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Exploring the Impact of Export Diversification on Energy-Mix Diversification: Role of Institutional Quality, Foreign Direct Investments and Research & Development

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Abstract

This research investigates the effects of export diversification (henceforth, EXD) on energy mix diversification for 26 European Union (EU) countries. To achieve this aim, we employ the quantile regression model and GMM estimator for 1995–2020. The primary outcome of this study is to identify the complexity of such two crucial factors. At lower levels of diversification, EXD has a negative impact on energy mix

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diversification; however, this effect becomes positive at higher level diversification. This situation underscores the significance of considering this factor when formulating energy policies. Specifically, exploring strategies to increase EXD in countries with limited energy diversity may be necessary. On the other hand, promoting EXD in countries with abundant energy diversity can contribute to a more robust and sustainable energy sector. This finding emphasizes the necessity of adopting an integrated approach in developing and implementing energy and export policies. The quantile regression analysis using different quantiles (percentages) can ensure quantile-based customized policies and strategies between export and energy diversifications to the EU policymakers. Therefore, EU policymakers should consider creating and implementing foreign trade and energy policies in a coordinated manner.

Keywords: Energy diversification, export diversification, EU countries, panel quantile regression, GMM, low-high quantiles

JEL Classification: F14, Q48, Q43, F21

1. Introduction

Export diversification (*EXD*) has been extensively studied for its role in economic growth and stability. Foundational understanding is provided by Hesse (2008) and Agosin (2007). However, recent studies, such as those by Klinger and Lederman (2004), extend this analysis to the impact of *EXD* on sectoral economic shifts, including energy. These studies suggest a broad export base can catalyze investment in new industries, including renewable energy. However, little is known about the impacts of *EXD* on the environment. As Sovacool (2011) described, energy diversification entails a multifaceted approach to energy production and consumption, reducing reliance on single sources and promoting environmental sustainability. Additionally, Shahbaz *et al*. (2019) noted that adopting environmentally friendly technology has significantly improved energy efficiency and reduced CO_2 emissions. The interplay between trade and energy strategies increasingly influences the global economic framework.

In this context, the fundamental research question that forms the starting point of our research is: *What is the impact of export diversity (EXD) on energy resource diversity?* The answer to this question is critically important, especially in transitioning from externally dependent and carbon-intensive energy systems to more secure and sustainable energy systems in the European Union countries.

While *EXD* has long been recognized as a stabilizing factor against market fluctuations, its potential impact on a country's energy policy still needs to be identified, particularly in diversifying energy sources.

The literature does not sufficiently discuss the effects of *EXD* on energy policies; filling this gap constitutes the original contribution of our study to the literature.

This research purposes to explore this intersection, especially relevant in the current era of foreign trade policy and energy policy. Although the concepts of *EXD* and energy diversification are seen as two concepts representing different sectors, in fact, these two concepts are complementary to each other for a country. For example, a country can support economic growth through *EXD*, which may increase its energy demand. In this case, increasing energy demand may increase the need for energy diversification. This may require diversifying energy sources and investing in various energy sources to improve the security of the energy supply. Hence, foreign trade policy through export diversification (*EXD*) and energy policy through energy diversification should be considered combined for this country.

Especially in EU countries with high dependence on fossil fuels, the relationship between *EXD* and energy supply security is essential in sustainable development strategies. In this context, our research purposes to show how the structural characteristics of foreign trade can contribute to energy transformation processes.

Therefore, this study examines the impact of *EXD* on energy diversification and produces policy implications for EU policymakers.

The link between *EXD* and energy supply security is important in sustainable development strategies, especially in EU countries with high dependence on fossil fuels. In this context, our study aims to show how the structural characteristics of foreign trade can contribute to energy transformation processes.

The theoretical background of this study, as we linked above, between *EXD* and energy diversification, was *directly* and *indirectly* inspired and supported by various theories and approaches in international trade. One of these is the Heckscher–Ohlin Theory by Ohlin (1933). This theory suggests that a country's specialization in trade and the diversity of its export products in foreign trade are closely related to its natural resources and factor endowments (factors of production). While a country decides which products to export based on the factors of production it has, these factors include a variety of resources, including energy resources. Another related theory is Ricardo's Comparative Advantage Theory, which was developed by Ricardo (1817). This theory suggests that a country performs better in certain goods and services and, therefore, has an advantage in exporting these products. In other words, this theory recommends that the country diversify its exports and create its export portfolio accordingly. For example, a country may gain an advantage in producing energy-intensive products by effectively using and diversifying its energy resources. Similarly, Linder's (1961) hypothesis proposes that a country's export diversification (*EXD*) is based on domestic market demands. If there is high demand for various products in the domestic market, the export portfolio will also consist of these products.

Therefore, domestic market demands significantly impact a country's foreign trade strategy and *EXD*. At this point, these export products may be energy-intensive sector products and, therefore, may determine the country's energy diversity. The sectoral Hirschman Index, developed by Hirschman (1945) and Herfindahl (1950), is the square root of the sum of the total squared shares of each industry's exports. It shows that exports in a country with a high Hirschman Index value are concentrated in specific sectors. This may mean low *EXD*. Therefore, these particular sectors may indicate a focus on energy-intensive sectors that may change this country's energy policy.

The theoretical approaches summarized above constitute the theoretical framework on which this study is based and show that the energy-*EXD* relationship should be addressed in a multidimensional manner. This theoretical background also allows for more comprehensive testing of this relationship, which has been ignored or treated limitedly in previous studies.

