The Impact of R&D Investments on Renewable Energy Transition. A Panel Data Approach

Adrian PETRE*
The Bucharest University of Economic Studies, Bucharest, Romania
**Corresponding author, petreadrian10@stud.ase.ro*

Doru Alexandru PLESEA
The Bucharest University of Economic Studies, Bucharest, Romania
pleseadoru@gmail.com

Abstract. *The transition to renewable energy is one of the main objectives at the level of the European Union to answer the problems related to global warming. In this context, the main objective of this study is to analyze the role of one of the drivers that can contribute to the achievement of this objective, namely research and development expenditure. Thus, based on a diversified research methodology, which includes in particular comparative analysis, descriptive analysis, and econometric analysis, we tested the role of research and development expenditure in stimulating final energy consumption from renewables and biofuels in the industrial sector using related statistical data from 13 European Union Member States between 2006 and 2022. The main results showed that research and development expenditure have a positive impact on the consumption of renewable energy in the industrial sector.*

Keywords: R&D, renewable energy, GDP per capita, transition, industry sector

Introduction

Currently, global warming is one of the main problems facing humanity, which is why it is imperative to undertake concrete reforms to mitigate the negative effects generated by this phenomenon.

Since one of the main causes of global warming is represented by the dependence on fossil energy sources, the transition to renewable energy (such as solar energy, wind energy, geothermal energy or marine energy) is a viable solution to gradually reduce the use of fossil fuels, with numerous direct advantages both for the environment (e.g. reducing pollution and greenhouse gas emissions) and economy (eg Improving energy efficiency and energy security), as well as social (eg protecting human health).

Within the European Union (EU), accelerating the transition to renewable energy sources and increasing energy efficiency is one of the main priorities (European Council, 2019). This objective is also supported by other representative institutions at the international level, such as the United Nations (UN) or the Organization of Economic Cooperation and Development (OECD).

Even if important progress is registered in terms of the production and consumption process of renewable energy, this process must continue to accelerate, and for this, it is essential to identify the main drivers, depending on different conditions. In this way, the appropriate reforms can be undertaken to lead to a long-term sustainable and inclusive transition.

Research and development (R&D) has the potential to stimulate the transition to renewable energy by contributing to the innovation of technologies associated with this type of energy (essential for production, storage, and distribution), increasing the level of education of individuals

DOI: 10.2478/picbe-2024-0152

regarding the necessity and opportunity of this transition and helping to create an effective institutional framework for such an objective.

Considering the importance and topicality of this subject and also the potential of R&D in this case, we proposed as our main objective in this paper the analysis of the impact of research and development expenditure on the final energy consumption from renewables and biofuels within the industrial sector of certain EU Member States.

We believe that through the methodology and statistical data used, we can obtain relevant results both for the business and governmental sectors, as well as for the academic environment and environmentalists.

Next, the article is structured as follows: Section 2 includes a synthesis of some of the most representative results obtained so far regarding renewable energy stimulation sources, Section 3 describes the research methodology applied and the statistical data, and Section 4 presents the empirical results. The paper ends with the main conclusions derived from the research, highlighting at the same time possible future research directions on this topic.

Literature review

At the level of specialized literature, there is an extensive series of studies that analyze the enablers of the transition to renewable energy. Their results differ depending on certain factors, such as the regions considered, the type and frequency of the indicators, or the applied research methodology.

Thus, Assi et al. (2021) developed research at the level of the ASEAN+3 group of countries through which they demonstrated the positive influence of innovation and real GDP per capita on the consumption of renewable energy, while Yi et al. (2024) suggest that digital economy development has a fundamental role in promoting renewable energy innovation.

Other factors identified as having a significant influence on this transition are economic growth, export growth, and institutional effectiveness (Rahman and Sultana, 2022), R&D (Shahnazi and Shabani, 2020), human capital (Sachan et al., 2023) or increasing the employment rate in advanced technology manufacturing (Tu et al., 2022).

