The role of moderating factors in the nexus natural resource rents and renewable energy adoption

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Abstract

This paper examines the intermediary role of carbon dioxide emissions and GDP per capita in the relationship between natural resource rents and renewable energy, with a specific focus on distinguishing between renewable energy consumption and production. Specifically, the paper aims to identify the threshold levels of carbon dioxide emissions and GDP per capita at which the negative relationship between natural resource or petroleum rents and renewable energy adoption may shift from negative to positive. Utilising the panel autoregressive distributed lag (ARDL) methodology, particularly the Pooled Mean Group (PMG) estimator, the paper demonstrates that natural resource and petroleum rents can promote both the consumption and production of renewable energy once GDP per capita surpasses a specific threshold, which varies between renewable energy consumption and production. Furthermore, the study finds that an increase in natural resource rents leads to a reduction in renewable energy consumption and production when CO2 emissions exceed a certain threshold. These findings are particularly relevant for European countries, which are at the forefront of international climate agreements, such as the Paris Agreement, and align with the objectives of Sustainable Development Goal 13 (SDG 13) on climate action.

1. INTRODUCTION

The increasing frequency and severity of climate change-related hazards have created an urgent need to transition to renewable energy, further intensified by growing geopolitical tensions that threaten energy security. In response, various initiatives have been implemented to accelerate this transition. While countries have shown commitment, the rate of renewable energy adoption varies significantly. This variation has sparked interest in understanding the factors driving renewable energy adoption and its interrelationship with non-renewable energy, natural resources, and key environmental and economic variables (Sudarsan et al., 2023; Ali et al., 2023; Poshnath et al., 2023; Kwilinski et al., 2024; Adanma and Ogunbiyi, 2024).

In this context, Ali et al. (2023) examine the impact of natural resource rents, technological innovation, renewable energy, and economic growth on the ecological footprint in the USA from 1970 to 2019. Using a Bootstrapping ARDL model, they find that while renewable energy improves environmental quality, natural resources worsen it. Additionally, technological innovation is significantly associated with ecological quality. Dada and Al-Faryan (2024) analyze the effect of per capita income, renewable energy, natural resources, trade, and urbanization on Saudi Arabia's material footprint from 1990 to 2019. Employing various econometric methods, such as ARDL, FMOLS, DOLS, and CCR, they discover that per capita income, trade, and urbanization increase the material footprint, contributing to ecological damage. Conversely, renewable energy and natural resource rents reduce the material footprint in both the short and long term. Yu et al. (2023) utilise Fourier-based approaches to explore the relationship between non-renewable energy, natural resources, and green economic recovery in selected countries. They find that economic recovery in eight of the ten nations studied relies on natural resource development, while sustainable energy supports economic recovery in Germany, Denmark, and France over the long term. Additionally, Italy, Malta, the UK, and Greece exemplify countries where the energy-led growth theory applies. Guo et al. (2023) argue that Sub-Saharan African (SSA) countries face challenges in achieving sustainable development due to misaligned energy and climate policies with human development goals. To address this gap, they assess the impact of renewable and non-renewable energy and natural resources on the sustainable development index for

28 SSA countries from 1990 to 2019. Their findings, based on Augmented Mean Group (AMG) and Common Correlated Effects Mean Group (CCEMG) estimations, indicate that while renewable energy and natural resources have positive but insignificant effects on sustainable development, fossil fuels significantly and negatively impact it.

While many of the aforementioned studies focus on the combined impact of renewable energy, non-renewable energy, and natural resources on key economic and environmental variables, few have specifically examined the impact of natural resources on energy transition, particularly on the consumption and production of renewable energy. For instance, Han et al. (2023) analyse the relationship between natural resources and renewable energy consumption across 162 developed and developing countries from 1990 to 2021. They find a positive and significant association, suggesting that natural resource extraction promotes renewable energy consumption. Additionally, their cross-sectional analysis reveals that this relationship is stronger in developed countries than in developing ones. Zhang et al. (2024) explore the nonlinear impact of natural resource dependence on renewable energy development and the role of government policy support in Chinese provinces. Using a Quantile Regression with Nonadditive Fixed Effects for Panel Data (QRPD) model, they discover that natural resource dependence influences renewable energy development in line with the "conditional resource curse" hypothesis, showing a U-shaped nonlinear relationship. Their findings suggest that natural resource dependence can enhance renewable energy development through green technology innovation and environmental regulation channels.

Assessing the relationship between natural resources and renewable energy is vital for several reasons. First, countries heavily reliant on natural resources, particularly fossil fuels, often face economic instability, weak governance, and slow economic diversification—conditions that contribute to the 'resource curse' and may impede renewable energy adoption (Zhang et al., 2024; Ross and Werker, 2024). Second, fossil fuel-dependent nations may find it challenging to align with global climate change mitigation efforts, underscoring the need to understand how these rents influence renewable energy development (Foster et al., 2024). Third, the use of natural resource rents can either promote or hinder investments in renewable energy (Alsagr and Ozturk, 2024; Boulanouar and Essid, 2023). If reinvested in the energy sector, these rents may boost renewable energy growth, but if they strengthen the fossil fuel industry, they could stifle progress. Finally, the impact of natural resource rents on renewable energy adoption may depend on factors such as economic development, governance quality, and infrastructure. Exploring these threshold effects is crucial to understanding when and how resource rents can either facilitate or obstruct the transition to renewable energy.

To address the critical link between natural resources and renewable energy, this paper makes several key contributions to the literature. First, it investigates the impact of natural resource and petroleum rents on renewable energy, distinguishing between renewable energy consumption and production across European countries. This analysis will assess whether natural resource and petroleum rents facilitate or hinder the renewable energy transition, focusing on both the consumption and production dimensions. Second, the paper explores threshold effects in this relationship, examining how variables such as carbon dioxide emissions and GDP per capita may influence these dynamics within European countries. Finally, the paper utilizes the panel ARDL model, especially the pool mean group (PMG) model to distinguish between the short- and long-term effects of natural resource and petroleum rents on renewable energy. Since short-term and long-term effects often require different policy approaches, understanding these differences enables policymakers to develop strategies that address immediate challenges while planning for sustainable, long-term energy transitions.

The rest of the paper is structured as follows: Section 2 presents the literature review, while Section 3 outlines the methodology used in the study. Section 4 presents the data and provides the estimation results of the various models. Finally, Section 5 concludes the paper.

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2. LITERATURE REVIEW

In the quest to reduce dependence on non-renewable energy, while addressing climate change-related issues, there has been a mounting interest in renewable energy and factors determining its deployment. This literature can be categorized into two strands. The first strand of literature focuses on the factors driving renewable energy consumption; the second concentrates on the drivers of renewable energy production. Despite the differences in the preferred measure of renewable energy deployment, there are similarities insofar as factors determining the deployment of renewable energy are concerned.