Export diversification (*EXD*) and energy diversification are crucial for a nation's economic sustainability and resilience. *EXD* allows a country to diversify its products and services, reducing reliance on a single sector or product. This diversification increases competitiveness, supports economic development, and creates jobs. On the other hand, energy diversification reduces reliance on a single energy source like fossil fuels, ensuring a stable energy supply. This diversification helps mitigate climate change and lower greenhouse gas emissions by switching to greener, more sustainable energy sources. It also encourages investment and innovation in renewable energy, boosting employment and the economy. Both export and energy diversification offer benefits for sustainability and economic resilience (Bai *et al*., 2025; Hoang *et al*., 2024; Işık *et al*., 2025a, 2024a, 2024b; Shahbaz, 2024; Sun *et al*., 2024; Klinger and Lederman, 2009, 2011). Diversifying exports allows for more resources and money for investments in renewable energy sources, opening opportunities for energy diversification. Energy diversification also makes energy-intensive businesses more competitive, reducing their reliance on costly, carbon-intensive energy sources (Bai *et al*., 2025; Elfarra *et al*., 2024; Işık *et al*., 2025b, 2024c, 2024d).

Therefore, our study highlights the importance of a holistic policy approach that addresses energy security, combating climate change, and economic diversity. In addition, our study offers concrete policy suggestions that foreign trade and energy policies should be designed together, making both theoretical and practical contributions to literature.

In such circumstances, our research contributes to the existing literature four folds: (i) This research investigates the link between *EXD* and energy mix diversification by considering the role of economic growth, foreign direct investment, institutional quality, and research

& development expenditures in energy diversification function using data for the EU for the period of 1995–2020. (ii) We apply White's and Breusch–Pagan and Cross-section Dependence tests to examine heterogeneity and cross-sectional independence. (iii) The panel unit root and cointegration tests are applied to investigate unit root properties and cointegration between the variables. (iv) We apply Quantile Regression to examine the effect of *EXD* on energy mix diversification, and the robustness of empirical results is tested by applying the GMM estimator. Our empirical findings reveal that *EXD*, economic growth, and institutional quality are essential in promoting energy diversification. Foreign direct investment and research & development expenditures have neutral and negative effects on energy mix diversification.

These four contributions provide some of the first comprehensive empirical findings on the *EXD*-energy diversity link, which is lacking in the literature, and aim to move the field forward. Our results have important implications not only for academics but also for policymakers.

2. Literature Review

The outcomes remain inconclusive since research studies rely on available data to conduct cross-country comparisons in the ongoing debate regarding the link between diverse exports and energy intensity. Iqbal *et al*. (2021) investigated the influence of *EXD* on CO_2 emissions in 37 Organization for Economic Cooperation and Development (OECD) countries. They discovered that diversifying exports increases CO_2 emissions. On the other hand, OECD countries include both developed and developing nations. Therefore, grasping the consequences of *EXD* is difficult without examining sub-panels in terms of development levels because development levels might alter the impact of *EXD* or concentration. Bashir *et al*. (2020) found that *EXD* considerably reduces energy intensity by accelerating trade liberalization and improving institutional quality in 19 OECD countries between 1990 and 2015. Kiliçarslan and Dumrul (2022) investigated how *EXD* contributes to energy demand for BRICS-T nations between 1995 and 2014, using panel cointegration tests, panel fully modified OLS (FMOLS), and panel dynamic OLS (DOLS) tests. In the long run, the findings revealed a negative link between energy demand and *EXD*.

The global view of the relationship between export and energy diversification is complex. The International Energy Agency (IEA) (Global Energy Review, 2019) publishes reports that show how diverse economic structures and export profiles impact energy policies. Regional studies, on the other hand, such as those focusing on Asia-Pacific Economic Cooperation (APEC) countries, show how specific economic objectives and resource availability influence energy diversity (Magazzino *et al*., 2022). To achieve energy efficiency in OECD countries, Doğan *et al*. (2022) examined the effects of institutional factors and the diversity of import products. They discovered that diversifying import products helps OECD nations lower their energy and carbon intensity (an increase in energy efficiency). Further, Shahzad *et al*. (2021) analyzed ten newly industrialized countries from 1971 to 2014 and found that diversifying export products reduces energy usage. Zeeshan *et al*. (2021) conducted a study for Indonesia, exploring how *EXD* can promote the adoption of environmental technologies and reduce energy demand, consequently enhancing environmental quality. Their findings underscore the importance of renewable energy and *EXD* for Indonesia's long-term prosperity.

The literature on the relationship between *EXD* and energy diversification is still nascent. Therefore, this research investigates the effects of *EXD* on energy diversification in European Union (EU) countries. This research contributes to the growing relevant literature within the framework of the following points based on the evaluations conducted thus far:

Exploring the Direct Influence of Export Diversification on Energy Diversification: The main distinguishing factor of this study from other research lies in the fact that this research investigates the direct impact of the *EXD* variable on energy diversification rather than its effects on dependent variables such as energy consumption, energy efficiency, energy usage, CO_2 emissions, or energy intensity, as investigated in other studies. This uniqueness allows this study to make an original contribution because it can emphasize the potential role of *EXD* in the sustainability and resilience of the energy sector. This offers a different perspective that can be valuable for policymakers shaping energy policies and sustainability strategies.