In addition, Amri (2016) identifies a bidirectional link between FDI and renewable energy consumption in developed countries.

On the other hand, Dogan et al. (2023) showed that environmental and energy taxes have a negative influence on the development of renewable energy in EU Member States. Their results are also confirmed by Lupu et al. (2023), both for the states of Western Europe and for those of Central and Eastern Europe. Another negative influence on the use of renewable energy is exerted by energy imports (Estevão and Lopes, 2024). Their analysis is based on data extracted for the Euro Zone between 2000 and 2019.

At the same time, at the level of scientific literature, several challenges are presented, that may appear in the process of transition to green energy, some of the most significant being the financial ones. For example, Eti et al. (2024) identify access to financing as the most important challenge for local renewable energy projects, and Osman et al. (2023) states that a factor that can make it difficult to develop renewable energy projects is the higher cost compared to other traditional energy sources, making them less profitable and competitive.

Regarding the potential sources of funding for different projects in this field, Feng et al. (2023) propose as a solution the expansion of green bonds.

Anton and Afloarei Nucu (2020) carried out a study over 25 years at the level of the EU Member States, from which it emerged that all the banking sector, the bond market, and the capital market have a positive impact on the consumption of renewable energy, specifying, however, that the capital market does not influence this transition in the separate case of the new member states.

Although the specialized literature that analyzes the determinants of the transition to renewable energy is complex, there is no consensus among researchers. Thus, our research has the role of contributing to the state of knowledge in the field.

Methodology

The research methodology applied with the objective of this work is diversified.

In the first part of the article, we used the method of critical comparative analysis of the specialized literature that deals with the subject of the transition to renewable energy, more precisely the impact of different factors in supporting this transition, so that we can observe some of the most important results obtained so far related to this topic.

Starting from these results, in the second part of our research we empirically analyzed, based on a panel data approach, the influence of research and development expenditure on the final energy consumption from renewables and biofuels in the industrial sector from the EU Member States (except Central-Eastern and Southeast EU Member States): Belgium, Denmark, Germany, France, Italy, Austria, Netherlands, Luxembourg, Ireland, Finland, Lithuania, Estonia and Sweden. We also excluded from our research Latvia and Malta (because it can be considered as outlier in the case of REI variable, with the highest and lowest values in the sample), and also Spain and Portugal (because it can be considered as outlier in the case of GERDB variable, with the lowest values in the sample).

The variables used in the research are presented in Table 1, and the data series are related to the 2006-2022 period.

Table 1. Description of the variables

Variable type	Variable name	Abbreviation	Description	Source of data
DEPENDENT VARIABLE	Final energy consumption - renewables and biofuels in industry sector	REI	Simplified energy balances – Annual, unit of measure was thousand tonnes of oil equivalent, but we divided final energy consumption in industry sector- renewables and biofuels by final energy consumption in industry sector - total and obtained the %	Eurostat, 2024a
INDEPENDENT VARIABLE	Gross domestic expenditure on R&D	GERDB	Gross domestic expenditure on R&D – Sector of performance: Business enterprise sector, Annual, % of GDP	Eurostat, 2024b
INDEPENDENT VARIABLE	Real GDP per capita	GDP	Control variable (economic development effect) – Annual, Chain linked volumes (2010), euro per capita.	Eurostat, 2024c

We chose to use panel analysis, which is a combination of time-series and cross-section variables, as it is a more efficient model that provides more information and measures statistical effects that individual time-series or cross-sectional analysis cannot contain.

Thus, our study is based on the following basic economic model:

$$REI_{it} = \alpha + \beta_1 GERDB_{it} + \beta_2 GDP_{it} + \varepsilon_{it} \quad \textbf{(1)}$$

The terms i and t in the above equation refer to each country and time, while β_1 and β_2 highlight the long-run elasticities of independent variables concerning the dependent ones. In this model α is a constant term and ε_{it} is the error term.

