Assessing the Differential Impact of Environmental Policy Stringency on Renewable Energy Consumption: Evidence from the Nordic and Southern European Economies

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Abstract

In response to growing climate concerns, stricter environmental regulations and renewable energy use have become cornerstone policies. Therefore, this study examines the effects of environmental policy stringency (EPS) on renewable energy consumption (REC) across the Nordic and Southern European nations. Further, it investigates whether there are any differential impacts based on variations in the degree of EPS and institutional capacity on REC. The study uses data from 1990 to 2020 and applies the panel Autoregressive Distributed Lag Pooled Mean Group (ARDL-PMG) framework to attain the objectives. The long-run coefficients of EPS revealed a positive effect on REC, underscoring the importance of stricter environmental regulations in fostering the clean energy transition. Further, the EPS interaction model reported a comparatively higher marginal effect on REC in the case of the Nordic economies, where environmental policies are relatively stricter. Additionally, technological innovation, foreign direct investment, and human development also seem to support renewable energy. Importantly, the estimation demonstrated a negative Error Correction Term (ECT), suggesting deviations from the long-run equilibrium gradually correct over time. Lastly, the analysis reveals a clear distinction: the long-run estimates are statistically significant, whereas the short-run coefficients are insignificant, indicating that short-term policy interventions do not immediately generate renewable energy. These findings underline the need for and importance of a well-coordinated long-term policy framework that integrates environmental policies with innovation, investment mobilisation towards clean energy, and human development.

Keywords: Renewable energy; environmental policy stringency; carbon emissions; Nordic bloc; Southern European countries; panel ARDL-PMG.

1. Introduction

Currently, an alarming rate of climate change, global warming, and worsening environmental pollution has been posing an existential threat globally, primarily driven by greenhouse gas emissions. Notably, biomass fuels such as crude oil, natural gas, coal, etc., contribute about 80% of the world's primary energy consumption, causing greenhouse gas (GHG) emissions (Athari, 2024). Growing environmental concerns jeopardise the survival of billions of people (Rahman and Alam, 2022). To overcome these issues, the role of clean energy and environmental regulations has become more important than ever. This is why policymakers and scholars have been reconfiguring the interrelationships among macroeconomic policy, environmental regulations, and energy policy over the last couple of decades. Recently, international institutions have made commitments to limit the global temperature rise to 1.5°C and attain the goal of net zero by 2050 (Antimiani et al., 2023). In this context, the accelerated transition from a fossil-fuel-dependent energy system to low-carbon and renewable alternatives is essential, helping to achieve sustainable development goals (SDGs): Goal 7 (affordable and clean energy) and Goal 13 (climate action).

The adoption of clean energy can support sustainable economic growth, lower emissions of GHGs, reduce reliance on non-renewable energy imports, and offer a healthy environment (Stern, 2022). This is why policymakers and governments across the world have been expediting the transition from traditional energy to renewable energy (RE) continuously through incentives and policy actions. Tax benefits, setting emission standards, cheaper credits, subsidies to clean energy sources, and promoting research and development are some of the steps that have been taken across the globe. Over the last couple of decades, renewable energy consumption (REC) has increased substantially. A record 700 GW of RE capacity was added globally in 2024 (IEA, 2025). According to the Energy Institute, RE doubled worldwide between 2017 and 2024, yet RE still contributed only about 8% of global energy demand. In OECD countries, RECs have increased from 1,110 terajoules in 1990 to 16,560 terajoules in 2019, indicating that OECD economies have specific importance, as the REC share has increased to about 57% in 2019 (BP Statistical Review of World Energy, 2022).

However, despite the accelerated growth of RE in the last few years, there are two points worth noting here. First, the growth of RE has been concentrated in a few countries such as the USA,

China, Brazil, OECD countries, and European countries. Second, fossil fuel-based energy sources are still meeting three-fourths of the world's energy demand. This means a larger part of the world is still lagging in access to clean energy. As a result, global CO_2 emissions continue to rise (Marra and Colantonio, 2021). This situation suggests the need for further intervention at economic, environmental, and energy policy levels. The primary objective of environmental regulation is to reduce pollutants without hindering the pace of economic growth. However, reconciling economic growth with environmental protection remains a significant challenge, as policy interventions often increase firms' expenses and trade-offs in economic efficiency and revenues (Van den Bergh, 2013). This is where the traditional energy transition from biofuels to RE and stricter environmental regulations become crucial in OECD economies and across the world. Hence, it is crucial to examine the stimulus of RE expansion.

