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Research Article

R&D Expenditures in Fossil Fuels vs. Renewable Energy: Insights on Energy Transition through Cross-Country Analysis

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Abstract: This study examines the impact of public R&D expenditures in the fossil fuel and renewable energy sectors on energy transition through the carbon intensity variable. The analysis uses Pedroni's Panel Cointegration Test and the Group Mean Panel Dynamic Ordinary Least Squares, utilizing data from 16 IEA countries between 1993 and 2022. Unlike previous studies that primarily focus on either general R&D expenditures or aggregate energy sector R&D, this study provides a comparative analysis of fossil and renewable sectors, addressing a significant gap in the literature. The findings reveal that public R&D expenditures in the renewable energy sector may significantly reduce carbon intensity, whereas public R&D expenditures in the fossil fuel sector increase carbon intensity. These results suggest that, contrary to the common assumption in the literature, the heterogeneous effects of R&D spending across subsectors of energy industry should be taken into account. Therefore, Redirecting R&D expenditures toward renewable energy technologies, rather than fossil energy sector, may accelerate the energy transition process.

Keywords: Energy Transition, carbon intensity, R&D
Jel Codes: O30, Q35, Q43

Fosil Yakıtlar ve Yenilenebilir Enerjide Ar-Ge Harcamaları: Enerji Geçişine Dair Panel Veri Analizinden Bulgular

Öz: Bu çalışma, fosil yakıt ve yenilenebilir enerji sektörlerinde kamu Ar-Ge harcamalarının, karbon yoğunluğu değişkeni aracılığıyla, enerji geçişi üzerindeki etkisi incelenmektedir. Analiz, 1993 ile 2022 yılları arasında İEA'ya üye 16 ülkeden alınan verilerle Pedroni'nin Panel Eşbütünleşme Testi ve Grup Ortalama Panel Dinamik En Küçük Kareler Yöntemi'ni kullanmaktadır. Önceki çalışmalardan farklı olarak, bu çalışma, genel Ar-Ge harcamaları ya da toplam enerji sektörü Ar-Ge'si üzerine odaklanmak yerine, fosil ve yenilenebilir enerji sektörlerini karşılaştırmalı bir şekilde analiz ederek literatürdeki önemli bir boşluğu doldurmaktadır. Bulgular, yenilenebilir enerji sektöründeki kamu Ar-Ge harcamalarının karbon yoğunluğunu önemli ölçüde azaltabileceğini, oysa fosil yakıtlar sektöründeki kamu Ar-Ge harcamalarının karbon yoğunluğunu artırabileceğini göstermektedir. Bu sonuçlar, literatürdeki yaygın varsayımın aksine, enerji endüstrisinin alt sektörlerinde Ar-Ge harcamalarının heterojen etkilerinin dikkate alınması gerekliliğini ortaya koymaktadır. Bu bağlamda, Ar-Ge harcamalarının fosil enerji sektöründen ziyade, yenilenebilir enerji teknolojilerine yoğunlaştırılması, enerji geçiş sürecini hızlandırabilir.

Anahtar Kelimeler: Enerji Geçişi, karbon yoğunluğu, Ar-Ge
Jel Kodları: O30, Q35, Q43

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1. Introduction

Global warming represents one of the most serious challenges confronting humanity in the modern era, fueled largely by the excessive carbon emission. Before the industrial revolution, global atmospheric greenhouse gas concentrations were approximately 278 ppm, while by 2022, this figure had surged to 421 ppm (Bashir et al., 2024; NOAA, 2022). While this rising carbon intensity pollutes the environment, at the same time it causes global warming. This global warming, on the other hand, is one of the main causes of almost all climatic disasters, such as excessive heat, floods in some regions and drought in others, as well as related water and food shortages. Moreover, these climatic problems are all tied to other socioeconomic problems due to the environmental crisis, such as income inequality and the dislocation of masses.

Since this is a global problem crossing over the borders, some international cooperations and initiatives are set to tackle this issue. Some of those initiatives are the Paris Climate Agreement, the EU Green Deal, and COP26. Additionally, the United Nations has set some goals to be achieved in terms of those environmental problems in their Sustainable Development Goals. Energy sector holds a significant place among these measures, as increasing energy consumption driven by rising demand on both the production and consumption sides is a major contributor to environmental problems. For this reason, moving away from fossil fuels toward renewable and environmentally friendly energy alternatives, a process known as the energy transition, has become essential (Kartal et al., 2024a; Wan et al., 2022; Shahbaz et al., 2013a; Kartal et al., 2024b).

Due to its significance, the energy sector is one of the first areas addressed when tackling environmental problems. However, since energy consumption is one of the most critical inputs for economic growth, economic growth and environmental issues often emerge as conflicting priorities for policymakers. In this framework, governments often prioritize advancing economic development over addressing environmental pollution in the trade-off between the two objectives (Caglar and Ulug, 2022). For this reason, academic studies focusing on the energy transition have gained significant momentum in recent decades, aiming to resolve this puzzle and develop environmental policies without hindering economic growth.

As shown in Figure 1 below, total R&D expenditures in the energy sector in IEA member countries increased until the 1980s. However, after the 1980s, these expenditures followed a downward trend, continuing until the 2000s. From the 2000s onwards, a notable recovery and strong upward trend in total R&D expenditures in the energy sector can be observed. This shift aligns with growing academic discussions and policy emphasis on the need for innovation and technological advancements to address environmental challenges. However, in most of the studies mentioned, either the general impact of R&D expenditures on carbon intensity and, consequently, the energy transition has been examined, or the focus has been specifically on the effect of R&D expenditures in the renewable energy sector(Su, Chen, and Lin 2023; Cheng and Yao, 2021) on the energy transition. These studies generally focus on the broad impact of R&D on carbon intensity, with few examining its effects at a more detailed level, and since innovations arising from R&D can be applied in various contexts, it remains unclear whether the specific impact of R&D on energy transition could be explicitly determined, leaving the understanding of its ecological innovation outcomes overly general and uncertain (Huang et al., 2021).