Exploring the Direct Influence of Export Diversification on Energy Diversification in the EU: The variables of export and energy diversification have been a central focus of this study, specifically within the context of the EU countries. The findings of this study may indicate that *EXD* has a significant influence on energy diversification. Therefore, the EU policymakers may consider promoting diversified exports to enhance the resilience and sustainability of their energy sectors. For example, suppose *EXD* has a negative effect on energy diversification. In that case, the EU policymakers may reconsider its energy import and trade policies to enhance energy independence, which could lead to a diversification of energy supply sources. EU countries represent a specific geographic region, and energy policies and trade have significant implications within this region. Therefore, including EU countries in the sample is essential for understanding regional energy strategies and managing energy independence. Additionally, the EU has adopted several regulations and policies concerning energy policies and objectives. Therefore, examining the effects of these policies and laws on energy diversification can also be instructive for other countries and regions.

Index-to-Index Relationship: Both indices of these variables can encompass multiple dimensions. For instance, the *EXD* index may include various factors such as changes in exports over time, disparities among different countries or regions, and the diversity of sectors. Similarly, the energy diversification index can encompass multiple dimensions, such as the diversity of energy sources, energy efficiency, and the distribution of energy production sectors. Consequently, analyses conducted using the indices of both variables enable considering these multifaceted dimensions, allowing for a more in-depth exploration of the relationship between *EXD* and energy diversification.

2.1. Factors Affecting Energy Diversification

2.1.1 The Impact of Economic Development on Energy Diversity

The last decade saw a rapid increase in the installed capacity of renewable energies in Europe, driven primarily by policies aimed at reducing fossil fuel imports and CO_2 emissions. This growth was further facilitated by technological advancements that reduced the generation costs of wind and solar power, indicating a direct link between economic development and the diversification of renewable energy sources. Europe has demonstrated a stable evolution in the diversity of its fuel mix at the aggregated EU28 level. This stability indicates a concerted effort towards maintaining a balanced energy portfolio despite economic fluctuations (Mattia De Rosa, 2022). There is a significant correlation between economic parameters and the energy balance in EU countries, encompassing aspects like demand, production, import, and energy export. While economic factors play a role, they are often less impactful than political developments or the country's overall level of energy development (Rokicki and Perkowska, 2021). Energy consumption diversity and efficiency in the EU's industrial sector have improved. This improvement reflects the varied levels of economic development, energy structures, societal wealth, and environmental awareness across the 27 EU countries. Such diversity suggests that economic development in these countries is closely tied to their unique energy needs and capabilities (Brodny and Tutak, 2022).

2.1.2. The Impact of Foreign Direct Investment on Energy Diversity

Foreign Direct Investment (*FDI*) plays a crucial role in shaping the energy landscape of the EU countries, influencing both renewable and non-renewable energy utilization. A study by Apergis and Pinar (2021) revealed a positive impact of *FDI* in 25 EU countries from 2003 to 2017. This suggests that *FDI* has been instrumental in bolstering renewable energy consumption within the EU, signifying a potential shift towards more sustainable energy practices. Rafaela Vital *et al*. (2022) indicate that *FDI* affects pollution via energy consumption and emphasizes the importance of energy transition in mitigating this effect. Notably, the transition towards renewable energy sources, driven partly by *FDI*, is key in fostering green growth. This is particularly pertinent as developing countries, often reliant on non-renewable energy sources to meet their energy demands, are increasingly considering renewable options. The broader investment conditions and the strength of climate policies are vital for creating a favorable environment for renewable energy. The extent to which these factors influence investment decisions varies depending on the origin of the investors, indicating that both domestic and international policies and market conditions play a significant role in shaping the impact of *FDI* on energy diversity (Knutsson and Flores, 2022).

2.1.3. The Impact of Institutional Quality on Energy Diversity

Institutional quality is closely linked to energy policies from production to consumption of fossil or renewable energies and plays a crucial role in developing effective policies within the energy sector. For example, Uzar (2020) analyzed 38 countries, including those in the EU, and found that institutional quality positively impacts renewable energy consumption. According to the study, at a 5% significance level, a 1% enhancement in institutional quality is associated with a long-term increase of 0.869% in renewable energy consumption. Wang *et al*. (2022) examined 32 OECD countries, including the EU countries, and found that higher levels of institutional quality increase renewable energy consumption. Sun *et al*. (2022) investigated 99 countries, including a member of the EU, and discovered that the quality of institutions plays a crucial role in enhancing energy efficiency. Furthermore, they observed that being in proximity to countries with a strong institutional framework has a beneficial impact on domestic energy efficiency.

2.1.4. The Impact of Research & Development Quality on Energy Diversity

Wong *et al*. (2013) investigated the impact of subsidies for renewable energy on renewable energy consumption in the OECD countries, including the EU nations. They found that these subsidies play a crucial role in promoting the consumption of renewable energy sources. *R&D* plays a vital role in advancing and enhancing renewable energy technologies. Churchill *et al*. (2021) investigated the link between *R&D* and non-renewable energy consumption in OECD countries, including the EU. They found a positive correlation between *R&D* activities and non-renewable energy consumption. According to the research by Gasser *et al*. (2022), it has been established that public *R&D* funding plays a crucial role in driving green energy innovation across 17 EU countries.