Nevertheless, there is literature that has examined the factors determining REC. The first set of studies has examined the social and economic aspects of REC (Omri and Nguyen, 2014; Chen et al., 2021; Somoye et al., 2022). The second set of literature is limited and focuses on assessing the effect of environmental regulations, specifically environmental policy stringency (EPS), in conjunction with socioeconomic dimensions, primarily based on OECD nations (Marra and Colantonio, 2021; Hassan et al., 2024; Athari, 2024; Bahl et al., 2026). The OECD developed the EPS as an index covering thirteen policy instruments, including market-based, non-market-based, and technological boosting regulations, that measure the degree to which environmental policies impose costs on environmentally damaging behaviours (Kruse et al., 2022). The recent evidence indicates that EPS has emerged as an important regulatory mechanism to catalyse the clean energy transition (Song et al., 2024). Third, a few studies have explored the heterogeneous effect of environmental regulations (Li et al., 2022; Badmus & Bisiriyu, 2025; Bahl et al., 2026). But hardly any study is available that examines the impact of EPS on REC, exclusively focusing on the Nordic bloc (Denmark, Finland, Norway, and Sweden) and Southern European economies (Greece, Italy, Portugal, and Spain). It is worth noting here that the institutional capacities of the Southern European economies are different from those of the Nordic countries. Nordic economies are known for higher EPS scores and greater RE use, whereas the Southern European nations have expanded their RE infrastructure in the last few years. Observing these differences, none of the studies has examined the differential effects of EPS on REC.

Against this backdrop, the current study fills the empirical gaps and makes a threefold contribution to the existing scholarly literature. First, this is probably the first study exclusively focused on the Nordic Bloc, which represents high baseline policy stringency, advanced institutional governance, and better RE infrastructure, and the Southern European nations, which exhibit relatively lower EPS paired with rapid growth in RECs in the previous few years, that explores the nexus between RE and EPS. Second, unlike the existing studies that have either examined static or dynamic aspects, utilising the panel Autoregressive Distributed Lag Pooled Mean Group (ARDL-PMG) framework developed by Pesaran et al. (1999), this study simultaneously captures short-run heterogeneous adjustments and long-run cointegration equilibria. Third, unlike the existing studies that use broad panel structures that mask the sub-regional dynamics, this study constructs an explicit interaction model (*EPS×Nordic*) to isolate the conditional effectiveness of EPS across differing institutional capacity. Fourth, the study has examined the underexplored impact of technological innovation, especially related to energy generation, transmission and distribution, on REC. Collectively, the contribution of this study is to guide the following two research questions:

Question 1: Do EPS and technological innovation related to energy transition, transmission, and distribution accelerate the RE transition?

Question 2: Do the long-run effects of EPS significantly differ based on variations in the degree of EPS and institutional capacity?

The rest of this paper is structured as follows: Section 2 covers the theoretical and empirical literature on environmental regulations and renewable energy. Section 3 presents the methodology and explains the data, theoretical model construction and econometric model specifications. Section 4 provides the results and empirical findings. Section 5 offers a comprehensive discussion of the results in light of existing literature. The last section concludes the study with crucial policy implications.

2. Environmental policy stringency and renewable energy: A literature review

In order to mitigate growing climate concerns, scholars are continuously studying the association between macroeconomic policy, environmental economics and energy dynamics (Apergis & Payne, 2010; Ozturk, 2010). In this context, the transition from fossil-fuel-dependent architecture

to RE systems can be important. Many studies have explored guiding factors of the RE transition (Ekholm et al., 2010; Pachauri & Jiang, 2008; Sharma & Dash, 2022b, 2022a; Q. Zhao et al., 2025). One set of existing literature has primarily focused on investigating the nexus between renewable energy and economic growth (Payne, 2010; Tugcu, 2012). The major hypotheses tested through this nexus are termed the 'Growth Hypothesis′, which considers RE to be one of the important factors in economic growth (Bhattacharya et al., 2016). In contrast, the ′Conversion Hypothesis' defines a unidirectional causality from economic growth to RE usage, implying that higher economic growth results in the incremental adoption of renewable energy (Apergis & Danuletiu, 2014). Nevertheless, the 'Feedback Hypothesis' bidirectionally defines this nexus between RE and economic growth, demonstrating a recursive relationship that reinforces each other in a virtuous cycle (Apergis & Payne, 2010; Rafindadi & Ozturk, 2017).