The variables were transformed into natural logarithms (LREI, RGERDB, and LGDP) to avoid potential heteroscedasticity and to facilitate the interpretation of the results.

Further, our econometric analysis involves several steps.

Initially, a number of preliminary statistical tests are determined to check the normality of our model:

- ***Multicollinearity test*** based on the correlation matrix between the variables, respectively by using the variance inflation factor (VIF). A VIF value greater than 10 indicates clear signs of multicollinearity within the model.
- ***Slope homogeneity test*** based on the Pesaran-Yamagata (2008) and Blomquist-Westerlund (2013) models, to check if the dataset is homogeneous. Within this models, the null hypothesis shows that between different units slope coefficients remain constant, while the alternative hypothesis identifies slope heterogeneity.
- ***Cross-sectional dependence test*** (CSD) based on the model developed by Pesaran (2004), to check if there is cross-sectional dependence across countries. The null hypothesis of this test is that there is no cross-sectional dependence between the units, while the alternative hypothesis shows that the units are interdependent. This test is indicated in the case of panels that include a small number of cross-sections and short periods.
- ***Stationarity test*** of the data series through the CIPS test (Pesaran, 2007). In this case, the null hypothesis denotes the fact that there is a unit root, and the alternative hypothesis is the fact that the variables are stationary. This test is part of the second generation of unit root tests and is indicated in the presence of cross-section dependencies.
- ***Co-integration test*** based on Westerlund (2005) to examine the long-run equilibrium between selected variables. The null hypothesis states that there is no co-integration, and the alternative hypothesis states that the panels are co-integrated.

After verifying these preliminary conditions, we employ the panel pooled mean group (PMG-ARDL) model approach to test the long-run relationship between the selected variables. This model requires that the long-run coefficients be the same, but allows differences between groups in terms of slope coefficients, short-run coefficients, and error variances. Within the PMG-ARDL model, the variables must be I(0) or I(1).

To test the robustness of the results, we will also apply the Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Square (DOLS) estimation models.

FMOLS accounts for serial correlation effects and takes care of small sample and endogeneity biases. DOLS is an alternative method to reduce endogenous response using 1st differenced regressors leads and lags.

These models have been used in various studies as techniques for verifying the validity and consistency of long-run dynamics between certain variables (eq Perone, 2024).

The last step consists of testing the causal relationship between the dependent variable and the independent ones. This approach is carried out using the Dumitrescu-Hurlin panel causality test (Dumitrescu and Hurlin, 2012), which has the advantage of addressing the cross-sectional dependency problem in panel analysis and generating relevant results for small data series. The null hypothesis implies heterogeneous causality, while the alternative hypothesis implies homogeneous causality.

Data processing was carried out in eViews and Stata.

Results and discussions

Table 2 shows the descriptive statistics of the variables.

Table 2. Descriptive statistics

Variables	REI	GERDB	GDP
Mean	11.16803	1.41819	37282.62
Median	6.75308	1.44	35870
Maximum	42.79186	2.67	8.83E+04
Minimum	0.506591	0.19	8.69E+03
Std. Dev.	11.40203	0.670074	17616.17
Skewness	1.473117	-0.033267	1.13403
Kurtosis	3.943678	1.83946	4.770256
Observations		221	

Source: Author's calculation in eViews.

We see the highest values of the standard deviation in the case of GDP (17616.17), and the lowest in the case of the GERDB variable (0.670074). On the other hand, the skewness results observed within the distributions vary between -0.033267 (GERDB) and 1.473117 (REI), indicating different levels of asymmetry of the distributions, while the kurtosis values are between 1.83946 (GERDB) and 4.770256 (GDP), showing mixed degrees of peakedness or flatness.

Next, Table 3 shows the results of the correlation matrix and the VIF test, highlighting the fact that there are no problems regarding multicollinearity among independent variables.