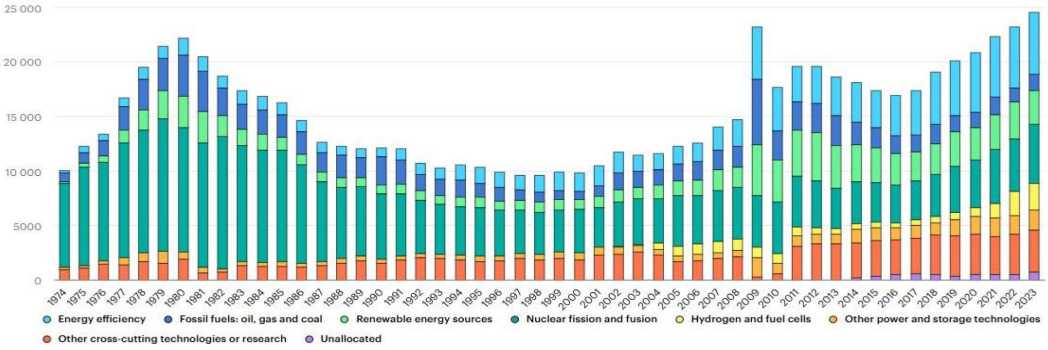

Figure 1. Total R&D Budgets in IEA Countries (2023 prices, Million EUR) **Source**: IEA

Therefore, in this work, to significantly contribute to the literature, the impact of R&D expenditures on carbon intensity has, to the best of our knowledge, been investigated for fossil and renewable energy sources separately for the first time. This is an important inquiry, as in recent decades, various policymakers and academic studies (Ouyang and Lin, 2014; Rentschler and Bazilian, 2017; Skovgaard and van Asselt, 2019; Arzaghi, and Squalli, 2023; Antimiani, et al., 2023). have called for the shift of fossil fuel subsidy policies in favor of renewable energy. The underlying argument of these approaches is the need for greater support for the renewable energy sector, which is seen as more effective in addressing climate change and environmental issues.

The significance of this issue becomes even clearer when considering that nonrenewable energy account for approximately 80% of the world's energy supply. (Opoku, et al., 2024). Given that fossil resources are currently more cost-effective than renewable resources, if the R&D budget allocated to fossil fuels leads to a reduction in production costs, the resulting increase in demand could potentially raise carbon intensity, rather than reduce it. On the other hand, particularly in regions where renewable resources are limited, if R&D expenditures on fossil energy sources contribute to improved energy efficiency and/or reduced carbon intensity per unit of production, these expenditures have the potential to positively influence the progression of the energy transition, similar to the expected impact of R&D spending on renewable energy. Therefore, this study aims to make a significant contribution by comparing the different effects of R&D investment in the renewable and fossil energy sectors on carbon intensity, setting it apart from other studies in the literature. This comparison is intended to offer meaningful insights for the academic literature and as well as policymakers.

In this context, this study examines the impact of public R&D expenditures on fossil and renewable energy sources on the energy transition through the carbon intensity variable. The study uses data from 1993 to 2022 and employs econometric methods, including cointegration tests and Pedroni's group mean Panel Dynamic Ordinary Least Squares method(Pedroni, 1999; Pedroni, 2001). Following the introduction of the study, the second section reviews the literature and highlights key arguments. In the third section, the methodological approach and preliminary tests, together with the datasets utilized, are explained and detailed. In the fourth section, findings from econometric techniques are discussed and compared with similar analyses in the literature. Finally, in the fifth section, conclusions drawn based on the findings and policy suggestions are offered.

2. Literature Review

In recent years, as the urgency of rising carbon emissions and related environmental problems becomes more visible, a number of studies investigate the issue of carbon intensity and energy transition. One important branch of these studies is related to the effect of R&D spending on carbon intensity and energy transition. In these studies, which were conducted for various cases and sectors, it is generally claimed that increasing R&D spending may boost the energy transition process by reducing carbon intensity through different channels. For example, Zhao et al. (2023), by using spatial econometrics techniques with data from China's provinces ranging from 2007 to 2019, have investigated the relationship between R&D and carbon intensity. According to their estimation results, R&D spending may reduce carbon emissions. Some other studies (Guo et al., 2019; Linnenluecke et al., 2019; Huang et al., 2020a; Böhringer et al., 2020; Luo and Zhang, 2022; Danish and Ulucak, 2022; Chen et al., 2023), with different techniques, have also achieved comparable results for different regions.

Beyond those studies, recently some other studies have been investigating the effect of R&D spending on carbon intensity, specifically in the energy sector. Since the energy industry is one of the most important sources of carbon intensity and a major factor in the energy transition process. One of the earliest of those studies was conducted by Garrone and Grilli (2010), where, according to their causality tests, public R&D investment hasn't been found to significantly affect carbon intensity or the carbon factor. Moreover, they found that carbon trends may affect the structure of energy R&D budgets. In contrast to the symmetric approach adopted in previous studies, Yanzhe and Ullah (2023) have adopted a nonlinear approach. In their analysis for China, they concluded that, according to the linear model, energy regulations and innovation contribute to the reduction of carbon intensity in the long term. However, according to the nonlinear model, positive shocks in energy R&D may reduce carbon intensity, but negative shocks have no effect.