3. Empirical Modeling, Methodology and Data Sources

The baseline model to examine the association among energy diversification (log*END*), export diversification (log*EXD*), economic development (log*PGDP*), *FDI*, institutional quality (*IQ*) and *R&D* can be prescribed as in Equation 1:

$$\log END_{i,t} = a_0 + a_1 \log EXD_{i,t} + a_2 \log PGDP_{i,t} + a_3 FDI_{i,t} + a_4 IQ_{i,t} + a_5 R\&D_{i,t} + \varepsilon_{i,t} \tag{1}$$

where, α_0 is an intercept; α_1, α_2, α_3, α_4, α_5, are elasticity coefficients; ε is an error term, *i* is cross-sections, *t* is time.

$$Q_{\log END_{i,t}}(\tau|x_{i,t}) = \beta_0 + \beta_1 \log EXD_{i,t} + \beta_1 \log PGDP_{i,t} + \beta_3 FDI_{i,t} + \beta_4 IQ_{i,t} + \\ + \beta_5 R\&D_{i,t} + \varepsilon_{i,t} \tag{2}$$

where $Q_{\log EXD_{i,t}}(\tau|x_{i,t})$ is the quantile distribution of $\log EXD_{i,t}$ (explained variable), constrained by the position of the explanatory and control variables; τ represents the quantile of each section (*i*).

Both the Quantile Regression and GMM estimator analyses will be performed to expand the analytical approach of this study and evaluate the results from different perspectives. The Quantile regression and GMM analyses represent different analytical approaches. Quantile Regression is appropriate for examining percentile-specific relationships, while GMM helps control endogeneity and address systematic error components. Therefore, analyzing both models will increase the depth of our study. For example, examining the changes in different percentiles of an independent variable, such as national income per capita GDP (log *PGDP*), can bring about many significant economic and social consequences. In other words, examining the effect of *PGDP* on energy diversification at different percentages can be an essential analytical approach in determining quantile-based customized energy policies and diversification strategies. Likewise, there may be an endogeneity problem in the relationship between the log *PGDP* and energy diversification (log *END*). Endogeneity may cause the relationship between these two variables to be misleading. Therefore, by controlling GMM endogeneity, an accurate and reliable evaluation of the relationship can be achieved. It is the same for other variables of both models.

Before conducting these two analyses, we should follow the following pre-tests. The critical consideration for using the panel quantile regression model is that the data should be heteroskedastic. We run White (1980) and Breusch–Pagan (1979) tests to examine heteroscedasticity. The general specification, which is estimated using the GMM estimator, can be prescribed as the following:

$$\log END_{i,t} = \lambda \; \log END_{i,t-1} + \theta_1 \log EXD_{i,t} + \boldsymbol{x}'_{i,t}\boldsymbol{\beta} + \alpha_i + u_{i,t} \tag{3}$$

where log$END_{i,t}$ is energy diversity of country i in year t, log$EXD_{i,t}$ is export diversity, $x'_{i,t}$ is a vector of control variables. In addition, α_i stand for country i fixed effects and $u_{i,t}$ is the residual term. λ is the parameter of the lagged dependent variable, θ_1 is the parameter of the independent variable, β is a vector of parameters of control variables.

To empirically investigate the impact of export diversification (*EXD*), economic development, *FDI* (foreign direct investment), institutional quality, and *R&D* (research and development) on energy diversification, a panel dataset is developed covering 26 EU countries spanning the period 1995–2020. Energy diversification, measured in an index, is applied as explained variable. *EXD*, measured in merchandise diversification indices of exports, is used as a core explanatory variable. Economic development, measured as GDP per capita, constant 2015 US$, the foreign direct investment (*FDI*), measured in net inflows, % of GDP, institutional quality, measured in government effectiveness index, and *R&D*, measured in research & development expenditures, % of GDP, are employed as control variables (See Table 1 for definition and sources of variables).

Table 1: Definition and Sources of Variables

Variable types	Notation	Name	Definition	LOG Transformation	Data Source
Explained variable	***END***	Energy Diversification	Energy Diversification Index	log*END*	Triguero-Ruiz et al. (2023)
Core explanatory variable	***EXD***	Export Diversification	Merchandise diversification indices of exports by country	log*EXD*	IMF
Control variables	***PGDP***	Economic development stage	GDP per capita, constant 2015 US$	log*PGDP*	WDI
	FDI	Foreign direct investment	Foreign direct investment, net inflows (% of GDP)	–	WDI
	IQ	Institutional Quality	Government effectiveness: Estimate, index	–	WDI
	R&D	Research and development	Research and development expenditure (% of GDP)	–	WDI

Source: Authors' own elaboration

According to the descriptive statistics of the studied variables in Table 2, the energy diversity index is 2.89 on average for EU countries from 1995–2020. The index of export diversity is 0.45 on average for the period studied. The average gross domestic product per capita is 30,982.29 USD. *FDI* shares 6.10 percent of GDP on average in EU countries. The institutional quality index counts as 1.16 on average. *R&D* averaged 1.54 percent of EU GDP in 1995–2020. The data on energy diversity, institutional quality, and *R&D* are platykurtic, whereas export diversity, per capita GDP, and *FDI* are leptokurtic. Energy diversity and institutional quality are negative regarding skewness, while export diversity, per capita GDP, *FDI*, and *R&D* have positive skewness.

Table 2: Descriptive Statistics

Variables	*END*	*EXD*	*PGDP*	*FDI*	*IQ*	*R&D*
Mean	2.89	0.45	30,982.29	6.10	1.16	1.54
Standard deviation	0.56	0.11	22,348.77	15.81	0.66	0.87
Minimum	1.17	0.23	3,537.32	−117.37	−0.56	−0.01
Maximum	3.98	0.84	112,418	234.46	2.35	3.87
Skewness	−0.27	0.98	1.22	5.07	−0.27	0.59
Kurtosis	2.37	3.95	4.71	77.59	2.03	2.38
Observations	676	676	676	676	676	676

Source: Authors' own calculations

4. Empirical Findings

First, we run the test for heteroskedasticity. The estimated coefficients are reported in Table 3. The null hypothesis is that the data is homoscedastic, whereas the alternative hypothesis refers to heteroskedastic data. The null hypothesis is rejected if the *p*-value is lower than 0.05. Due to the results, heteroskedasticity exists in the data.