Table 3. The results of multicollinearity test

	LREI	LGERDB	LGDP
LREI	**1**		
LGERDB	0.3729	**1**	
LGDP	-0.0878	0.4944	**1**
VIF		1.32	
1/VIF		0.755547	

Source: Author's calculation in Stata

The next preliminary tests carried out are related to cross-sectional dependence and slope homogeneity (Table 4).

Table 4. The results of cross-sectional dependence and slope homogeneity tests

Var.	CD-test		Pesaran, Yamagata. 2008 (Blomquist, Westerlund. 2013)	
LREI	11.14820***		Delta	p-value
LGERDB	3.699534***		7.407 (5.176)	0.000
LGDP	24.34245***	adj.	8.471 (5.919)	0.000
H0: no cross-sectional dependency		H0: homogenous slope		
H1: cross-sectional dependency		H1: heterogeneous slope		

∗∗∗p < 0.01, ∗∗p < 0.05, ∗p < 0.1.; Blomquist, Westerlund. 2013 test results in parenthesis.
Note: the slope homogeneity test is done using the command "xthst" in Stata

Source: Author's calculation in eViews (CSD) and Stata (slope homogeneity test).

The results in Table 4 show that the null hypothesis of no cross-sectional dependency is rejected at 1% level for all variables, confirming that the dataset under investigation registers cross-sectional dependency. On the other hand, both the results of the Pesaran-Yamagata test (2008) and Blomquist-Westerlund test (2013) highlight that the null hypothesis of slope homogeneity is rejected at 1% level of significance.

Next, we examined the stationarity of the variables included in the analysis. Considering the presence of cross-sectional dependency in the dataset, we used a second generation of unit root tests (CIPS). Table 5 summarizes the results of the unit root test, showing that all the variables are stationary at 1st difference for 0.01 level of significance.

Table 5. Unit root test results

Var	CIPS	
	I(0)	**I(1)**
LREI	–1.786	**–3.966*****
LGERDB	–1.755	**–3.255*****
LGDP	–1.852	**–3.081*****

∗∗∗p < 0.01, ∗∗p < 0.05, ∗p < 0.1.

Note: Pesaran Panel Unit Root Test (CIPS)

Method: AIC (1)

Deterministics chosen: constant

Note: the unit root test is done using the command "xtcips" in Stata

Source: Author's calculation in Stata.

Finally, the Westerlund cointegration test results, shown in Table 6, validate the long-run relationship among the variables by rejecting the null hypothesis of no co-integration.

DOI: 10.2478/picbe-2024-0152, pp. 1808-1818, ISSN 2558-9652 |
Proceedings of the 18th International Conference on Business Excellence 2024

Table 6. Westerlund test for co-integration

Westerlund test for co-integration		
	Statistic	**p-value**
Variance ratio	-1.9625	0.0249
∗∗∗p < 0.01, ∗∗p < 0.05, ∗p < 0.1.		
H0: No cointegration		
H1: All panels are cointegrated		

Source: Author's calculation in Stata.

The results of the preliminary tests indicate that the estimation techniques chosen for this analysis are appropriate.

Next, we proceeded to determine the PMG-ARDL model to investigate the relationship between the dependent variable and the independent variables, and Table 7 presents the results obtained.

Table 7. The results of Panel PMG-ARDL model

(Dependent var: LREI): Panel PMG-ARDL model (1,1,1)				
Explanatory Variables	Coefficient	Std. Error	t-Statistic	Prob.
Long Run Equation				
LGERDB	0.254002	0.117716	2.157759	0.0323
LGDP	0.194608	0.003564	54.60323	0.0000
Short Run Equation				
COINTEQ01	-0.110056	0.046865	-2.34838	0.0199
D(LGERDB)	-0.290503	0.170365	-1.705174	0.0899
D(LGDP)	-0.395204	0.305151	-1.295106	0.1969
Note: Maximum dependent lags: 1 (Automatic selection), Model selection method: AIC, Dynamic regressors (1 lag, automatic), Fixed regressors:				

Source: Author's calculation in eViews.