Some other studies have investigated specifically the effect of energy efficiency and emission reduction technologies on carbon intensity. In this perspective, Huang et al. (2021) analyzed the Chinese provincial data through various techniques and concluded that energy-saving R&D investments are beneficial for carbon intensity, while these benefits are higher when they come from private enterprises. Gu et al. (2020) also investigated the effects of patents for similar technologies on carbon intensity for Chinese provinces and achieved a similar conclusion to Huang et al. (2021).

As it is investigated in the literature, differently from general R&D spending, specifically R&D in the energy sector may yield different effects on carbon intensity. Similarly, R&D spending in the energy sector may also yield different effects for different subsectors of the energy industry, due to heterogeneity among them. Cheng and Yao (2021), for example, analyzed the effect of R&D spending specifically in the renewable energy sector for Chinese provinces and concluded that a 1% increase in renewable energy R&D spending may yield a reduction in carbon intensity by 0.051% in the long term. Xin et al. (2022) specifically focused on renewable energy innovation in Chinese manufacturing sectors through spatial econometrics techniques and concluded that this R&D spending helps to reduce carbon intensity in central provinces and neighboring provinces.

Similarly, Su, Chen, and Lin (2023) explored the mechanisms through which renewable energy innovation influences energy transition, using data from 30 Chinese provinces from 2006 to 2017. Their findings indicate that innovations in wind and solar energy make comparatively larger contributions to the growth of carbon productivity. They also suggest that renewable energy innovation is more likely to improve carbon productivity in regions with higher coal consumption, highlighting coal dependency as a critical channel through which renewable innovation impacts the energy transition. In addition to renewable energy, some studies also explore R&D investments in other energy types. For instance, Pata et al. (2024) examine the impact of R&D investments in renewable and nuclear energy on the carbon intensity in Germany between the first quarter of 2000 and the fourth quarter of 2020. Their findings indicate that R&D spending in both renewable and nuclear energy have a growing influence on the energy transition.

The majority of studies in the literature focus on China, as the country, often referred to as the factory of the world, has, not surprisingly, been addressing environmental challenges and striving to reduce carbon intensity, particularly in relation to high levels of air pollution. However, some studies have also examined groups of countries using a panel econometric approach. For instance, Kartal et al. (2024a) conducted a study on Nordic countries to explore the effects of renewable energy R&D investments on carbon dioxide emissions. Utilizing the wavelet local multiple correlation (WLMC) model and data spanning from 2000 to 2021, they applied various specifications and cases within the TWLMC framework. Their analysis yielded mixed results. Another recent study (Bashir et al., 2024) investigates the relationship between energy transition and environmental technologies in the G20 countries over the period 1995-2019. Their findings indicate that environmental innovations support the progress of the energy transition, while reliance on fossil fuels and environmental degradation impede it.

Zhu, Liao, and Liu (2021) also used a panel dataset covering 18 IEA members to investigate the impact of energy R&D policies on energy mix and conservation. Their findings indicate that public energy R&D reduced overall energy intensity by 12% and accounted 39% to the decarbonization. Additionally, the effectiveness of energy R&D

policies are claimed to vary across countries. Finally, Caglar and Ulug (2022) analyze the role of energy efficiency R&D budgets in the transition to green energy for Canada, USA, France, Germany, and Japan from 1985 to 2019, using AMG and CCEMG methods. Their findings suggest that the allocated budgets for energy efficiency R&D are insufficient to significantly improve environmental quality.

While most studies highlight the positive impact of energy R&D on carbon intensity at the macro level, Li et al. (2021) examine this issue from a microeconomic perspective, focusing on firms. Analyzing data from public firms in 52 countries (2002–2015), they find that while R&D plays a critical role in reducing carbon emissions, its marginal effect diminishes over time. Additionally, their study identifies an inverted U-shaped relationship, with R&D's optimal impact occurring when it accounts for 22.91% of a firm's operational expenses.

In conclusion, the reviewed literature predominantly focuses on the impact of overall R&D expenditures and renewable energy sector R&D investments on energy transition, or more specifically, carbon transition. Therefore, the following empirical analysis makes a significant contribution to the literature by separately examining the effects of both renewable and fossil energy innovation expenditures on carbon intensity in a selected group of IEA countries with available data.

3. Empirical Methodology

This study explores the influence of public R&D expenditures in the fossil fuel and renewable energy sectors on carbon intensity, which is considered a key indicator of energy transition. Before outlining the methodology, the datasets employed in the analysis will be carefully examined. All variables, including the dependent and control variables, have been identified through an extensive review of the relevant literature.

The dependent variable, carbon intensity, is utilized in this study as it is the most commonly employed indicator of energy transition in the literature. The data for carbon intensity is sourced from the World Bank's World Development Indicators. It measures the emission of all greenhouse gases, expressed in kilograms of carbon dioxide equivalent per constant 2015 Million US dollars of GDP. The primary independent variables, namely public R&D expenditures in the fossil fuel and renewable energy sectors, are obtained from the International Energy Agency in terms of millions of dollars. R&D activities in Fossil fuel sector can be categorized in various form such as extracting, converting, generating, transporting, distributing, controlling, use of energy and according to (IEA, 2011) some of R&D activities are listed below:

*Rental expenses; social security and pension schemes for RD&D workforce.

*Enhancing refinery performance, optimizing product blends, and minimizing environmental impacts associated with refineries and refined products.

*Assessment and evaluation of transportation and pipeline network systems.

*Development of sub-sea pipelines and large-scale underwater storage facilities.

*Improvement in efficiency of natural gas liquefaction and vaporization processes.

*Safety in LNG storage and transportation, gasification of naphtha and feedstocks.

*Transporting natural gas in compact hydrate forms.

*Innovations in micro, multi-fuel gas turbines, combustion systems, turbo machinery; refinement of combustion and flue gas cleanup, excluding CO2 extraction.