Table 3: White's and Breusch–Pagan Test for Heteroskedasticity

White's test	0.00
Breusch–Pagan test for heteroskedasticity	0.00

Source: Authors' own calculations

Table 4 denotes the results of the cross-sectional dependence (CD) and (IPS, CIPS) unit root tests.

Table 4: Cross-section Dependence and Panel Unit Root Analysis

Variables	CD test	IPS test		CIPS test	
		Level	1st Difference	Level	1st Difference
log*END*	25.45***	1.95	−7.06***	−2.02	−4.22***
log*EXD*	2.55**	−0.53	−8.12***	−2.28**	−5.28***
log*PGDP*	77.27***	−3.14***	−3.19***	−2.07*	−3.13***
FDI	18.97***	−4.86***	−10.97***	−3.23***	−5.76***
IQ	3.20***	−0.39	−6.95***	−1.54	−4.59***
R&D	31.72***	3.89	−4.79***	−1.52	−3.61***

Note: *** and ** represent statistical significance at 1% and 5% levels, respectively. The cross-section dependence test's null hypothesis is no cross-section dependence. Based on the AIC criterion, the lag length is selected as 2.

Source: Authors' own calculations

Table 4 presents the results of panel unit root tests (IPS and CIPS) and cross-section dependence (CD) for the variables included in the model.

CD Test (Cross-section Dependence): Statistically significant CD test values for all variables indicate a significant level of cross-section dependence between the series (for example, CD = 77.27*** for log *PGDP*). This shows that inter-country dependence cannot be ignored in panel data.

IPS and CIPS Panel Unit Root Tests: Most variables are not stationary at the level values, but when their first differences are taken, all variables become stationary. For example, for log *EXD*, IPS is not stationary at the level but becomes stationary at the first difference (−2.28**, −5.28***).

These findings reveal that the variables included in the analysis contain a unit root, but stationarity is achieved when the difference is taken; therefore, switching to panel cointegration tests is methodologically necessary.

Consequently, we might proceed with model estimations. Table 6 represents the results of POLS (pooled OLS) and fixed effect regressions. Due to the results of both models, the effect of export diversity (log *EXD*) on energy diversity (log *END*) is marginally significant, which gives an assumption about no linear impact between them. On this occasion, we proceed to estimate the panel quantile regression model.

Table 5: Panel Cointegration Analysis

	Statistic	*p*-value
Pedroni test		
Modified PP *t*	4.67	0.00
PP *t*	–1.92	0.02
ADF *t*	–2.00	0.02
Westerlund test		
Variance ratio	2.75	0.00

Note: *** and ** represent statistical significance at 1% and 5% levels, respectively.
Source: Authors' own calculations

Table 5 shows the results of the Pedroni and Westerlund panel cointegration tests, which were conducted to determine whether there is a long-term relationship between the variables in the model.

Pedroni Test: The modified PP *t*, PP *t*, and ADF *t* statistics were calculated as 4.67 (p = 0.00), −1.92 (p = 0.02), and −2.00 (p = 0.02), respectively. These results show a statistically significant cointegration relationship between the variables.

Westerlund Test: The variance ratio is 2.75, and the *p*-value is 0.00. This is an additional finding supporting the existence of cointegration.

When both test results are evaluated together, it is concluded that there is a long-term balanced relationship between *EXD*, energy diversity, and other control variables (log *PGDP*, *FDI*, *IQ*, *R&D*).

Consequently, we may proceed with model estimations. Table 6 represents the results of POLS (pooled OLS) and fixed-effect regressions. Based on the results of both models, the effect of export diversity (log *EXD*) on energy diversity (log *END*) is marginally significant, which implies that there is no linear effect between them. On this occasion, we proceed to estimate the panel quantile regression model.

Table 6: Baseline Models Results

	M (1)	M (2)
	POLS	**Fixed Effect**
log*EXD*	0.06*	0.06*
log*PGDP*	0.02	0.02
FDI	0.00	0.00
IQ	0.00	0.00
R&D	0.00	0.00
Constant	0.73***	0.85**
Individual fixed effects	Yes	Yes
Time fixed effects	Yes	Yes

Source: Authors' own calculations

Table 7: The Estimated Coefficients by the Means of Quantile Regression

Dependent variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
log*END*	10%	20%	30%	40%	50%	60%	70%	80%	90%
log*EXD*	−0.14***	−0.07***	0.04***	0.13***	0.09***	0.14***	0.19***	0.16***	0.14***
log*PGDP*	0.34***	0.23***	0.18***	0.17***	0.13***	0.12***	0.10***	0.09***	0.07***
FDI	−0.00	−0.00	0.00	0.00**	0.00	0.00***	0.00***	−0.00	−0.00
IQ	−0.01	0.04***	0.04***	0.04***	0.05***	0.07***	0.07***	0.07***	0.08***
R&D	−0.17***	−0.23***	−0.20***	−0.21***	−0.17***	−0.16***	−0.15***	−0.13***	−0.12***
Individual fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Mean acceptance rate	0.50	0.43	0.45	0.37	0.39	0.50	0.21	0.37	0.45
N	676	676	676	676	676	676	676	676	676