Moving further, modern empirical evidence suggests that economic growth is not a sufficient determinant of energy transition (Wolde-Rufael & Mulali, 2016; Hassan et al., 2023; Sharma & Dash, 2024). Instead, public policy instruments such as EPS seem more effective in this transition (Botta & Koźluk, 2014; Hassan et al., 2024). The OECD-designed EPS is composed of both market-based instruments like carbon taxes and non-market tools such as strict emission ceilings and technology standards (Botta & Koźluk, 2014; Zhao et al., 2025). The stringent environmental regulations are a countermeasure to internalise the negative externalities (Hassan et al., 2023). However, the effectiveness of EPS is bounded by institutional capacity, exogenous shocks, governance, international capital inflows, and social structure (Athari, 2024).

Hassan et al. (2024) studied 32 OECD countries by applying dynamic panel data techniques and found that greater EPS significantly increases REC. The virtuous cycle starts with carbon taxes, emission standards, and energy-related policies, raising the prices of fossil-based energy sources that incentivise clean technology adoption. Athari (2024), in his study on OECD countries using System GMM and Panel Quantile Regression, observes that EPS stabilises clean energy investments during periods of macroeconomic instability. Further, this study reported that global economic policy uncertainty deters investment in renewable energy due to financial volatility, but EPS acts as an automatic stabiliser (Athari, 2024). In developing economies, the EPS functions as a "force multiplier" for emissions reduction. Zhao et al. (2025) studied BRICS-T economies from 1990 to 2020 using Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary

Least Squares (DOLS) models and found that RE inherently reduces carbon emissions. However, its abatement efficiency is conditional on regulatory rigour. In the absence of stricter environmental regulations, efforts to deploy RE often supplement rather than replace fossil fuel generation (Zhao et al., 2025).

Furthermore, the nexus of foreign capital and EPS plays a crucial role in clean energy adoption. Two competing theoretical paradigms broadly document the literature on the relationship between Foreign Direct Investment (FDI) and EPS. First is the 'Pollution Haven Hypothesis', which explains that multinational corporations relocate their carbon-intensive manufacturing to countries with weak environmental regulations to avoid heavy compliance costs (Walter & Ugelstad, 1979). Second is the 'Pollution Halo Hypothesis', which posits that foreign investors transfer superior, energy-efficient and green technologies and management practices to host countries. Recent studies have underlined the role of EPS in determining the effects of foreign capital on a host country (Akbulut & Yereli, 2023). These studies identified threshold effects, assessing that when a host country's EPS falls below a critical threshold of 2.22 to 2.88, FDI operates under the pollution haven mechanism. In contrast, higher policy stringency causes a shift towards the pollution halo dynamic, attracting high-tech capital and facilitating clean technology transfers that encourage renewable energy (Akbulut & Yereli, 2023). However, there is no consensus on the relation of FDI with the REC demand (Fan & Hao, 2020; Sengupta et al., 2026).

Furthermore, studies suggest that technological innovation is a significant driver of RE demand (Athari, 2024). Innovation-supported policies stimulate research and development, diminishing the cost of RE technology and improving its efficiency. This process boosts RE capacity and facilitates the diffusion of green technology. This phenomenon is congruent with the Porter hypothesis, which states that well-designed environmental regulations can accelerate innovation and enhance the competitiveness of RE technology (Porter & Linde, 1995). Hence, EPS influences REC not only by punishing carbon producers but also by enhancing the technology and attractiveness of clean energy sources. Recent studies underline the complementary role of clean energy and green innovation in improving the positive outcome of policy stringency. A study based on G11 economies using the CS-ARDL estimator found that EPS, REC, and green investment substantially improve environmental sustainability (Fatima et al., 2025). Dabbous et al. (2025) utilising data from 32 OECD economies, show a positive association between EPS, environmental

awareness, and energy resilience. Country-specific studies also indicate a similar linkage between REC and EPS. For instance, Bahl et al. (2026a) studied India, taking data from 2000 to 2022, employing dynamic ARDL and quantile ARDL models, and found positive effects of policy stringency and environmental taxes on REC. This study further finds that the impact of environmental regulations becomes more effective at higher levels of clean energy penetration, indicating that the effectiveness of policies depends upon the maturity of RE markets. This heterogeneity in the impacts of environmental policies demands a more comprehensive understanding for designing effective energy policies.