The results of the PMG-ARDL model show that the impact of R&D expenditure on final energy consumption - renewables and biofuels in the industrial sector is statistically insignificant in the short-run, but it becomes statistically significant in the long-run. It is important to notice that the impact of LGERDB on LREI is positive in the long-run. This situation is also valid in the case of the second independent variable.

Next, to test the robustness of the results obtained by the PMG-ARDL method, we applied the FMOLS and DOLS regression approaches, and the results are provided in Table 8 and Table 9 respectively.

Table 8. The results of the FMOLS model

(Dependent var: LREI): Panel Fully Modified Least Squares (FMOLS)				
Explanatory Variables	Coefficient	Std. Error	t-Statistic	Prob.
LGERDB	0.650027	0.161348	4.028735	0.0001
LGDP	-0.716813	0.261108	-2.745276	0.0066
R-squared	0.941416			
Adjusted R-squared	0.937167			
S.E. of regression	0.267631			

(Dependent var: LREI): Panel Fully Modified Least Squares (FMOLS)				
Explanatory Variables	Coefficient	Std. Error	t-Statistic	Prob.
Long-run variance	0.162292			
Mean dependent var	1.914882			
S.D. dependent var	1.067679			
Sum squared resid	13.82385			

Note: Panel method: Pooled estimation, Cointegrating equation deterministics: C, Coefficient covariance computed using sandwich method, Long-run covariance estimates (Prewhitening with lags from AIC maxlags=1, Bartlett kernel, Newey-West fixed bandwidth)

Source: Author's calculation in eViews.

Table 9. The results of the DOLS model

(Dependent var: LREI): Panel Dynamic Least Squares (DOLS)				
Explanatory Variables	Coefficient	Std. Error	t-Statistic	Prob.
LGERDB	0.872717	0.171598	5.08583	0.0000
LGDP	-0.383732	0.351842	-1.090637	0.2776
R-squared	0.966983			
Adjusted R-squared	0.947007			
S.E. of regression	0.24968			
Long-run variance	0.058436			
Mean dependent var	1.902006			
S.D. dependent var	1.084609			
Sum squared resid	7.418451			

Note: Panel method: Pooled estimation, Cointegrating equation deterministics: C, Automatic leads and lags specification (based on AIC criterion, max=1), Coefficient covariance computed using sandwich method, Long-run variances (Bartlett kernel, Newey-West fixed bandwidth) used for coefficient covariances

Source: Author's calculation in eViews.

The results reported in Table 8 and Table 9 initially demonstrate that both regression models are statistically significant (R-squared is 0.94 for FMOLS and R-squared is 0.97 for DOLS) and highlight the positive influence of LGERDB on LREI, but of different magnitudes.

Unlike the PMG-ARDL estimate, the LGDP control variable appears with negative impact on LREI in FMOLS model and with no statistically significant influence in DOLS model.

In this case, we can state that the FMOLS and DOLS models reinforce the results obtained based on the PMG-ARDL model regarding the positive long-term influence of the LGERDB variable on the LREI variable.

Finally, considering the results up to this point, we used the test proposed by Dumitrescu and Hurlin (2012) to investigate the causality links between the dependent and independent variables, and the results are reported in Table 10.

Table 10. The results of Dumitrescu-Hurlin causality test

(Dependent var: LREI): Pairwise Dumitrescu Hurlin Panel Causality Tests			
Null Hypothesis:	W-Stat.	Zbar-Stat.	Prob.
LGERDB does not homogeneously cause LREI	4.4082	6.02771	0.0000
LREI does not homogeneously cause LGERDB	1.17855	-0.00611	0.9951
LGDP does not homogeneously cause LREI	2.93325	3.27213	0.0011
LREI does not homogeneously cause LGDP	3.54667	4.41815	1E-05
LGDP does not homogeneously cause LGERDB	3.17009	3.71459	0.0002
LGERDB does not homogeneously cause LGDP	2.7078	2.85093	0.0044
Note: Lags: 1			

Source: Author's calculation in eViews.