Note: *** and ** represent statistical significance at 1% and 5% levels, respectively.
Source: Authors' own calculations

Due to the results in Table 7, *EXD* negatively impacts energy diversity (log *END*) in low quantiles 10% and 20%, whereas in all other quantiles (30–90%), the effect becomes positive. This suggests that export diversity (log *EXD*) is a key factor in energy diversification. This means lower *EXD* is associated with lower energy diversification, and higher *EXD* is associated with higher energy diversification. This result may provide policymakers with some valuable insights. Firstly, it confirms the importance of *EXD* for energy diversification. Secondly, in lower quantiles (between 10% and 20%), where *EXD* hurts energy diversification, policymakers may need to look at ways to improve *EXD* to support energy diversification. On the other hand, in higher quantiles (from 30% to 90%) where energy diversification is positively impacted by *EXD*, increasing and sustaining higher export diversification may be a helpful policy approach to strengthen energy diversification. All in all, policymakers should actively support *EXD* to enhance diversification and improve energy resilience and sustainability.

Economic development (log *PGDP*) always has a positive impact on energy diversity (log *END*) in all quantiles (10–90%). This indicates that as economic development increases, energy diversification also increases. For policymakers, the consistent positive effect of economic development (log *PGDP*) on diversification (all quantile groups) highlights the importance of policies that drive economic growth. Increased economic growth provides the financial resources to invest in a diverse energy mix, including renewables, energy efficiency technologies, and alternative energy sources. This not only improves energy security and resilience but also reduces environmental impact. Policymakers should focus on driving economic growth to create a resilient, sustainable, and secure energy sector that can withstand supply disruptions and contribute to environmental sustainability. The effect of *FDI* on energy diversity (log *END*) can be postulated as neutral since the coefficients are equal to zero even though they are significant in quantiles 40%, 60%, and 70%.

Institutional quality (*IQ*) positively affects energy diversity (log *END*) in all quantiles except 10%. This demonstrates the positive effect of good institutional quality on energy diversification. As a result, policymakers can enhance sustainability and resilience in the energy sector by focusing on institutional quality. Improved institutional quality can lead to better governance and better policy formulation and implementation. This can lead to more efficient energy resource utilization and promote energy diversification. It should also be noted that the impact of institutional quality is unfavorable within the 10th percentile group. This observation suggests that institutional quality does not positively influence energy diversification in EU countries with relatively low incomes.

Consequently, policymakers in these nations should formulate comprehensive strategies that enhance institutional quality while also considering other economic and social factors. *R&D* negatively impacts on energy diversity (log *END*) in all quantiles (10–90%). This result suggests that policymakers need to plan the sustainability of *R&D* activities in the energy sector and how they can be more compatible with energy diversification goals. In addition, they need to be involved in shaping energy policies and incentives to reduce the negative effects of *R&D* activities.

Table 8: GMM Estimator Analysis.

	Dependent Variable: log *END*			
Independent variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**
log*END*(–1)	0.66***	0.66***	0.66***	0.63***
log*EXD*	0.05	0.02	0.04	0.08***
log*PGDP*	−0.06***	−0.06***	−0.05***	−0.03**
FDI		−0.00	−0.00**	−0.00**
IQ			−0.00	−0.01***
R&D				−0.02***
Constant	1.01***	0.99***	0.93***	0.83***
AR(1)	0.02	0.01	0.02	0.02
AR(2)	0.67	0.69	0.67	0.66
Sargan–Hansen test: *p*-value	0.12	0.19	0.33	0.27
***N* of groups > linear moment conditions**	26 > 10	26 > 14	26 > 18	26 > 22

Note: *** and ** represent statistical significance at 1% and 5% levels, respectively.
Source: Authors' own calculations

Following quantile regression model results, we employ the GMM estimator that utilizes a set of moment conditions to account for potential measurement errors and improve the efficiency of parameter estimation in our analysis. Test results of the GMM estimator are reported in Table 8. According to the two-step version of the difference GMM estimator, Model 4 is the best specification since it does not suffer from serial correlation and instrument overidentification. More importantly, all coefficients employed in Model 4 are statistically significant, proving the instruments' relevance to cope with endogeneity. Accordingly, firstly, the lagged variable (log*END*(−1)) shows a positive, strong, and significant relationship with energy diversification. Therefore, a 1% increase in lagged energy diversification leads to a 0.63% increase in current energy diversification. This suggests that increased past energy diversification would positively impact current energy diversification in the EU countries. This positive relationship emphasizes the importance of policymakers past policy decisions. Policymakers should consider these results to continue strategies that have been successful in the past or to invest more in these areas. Thus, policymakers can develop strategies to allocate more resources to energy policies that have proven successful and to support innovation in these areas.

Secondly, log*EXD* demonstrates a positive and statistically significant relationship with energy diversification. This sign affirms the result of the quantile analysis since the relation is positive in more and higher quantiles (30–90%). Therefore, a 1% increase in log*EXD* leads to a 0.08% increase in energy diversification. This result shows a way for policymakers who want to increase energy diversification to how foreign trade can be integrated with diversification strategies. Policymakers should consider strategies to diversify imports of energy sources or provide access to new energy sources through foreign trade. Thirdly, energy diversification experiences a significant and negative relationship with log*PGDP.* Consequently, a rise of 1% in log*PGDP* results in a decline of −0.03% in energy diversification. According to this result, policymakers should consider balancing energy diversification and economic growth goals. This requires considering how diversification of energy sources can be integrated into economic growth. Strategies such as investing in sectors providing economic growth or developing policies encouraging economic growth through energy diversification can be considered. Fourthly, *FDI* exhibits a neutral relationship with energy diversification, validating quantile results. In this case, policymakers should not consider *FDI* as a key factor for developing or changing energy diversification policies. Instead, they should consider other factors (*e.g.*, technological innovation, energy efficiency incentives, environmental sustainability) when setting and implementing energy diversification goals.