In short, the present study reviews the studies on renewable energy, environmental regulations, and policies. Together, existing literature suggests that environmental regulations can have a stronger impact when embedded within an ecosystem of technological development, economic growth, better institutional capacity, and green investment. Nevertheless, based on this literature review, we observe three key points. First, the literature that explores the influence of environmental policies on RE provides evidence of positive effects of EPS. Second, no literature to date has examined differential effects of EPS on different sets of economies having different institutional capacities. Third, the effects of technological innovation and human development on RE are underexplored. Thus, this study is an endeavour to fill these research gaps.

3. Data and methodology

3.1. Data

Broadly, this study aims to examine the effects of EPS on REC and to explore whether a differential impact exists based on variations in the degree of EPS and institutional capacity. The eight sample countries include the Nordic Bloc (Denmark, Finland, Norway, and Sweden) and the Southern European countries (Greece, Italy, Portugal, and Spain). We have used annual data publicly available from the OECD, World Development Indicators (WDI), and the UNDP from 1990 to 2020. The countries have been chosen based on the research gaps, while the data period is selected based on its availability. The dependent variable is REC, and the primary explanatory variable is the EPS. Remaining variables include per capita GDP, FDI inflows, patents, and the human development index (HDI). Table 1 presents the measurements and descriptions of the variables used in this study, along with their sources.

The Nordic Bloc has among the highest EPS values, while the Southern European nations have less stringent policies but higher renewable energy growth. The clear differences and patterns in the EPS and REC across both groups of countries can be observed in Figures 1, 2, and 3 over the period of time. Figure 1 displays the improvements in the EPS score from 1990 to 2020 for both sets of economies. The thickness of the graphs (i.e., the four bottom slides) belonging to the Nordic bloc suggests their historically high EPS values from 1990 that have become even higher by 2020 relative to the Southern European countries.

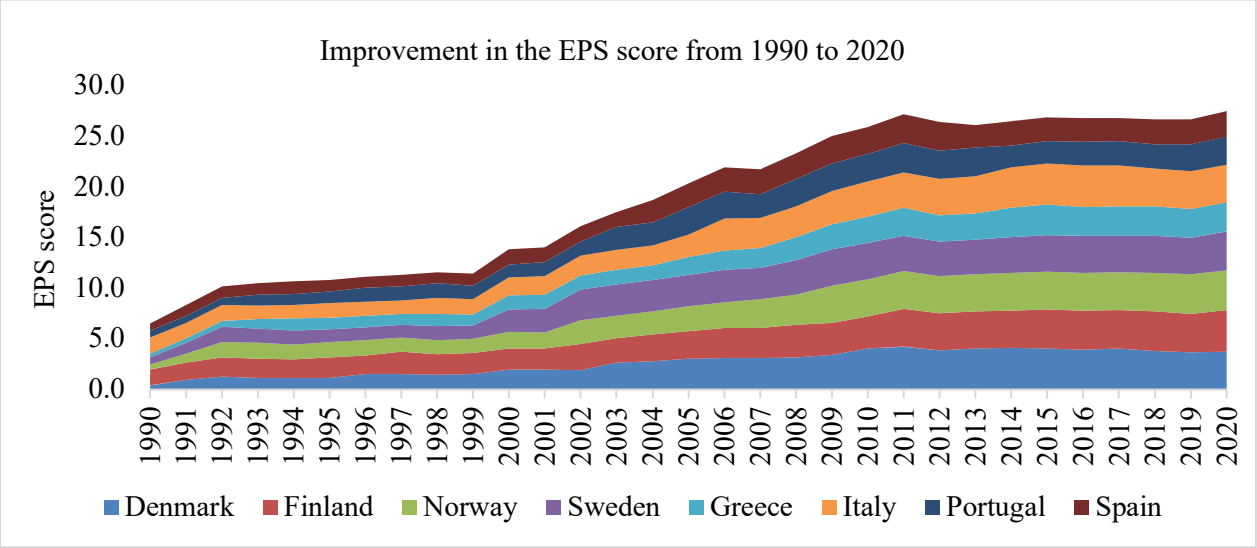


Figure 1: Improvement in the EPS score from 1990 to 2020 across the Nordic and the Southern European nations
Source: Authors' own presentation