It is argued that adaptation to modern technologies is typically low. This is because of high sunk costs and insufficient market size as the primary obstacles to modern technology (Farrokhi et al., 2024). A similar observation has been made regarding renewable energy deployment in developing economies; it remains disappointingly low. Theories of economic development suggest that a big push is necessary for the economy to undo the initial inertia of a stagnant economy. However, the capacity to impart this big initial momentum is, to a large degree, dependent on the country's economic standing. Against this, several studies explored the role of economic standing or performance in renewable energy adaptation. Papież et al. (2018) investigated determinants of renewable energy in the European Union and found that economic growth bolsters the deployment of renewable energy. In the OECD countries, Su et al. (2021) find a positive relationship between renewable energy and economic GDP. Uzar (2020) investigated a panel of 38 countries and uncovered a positive relationship between economic growth and renewable energy in the short term but a negative link in the long run. Several other studies have examined the economic growth-renewable energy nexus and support the notion of a positive link (Abanda et al., 2012; Apergis & Payne, 2012). However, other studies document a negative relation effect of economic growth on renewable energy deployment; others find no significant association (Aguirre & Ibikunle, 2014).

Other studies evaluated the impact of the labour market on the adaptation to modern technologies, including renewable energy. Augmenting the standard quantitative trade model to include technology adaptation and labour market inefficiencies, Farrokhi et al. (2024) show that labour market distortions, defined as the labour market wedge causing the gap between the cost of labour to the firm and payment to the worker(s), barricades the adoption of new technologies. In the same vein, Acemoglu and Zilibotti (2001) opines that the low adaption of modern technologies, particularly in developing nations, is attributable to the quality of the labour force. They argue that most technology used in developing economies is imported from advanced economies, such as the OECD, and is tailored to the skill set available in the developed countries (Acemoglu & Zilibotti, 2001). This skills mismatch, in turn, creates a barrier to the deployment of modern technology in developing nations. Therefore, modern technologies' adoption in developing countries may result in higher levels of unemployment. This view is supported by Rivers (2013). He employed a general equilibrium model to analyze the link between unemployment and renewable energy and documented an inverse relationship. Hence, the slow rate of renewable energy deployment can partly be ascribed to labour market deficiencies. Tu et al. (2022) the random effects GLS approach to investigate how unemployment affects renewable energy deployment in the 27 EU countries during the period 2011-2020. These scholars reported that growth in the unemployment rate negatively affects renewable energy deployment.

Factors such as unemployment, and soaring government debt, among others, are significant determinants for renewable energy production in Central and Eastern Europe and the Caucasus and Central Asia (CEECCA) (Przychodzen & Przychodzen, 2020). These scholars reported that foreign direct investment (FDI) exerts no significant influence over renewable energy deployment. They assert this is because FDI is typically not geared toward alternative energy generation. Lin and Omoju (2017) are consistent with Przychodzen and Przychodzen (2020), foreign direct investment does not promote renewable energy deployment. Using a Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS), Lin and Omoju (2017) documented that financial development and trade openness positively affect renewable energy employment.

The importance of the regulatory environment and quality of institutions has long been established in the literature (Acemoglu, 2010; Acemoglu & Robinson, 2008; Glaeser et al., 2004). Hence, there is no shortage of literature investigating the impact of institutions and regulations on economic development, especially in developing countries. The focus has since shifted from economic growth to modern technologies' deployment. The findings of the literature on whether political and institutional factors influence renewable energy development are mixed. There is a strand that finds a positive relationship, whereas the other documents an insignificant association. Shang et al. (2022) employ an ARDL model to explore the importance of climate policy uncertainty on renewable energy consumption. These scholars uncovered that policy uncertainty does not significantly affect renewable energy consumption. It was concluded, therefore, that climate change mitigating policy does not alter people's behaviors insofar as renewable (non-renewable) energy is concerned. Shafiullah et al. (2021) use a nonparametric approach to investigate the effect of economic policy uncertainty (EPU) in the U.S. between 1986 and 2019. They uncover that policy uncertainty adversely affects renewable energy consumption. Thus, a clear policy direction is important for renewable energy development. A similar study Yi et al. (2023) examined the relationship between EPU and renewable energy consumption. In this study, these scholars account for three crucial issues namely heterogeneity, cross-section dependence, and endogeneity by utilizing.   Aguirre and Ibikunle (2014) reports that 'some' energy policies impede renewable energy investments. Liu et al. (2019) attempt to establish how various policy variables impacted the adoption of renewable energy in a panel of 29 countries. They found that fiscal and financial incentives, such as grants, positively affect the installation of renewable energy. However, these scholars also note that tax instruments do not significantly influence the adoption of renewable energy. A similar observation is made by Hu et al. (2022); they demonstrate that tax support, amongst other things, has an insignificant effect on renewable energy deployment.

The ongoing Russia-Ukraine conflict and the rising geopolitical tensions pose significant threats to energy security. Consequently, renewable energy has been viewed as a stratagem to mitigate energy security risks (Cergibozan, 2022). Thus, other studies have begun to evaluate whether energy insecurities affect renewable energy development. Conflicting results have been documented in the literature. For example, Aguirre and Ibikunle (2014) employed FEVD and PCSE approaches to investigate potential drives of renewable energy from 1990-2010. They document that energy (in)security does not play a significant role in renewable energy development. Lucas et al. (2016), on the other hand, employed different indicators to measure energy security. They find that energy security matters for renewable energy deployment. In this vein, Khan et al. (2023) employed a wavelet approach to investigate the impact of energy security on renewable energy adoption, and it was found that energy security positively influences renewable energy deployment.

The impact of natural resources on economic development has been a longstanding debate in the literature. More recently, attention has shifted to examining how natural resources influence renewable energy deployment, with some studies suggesting that natural resource wealth can either encourage or inhibit investments in renewable energy. For example, Ahmadov and Van Der Borg (2019) investigated the effect of natural resources on renewable energy production. They found that, overall, natural resources positively affect renewable energy production. However, they find that natural resources, such as petroleum impede natural resources. Gorji and Martek (2023) used feasible generalized least squares (F-GLS) and GMM to evaluate the effects of natural resources on renewable energy deployment. The authors find that natural resources have a positive effect on renewable energy. This is at odds with Lin and Omoju (2017), who reported that oil prices have adversely affected renewable energy deployment. Han et al. (2023) used fixed effects and autoregressive fixed effects to assess the role of natural resources. They documented that natural resources have positively influenced renewable energy consumption. Yu et al. (2023) employed a bootstrap quantile regression to show that coal, oil, mineral, and natural gas prices hinder renewable energy deployment. Zhao et al. (2023) also reported a negative effect of natural resources on renewable energy adoption.