The outcomes of panel causality analysis demonstrate a unidirectional causal association with statistical significance between LGERDB and LREI (LGERDB causes LREI) within the industrial sector, which reinforces our previous results.

We also note that between the control variable LGDP and LREI, there is a bidirectional causal relationship (LGDP causes LREI and LREI causes LGDP).

Our results are in line with those obtained by Kocsis and Kiss (2015) in terms of the positive relationship between R&D expenditure and renewable energy consumption.

Conclusion

Through this empirical research, we have shown that research and development expenditure positively influences the consumption of renewable energy in the industrial sector of the selected EU Member States.

In this context, we can consider that R&D expenses are an important strategy for the sustainable transition to an economic model based on renewable energy and that it is absolutely necessary to support such expenses within companies.

We believe that some reforms that could increasingly stimulate R&D expenditure must involve the business sector, the government sector, and the academic environment.

On the one hand, the government sector can support this approach through tax facilities and subsidies for innovative companies and through public-private partnerships within the companies' R&D projects.

On the other hand, the academic environment can also have a decisive role through the education and training of specialists and the transfer of knowledge and technology to the private sector. In this regard the academic programs must be permanently adapted to the real requirements of the economy.

We also consider it essential to promote a culture of continuous development and innovation within companies.

Because the number of independent variables that we used could be considered as a limitation of the present study, it can be expanded in the future by including in the analysis some additional factors that can influence the sustainable transition to renewable energy within different economic sectors in specific regions.

Acknowledgement
This paper was co-financed by The Bucharest University of Economic Studies during the PhD program.

References
Amri, F. (2016). The relationship amongst energy consumption, foreign direct investment and output in developed and developing countries. *Renewable and Sustainable Energy Reviews*, 64, 694-702, ISSN 1364-0321. https://doi.org/10.1016/j.rser.2016.06.065

Anton, S.G., & Afloarei Nucu, A.E. (2020). The effect of financial development on renewable energy consumption. A panel data approach. *Renewable Energy*, 147, Part 1, 330-338, ISSN 0960-1481. https://doi.org/10.1016/j.renene.2019.09.005

Assi, A.F., Isiksal, A.Z., & Tursoy, T. (2021). Renewable energy consumption, financial development, environmental pollution, and innovations in the ASEAN + 3 group: Evidence from (P-ARDL) model. *Renewable Energy*, 165, Part 1, 689-700, ISSN 0960-1481. https://doi.org/10.1016/j.renene.2020.11.052

Blomquist, J., & Westerlund, J. (2013). Testing slope homogeneity in large panels with serial correlation. *Economics Letters*, 121(3), 374-378.

Dogan, E., Hodžić, S., & Šikić, T.F. (2023). Do energy and environmental taxes stimulate or inhibit renewable energy deployment in the European Union?. *Renewable Energy*, 202, 1138-1145, ISSN 0960-1481. https://doi.org/10.1016/j.renene.2022.11.107

Dumitrescu, E. I., & Hurlin, C. (2012). Testing for Granger non-causality in heterogeneous panels. *Economic modelling*, 29(4), 1450-1460.

Estevão, J., & José Dias Lopes (2024). SDG7 and renewable energy consumption: The influence of energy sources. *Technological Forecasting and Social Change*, 198, 123004, ISSN 0040-1625. https://doi.org/10.1016/j.techfore.2023.123004

Eti, S., Yüksel, S., Dinçer, H., Kalkavan, H., Hacioglu, U., Mikhaylov, A., Danish, M.S.S., & Pinter, G. (2024). Assessment of technical and financial challenges for renewable energy project alternatives. *Cleaner Engineering and Technology*, 18, 100719, ISSN 2666-7908. https://doi.org/10.1016/j.clet.2023.100719

