency of policy implementation, and the time required for environmental investments to generate measurable outcomes. Moreover, increasing environmental protection expenditures may partly reflect a policy response to rising environmental pressures rather than an immediate improvement in environmental quality. Therefore, the estimated positive coefficient should also be interpreted in light of these alternative mechanisms. This interpretation is also consistent with the characteristics of the Turkish economy during the sample period, where industrial expansion and economic growth generally outpaced the environmental gains achieved through environmental protection expenditures.

The statistical significance of the sine and cosine terms further indicates that the long-run relationship is characterized by nonlinear structural changes rather than a purely linear adjustment process. In the case of Türkiye, these structural changes may reflect the gradual evolution of environmental policies, the energy transition process, and the country's adaptation to international environmental commitments during the sample period. In this context, these findings suggest that the short- and medium-term effects of environmental protection expenditures on expanding production scale outweigh their emission-reducing effects, as compositional and technical effects have not yet become sufficiently dominant. Consequently, the emission-reducing effects of environmental expenditures may become more pronounced as structural transformation, changes in the energy mix, and technological advancements gain momentum.

The REC coefficient is negative and statistically significant at the 10% level in both estimation methods. The FMOLS estimates indicate that a one-unit increase in renewable energy consumption is associated with an approximately 1.44-unit reduction in industrial emissions, while the DOLS estimates yield a similar coefficient, confirming the stability of this long-run relationship. This indicates that increases in renewable energy use are inversely related to industrial emissions over the long term. This finding is consistent with the extensive literature reporting a negative long-run association between renewable energy consumption and carbon emissions [71–73]. Furthermore, it supports the view that the use of renewable energy sources can help reduce environmental negative externalities by improving carbon efficiency in production processes [74]. This finding suggests that the use of renewable energy may help mitigate emission pressures even in an economic structure where scale effects remain dominant.

The FMOLS and DOLS results presented in Table 4b show that the $\ln_EPE$ coefficient is positive and highly significant. This finding, consistent with the results in Table 4a, reveals that environmental protection expenditures are positively associated with increases in energy-based emissions. The results confirm the main model's findings and demonstrate that environmental public expenditures exhibit similar dynamics across different emission indicators. The findings are consistent with the literature, which argues that public expenditures can expand economic activity through scale effects in the short and medium term, particularly in fossil fuel-intensive energy systems [42,70]. This suggests that environmental protection expenditures alone may not be sufficient, and that the emission-reducing effect depends largely on the depth of the energy transition and institutional capacity. This finding reinforces the main model results for the energy sector and suggests that the emission-reducing effects of environmental expenditures may become more pronounced through a transition toward low-carbon energy systems [16,19].

In Table 4b, the REC coefficient is negative and statistically significant in both methods, supporting the findings of Model 1. This result indicates that renewable energy consumption is associated with lower emissions in the long run, even under alternative model specifications. The findings suggest that shifting from fossil fuel-based energy production toward renewable energy sources may help reduce emissions and are conceptually consistent with the stock externality approach, which emphasizes that the effects of environmental policies emerge over time [6,75]. The results also show that environmental protection expenditures currently operate mainly through scale effects rather than emission-reducing technical transformations. In contrast, renewable energy use appears to play a more effective role in reducing environmental pressures by changing the energy mix. Therefore, long-term emission reductions are likely to depend on investments in renewable energy, low-carbon technologies, and structural transformation.

4. Conclusions

Today, many environmental problems arise not only from current emission flows but also from pollution stocks that accumulate over time and create long-term environmental pressures. Therefore, environmental externalities should be evaluated not only through short-term effects but also through long-term accumulation dynamics. This study examines the relationship between environmental protection expenditures, industrial emissions, and renewable energy consumption in Türkiye between 1990 and 2023 within the framework of stock externalities theory. Türkiye was selected because it is a developing and industrialising economy that is increasingly influenced by international environmental commitments such as the European Green Deal and the Paris Climate Agreement. Methodologically, the Fourier-based cointegration approach allows gradual structural changes and energy transition processes to be incorporated into the analysis more flexibly than traditional linear models.

The findings reveal a long-term relationship between industrial emissions and environmental protection expenditures in Türkiye and support the dominance of scale effects in the economy [16,40,42,44,76]. The results suggest that environmental expenditures increase together with production activity rather than creating sufficient technical transformation to reduce emissions. In contrast, renewable energy consumption has a negative effect on emissions, indicating that environmental sustainability depends more on technological transformation than on the size of expenditures alone [47,48,52]. Overall, the findings imply that renewable energy transition and structural transformation play a more important role in reducing emissions than traditional environmental expenditures. This study is subject to certain limitations. First, the analysis focuses exclusively on the case of Türkiye; therefore, caution should be exercised when generalizing the findings to other countries. Second, stock externalities are proxied by industrial emissions, and future research may extend the analysis by employing alternative indicators of environmental stock accumulation and broader cross-country datasets. Despite these limitations, this study contributes to the literature both theoretically and empirically by examining environmental degradation within the stock externality framework and by providing new evidence on the long-run relationship between environmental protection expenditures, renewable energy consumption, and industrial emissions using a Fourier-based cointegration approach. In this regard, the following policy recommendations emerge:

- Environmental protection expenditures are still largely directed toward reactive measures such as waste management and environmental clean-up. Public resources should instead focus more on clean production technologies that reduce emissions at their source.
- Sectoral transformation policies should support the transition to low-carbon production technologies, especially in carbon-intensive sectors such as energy, cement, chemicals, and iron-steel industries. Environmental expenditures should contribute to production transformation rather than only covering compliance costs.
- Current environmental policies mainly target flow externalities. However, the stock externality perspective requires policies to also consider cumulative carbon accumulation and long-term ecological damage.
- Local governments should expand environmental expenditures beyond cleaning and waste services toward long-term emission reduction investments such as low-carbon transport, energy-efficient infrastructure, and smart city systems.

However, this study also has certain limitations. The use of annual macroeconomic data limits the ability to observe heterogeneity across sectors. Future studies examining this relationship at the micro or sectoral level will therefore contribute to a better understanding of stock externalities. Additionally, comparative country analyses focusing on institutional structures and levels of technological advancement could inform the development of tailored policy sets for economies at different stages of development.

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