The relationship between institutional quality and energy diversification shows a significant and negative correlation with *IQ,* affirming the result of quantile analysis. Consequently, a %1 rise in *IQ* results in a reduction of 0.01% in energy diversification. Accordingly, focusing on institutional quality issues may be more critical for developing and implementing energy diversification policies. Policymakers should aim to make the energy sector more efficient and diverse through institutional reforms. These reforms will increase institutional quality and make the energy sector fairer and more competitive. Finally, the relationship between *R&D* and energy diversification is negative and statistically significant, justifying quantile results. Consequently, a 1% rise in *R&D* results in a decline of −0.02% in energy diversification. High *R&D* expenditures are often used to discover and develop new technologies and energy sources. However, this result shows that these investments have a negative impact in terms of energy diversification. This result highlights the need to review energy diversification targets. Policymakers should consider aligning *R&D* spending with energy diversification goals. *R&D* spending can be directed to encourage more efficient use of energy resources and the development of clean energy technologies. Policymakers should use *R&D* as a supporting part of energy diversification strategies.

5. Discussion

This research analyzed the effects of export diversification (*EXD*) on energy diversification in European Union countries using panel data methods. The findings reveal that *EXD* has a non-linear relationship with energy diversification. Especially in low quantiles (10% and 20%), *EXD* has a negative effect on energy diversification, while in medium and high quantiles (30–90%), this effect becomes positive. This shows that the effect of *EXD* may vary depending on the country's current energy diversification level.

These findings are consistent with some studies in literature and contradict others. For example, Iqbal *et al*. (2021) stated that *EXD* causes environmental negativities by increasing CO_2 emissions, which points to the negative impact of *EXD* in terms of energy diversity. In contrast, studies such as Bashir *et al*. (2020) suggest that *EXD* reduces energy density and contributes to a more efficient energy structure. Our finding establishes a balance between these two approaches; it emphasizes that the impact of *EXD* may vary depending on the country's current situation.

Our study also shows that *EXD* is related to energy demand, similar to the study conducted by Kiliçarslan and Dumrul (2022) for BRICS-T countries. However, our current study fills an essential gap in the literature by focusing directly on energy diversification. In this respect, focusing directly on the diversification of energy sources instead of indirect indicators such as energy consumption, efficiency, or CO_2 emissions is one of the unique contributions of our study.

In addition, factors such as economic growth and institutional quality also affect energy diversity. In particular, the positive effect of economic growth on all quantile groups reveals that energy diversity targets should be integrated with economic development policies. This situation coincides with studies by Brodny and Tutak (2022) and Rokicki and Perkowska

(2021), which confirm that economic development directly affects the structure of energy systems.

The fact that *FDI*'s effect is generally neutral may contradict the positive effects reported in some studies, such as those of Apergis and Pinar (2021). This suggests that the impact of *FDI* on energy diversification may be related not only to the amount but also to the quality of the investment and the types of energy it is directed towards. In particular, in EU countries, whether *FDI* is directed towards renewable energy or fossil fuel infrastructure makes this difference.

The positive effect of institutional quality is particularly evident in high-quantile groups, consistent with findings in studies such as Uzar (2020) and Wang *et al*. (2022). However, the fact that this effect is weak or negative in low-quantile groups suggests that institutional reforms are not immediately reflected in energy policies in low-diversity countries or that other obstacles exist.

The negative impact of research and development (*R&D*) expenditures on energy diversity contradicts some expectations in the literature. For example, Churchill *et al*. (2021) argue that *R&D* expenditures should support the energy transition. In this case, the direction and output of *R&D* may not align with energy diversity goals. For *R&D* expenditures to yield effective results, policymakers must develop thematic guidance and incentive mechanisms.

As a result, this study reveals that the impact of *EXD* on energy diversity is contextual and varies according to countries' current structural levels. Therefore, policymakers must develop multidimensional and coordinated strategies rather than one-dimensional ones. Export structure diversification strategies should be addressed in an integrated manner with energy diversity targets, and energy policies should cover not only supply security but also economic structure, institutional capacity, and technological development elements.

VI. Conclusion and Policy Implications

This study examined the relationships between energy diversification and various factors, including export diversification (*EXD*), economic development, institutional quality, and research & development activities. The results of the quantile regression analysis and the GMM estimator indicate that all these factors, except foreign direct investment, are crucial in energy diversification. However, while both models found the same sign (positive) relation between *EXD* and energy diversification, the quantile regression found a positive relation between GDP per capita and energy diversification, and the GMM found this relation to be negative. Similarly, both models found the same (negative) relation between research and development (*R&D*) and energy diversification. However, while the quantile regression analysis found a positive relation between institutional quality, the GMM estimator found this relation negative. Both models found neutral relations between foreign direct investment and energy diversification.

These differences reveal the importance of conducting the study with a multi-model approach and that policy recommendations may differ according to different country groups or levels of diversity. Therefore, when developing policies for energy diversity, the countries' *EXD* levels, institutional quality structures, and economic development levels should be considered.