Figure 2 shows the trends of REC from 1990 to 2020 for the groups of countries. This suggests that the share of REC in total energy consumption has increased over time across both groups. However, the share of REC in total energy for the Nordic bloc is higher, where the EPS is also higher, which provides preliminary evidence of an association between EPS and REC.

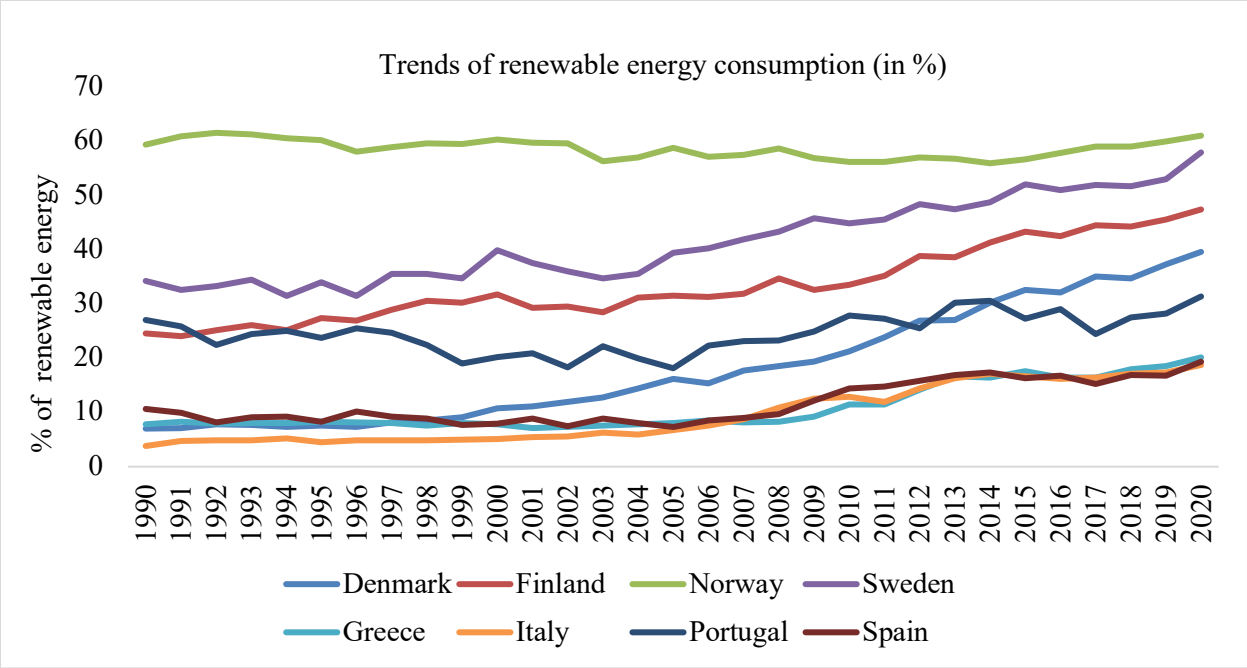


Figure 2: Trends of REC from 1990 to 2020 across the Nordic bloc and the Southern European countries
Source: Authors' own presentation

Figure 3 depicts REC for both groups in 1990 and 2020. This indicates that the REC has increased across all the countries in the last three decades. However, the share of REC has increased more in the Nordic bloc than in SE nations. Exceptionally, Norway has had the highest EPS from the beginning, as well as the highest renewable energy consumption; consequently, REC has stagnated.