3. METHODOLOGY

The paper assesses the separate effects of both the natural resources rent and petroleum rents on renewable energy consumption and production. To this end, the following ARDL model is used:

$$y_t = \delta + \theta y_{t-1} + \emptyset 0 X_t + \emptyset 1 X_{t-1} + \in_t \qquad (1)$$

Where y_t denotes renewable energy consumption (RECONS) and renewable energy production (REPROD). X_t is a vector that contains the key regressors, namely total natural resource rent (TRRENT) and petroleum rents (PRENT) together with key control variables. It is worth noting that besides the above-mentioned key variables included in the vectors X_t and X_{t-1}, these vectors also include key control variables such as GDP per Capita (GDPC), GDP Growth (GDGRW), CO_2 Emission (CO_2), energy dependence (EDEP), and environmental taxes (ENVIRO). To account for the threshold effects of the two key variables, namely total resource rents and petroleum rents, on renewable energy production and consumption, interactive variables such as $TRCO_2$, TRLGDPC, $PRCO_2$, and PRGDPGRW are constructed. $TRCO_2$ and TRLGDPC are constructed by multiplying TRRENT by CO_2 and LGDPC, respectively. $PRCO_2$ and PRGDPGRW are constructed by multiplying PRRENT by CO_2 and GDPGRW, respectively. All the variables are expressed in their natural logarithm.

To derive the error correction form of the cointegrated ARDL model, we subtract y_{t-1} at the left and right hands of Equation 1 to yield:

$$\Delta y_t = \delta + (\theta - 1) y_{t-1} + \emptyset 0 X_t + \emptyset 1 X_{t-1} + \in_t \qquad (2)$$

When we add and subtract $\emptyset 0 X_t$ from the left side of Equation 2, we have

$$\Delta y_t = \delta + (\theta - 1) y_{t-1} + \emptyset 0 \Delta X_t + (\emptyset 1 + \emptyset 0) X_{t-1} + \in_t \qquad (3)$$

Rearranging Equation 3 yields the error correction form of the ARDL model such as

$$\Delta y_t = -(1 - \theta)\left(y_{t-1} - \frac{\delta}{1-\theta} - \frac{\emptyset 1 + \emptyset 0}{1-\theta} X_{t-1}\right) + \emptyset 0 \Delta X_t + \in_t \qquad (4)$$

Where $\gamma = (1 - \theta)$ is the speed of adjustment

$\alpha = \frac{\delta}{1-\theta}$ and $\beta = \frac{\emptyset 1+\emptyset 0}{1-\theta}$

Pesaran et al. (1999) show that Equation 4 can be estimated as *N(cross-section)* separate regressions and calculate the coefficient means. Such estimation yields the model called an ARDL mean group (MG) estimator. It is also possible to pool the data and assume that the slope coefficients and error variances are identical in the short and long term. Pesaran et al. (1999) name this estimator the cointegrated dynamic fixed effect (DFE). Lastly, the authors suggest an intermediate procedure, the pooled mean group (PMG) estimator, which constrains long-run coefficients to be identical but allows short-run coefficients and error variances to differ across groups.

This paper employs three estimators of the panel ARDL model—Mean Group (MG), Pooled Mean Group (PMG), and Dynamic Fixed Effects (DFE)—and selects the most efficient model using the Hausman test. As discussed in subsequent sections, the Hausman test helps determine whether the PMG or MG estimators are more appropriate by testing for consistency and efficiency, guiding the selection of the best-fitting model for the data

Given the focus on the threshold effect of CO2 and LGDPC on the relationship between total natural resource rents and renewable energy consumption, for example, the following model is estimated based on the MG-, PMG- and DFE-ARDL method:

$$\begin{aligned}&\Delta RECONSi_{it} = -(1-\theta)(RECONS_{it-1} - \alpha_i - \beta_{1i}TRRENT_{it-1} - \\ &\beta_{2i}LGDPC_{it-1} - \beta_{3i}EDEP_{it-1} - \beta_{4i}ENVIRO_{it-1} - \beta_{5i}TRRENT * CO2_{it-1}) + \\ &\emptyset_1 \Delta TRRENT_{it-1} + \emptyset_2 \Delta LGDPC_{it-1} + \emptyset_3 \Delta EDEP_{it-1} + \emptyset_4 \Delta ENVIRO_{it-1} + \emptyset_5 \Delta TRRENT * \\ &CO2_{it-1} + \in_t\end{aligned} \tag{5}$$

In Equation 5, the threshold effect of CO2 emissions in the relationship between renewable energy consumption (RECONS) and total natural resource rents (TRRENT) can be observed both in the long and short term. In the long term, the relationship is expressed as:

$$\frac{d(RECONS_{it-1})}{d(TRRENT_{it-1})} = \beta_{1i} + \beta_{5i}CO2_{it-1} \tag{6}$$

Equation 6 captures the threshold effect of CO2 emissions on the link between total natural resource rents and renewable energy consumption in the long term. This indicates that the impact of

TRRENT on RECONS depends on CO2 emissions, where β_{5i} represents the moderating effect of CO2 levels.

In the short term, the threshold effect is identified as follows:

$$\frac{d(\Delta RECONS_{it-1})}{d(\Delta TRRENT_{it-1})} = \emptyset_{1i} + \emptyset_{5i}\Delta CO2_{it-1} \qquad (7)$$

This equation shows the short-term dynamics, where $\emptyset_{5i}$ captures the role of changes in CO2 emissions in moderating the relationship between changes in natural resource rents and renewable energy consumption.

Finally, the speed of adjustment towards the long-term equilibrium is given by $\gamma = (1 - \theta)$, as defined in Equation 5. This parameter reflects how quickly deviations from the long-term equilibrium are corrected.

Using the ARDL cointegration method, the paper estimates a total of eight models: four focused on the drivers of renewable energy consumption and the other four on the drivers of renewable energy production. Models 1 and 2 assess the relationship between renewable energy consumption and total natural resource rents, incorporating the roles of carbon dioxide emissions and GDP per capita, respectively. Models 3 and 4 explore the relationship between renewable energy consumption and petroleum rents, again accounting for the influence of carbon dioxide and GDP per capita, respectively. For instance, Model 4 is expressed as follows:

$$\Delta RECONSi_{it} = -(1-\theta)(RECONS_{it-1} - \alpha_i - \beta_{1i}PRENT_{it-1} - \beta_{2i}LGDPC_{it-1} - \beta_{3i}EDEP_{it-1} - \beta_{4i}ENVIRO_{it-1} - \beta_{5i}PRENT * GDPC_{it-1}) + \emptyset_1\Delta PRENT_{it-1} + \emptyset_2\Delta LGDPC_{it-1} + \emptyset_3\Delta EDEP_{it-1} + \emptyset_4\Delta ENVIRO_{it-1} + \emptyset_5\Delta PRENT * GDPC_{it-1} + \in_t \qquad (8)$$

Models 5 and 6 examine the relationship between renewable energy production and total natural resource rents, considering the roles of carbon dioxide emissions and GDP per capita, respectively. Models 7 and 8 assess the influence of carbon dioxide and GDP per capita on the relationship between renewable energy production and petroleum rents. For instance, Model 7 is expressed as follows:

$$\Delta REPRODi_{it} = -(1-\theta)(RECONS_{it-1} - \alpha_i - \beta_{1i}PRENT_{it-1} - \beta_{2i}LGDPC_{it-1} - \beta_{3i}EDEP_{it-1} - \beta_{4i}ENVIRO_{it-1} - \beta_{5i}PRENT * CO2_{it-1}) + \emptyset_1\Delta PRENT_{it-1} + \emptyset_2\Delta LGDPC_{it-1} + \emptyset_3\Delta EDEP_{it-1} + \emptyset_4\Delta ENVIRO_{it-1} + \emptyset_5\Delta PRENT * CO2_{it-1} + \in_t \qquad (9)$$

4. DATA, ESTIMATION, AND RESULTS

The paper utilizes annual data from 1997 to 2023 for a cross-section of 29 European countries. The sample period is selected based on data availability. The full list of variables and countries included in the empirical analysis can be found in the appendix, specifically in Tables A1 and A2.