*Advanced techniques and equipment for both onshore and offshore deep drilling.

*Coal preparation, such as the removal of impurities, crushing, and dewatering.

*Modernization, retrofitting, and extending the operational lifespan of power plants.

*Conversion of CO2 into mineral carbonates, monitoring and underground CO2.

The trade variable, obtained from the World Development Indicators (WDI), quantifies trade openness by calculating the total value of imports and exports as a percentage of GDP. This variable is included because countries with greater openness to international trade may exhibit different dynamics regarding carbon intensity compared to less trade-dependent nations. Additionally, urbanization is included as a control variable, measured as the percentage of the urban population relative to the total population, and is also sourced from the World Development Indicators. This is based on the premise that carbon intensity in urban areas may differ significantly from that in rural areas due to variations in consumption and production patterns. Finally, total natural resource rents, which include oil, natural gas, coal, mineral, and forest rents as a percentage of GDP, is added as a control variable to examine its potential impact on carbon intensity. This data is also sourced from the World Development Indicators. This represents a significant and original contribution to the literature, as, to the best of our knowledge, this is the first study to explore this specific relationship within this particular body of research. This is an important inquiry, since countries rich in natural resources, such as oil and gas, may have less incentive to prioritize reducing carbon intensity or accelerating the energy transition process. Table 1 provides a detailed summary of the descriptive statistics for all datasets.

Table 1. Descriptive Statistics

Variable	Obs	Mean	Std. Dv.	Min	Max	Database
Carbon Intensity	480	229517	98605	45684	504265	World Bank
Fossil Energy Public R&D	480	99.38	261.99	0	4635.1	IEA
Renewable Energy Public R&D	480	136.27	258.35	1.64	3045.8	IEA
Trade Openness	480	69.95	28.77	15.72	176.71	World Bank
Urbanization	480	78.99	7.56	57.11	92.88	World Bank
Total Natural Resource Rent	480	1.03	2.00	0.008	12.61	World Bank

This study utilizes 30 years of annual data, spanning from 1993 to 2022, for 16 member countries of the International Energy Agency (IEA). These countries, Austria, Canada, Denmark, Finland, France, Germany, Italy, Japan, the Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, the United Kingdom, and the United States are selected based on the availability of comprehensive and complete data records throughout the study period. Moreover, due to the wide range of values in the data for public R&D expenditures in the renewable and fossil energy sectors, which are expressed in millions of dollars, the natural logarithmic transformation of these variables has been applied to normalize the data and reduce the impact of extreme values, together with carbon intensity data.

Table 2. Correlation Analyses

	Carbon	rerd	ferd	to	urb	rent
Carbon	1.00					
rerd	0.04	1.00				
ferd	0.26	0.59	1.00			
to	-0.48	-0.16	-0.39	1.00		
urb	0.00	0.09	0.10	-0.03	1.00	
rent	-0.09	-0.22	0.20	-0.00	0.09	1.00

Correlation analysis for variables is conducted and findings are listed in table 2. Also, all analyses are performed using Stata 15.0 software. Upon completing the data collection, the subsequent step involved the development of the estimation models, as outlined in Equation 1 and Equation 2 below where carbon, ferd, rerd, to, urb and rent implies fossil energy public R&D spending, renewable energy public R&D spending, trade openness, urbanization and total natural resource rent, respectively.

In constructing the model and selecting proxy variables, insights from the literature were utilized. Carbon intensity was chosen as the main dependent variable, as it has been widely applied in previous studies (Gu et al., 2020; Cheng and Yao, 2021; Huang et al., 2021). R&D spending in the fossil energy and renewable energy sectors was identified as the main independent variable. Although patent stocks or applications have sometimes been used as proxies for R&D, R&D spending was selected as the proxy variable for R&D

activities due to its frequent use in the literature (Garrone and Grilli, 2010; Huang et al., 2020b; Mahmood et al., 2024).

Trade openness, another variable frequently addressed in the literature (Huang et al., 2020b; Su, Chen, and Lin, 2023; Mahmood et al., 2024), was included as a control variable because a higher volume of international trade is associated with increased carbon intensity. Urbanization was also considered a factor that could raise carbon intensity through increased production and consumption. Therefore, it was incorporated as a control variable in reference to the literature (Gu et al., 2020; Huang et al., 2020b; Cheng and Yao, 2021).

Models Estimation: To account for potential correlation among R&D spending in fossil energy and R&D spending in renewable energy sector two different model is estimated. Estimated models are expressed in the equaition 1 and equation 2 below.

$$LnCarbon_{it} = \beta_0 + \beta_1 Ln\mathrm{rerd}_{it} + \beta_2 \mathrm{to}_{it} + \beta_3 \mathrm{urb}_{it} + +\beta_4 \mathrm{rent}_{it} + \mathrm{u}_{it} \quad (1)$$

$$LnCarbon_{it} = \beta_0 + \beta_1 Ln\mathrm{ferd}_{it} + \beta_2 \mathrm{to}_{it} + \beta_3 \mathrm{urb}_{it} + +\beta_4 \mathrm{rent}_{it} + \mathrm{u}_{it} \quad (2)$$

In contemporary econometrics, the range of available panel data techniques is expanding rapidly. However, each of these techniques comes with its own set of advantages, disadvantages, and specific prerequisites for their application. As a result, conducting preliminary tests is essential to determine the most appropriate technique for the dataset at hand. Among these, slope homogeneity tests and cross-sectional dependency tests are particularly important, especially when analyzing panel data that encompasses multiple countries, as such data often exhibits unit-specific and time-specific effects. Accordingly, this study begins by performing these two critical preliminary tests.