Eurostat, 2024a. Simplified energy balances [online] Available at : https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_s__custom_10564297/default/table?lang=en [Accessed 28 February 2024]

Eurostat, 2024b. GERD by sector of performance [online] Available at: https://ec.europa.eu/eurostat/databrowser/view/rd_e_gerdtot__custom_10564314/default/table?lang=en [Accessed 08 February 2024]

Eurostat, 2024c. Real GDP per capita [online] Available at: https://ec.europa.eu/eurostat/databrowser/view/sdg_08_10__custom_10564319/default/table?lang=en [Accessed 09 February 2024]

European Council (2019). *A new strategic agenda 2019 – 2024*. Retrieved from https://www.consilium.europa.eu/en/eu-strategic-agenda-2019-2024/

Feng, Y., Xiao, Z., Zhou, J., & Ni, G. (2023). Asymmetrically examining the impact of green finance and renewable energy consumption on environmental degradation and renewable energy investment: The impact of the COVID-19 outbreak on the Chinese economy. *Energy Reports*, 9, 5458-5472, ISSN 2352-4847. https://doi.org/10.1016/j.egyr.2023.04.361

Kocsis, I., & Kiss, J. T. (2014). Renewable energy consumption, R&D and GDP in European Union countries. *Environmental Engineering and Management Journal*, 13(11), 2825-2830.

Lupu, I., Hurduzeu, G., Lupu, R., Popescu, M.F. and Gavrilescu, C., 2023. Drivers for Renewable Energy Consumption in European Union Countries. A Panel Data Insight. Amfiteatru Economic, 25(63), pp. 380-396

Osman, A.I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., Rooney, D.W., & Yap, PS. (2023). Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. *Environmental Chemistry Letters*, 741–764. https://doi.org/10.1007/s10311-022-01532-8

Perone, G. (2024). The relationship between renewable energy production and CO2 emissions in 27 OECD countries: A panel cointegration and Granger non-causality approach. *Journal of Cleaner Production*, 434, 139655, ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2023.139655

Pesaran, M. H. (2004). *General diagnostic tests for cross section dependence in panels*. SSRN 572504.

Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *Journal of applied econometrics*, 22(2), 265-312

Pesaran, M. H., & Yamagata, T. (2008). Testing slope homogeneity in large panels. *Journal of Econometrics*, 142(1), 50-93, ISSN 0304-4076. https://doi.org/10.1016/j.jeconom.2007.05.010

Rahman, M.M., & Sultana, N. (2022). Impacts of institutional quality, economic growth, and exports on renewable energy: Emerging countries perspective. *Renewable Energy*, 189, 938-951, ISSN 0960-1481. https://doi.org/10.1016/j.renene.2022.03.034

Sachan, A., Sahu, U.K., Pradhan, A.K., & Thomas, R. (2023). Examining the drivers of renewable energy consumption: Evidence from BRICS nations. *Renewable Energy*, 202, 1402-1411, ISSN 0960-1481. https://doi.org/10.1016/j.renene.2022.11.080

Shahnazi, R., & Shabani, Z.D., (2020). Do renewable energy production spillovers matter in the EU?. *Renewable Energy*, 150, 786-796, ISSN 0960-1481. https://doi.org/10.1016/j.renene.2019.12.123

Tu, Y-X., Kubatko, O., Piven, V., Sotnyk, I., & Kurbatova, T. (2022). Determinants of Renewable Energy Development: Evidence from the EU Countries. *Energies*, 15(19), 7093. https://doi.org/10.3390/en15197093

Westerlund, J. (2005). New simple tests for panel cointegration. *Econometric Reviews*, 24(3), 297-316.

Yi, J., Dai, S., Li, L., & Cheng, J. (2024). How does digital economy development affect renewable energy innovation?. *Renewable and Sustainable Energy Reviews*, 192, 114221, ISSN 1364-0321. https://doi.org/10.1016/j.rser.2023.114221.