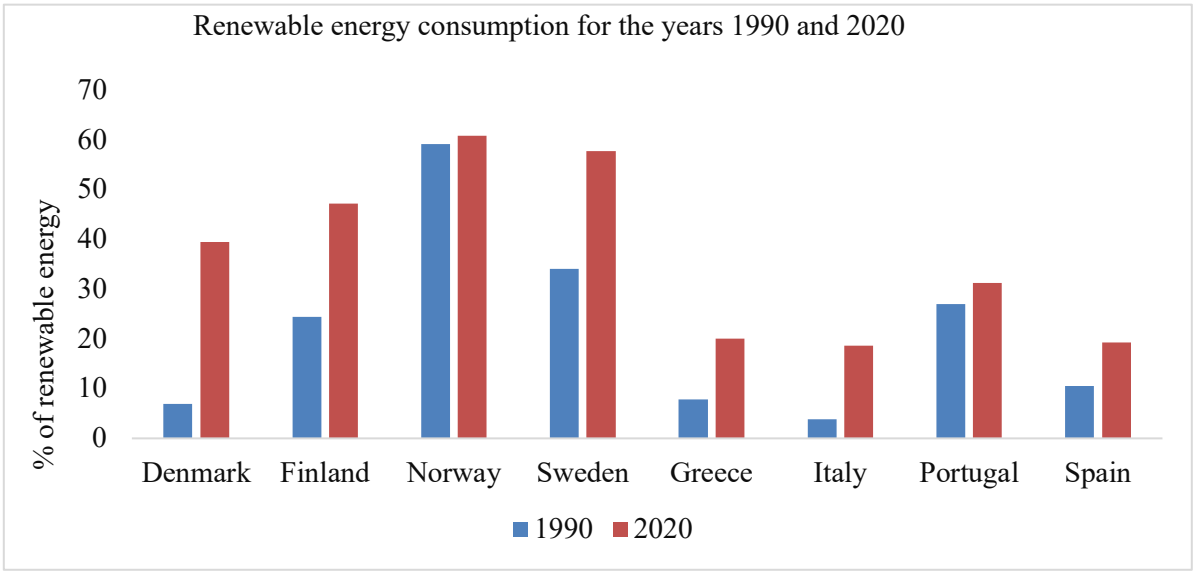


Figure 3: The REC for the Nordic bloc and Southern European countries (Years 1990 and 2020)
Source: Authors' own presentation

3.2. Theoretical model construction

This study examines the impact of EPS on REC using panel data. Specifically, the analysis distinguishes between Southern European and Nordic countries. It specifically analyses the regional heterogeneity across two different sets of economies in their institutional capacities. The Nordic countries are characterised by relatively stringent environmental regulations, while the Southern European nations have historically had less stringent policies, with significant growth in RE in later periods. To achieve this objective, the existing literature suggests two perspectives on empirical models. The first perspective is based on the neoclassical demand function, where demand for goods and services is a function of price and income. The second perspective emphasises the determinants of energy consumption. This study adopts the extended neoclassical demand function, as several previous studies have used it to examine the effects of environmental policy on REC (Li et al., 2022; Hassan et al., 2024).

Thus, the basic empirical model of this research is a function of REC, macroeconomic variables, technological innovation, and environmental variables.

$$REC_{it} = \alpha_i + \beta_1 EPS_{it} + \beta_2 PCGDP_{it} + \beta_3 FDI_{it} + \beta_4 PAT_{it} + \beta_5 HDI_{it} + e_{it} \quad (1)$$

Thus, REC adoption is determined by environmental policy stringency, per capita GDP (PCGDP), FDI inflows, patents (PAT), and HDI. The t = (1990…2020) periods for which data on EPS have been taken; 'i' refers to each country of the sample, and 'e' includes effects of all the variables not included in the model. It should be noted that EPS is an environmental variable, PCGDP and FDI are economic variables, a patent is an indicator of technological innovation, and HDI is an indicator of human development. Existing studies suggest that EPS plays a crucial role in improving REC, especially in higher-income economies where regulatory frameworks are stronger (Hassan et al., 2024; Wang et al., 2020). Among economic determinants, per capita GDP is expected to impact the REC positively. However, prior literature suggests a non-linear relationship, where economic growth first increases dependence on traditional energy before facilitating the transition to clean energy as income increases (Sengupta et al., 2026).