Table 3. CD and Homogeneity Tests

Cross Sectional Dependency Tests						
	LM Test Statistic	P-value	LM Adj. Statistic	P-value	LM CD Statistic	P-value
1st Model	240.7	0.00***	18.60	0.00***	5.33	0.00***
2nd Model	240.8	0.00***	18.65	0.00***	5.13	0.00***
Homogeneity Tests						
			Δ	p-value	Δadj	p-value
1st Model			26.38	0.00***	29.50	0.00***
2nd Model			26.08	0.00***	29.16	0.00***

The analysis begins by testing for slope homogeneity using the Delta test developed by Pesaran and Yamagata (2008). To identify cross-sectional dependency, three approaches are applied: the LM test by Breusch and Pagan (1980), the CD test by Pesaran (2004), and the bias-adjusted LM test from Pesaran et al. (2008). As reported in Table 3, all methods confirm significant cross-sectional dependency. Moreover, the Delta test results indicate slope heterogeneity by rejecting the null hypothesis of homogeneity.

Conducting a stationarity test is an essential step in panel data analysis to ensure the reliability and validity of econometric results. Non-stationary data can lead to spurious regression results, as trends or unit roots may distort relationships between variables. In panel data, where observations span both cross-sections and time periods, testing for stationarity is particularly critical, as non-stationarity in individual units or across the panel can undermine the assumptions of many econometric techniques. Ensuring stationarity enables more robust estimation of long-term relationships.

Given the strong evidence of cross-sectional dependency revealed by the cross-sectional dependency tests, this study employs the Multivariate Augmented Dickey-Fuller (MADF) test, a second-generation unit root test developed by Taylor and Sarno (1998), which accounts for such dependencies. As shown in Table 4, the null hypothesis of non-stationarity is rejected for all variables at the 1% significance level, indicating that the series are stationary. This approach ensures that the stationarity properties of the data are robustly assessed while accounting for the interconnected nature of the cross-sectional units. In addition to its suitability for addressing cross-sectional dependency, the Multivariate Augmented Dickey-Fuller (MADF) test is particularly appropriate for datasets where the number of time observations exceeds the number of cross-sectional units. Given the structure of this study, with 30 years of time observations and 16 cross-sectional units, the MADF test satisfies this prerequisite and is deemed an appropriate choice for robust stationarity analysis. As shown in Table 4, the test statistics for all variables exceed the critical value at the 5% statistical significance level, indicating that the series are stationary.

Table 4. MADF Unit Root Test

	MADF	5% Critical Values
carbon	41.51	27.49
ferd	215.98	27.49
rerd	116.36	27.49
to	146.84	27.49
urb	16228.08	27.49
rent	160.96	27.49

Panel cointegration testing is conducted to assess the long-run relationships between variables in panel data analysis. This test is essential to determine whether a stable, long-term equilibrium relationship exists between the variables. By testing for cointegration, it can be confirmed whether non-stationary series move together over time, suggesting a meaningful connection. After confirming that the series are stationary through unit root tests, cointegration tests are conducted to confirm the robustness of results from the following parameter estimations. This is important to verify that the relationship among variables is not spurious. Therefore, in this part, Pedroni's (1999, 2004) cointegration test is employed. In this process, to account for cross-sectional dependency, the data is demeaned as suggested by Levin et al. (2002). The findings of this test imply a cointegration relationship among variables, and details are discussed in the next section.

There are various econometric techniques that can be used depending on the existence of cross-sectional dependency. The first-generation estimators are not capable of addressing cross-sectional dependency, while second-generation estimators are capable of handling this issue. For this reason, the Group Mean Panel Dynamic Ordinary Least Squares estimator, introduced by Pedroni (2001), which is a second-generation estimator, is chosen to account for both cross-sectional dependency and the heterogeneous characteristics of our data (Celik et al., 2024). This technique is based on the dynamic OLS structure for panel data through the integration of cointegrated regression and addressing the endogenous feedback effects through the inclusion of lead and lagged differences of the explanatory variables (Pedroni, 2001; Neal, 2014; Bektaş and Ursavaş, 2023).

$$Y_{it} = \mu_i = \beta_i X_{it} + u_{it} i = 1, \dots, N t = 1, \dots, T \tag{3}$$

As explained by Tanil et al. (2023) through Equations 3, 4, and 5, the cointegration model in Equation 3, which exhibits heterogeneity across units, is estimated for each unit using the DOLS method with lagged and leading values, and the results are subsequently aggregated across the panel using the MG approach.

$$\hat{\beta}_{PGMPDOLS} = N^{-1} \left[\sum_{i=1}^{N} \left(\sum_{t=1}^{T} (Z_{it} Z'_{it}) \right)^{-1} \right] \left(\sum_{t=1}^{T} (Z_{it} \bar{y}_{it}) \right) \tag{4}$$

$$t_{\hat{\beta}_{DOLS,i}} = N^{-1} \sum_{t=1}^{T} t_{\beta_{DOLS,i}} \tag{5}$$

Additionally, Equation 4 represents the vector of explanatory variables, while Equation 5 outlines the calculation of Pedroni's group mean Panel Dynamic Ordinary

Least Squares test statistic (Tanil et al., 2023). This approach is implemented using the Stata command "xtpedroni," developed by Neal T. (2014). The estimation results for both the cointegration tests and parameter estimates are presented in the following section on findings and discussion.

4. Findings and Discussion

In this section, the findings of the Pedroni cointegration test and Pedroni's group mean Panel Dynamic Ordinary Least Squares technique, summarized in the previous section's methodological framework, is explained and discussed. First, as shown in Table 5 below, with Newey West three lags, 1 augmented lags and panel mean included, cointegration relationships among the variables are identified at varying significance level based on the Phillips Perron t and Augmented Dickey Fuller t test statistics, and Modified Phillips Perron t test. In light of these results, the study proceeds with parameter estimations.