The first step of the analysis involved performing unit root tests on all variables. Several tests were employed, including the Levin-Lin-Chu (LLC) test, Im-Pesaran-Shin (IPS) test, and the Fisher-type test, particularly the Augmented Dickey-Fuller (ADF) test. Table 1 presents the results of the unit root tests at the level, while Table 2 provides the results at the first difference for variables that were found non-stationary at the level.

Table 1. Unit root test of variables at level

Variables	LLC	IPS	ADF
	Adjusted-t statistics	t-bar statistics	inverse Chi-Square
RECONS	7.1677	0.556	10.2128
REPROD	7.0921	0.2997	14.2314
TRRENT	--	--	53.3421
PRENT	--	--	92.2053**
CO2	5.335	-0.4852	22.0842
EDEP	-0.8759	-2.5798	61.8571
ENVTAX	--	--	6.8557
GDPC	9.1219	0.3524	1.4776
GDPGRW	-9.4855***	-4.337***	262.20***

** and *** denote rejection of the null hypothesis of unit root at 5% and 1%, respectively, empty space means that statistics are not provided given that IPS and llc apply to balanced panel data.

Table 2. unit root test of variable at first difference

Variables	LLC	IPS	ADF
	adjusted t statistics	t-bar statistics	inverse Chi-Square
RECONS	-15.2052***	-4.1211***	224.6734***
REPROD	-16.1471***	-4.2032***	281.4163***
TRRENT	--	--	465.2912***
CO2	-18.3776***	-4.764***	289.6408***
EDEP	-21.8306***	-5.6675***	418.3742***
ENVTAX	--	--	229.3593***
GDPC	-18.0659***	-4.6159***	216.3467***

** and *** denote rejection of the null hypothesis of unit root at 5% and 1%, respectively, empty space means that statistics are not provided given that IPS and llc apply to balanced panel data.

The results of the unit root tests, as shown in Tables 1 and 2, reveal that most of the variables are integrated of order one, denoted as I(1), meaning they become stationary only after taking their first differences. However, there are exceptions: the variables PRENT and GDPGRW are found to be stationary at their levels, denoted as I(0). This indicates that PRENT and GDPGRW do not require differencing to achieve stationarity, as their statistical properties, such as mean and variance, remain stable over time. The combination of both I(0) and I(1) variables provides a solid basis for applying the ARDL cointegration approach (Pesaran et al., 2001).

In the second step of our analysis, we conduct an initial test for cointegration using the Pedroni test. This test is suitable for examining cointegrating relationships in panels with large N and T and can accommodate mixed levels of integration[1]. We calculate three test statistics from the Pedroni test under the null hypothesis of no cointegration: the Modified Phillips-Perron, Phillips-Perron, and ADF statistics.

Table 3. Pedroni test of cointegration

Models	Modified Phillips-Perron	Phillips-Perron	ADF
Model 1	5.8843***	-3.3289***	-2.4675***
Model 2	5.8843***	-3.2898***	-3.3719***
Model 3	7.0789**	-2.7883***	-3.1981***
Model 4	7.7064***	-2.4279***	-1.6486**
Model 5	6.9032***	-8.5015***	-5.8452***
Model 6	6.4034***	-6.5617***	-5.8087***
Model 7	7.5078***	-5.3305***	-4.4768***
Model 8	77028***	-4.6260***	-3.7756***

** and *** denote rejection of the null hypothesis of no cointegration at 5% and 1%, respectively.

The results of the Pedroni cointegration test show that the null hypothesis of no cointegration is rejected at 1% level, confirming a possible cointegration between the variables included in each model.

In the final step, related to model estimation, the paper proposes using three estimators within the panel ARDL framework: the Mean Group (MG), Pooled Mean Group (PMG), and Dynamic Fixed Effects (DFE) estimators. Each of these estimators captures different dynamics and accounts for heterogeneity across cross-sectional units in panel ARDL (Autoregressive Distributed Lag) models.

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[1] The final determination of whether cointegration exists between the variables is based on the sign and significance level of the error correction terms in the various Panel ARDL models

The Mean Group (MG) estimator fits separate ARDL models and averages the coefficients across all units. It assumes that all parameters, including long-run and short-run coefficients, are heterogeneous across units or cross sections, reflecting unique characteristics of each entity.

The Pooled Mean Group (PMG) estimator allows for variation in short-run coefficients, speed of adjustment, and error variances across units while imposing homogeneity on the long-run coefficients. This implies that while short-run dynamics differ across units, the long-run relationships are assumed to be identical.

The Dynamic Fixed Effects (DFE) estimator imposes homogeneity on both the long-run and short-run coefficients across all units, using fixed effects to account for unit-specific heterogeneity. This model assumes that the long-run and short-run coefficients are uniform across all cross-sectional units.

To determine the most suitable panel estimator for each model (from Model 1 to Model 8), we performed the Hausman test, with the results presented in Table 4. The Hausman test is essential for selecting between the Mean Group (MG), Pooled Mean Group (PMG), and Dynamic Fixed Effects (DFE) estimators, as it evaluates the consistency and efficiency of these models. The null hypothesis of this test is that there is no systematic difference between the estimators, meaning the more efficient model is preferred.

It's important to note that when applying the Hausman test in the context of panel ARDL models, the null and alternative hypotheses are based on the assumptions about the homogeneity of long-run coefficients and the efficiency of the estimators. This allows for a robust comparison of the MG, PMG, and DFE models to identify which provides the best fit for the data.

Based on the statistics in Table 4, our final selection indicates that the panel ARDL model with the Pooled Mean Group (PMG) estimator is more efficient for all the eight models. This suggests that the PMG estimator better accounts for the dynamics present in all the models.

The eight models estimated using the PMG estimators underscore the significance of the interaction effects, particularly the moderating roles of CO2 emissions and GDP per capita, in evaluating the impact of total natural resource rents and petroleum rents on renewable energy consumption and production. These interaction terms reveal how the influence of natural resource and petroleum rents is shaped by varying levels of CO2 emissions and economic growth. Specifically, the models demonstrate that CO2 and GDP per capita act as key factors that can either amplify or mitigate the effects of natural resource rents on the renewable energy transition, offering deeper insights into the dynamics of sustainable energy development.