Foreign capital flows also play an important role in shaping the REC by diffusing renewable technology and innovation across the globe. However, empirical studies indicate ambiguous

effects of FDI on REC (Fan & Hao, 2020; Sengupta et al., 2026). Further, research suggests that technological innovation captured by patents is a significant driver of renewable energy demand. Innovations diminish the cost of RE technology and improve its efficiency, thereby boosting RE capacity. In addition, HDI demonstrates the overall development of human beings with respect to health, education, and economic conditions. Basically, it enhances people's capacity to adopt new things, but its impact on renewable energy adoption has remained largely unexplored. Thus, the ambiguity and heterogeneity of the key factors necessitate a more comprehensive understanding for designing effective energy policies.

To address the issue of outliers and heteroscedasticity, we take natural logarithmic values of the variables REC, PCGDP, and PAT. The log values further reduce variability, smooth data, and enable easier interpretations of coefficients. Nevertheless, patents are valued at zero for a few years, making log transformation meaningless. To resolve this issue, a new variable (*PAT1)* has been formed by adding one to the respective original values. Then the log value of *PAT1* has been included in the model. Thus, the model becomes:

$$lnREC_{it} = \alpha_i + \beta_1 EPS_{it} + \beta_2 lnPCGDP_{it} + \beta_3 FDI_{it} + \beta_4 lnPAT1_{it} + \beta_5 HDI_{it} + e_{it} \quad (2)$$

One important contribution of this research is the specific modelling of the heterogeneity effect of EPS across both groups. Considering the structural differences between the Southern European and Nordic economies—specifically regarding renewable energy infrastructure, institutional quality, and policy implementation—these factors are likely to affect the EPS impact on REC. To examine this heterogeneity, an interaction between EPS and a regional dummy variable has been used. This variable is treated as a binary variable, taking the value of 1 for the Nordic bloc and 0 for the Southern European economies. The interaction model becomes:

$$lnREC_{it} = \alpha_i + \beta_1 EPS_{it} + \beta_2 (EPS_{it} * Nordic_i) + \beta_3 lnPCGDP_{it} + \beta_4 FDI_{it} + \beta_5 lnPAT1_{it} + \beta_6 HDI_{it} + e_{it} \quad (3)$$

In this equation, β_1 refers to the effects of EPS on REC for the base group (the Southern European nations), and β_2 provides a differential impact for the Nordic nations. Hence, the collective effect in the Nordic countries is given by $\beta_1 + \beta_2$. This approach provides a more rigorous framework for examining heterogeneity rather than estimating separate models for each group of countries.

Table 1
Variables' definition/description

Variables/Acronym	Explanation	Sources	Expected relation
Renewable energy consumption (REC)	The REC has been defined as the share (in %) of renewable energy in the total energy consumption.	WDI	
Environmental policy stringency index (EPS)	EPS is the index released by the OECD, ranging from 0 (least stringent) to 6 (most stringent).	OECD	+
Human development index (HDI)	The HDI is defined as a composite measure of a country's average achievements in three fundamental elements of human development: education, health, and standard of living.	UNDP	?
Per capita GDP (PCGDP)	It is the GDP (at a constant 2015 USD) divided by the general population.	WDI	?
Foreign direct investment (FDI)	It has been measured as the net inflow of FDI as a % of GDP.	WDI	?
Patents (PAT)	The study has considered patents applied for associated with energy generation, transmission, and distribution.	OECD	+

3.3. Econometric model

This study applies the Panel Autoregressive Distributed Lag Pooled Mean Group (ARDL-PMG) estimator developed by Pesaran et al. (1999). The model is guided by the objective of analysing both short- and long-run associations and the structure of the data. Scholars also suggest that panel data estimation is better than time series estimation because it provides more information, captures more variability, has less collinearity, offers more degrees of freedom, and is more useful for analysing the dynamics of change (Baltagi, 2005). The PMG estimation is appropriate for a panel with a small cross-section dimension (N) and a large time dimension (T). Unlike the mean group (MG) estimator, which allows for complete heterogeneity across the panel by estimating separate regressions for each nation and averaging the coefficients, the PMG estimator assumes some degree of homogeneity in the long-run coefficients. It keeps short-run dynamics, error variances and intercepts varying across the nations (Lee & Wang, 2015). Furthermore, researchers point out that Panel ARDL is more appropriate than other related methods, such as the Generalised Method of Moments, fixed effects, and instrumental variables, when the objective is to analyse short- and long-run dynamics simultaneously (Da Silva et al., 2018). Moreover, the panel ARDL diminishes the problem of endogeneity by including the lagged value within the model itself (Blackburne & Frank, 2007).