Table 5. Pedroni Cointegration Test Group Statistics

1st Model	Statistic	P Value
Modified Phillips Perron t	1.94**	0.02
Phillips Perron t	-1.45*	0.07
Augmented Dickey Fuller t	-2.27**	0.01
2nd Model		
Modified Phillips Perron t	1.89**	0.02
Phillips Perron t	-1.65**	0.04
Augmented Dickey Fuller t	-2.08**	0.01

Note: * and ** indicates significance at 10% and 5% respectively.

Table 6 and table 7 presents the Pedroni's group mean Panel Dynamic Ordinary Least Squares estimates with one lags and leads, revealing several noteworthy relationships among the variables analyzed, as all t-statistics are significant, surpassing the critical values at the 1% and 5% significance levels. The first notable finding here relates to the evidence indicating the carbon intensity reducing effect of R&D expenditures in the renewable energy sector according to findings of the first model. More specifically, at a 1% significance level, the estimations suggest that a 1% increase in public R&D expenditures in the renewable energy sector is expected to reduce carbon intensity by 0.068%. On the other hand, in contrast, according to estimations findings of second model listed in table 7, at a 1% significance level, a 1% increase in public R&D expenditures in the fossil energy sector is expected to increase carbon intensity by 0.014%. Moreover, detailed estimation findings for country specific cases are listed in the table 8 and table 9 in the appendix.

Table 6. Pedroni's Group Mean Panel Dynamic Ordinary Least Squares Estimator

1st Model	coefficients	t statistics
LnRerd	-0.068***	-3.16
To	0.00**	-2.45
Urb	0.020***	21.25
Rent	0.025***	7.25

Note: ***, ** indicates significance at 1% and 5% respectively. $T_{0.99}$: 2,94; $T_{0.95}$: 2,13

Table 7. Pedroni's Group Mean Panel Dynamic Ordinary Least Squares Estimator

2ndModel	coefficients	t statistics
LnFerd	0.014***	3.29
To	0.00**	2.72
Urb	0.046***	9.60
Rent	-0.038	0.77

Note: ***, ** indicates significance at 1% and 5% respectively. $T_{0.99}$: 2,94; $T_{0.95}$: 2,13

As no other comprehensive study has been conducted to investigate the effect of R&D in the fossil fuel sector, most research has focused either on general energy sector R&D or on the relationship between overall R&D spending and carbon intensity. In this context, the results for the renewable energy sector are compared with the limited findings available in the literature, and it appears that these results align with the existing body of research (Cheng and Yao, 2021; Xin et al., 2022; Su, Chen, and Lin, 2023). Su, Chen, and Lin (2023) argue that the reduction in carbon intensity resulting from investments in renewable energy R&D is primarily driven by the optimization of the energy structure, where innovations in renewable energy technologies enhance the overall efficiency of the electricity industry's supply chain, with the remaining impact stemming from improved power operation efficiency, particularly through R&D advancements in wind and solar energy, which contribute significantly to the reduction of carbon intensity.

This contrasting difference in the effect of R&D spending on carbon intensity in the two sectors can be explained through various channels. Fossil energy R&D may primarily aims to enhance extraction efficiency, reduce operational costs, and increase energy output, rather than directly focusing on carbon emission reduction. These efficiency-boosting effects of R&D investments in the fossil fuel sector could make the fossil energy sector more attractive and more profitable for investors and players in the industry. Therefore, even if there may be some efficiency gains in terms of carbon intensity, this effect may be canceled out by the increase in demand through the rebound effect. Moreover, R&D in the fossil energy sector may increase the path dependency in the sector, making energy transition to cleaner alternatives, such as renewable energy sources, more difficult.

On the other hand, R&D activities in the renewable energy sector may be more centered on decarbonization aims and environmental considerations. Since renewable energy is still a more costly alternative in terms of financial considerations, the general motivation in the sector, both on the supply and demand sides, is more environmentally centered. Moreover, considering fierce international competition in all domains, governments all around the world push regulatory frameworks in the energy sector to reduce costs to support local firms, and these governmental supports are generally in favor of the fossil energy sector. Additionally, since the fossil energy sector has matured over more than a hundred years, it is difficult to expect revolutionary changes through R&D spending in this sector in terms of carbon intensity. On the other hand, the renewable energy sector is quite new and still in the innovation phase in comparison to fossil fuel sectors. Therefore, a groundbreaking change in terms of decarbonization is more likely to be seen in the renewable energy sector than in the fossil energy sector.

As another important factor on carbon intensity, trade openness is also included in the study as one of the control variables. According to parameter estimations for both first and second model at a 5% significance level, trade openness has very minor effect on carbon intensity. This finding is consistent with some parts of the literature, as findings regarding trade openness are mixed. For example, Huang et al. (2018) concluded that rising volumes in both exports and imports benefit the decarbonization efforts in China. Several other studies (Shahbaz et al., 2013b; Ren et al., 2014; Zhang and Zhang, 2018; Li et al., 2021) also concluded that trade openness and, therefore, rising international trade volume can boost decarbonization.

Huang et al. (2018) suggested that this positive effect of trade openness may be connected to the simultaneous rise of R&D-related FDI activities. Jayanthakumaran and Liu (2012) proposed an alternative view regarding the channels between trade openness and carbon intensity. According to the authors, increasing trade openness could boost economic growth, and economic agents could afford more expensive and environmentally friendly products and services. Huang et al. (2021) also analyzed the effect of trade openness on carbon intensity and concluded that this variation of findings in the literature may be attributed to the varied technological absorption capacities and other regional variations of countries.