Table 4 Hausman test for estimator selection between MG, PMG, and DFE

	MG or PMG	DFE or PMG	MG or DFE	Final selection
Model 1	chi2(4)= 0.4748	chi2(4)= 158.73***	chi2(4)= 0.29	PMG
selection	PMG	DFE	DFE	
Model 2	Chi2(4)= 5.75	chi2(4) = 316.56***	chi2(4) = 0.15	PMG
selection	---	DFE	DFE	
Model 3	chi2(4)=1.12	chi2(4)= 8.31*	chi2(4)=0.06	PMG
selection	PMG	DFE	DFE	
Model 4	chi2(4)=5.67	chi2(4)=119.04***	chi2(4)=0.10	PMG
selection	PMG	DFE	DFE	
Model 5	Chi2(5) = 1.55	Chi2(5)= 491.26***	Chi2(5)=0.10	PMG
Selection	PMG	DFE	DFE	
Model 6	chi2(5)=0.8270	chi2(5)=576.67***	chi2(5)=0.12	PMG
selection	PMG	DFE	DFE	
Model 7	chi2(5)= 2.86	chi2(5)=340.45***	chi2(5)= 0.13	PMG
Selection	PMG	DFE	DFE	
Model 8	Chi2(5)=3.65	Chi2(5)=1260.85***	Chi2(5)=3.65	PMG
Selection	PMG	DFE	DFE	

Note: the null and alternative hypotheses are formulated based on the assumptions about the homogeneity of the long-run coefficients and the efficiency of the estimators.

To demonstrate that the interactive model better captures the relationship between natural resource rents and renewable energy than a simple linear model, we compare the estimation of two models using the DFE estimator[2] to assess the effect of petroleum rents (PRENT) on renewable energy consumption (RECONS). The results in Table 5 indicate that, in the linear model, PRENT has no significant impact on renewable energy consumption in either the short or long term. However, in the interactive model, which includes the interaction between PRENT and CO2, the long-term effect of PRENT on renewable energy consumption becomes significant, highlighting the importance of accounting for moderating variables.

Table 5. linear and nonlinear models on the effects of petroleum rents on renewable energy consumption

Variables	Linear model	interactive model

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[2] Although the estimation is primarily illustrative, the similarity between the DFE and PMG models results in the homogeneity of their long-term coefficients.

		Coefficients	Coefficients
Long-run results	MARKCAP	1.4012**	1.3286**
	PRENT	0.9251	4.1758***
	CO2	-2.2261***	-1.7926***
	EDEP	-0.0051	0.01724
	ENVTAX	2.0677	1.454
	GDPGRW	-0.4321	-0.4323
	PRENT*CO2		-0.3040**
ECM Coefficient	ECM(-1)	-0.2086***	-0.2098***
Short-term results	ΔPRENT	-0.3025	-1.1276***
	ΔCO2	-0.5774***	0.0917**
	ΔEDEP	0.0120**	0.0025
	ΔENVTAX	-0.1435	0.0547
	ΔGDPGRW	0.6634***	0.0677***
	ΔPRENT*CO2		0.09177**

Table 6 presents the estimation of all eight models using the PMG estimators, as guided by the Hausman test. Based on the characteristics of the PMG estimator, the long-term coefficients, which are homogeneous across units (pooled estimation), are reported in Table 6. The short-term coefficients, which are heterogeneous, are reported in Table 7, showing the variation in coefficients for each cross-sectional unit.

Table 6. Long-term estimation of the PMG estimators of all the models

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Variables	**Coefficients**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficent**	**coefficient**	**Coefficient**
TRRENT	0.59*	-1.91***			1.3***	-0.01		
PRENT			0.39***	-18.64***			-0.1**	-54.03***
CO2	-1.65***	-1.52***		-3.05***	-0.08***	-0.14***	-0.22***	-4.51***
EDEP	-0.003	0.003**	-0.02***					
ENVTAX	0.53***	0.76***		0.8	0.93***	0.034***	-0.09	-0.99
GDPGRW					-0.07***			
GDPC			1.06***			0.34***	1.56***	22.85
TRRENT*GDPC		0.19***				0.003*		
TRRENT*CO2	-0.05*				-0.11***			
PRENT*CO2			-0.07***				0.01***	
PRENT*GDPC				1.93***				5.32

Table 7 Short-term heterogenous estimation of the PMG estimators of all the models

a. Model 1

COUNTRY	ECM(-1)	ΔTRRENT	ΔCO2	ΔEDEP	ΔENVTAX	ΔTRRENT*CO2
LUXEMBURG	-0.2251**	-18.8573	-7.2008**	0.0091	4.4079***	0.8333
FRANCE	-0.5998***	58.9177**	-4.1084**	-0.012	-0.7961***	-10.1355***
SPAIN	-0.6618***	-5.7616	-0.5464	-0.0224***	-0.5508***	0.9054
GERMANY	-0.0773***	9.9315	1.5583	-0.0240**	-0.342	-1.0316
HUNGARY	-0.2823**	3.2086	2.007	-0.0071	-1.0658****	-0.6545
CZECH REPUBLIC	-0.3425**	0.1521	-0.1286	0.0104***	0.09421	-0.0173
SLOVAKIA	-0.7841***	-3.2192	0.9216	0.0113**	0.8277**	0.4314
GREECE	-0.4565***	-1.349	-0.3417	0.0004	0.2942	0.1428

Table 7. continued

b. Model 2

COUNTRY	ECM(-1)	ΔTRRENT	ΔCO2	ΔEDEP	ΔENVTAX	ΔTRRENT*GDPC
Netherlands	-0,1259**	0.2209	-2.5947***	-0.006	-0.0487	0.2209
Luxembourg	-0.4402***	15.4430**	-0.2372	-0.0079	2.3255	-1.352**
France	-0.4426***	-5.4693*	1.1688**	-0.0213	-0.3525	0.5225*
Spain	-1.4334***	-14.0600***	1.5759***	-0.0238***	-0.5668***	1.359***
Germany	-0.0875***	0.8994	0.0942	-0.2118	-0.5541	-0.0834
Poland	-0.9080***	-4.1734***	-0.8719***	-0.1001***	-0.1204	0.4337***
Hungary	-0.1384***	-5.4537	0.182	-0.0084	-0.9957***	0.5379
Czech Republic	-0.1505***	-0.5429	-0.4666**	0.0074**	0.1549	0.0478
Slovak Republic	-0.8559***	-6.1073	1.8012***	0.0242***	-0.8136***	0.6054
Italy	-0.1401***	-11.8006**	-0.1879	-0.0092	-0.4914*	1.1337**
Greece	-0.5968**	5.7700*	0.0633	-0.0021	0.5114*	-0.5674*
Latvia	-0.0803**	-3.7331**	-0.7554***	-0.00001	0.05221	0.3837**
Sweden	-0.1343***	12.6415***	-0.3085**	-0.0006	-0.0508	-1.1841***

c. Model 3

COUNTRY	ECM(-1)	ΔPRENT	ΔEDEP	ΔGDPC	ΔPRENT*CO2
Luxembourg	-0.2449***	8.9497	0.0327	2.9485	-0.3906
France	-0.3978***	-0.5605***	-0.016	-0.8938	0.0846***
Slovak Republic	-0.8160***	-1.2427***	0.0324***	0.2316	0.1493***
Bulgaria	-0.8181***	0.3315***	0.0016	0.4238	-0.0424***