The positive effect of export diversification (*EXD*) on energy mix diversification suggests that the EU should aggressively negotiate and sign trade agreements with all nations, particularly those with established and developing economies, aiming for reduced trade barriers, fair and open trade, and opening new markets for EU exporters. The EU should also implement laws to support businesses' export efforts, offering financial incentives, tax exemptions, and grants or loans explicitly tailored for exports. Targeted export marketing initiatives can increase public knowledge of EU energy goods and services' competitiveness, dependability, and quality. SMEs often face difficulties entering global markets, so the EU should fund initiatives to help them enter foreign markets. Prioritizing research and development in energy diversification and promoting innovation in clean energy technology will help the EU create cutting-edge goods and services with a competitive advantage in global markets. Infrastructure investments, such as ports, railroads, and energy transport networks, will increase the competitiveness of EU energy exports. To build lasting relationships and ensure a variety of energy sources, the EU should take a proactive stance in energy diplomacy, collaborating on research & development, easing investment in energy infrastructure, and forming energy agreements. Promoting renewable energy sources for both production and consumption will help diversify the energy mix and strengthen the EU's standing as a top exporter of clean energy technology.

These policy recommendations are directly related to the study's findings. However, to increase their applicability for policymakers, they should be differentiated according to each country's current export and energy structure. For example, more emphasis should be placed on energy diplomacy in countries with low *EXD* levels.

Further, our findings offer valuable insights for formulating energy policies and promoting sustainable energy diversification. Policymakers can utilize these factors to make informed decisions that ensure the security and sustainability of the energy sector. One of the key takeaways from this research is its focus on crucial topics like energy diversification and export diversity, which are the main scope of this study. The study provides a perspective that is particularly relevant for the future and sustainability of the energy industry. Its direct examination of the relationship between export diversity and energy diversification sets it apart from other studies, which offer a fresh approach to developing energy policies and sustainability strategies.

Furthermore, this study presents results in various quantile groups, which enhances its robustness and generalizability. As a result, policymakers in the energy sector and sustainability can benefit from a more comprehensive and detailed perspective. So, they can create quintile-based customized energy and economic policies proactively and efficiently. This may mean that the EU policymakers may need to formulate and implement their foreign trade policies (through export diversification) and energy policies together.

Another important contribution of our study is that it provides a detailed strategy development opportunity for decision-makers and analyzes policy effects at different *EXD* levels, an approach rarely seen in empirical literature. In addition, the findings go beyond policies focusing on the energy-import balance and indicate that trade policies such as *EXD* should be considered together with energy policies.

Several studies in the relevant literature, including ours, offer policy recommendations to EU policymakers for developing strategies in this direction. For instance, Lee and Ho (2022) examined the relationship between export diversification and energy intensity across 121 countries, including EU member states. Their findings revealed a negative relationship, suggesting that greater export diversification may lead to increased energy intensity and reduced renewable energy consumption. This outcome can reflect EU countries' dependence on fossil fuel imports, highlighting the need for greater energy diversification. The authors also emphasize that policies should be formulated to address this issue. Similarly, Khan *et al*. (2021) concluded that export diversification increases CO_2 emissions, further supporting the findings of Lee and Shan-Ju Ho (2022). In contrast, based on two different models, our study finds a positive relationship, indicating that export diversification contributes to energy mix diversification.

In another study, Radulescu and Sulger (2022) evaluate the dependence of 17 EU countries on fossil energy imports as the biggest obstacle to the increase of renewable energy. Therefore, this study implicitly concludes that these countries cannot experience energy diversification due to this dependence. In the same direction, the *REPowerEU Plan, created by the EU Commission in 2021, envisages increasing energy supply diversity to reduce EU countries' dependence on energy imports. This study's use of indices in its analysis also helps us better understand the complexity of energy diversification and export diversity, making the re-*

sults more pertinent to policymakers. Therefore, this study makes significant contributions to the future and sustainability of the energy industry and distinguishes itself from other similar studies. Finally, the EU, as a union, prioritizes energy independence and sustainable energy sources, and this study's findings can aid policymakers in comprehending their objectives for energy diversification. This, in turn, can lead to the creation of more efficient and proactive combined energy and trade policy in the EU.

For future research, it would be valuable to explore the impact of variables not considered in this study, such as energy supply security, green financing structures, carbon tax policies, and energy import dependency, on the relationship between energy diversity and *EXD*. Additionally, similar analyses should be performed for developing countries, energy-exporting nations, or regional unions.

Another suggestion for future research is to address the relationship between export and energy diversification using spatial analysis techniques. Especially in the European Union, geographical proximity, energy infrastructure connections, and the level of trade integration among countries may affect the strength of this relationship. In this context, analyses using models that include spatial dependency and spillover effects can reveal not only the impact of *EXD* on a country's energy policies but also its impact on neighboring countries.

In addition, since our study focuses on the period 1995–2020, it should be noted that recent global developments (Ongan *et al*., 2025) (like uncertainties, *e.g.*, the COVID-19 pandemic, the Russia-Ukraine war, European energy crises, and supply chain disruptions) have significantly affected both the energy supply structure and foreign trade patterns in the European Union countries. These developments have reshaped policies, especially regarding energy security, import dependency, and renewable energy investments. Therefore, the findings cover a period in which such structural changes have not yet been fully reflected, and it would be helpful for future studies to evaluate these effects more comprehensively by including the period after 2021.

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