The literature extensively examines China due to its persistent environmental pollution challenges. As highlighted by Huang et al. (2020a), China, being a highly export-driven economy, has focused on accelerating economic growth by loosening certain environmental regulations and adopting fiscal policies that favor export-oriented industries. This approach has led multinational corporations to shift many energy-intensive sub-sectors to China. Consequently, studies presenting findings that contradict ours may reflect the adverse effects of trade openness on carbon intensity in such contexts.

The findings on urbanization reveal that a 1% increase in the urbanization rate leads to an 2% (0.02*100) for the first model and 4,6% (0.046*100) for the second model increase in carbon intensity, ceteris paribus, at a 1% significance level. These results are also consistent with the existing literature (Dong et al., 2016; Su, Chen, and Lin, 2023; Pata et al., 2024). As urbanization leads to the concentration of production factors, it fosters economic development, which in turn may result in an increase in carbon intensity (Su, Chen, and Lin, 2023).

Reviewing the estimation findings regarding Total Natural Resource Rent, it appears that a 1% increase in the share of Total Natural Resource Rent leads to %2,5 (0,025*100) increase in carbon intensity according to first model, ceteris paribus, at a 1% significance level. On the other hand, in the second model there is no statistically meaningful estimation for Total Natural Resource Rent which implies that findings should be evaluated cautiously. This result aligns with numerous other studies as well (Zhang et al., 2023; Nwani et al., 2023; Bosah et al., 2024) observed in the literature. The rise in carbon intensity associated with higher Total Natural Resource Rent can be explained by some interconnected factors. First, much of the resource rent is often derived from fossil fuel extraction, which directly contributes to increased carbon emissions due to the carbon intensive nature of these resources. Second, rising natural resources rent provides an important cost advantage to those countries, boosts economic growth, and in turn may increase carbon intensity. Finally, for resource-rich countries, it may be more difficult to move away from fossil fuels due to path dependency, which prevents them from speeding up the energy transition process.

5. Conclusion and Policy Implications

Ever-rising environmental problems, since the industrial revolution, provide evidence for the urgent need for decarbonization of our economies. Energy transition, which implies moving away from fossil fuels to less carbon-intensive sources, may be an important tool in this regard. Accelerating this transition requires significant spending in energy R&D, which fosters innovation, improves energy efficiency, and reduces the costs of renewable technologies. Enhanced energy R&D efforts can drive the adoption of cleaner energy systems at a faster pace, mitigating environmental impacts more effectively.

This study investigates the impact of public R&D expenditures on fossil energy sources and renewable energy sources on carbon intensity. The analysis utilizes annual data from 1993 to 2022 for 16 member countries of the International Energy Agency (IEA) with available records. Control variables include trade openness (as a percentage of GDP), urbanization (as a percentage of the total population), and total natural resource rents (as a percentage of GDP), the latter of which is considered for the first time in the mentioned literature, as far as is known. The Pedroni cointegration test and Pedroni's Group Mean Panel Dynamic Ordinary Least Squares method (Pedroni, 1999; Pedroni, 2001) are employed to examine long-term relationships.

Firstly, based on all three statistics of the Pedroni cointegration test, a statistically significant assocation is identified among all independent variables in the estimation equation and carbon intensity. Moreover, according to the results of Pedroni's Group Mean Panel Dynamic Ordinary Least Squares method, public R&D expenditures in the renewable energy sector are found to have a statistically significant effect in reducing carbon intensity. In contrast, public R&D expenditures in the fossil energy sector are observed to increase carbon intensity. Furthermore, it is found that increases in urbanization, and natural resource rents have a statistically significant tendency to raise carbon intensity, potentially hindering progress in energy transition efforts. Conversely, it has been observed that an increase in trade openness may lead to a reduction in carbon intensity.

The most notable finding here is that, as expected, public R&D expenditures in the renewable energy sector reduce carbon intensity, while public R&D expenditures in the fossil energy sector tend to increase carbon intensity. This is an interesting finding and may provide new insight into the literature. Since, as far as investigated, only the effect of R&D in the renewable energy sector has been researched, and this study is the first comparative study regarding those two alternative sources. Possible reasons for these contrasting findings have already been explained in the discussion section in terms of governments' inclination to support fossil fuels due to international competition, the rebound effect, path dependency, the possibility of R&D in the renewable energy sector targeting decarbonization, while in fossil fuels, targeting the reduction of financial costs, and the difference in the maturity of these sectors. Departing from those findings, the best policy suggestion could be highlighting the heterogeneity among subsectors of the energy industry. Therefore, allocating a higher share of R&D budgets to the renewable energy sector can speed up the energy transition and help decarbonization efforts.

Since natural resource rent is often overlooked in the related literature, such an important factor in carbon intensity, previous studies may be misleading in their estimations. Therefore, the estimations regarding natural resource rent are also important to mention. Estimations reveal that rising natural resource rent may be associated with rising carbon intensity. This may be due to the potential attractiveness of the sector for resource-rich countries, which causes overutilization of those mostly carbon-intensive sources. This result implies that resource-rich countries should invest in their future and prioritize energy transition.

This study is based on the domain of public R&D spending. As in other R&D sectors, R&D in energy sectors involves high sunk cost risk for private sectors. Since costly R&D activities do not always guarantee that private firms will create financially profitable outputs, nor can it be guaranteed that those potential profits will be locked in only by those companies. Therefore, due to this problem, it is important for the public sector to take the lead in this domain. Relying only on the market mechanism to bring the expected potential benefits of R&D activities may not be sufficient. It is therefore essential for public resources to be allocated to support R&D in this sector, ensuring that the broader societal benefits of innovation are realized.