Table 7. continued

d. Model 4

COUNTRY	ECM(-1)	ΔPRENT	ΔCO2	ΔENVTAX	ΔPRENT*GDPC
United Kingdom	-0.0780***	1.3916	-0.0448	0.2116	-0.1323
Ireland	-0.0645***	-5.3673*	-0.082	-0.6639	0.4952*
Netherlands	-0.0284***	-1;5479	-0.1298**	0.0318	0.1398
Belgium	-0.0516***	-4160.846	0.1185***	0.3354	395.1797
France	-0.0285**	4.6441	0.1676**	-0.116	-0.4493
Spain	-0.0368*	2.5797	-0.141	-0.4497	-0.2479
Germany	-0.0202***	-1.537	-0.0168*	-0.5083*	0.1463
Hungary	-0.0242**	1.8888	0.0332	-0.493	-0.1964
Czech Republic	-0.0164**	-0.0285	0.0403*	0.3675**	-0.0032
Slovak Republic	-0.1127***	0.4878	0.3000***	-0.3721	-0.0652
Italy	-0.0359***	3.7883	-0.2056**	-0.232	-0.3501
Romania	-0.0397***	0.6508	0.0774*	0.2240***	-0.0617

e. Model 5

COUNTRY	ECM(-1)	ΔTRRENT	ΔCO2	ΔENVTAX	ΔGDPGRW	ΔTRRENT*CO2
France	-0.3941***	14.0066	0.3903	-0.4821	0.0141	-1.925
Germany	-0.0551**	1.4561	0.0246	-0.462	0.0085**	-0.1692
Poland	-0.0672**	0.2887	0.0867	-0.0346	-0.0134***	-0.0353
Hungary	-0.2234**	0.4878	0.1769	-0.5563**	0.0242***	-0.1345
Czech Republic	-0.1450***	-0.9893***	-0.0460**	0.6006**	0.0022	0.0841***
Slovak Republic	-0.2334**	-9.2722	-0.2558	-0.1973	0.0101	1.308
Italy	-0.1892*	1.566	0.0132	-0.443	-0.0028	-0.1511
Estonia	-0.0761**	-0.4917*	-0.0075	-0.1938	0.003	0.0347

Table 7 continued

f. Model 6

COUNTRY	ECM(-1)	ΔTRRENT	ΔCO2	ΔENVTAX	ΔGDPC	ΔTRRENT*GDPC
Ireland	-0.2317***	-0.02269	-0.1300*	-0.3924	0.8384	-0.0007
France	-0.6383***	7.7371	0.2544***	-0.4495	-0.6167	-0.0335
Spain	-0.3444**	-16.3633	-0.1402	0.192	-0.6547	0.0897
Portugal	-0.5796**	-0.2468	-0.1930**	0.3311	0.9	-0.002
Germany	-0.0560**	-1.2335***	0.0167	-0.7858***	1.1201	0.0132**
Slovak Republic	-0.3730***	-1.9983	0.1401**	-0.5186**	-0.0693	0.0618
Italy	-0.1483*	1.3168	0.1248	-0.3918	-3.4733***	-0.0031
Croatia	-0.5143**	-0.3202	-0.0777	0.523	-0.9794	0.0217
Slovenia	-0.4955***	-1.3242	-0.0086	-0.3007*	-1.6594**	0.0445*
Greece	-0.7778*	-0.5189***	0.0098	0.2241	0.406	0.0038
Romania	-0.3428***	-0.1182*	-0.1139**	0.1609	0.7180***	0.0226
Estonia	-0.1174**	0.1783	0.0366***	-0.3805**	-0.5442**	-0.0337
Latvia	-0.5365***	-0.0765	-0.0279	0.3966**	-0.1717	0.0296
Sweden	-0.3414***	-0.4870**	0.0089	0.5516*	0.5838	0.0239**

Table 7. continued

g. Model 7

COUNTRY	ECM(-1)	ΔPRENT	ΔCO2	ΔENVTAX	ΔGDPC	ΔPRENT*CO2
Ireland	-0.2148***	-0.0351	-0.0445	0.2601	-0.5208	-0.0059
France	-0.5114***	-1.2865*	-0.2285	-0.196	0.5031	0.2196*
Spain	-0.4256**	0.6546	-0.0413	-0.2651	0.6803	-0.0871
Germany	-0.0639**	-1.5089	-0.6205	-1.2275**	0.7953	0.1606
Poland	-0.3042**	-0.8977	-0.3306	0.0275	-1.6804**	0.1052
Austria	-1.3252***	-0.8369	-0.32	-0.4104	0.1709	0.096
Czech Republic	-0.2128*	-0.1825	-0.0371	0.1844	-0.6687	0.0155
Slovak Republic	-0.5248***	-0.6035	0.1491	0.0271	-0.4969	0.063
Italy	-0.2941***	1.4831*	0.6417	-0.1183	-3.0400***	-0.1728
Slovenia	-0.6543***	0.4934	0.1097	-0.2923*	-2.401***	-0.0696
Bulgaria	-0.4050**	1.2371**	0.3997**	0.1811	-0.7995	-0.1944***
Romania	-0.2545***	-0.5011	-0.8192	0.1305	0.5997	0.1292
Norway	-0.5094**	0.0408	0.0309	0.1869	1.1738	-0.0029

h. Model 8

COUNTRY	ECM(-1)	ΔPRENT	ΔCO2	ΔENVTAX	ΔGDPC	ΔPRENT*GDPC
United Kingdom	-0.0456***	-14.1519	-0.0182	0.5123	-9.4481	1.3585
Ireland	-0.0870***	-65.2559***	-0.8413***	-4.467**	-8.0682	6.0795***
France	-0.2939***	600.233***	6.0750***	1.4156	161.9482***	-57.2404***
Spain	-0.2178*	121.7572	-1.5942*	2.8925	28.6243	-11.7483
Poland	-0.0284**	27.0227*	0.6480**	0.9905	-5.8564	-2.8178*
Italy	-0.5316***	21.0767	1.0633	-3.0234	-27.8174	-1.9655
Bulgaria	-0.2795***	18.4449	0.2524	1.7225**	2.9377	-1.9086
Romania	-0.0364**	4.8834	-1.3109**	1.0141	12.2619	-0.4662
Lithuania	-0.0354**	-2.7047	-0.2588	1.3143	-3.5259	0.2536

From Table 6, the results of Model 1, which examines the moderating effect of CO2 on the long-term relationship between natural resource rents and renewable energy consumption, are represented by the following equation:

$$\frac{d(RECONS)}{d(TRRENT)} = 0.59 - 0.05C02$$

This equation suggests that an increase in natural resource rents leads to higher renewable energy consumption until CO2 emissions reach a threshold of 11.80 megatons. Beyond this point, further increases in CO2 emissions result in a negative relationship between natural resource rents and renewable energy consumption.