However, given the potential fiscal pressures that extensive public investments in energy R&D may place on the budget, it is imperative to reallocate energy subsidies and policies from the less efficient fossil energy sector to the renewable energy sector. In today’s highly competitive global economy, shifting subsidies from the fossil energy sector, where they are mainly used to support the financial interests of domestic industries, towards the renewable energy sector and other carbon-friendly industries is essential for promoting energy transition and addressing climate challenges effectively.

While the reasons and benefits of public sector-led R&D efforts in the energy sector have been outlined, it is equally important to emphasize the collaboration between public institutions, higher education establishments and industries. This partnership plays a crucial role in ensuring the more efficient allocation and utilization of financial resources. Moreover, it is crucial for regional and local governments to be involved in R&D planning alongside central governments. This is particularly important given the regional disparities within countries, where differences in energy sector demands, resource availability, and development levels may lead to varying rates of absorption and application of R&D outputs across different regions.

This study has several limitations that offer valuable opportunities for future research. Categorization of subsectors of the energy industry was kept in the most basic classification as fossil and renewable sources, due to data constraints. Therefore, in future studies, if these data constraints are exceeded, the effect of R&D on carbon intensity can be investigated in terms of various other subsectors, such as solar, wind, geothermal, coal, natural gas, etc. Moreover, analyzing countries separately according to income levels may yield better estimations and offer a better understanding of the issue, since the public R&D budget may be highly correlated with the development level. Additionally, in this study, as in most of the studies in the literature, carbon intensity is used as a proxy for energy transition. However, if a more comprehensive index to proxy energy transition is achieved, estimations can yield a multidimensional understanding of the energy transition issue. Finally, as is done in one of the reviewed micro-level studies, the level at which positive marginal benefits of R&D spending on carbon intensity can be achieved can be investigated using macro-level data.

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Appendix

Table 8. Pedroni's Group Mean Panel Dynamic Ordinary Least Squares Estimator (Country Spesific Estimates)

1st Model	lnrerd	to	urb	rent
Austria	-0.25(-6.89)	0.02(6.97)	0.01(2.89)	0.24(7.84)
Canada	0.12(0.86)	0.00(1.06)	-0.11(-5.32)	-0.02(-1.92)
Denmark	-0.32(-3.94)	-0.01(-1.03)	0.35(7.12)	0.24(5.96)
Finland	-0.13(-5.48)	-0.00(-0.99)	0.21(9.71)	-0.16(-5.55)
France	-0.01(-1.25)	-0.02(-4.75)	0.10(4.41)	0.08(2.28)
Germany	0.08(1.87)	0.00(3.25)	0.031(3.25)	0.06(3.97)
Italy	-0.08(-1.53)	0.03(3.83)	-0.15(-4.13)	-0.01(-0.30)
Japan	-0.03(-4.32)	-0.01(-5.54)	0.03(55.32)	0.13(12.08)
Netherlands	-0.10(-2.87)	-0.00(-0.51)	-0.00(-0.76)	0.10(3.96)
New Zealand	-0.22(-5.67)	-0.02(-7.10)	0.10(5.20)	0.12(5.12)
Norway	0.06(18.92)	-0.01(-9.25)	0.01(1.89)	-0.01(-3.76)
Spain	0.19(3.10)	0.00(1.03)	-0.16(-3.19)	0.10(1.25)
Sweden	-3.37(-3.47)	-0.04(-4.53)	0.07(2.10)	-0.31(-3.41)
Switzerland	-0.05(-2.7)	0.00(0.79)	0.01(3.11)	0.08(3.31)
United Kingdom	0.03(0.56)	0.01(2.90)	-0.23(-2.96)	-0.22(-0.54)
United States	0.00(0.16)	0.00(5.54)	0.04(6.33)	-0.03(-1.27)

Table 9. Pedroni's Group Mean Panel Dynamic Ordinary Least Squares Estimator (Country Spesific Estimates)

2nd Model	lnferd	to	urb	rent
Austria	-0.02 (-0.94)	0.03(4.96)	0.04 (4.24)	0.14(2.55)
Canada	0.05 (1.34)	0.00 (1.07)	-0.10 (-4.04)	-0.02(-1.70)
Denmark	0.01 (0.17)	-0.01(-0.50)	0.22 (2.11)	0.15 (3.49)
Finland	-0.02(-0.89)	0.00 (0.79)	0.24(6.49)	-0.03 (-1.06)
France	-0.06(-4.18)	0.02(2.90)	0.18(5.30)	-0.22(-3.75)
Germany	0.00(0.16)	0.00(0.99)	0.01(1.78)	0.08(4.13)
Italy	0.07(11.58)	-0.02(-3.73)	0.12(4.54)	0.02(0.91)
Japan	-0.02(-1.36)	-0.01(-5.37)	0.02(12.9)	0.08(3.94)
Netherlands	0.01(0.25)	-0.00(-0.52)	0.00(0.23)	0.12(3.77)
New Zealand	0.02(0.89)	-0.01(-3.67)	0.05(2.39)	0.02(1.09)
Norway	0.13(4.37)	0.00(0.15)	0.03(2.60)	-0.01(-3.87)
Spain	0.017(1.54)	0.00(0.07)	-0.19(-3.82)	0.09(1.18)
Sweden	-0.08(-7.77)	-0.02(-3.8)	0.23(11.21)	-0.21(-3.25)
Switzerland	0.04(2.20)	0.00(3.4)	0.01(2.57)	0.03(2.02)
United Kingdom	0.08(5.23)	0.02(10.28)	-0.21(-12.93)	-0.90(-6.80)
United States	0.01(0.58)	0.00(3.86)	0.03(2.84)	0.01(0.44)