The results of Model 2, which illustrate the moderating role of GDP per capita in the long-term relationship between natural resource rents and renewable energy consumption, are represented by the following equation:

$$\frac{d(RECONS)}{d(TRRENT)} = -1.91 + 0.19\,GDPC$$

This equation suggests that an increase in natural resource rents may initially lead to a decrease in renewable energy consumption until GDP per capita reaches a level of 10.05 (equivalent to €23,155.79 per year)[3]. Beyond this threshold, any further increase in GDP per capita will encourage higher renewable energy consumption.

The results of Model 3, which mainly present the role of $C0_2$ emission in the long-term relationship between petroleum rent and renewable energy consumption, is represented by the following equation:

$$\frac{d(RECONS)}{d(PRENT)} = 0.39 - 0.07C02$$

This equation indicates that the relationship between petroleum rents and renewable energy consumption is positive until CO2 emissions reach a threshold of 5.57 megatons. Beyond this point, any further increase in CO2 emissions will result in a long-term negative relationship between petroleum rents and renewable energy consumption.

The results of Model 4, which demonstrate the mediating role of GDP per capita in the relationship between petroleum rents and renewable energy consumption, are represented by the following equation:

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[3] The data was transformed using a logarithmic scale, where a value of 10.05 corresponds to the logarithmic transformation. When converted back to the original scale, this value equals €23,155.79.

$$\frac{d(RECONS)}{d(PRENT)} = -18.64 + 1.93\, GDPC$$

This equation indicates that an increase in petroleum rents leads to a decrease in renewable energy consumption until GDP per capita reaches 9.66 (€15,677.78). Beyond this threshold, any further increase in petroleum rents will result in an increase in renewable energy consumption.

Model 5 primarily highlights the moderating role of CO2 emissions in the relationship between natural resource rents and renewable energy production. This relationship is expressed by the following equation:

$$\frac{d(REPROD)}{d(TRRENT)} = 1.3 - 0.11\, CO2$$

This relationship shows that the increase in natural resource rent encourages the production of renewable energy until the level of CO2 reaches a threshold of 11.82 megaton. from this threshold level, any increase in natural resource rent leads to the decrease in the production of renewable energy.

Model 6 highlights the role of GDP per capita in the relationship between natural resource rents and renewable energy production. This relationship is expressed by the following equation:

$$\frac{d(REPROD)}{d(TRRENT)} = -0.01 + 0.003\, GDPC$$

This equation indicates that the relationship between natural resource rents and renewable energy production is negative until GDP per capita reaches a threshold of 3.33. Beyond this point, any further increase in GDP per capita will promote the production of renewable energy.

Model 7 evaluates the relationship between renewable energy production and petroleum rents, factoring in the moderating role of CO2 emissions. This relationship is expressed by the following equation:

$$\frac{d(REPROD)}{d(PRENT)} = -0.1 + 0.01\, CO2$$

This equation shows that the increase in petroleum rent decreases renewable energy production until the level CO2 emission reaches the threshold level of 10 megaton. At this threshold, any increase in CO2 will lead to the increase in petroleum rent to encourage the production of renewable energy.

Model 8 illustrates the role of GDP per capita in the relationship between petroleum rents and renewable energy production. The equation derived from the results in Table 6 demonstrates this relationship:

$$\frac{d(REPROD)}{d(PRENT)} = -54.03 + 5.32\, GDPC$$

This equation indicates that an increase in petroleum rents reduces the incentive for renewable energy production until GDP per capita reaches 10.16 (€25,848.30). Beyond this threshold, any further increase in petroleum rents encourages renewable energy production.

The results from various models can be distilled into several key points. First, natural resource and petroleum rents encourage the consumption and production of renewable energy once GDP per capita surpasses a specific threshold, which differs for renewable energy consumption and production. Below this threshold, an increase in natural resource and petroleum rents actually hampers renewable energy consumption and production. Second, an increase in natural resource rent results in a decrease in the consumption and production of renewable energy when CO2 emissions reach a certain threshold level. Lastly, in contrast to natural resource rent, an increase in petroleum rent leads to an increase in renewable energy production when CO2 emissions reach a threshold level of 10.

To understand the first observation that natural resource and petroleum rents stimulate the consumption and production of renewable energy once GDP per capita reaches a certain threshold, it is crucial to consider the financial realities of energy transition costs. Many studies alluded that transitioning from non-renewable sources of energy to renewable ones is costly (Li & Trutnevyte, 2017; Persad et al., 2024; Stringer & Joanis, 2022). This reality suggests that higher economic and financial wealth should enable more substantial investments in renewable energy, facilitating a shift away from traditional, non-renewable sources as a country's financial capacity improves.

It may be argued that countries that depend heavily on natural resources, particularly non-renewable ones, to drive economic growth often face significant challenges in transitioning to renewable energy. This reluctance stems from the fear of losing critical revenue sources which are integral to their economies. However, as these countries experience increases in GDP per capita, they may find themselves in a better position to finance cleaner energy initiatives. The increase in GDP per capita can expand their financial capabilities, thereby facilitating greater investment in renewable energy technologies.

As nations become wealthier, surplus resources can be channeled towards developing sustainable energy infrastructure (Altenburg & Rodrik, 2017; Bridge et al., 2018; Glemarec, 2012), a shift that is often driven by the dual pressures of needing sustainable development and responding to the escalating environmental costs associated with the continued use of fossil fuels. Thus, while the initial dependency on non-renewable resources poses a significant challenge, economic growth provides an opportunity to diversify energy sources and embrace more sustainable practices, ultimately contributing to global efforts to combat climate change.

The second observation highlights that an increase in natural resource rent leads to a decrease in the consumption and production of renewable energy when CO2 emissions surpass a certain threshold. This finding underscores the significant role that the quantity of carbon dioxide plays in energy transitions. The results reported in Table 6 show an unconditional negative relationship between CO2 emissions and renewable energy consumption and production in all models, illustrating that increases in renewable energy production and consumption typically lead to reductions in CO2 emissions. However, when the impact of CO2 is factored or conditioned into the dynamic between natural resource rent and renewable energy, the results show that the increase in natural resource rent decreases renewable energy consumption and production when CO2 surpasses a certain threshold.

This conditional outcome may suggest that in economies heavily reliant on natural resources for revenue, an increase in natural resource rent that results in CO2 emissions exceeding a specific threshold can hinder the transition to clean energy. This is because these economies face a significant dilemma: pursuing increased revenue from natural resources often leads to higher CO2 emissions, which in turn makes it challenging to shift towards cleaner energy solutions without jeopardizing their main income source. For example, when examining the links between renewable and non-renewable energy use, CO2 emissions, and economic growth in various economies, Dissanayake et al. (2023) highlight that in economies heavily reliant on natural resources, there is a significant relationship between economic growth and CO2 emissions, which can hinder the transition to renewable energy. Likewise, Amin et al. (2024) show that an abundance of natural resources is positively correlated with higher CO2 emissions, which can impede efforts to transition to renewable energy. We postulate that this phenomenon may be dubbed as the 'natural resource curse for energy transition'.

The last observation that an increase in petroleum rent leads to an increase in renewable energy production when CO2 emissions surpass a certain threshold may reveal the commitment of many European countries' producers of fossil energies to commit to the United Nations Sustainable Development Goal (SDG 13: Climate action) that specifically addresses the reduction of CO2 emissions. European countries are often at the forefront of international climate agreements, such as the Paris Agreement, which align with SDG 13. These commitments require tangible actions to reduce CO2 emissions (Akpuokwe et al., 2024; Dovie, 2019; Trotter et al., 2022).

Table 7 present the short-term heterogenous estimation of the eight models for all the countries. It is worth noting that we reported only countries where the cointegration relationship holds among the key variables of the study, explaining their long-run relationship with a given speed of adjustment (ECM (-1)) in case of possible short-run deviation. Concerning the speed of adjustment, the results reported in Table 7 show that for model 1,   Slovakia has the highest speed of adjustment, showing that more than 78% of the deviation between natural resource rent and renewable energy consumption correct in the same year. This reality shows that the tendency of the two variables to remain related. In the same model, FRANCE is the only country where the threshold of CO2 emission holds in the relationship between natural resource rent and renewable energy consumption. The short-term threshold of 10.1 megaton of CO2 beyond which the relationship between natural resources and renewable energy becomes negative is relatively less than in the long term.

Other results of the short-term adjustments show that the following countries have the highest speed of adjustment for the different models in the relationship between natural resource rent or petroleum rent and renewable energy: Poland for model 2, Bulgaria for model 3, UK for model 4, Poland for model 5, Greece for model 6, Slovenia for model 7 and Italy for model 8.

The higher speed adjustment depicted by these countries show that they may have implemented strong policies, regulations, or incentives aimed at using rents from the natural resources (such as fossil fuels) to transition toward renewable energy. This could lead to a faster correction when there is a deviation from the long-run equilibrium relationship between natural resource use and renewable energy production or consumption. Moreover, these countries may have adopted or developed advanced technologies that facilitate a quicker shift from traditional natural resources to renewable energy sources during the period of the analysis. This may not indicate that there are countries with highest pace of energy transition.

These findings provide critical insights for European policymakers as they address the intricate challenges of the energy sector and climate change. By gaining a deeper understanding of the complex relationships between natural resource and petroleum rents, and the transition to renewable energy—particularly the moderating roles of GDP per capita and environmental sustainability, as reflected in CO2 emissions—policymakers can more effectively tailor strategies to support sustainable energy transitions. This nuanced approach allows for the development of policies that balance economic growth with environmental protection, ensuring that national energy strategies are in harmony with broader European Union goals, such as the European Green Deal, as well as international commitments like the Paris Agreement. By leveraging these insights, European policymakers can accelerate the shift towards a low-carbon, resilient economy while addressing both economic and environmental dimensions of the energy transition.

Conclusion

This paper investigated the intermediary role of carbon dioxide (CO2) emissions and GDP per capita in the impact of natural resource and petroleum on renewable energy, offering a nuanced analysis that differentiates between renewable energy consumption and renewable energy production. Specifically, the paper aimed to explore how natural resource wealth, measured by rents from resources such petroleum and other fossil related resources, influences the development of the renewable energy sector. The study pays particular attention to the moderating effects of economic growth, represented by GDP per capita, and environmental sustainability, reflected in CO2 emissions. To this end, the paper applies three estimators of the panel ARDL model to delineate between the the long- and short-run relationship in the determination of the thresholds of the moderating factors. The results of the empirical analysis show that natural resource and petroleum rents encourage the consumption and production of renewable energy once GDP per capita surpasses a specific threshold, which differs for renewable energy consumption and production. For example, the increase in petroleum rent leads to a decrease in renewable energy until the level of GDP per capita reaches 9.66 (€15677.78). beyond this threshold, any increase in petroleum rent will lead to the increase in renewable energy consumption. Moreover, the results reveal that an increase in natural resource rent results in a decrease in the consumption and production of renewable energy when CO2 emissions reach a certain threshold level and that an increase in petroleum rent leads to an increase in renewable energy production when CO2 emissions reach a threshold level of 10 megatons.

The short-term results show that European countries that are not necessary the leading economies in Europe have the highest speed of adjustment for the different models in the relationship between natural resource rent or petroleum rent and renewable energy. The higher speed adjustment depicted by these countries may imply that they have implemented strong policies, regulations, or incentives aimed at using rents from the natural resources (such as fossil fuels) to transition toward renewable energy.

These findings offer valuable insights for policymakers in Europe, particularly as they navigate the complexities of the energy sector and climate change. By deepening their understanding of the intricate interactions between natural resources and petroleum rents and renewable energy transition, especially the moderating effects of economic growth, represented by GDP per capita, and environmental sustainability, reflected in CO2 emissions in this interaction, European policymakers will be able to align national energy policies with broader European Union goals, such as the European Green Deal, and international commitments, like the Paris Agreement, ultimately accelerating progress toward achieving long-term climate objectives and fostering a resilient, low-carbon economy.

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Appendix

Table A1. Variable description

No	Variable name	Identifier	Description	Source
1	Corruption		Corruption Perception Index	Transparency International
2	GDP per Capita		Annual percentage growth rate of GDP per capita based on constant local currency.	World Bank national accounts data, and OECD National Accounts data files.
3	GDP Growth		Annual percentage growth rate of GDP at market prices based on constant local currency.	World Bank national accounts data, and OECD National Accounts data files.
4	CO2 Emission		Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring.	Emissions data are sourced from Climate Watch Historical GHG Emissions (1990-2020). 2023. Washington, DC: World Resources Institute. Available online at: https://www.climatewatchdata.org/ghg-emissions
5	Total Resource Rents		Per capita total natural resource rents in constant	World Development Indicator (Data Bank)
6	Environmental Taxes		Environmental Taxes and Expenditures	World Development Indicator (World Bank Data) and EuroStat
7	Green bond		S&P Green Bond Index	Refinitiv DataStream
8	Petroleum rent		Oil rents are the difference between the value of crude oil production at regional prices and total costs of production.	World Development Indicator (World Bank Data)
9	Renewable energy production		Electricity production from renewable sources, excluding hydroelectric, includes geothermal, solar, tides, wind, biomass, and biofuels.	IEA Statistics © OECD/IEA 2014 (https://www.iea.org/data-and-statistics), subject to https://www.iea.org/terms/ and EuroStat
10	Renewable energy consumption		Renewable energy consumption is the share of renewable energy in total final energy consumption.	IEA, IRENA, UNSD, World Bank, WHO. 2023. Tracking SDG 7: The Energy Progress Report. World Bank
11	Market Capitalisation		Market Capitalisation	World Development Indicator (World Bank Data)

Table A2. Countries included in the analysis

United Kingdom
Ireland
Netherlands
Belgium
Luxembourg
France
Spain
Portugal
Germany
Poland
Hungary
Czech Republic
Slovak Republic
Italy
Malta
Croatia
Slovenia
Greece
Cyprus
Bulgaria
Estonia
Latvia
Lithuania
Finland
Sweden
Norway
Denmark
Romania
Austria