The study uses the ARDL (p, q) panel as explained by Pesaran et al. (1999). Let X_{it} represent the vector of independent variables that are included in equation (3) for the group i and time t. Then the model with several determinants of REC can be expressed:

$$REC_{it} = \sum_{j=1}^{p} \delta_{ij} REC_{i,t-j} + \sum_{j=0}^{q} \rho'_{ij} X_{i,t-j} + \omega_i + e_{it} \quad (4)$$

In this equation, ρ'_{ij} refers to the coefficient vector, and ω_i represents fixed effects. The e_{it} denotes the random disturbance variable independently distributed across time and groups, with constant variance and zero mean value. The model is then reparametrised into the error correction model to simultaneously analyse the long-run equilibrium association and short-run dynamics as follows:

$$REC_{it} = \theta_i \left(REC_{i,t-1} - \beta' X_{it} \right) + \sum_{j=1}^{p-1} \delta_{ij} \Delta REC_{i,t-j} + \sum_{j=0}^{q-1} \phi'_{ij} \Delta X_{i,t-j} + \omega_i + e_{it} \quad (5)$$

Where θ_i is the coefficient of error correction, determining the pace of adjustment towards the long-run equilibrium, and β'measures the impact of independent variables on the REC in the long run. Negative and statistically significant values of the error correction coefficient confirm the presence of a stable long-run equilibrium among the variables. Δ is the first difference operator. The coefficients δ_{ij} and ϕ'_{ij}denote the dynamics of the short run.

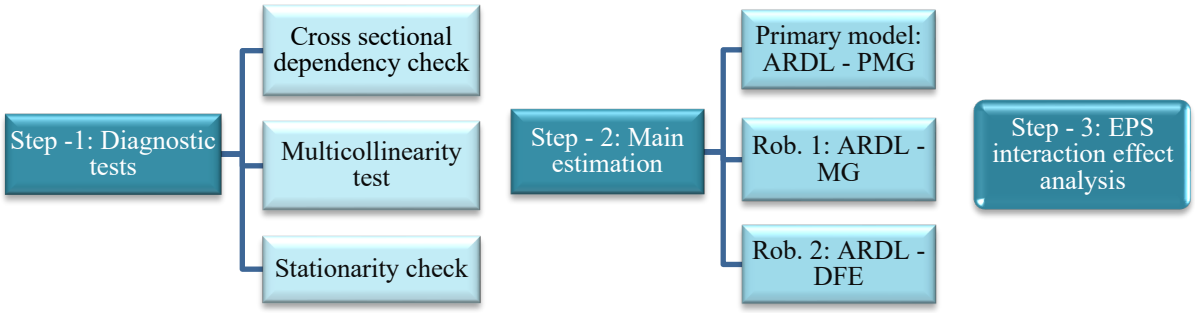


Figure 4. Estimation and data analysis procedure of the study
Source: Authors' own presentation

Figure 4 illustrates the procedure of estimation and data analysis of the study. In the first step, essential diagnostics have been conducted, including tests for cross-sectional dependence (CSD) of panel units, multicollinearity, and stationarity. These tests validate the underlying assumption of the panel data estimation. However, the study did not conduct a separate panel cointegration test, since the PMG estimator based on the ARDL framework inherently estimates both short- and long-run dynamics simultaneously. The presence of a stable long-run association is examined

through the sign and significance of the error correction term (ECT). Thus, under the panel ARDL-PMG, ECT serves as evidence of cointegration. In the second step, long-run and short-run relationships have been estimated using a panel ARDL-PMG estimator. Mean Group and Dynamic Fixed Effects (DFE) estimators have been employed as robustness checks to validate the consistency of the results. Additionally, the Hausman specification test has been conducted between PMG and MG to determine whether PMG is preferred over MG estimates. In the third step, the study examines the interaction effect of EPS on the Nordic bloc nations. The details of these outcomes have been presented in the following sections.

4. Results

4.1. Descriptive statistics

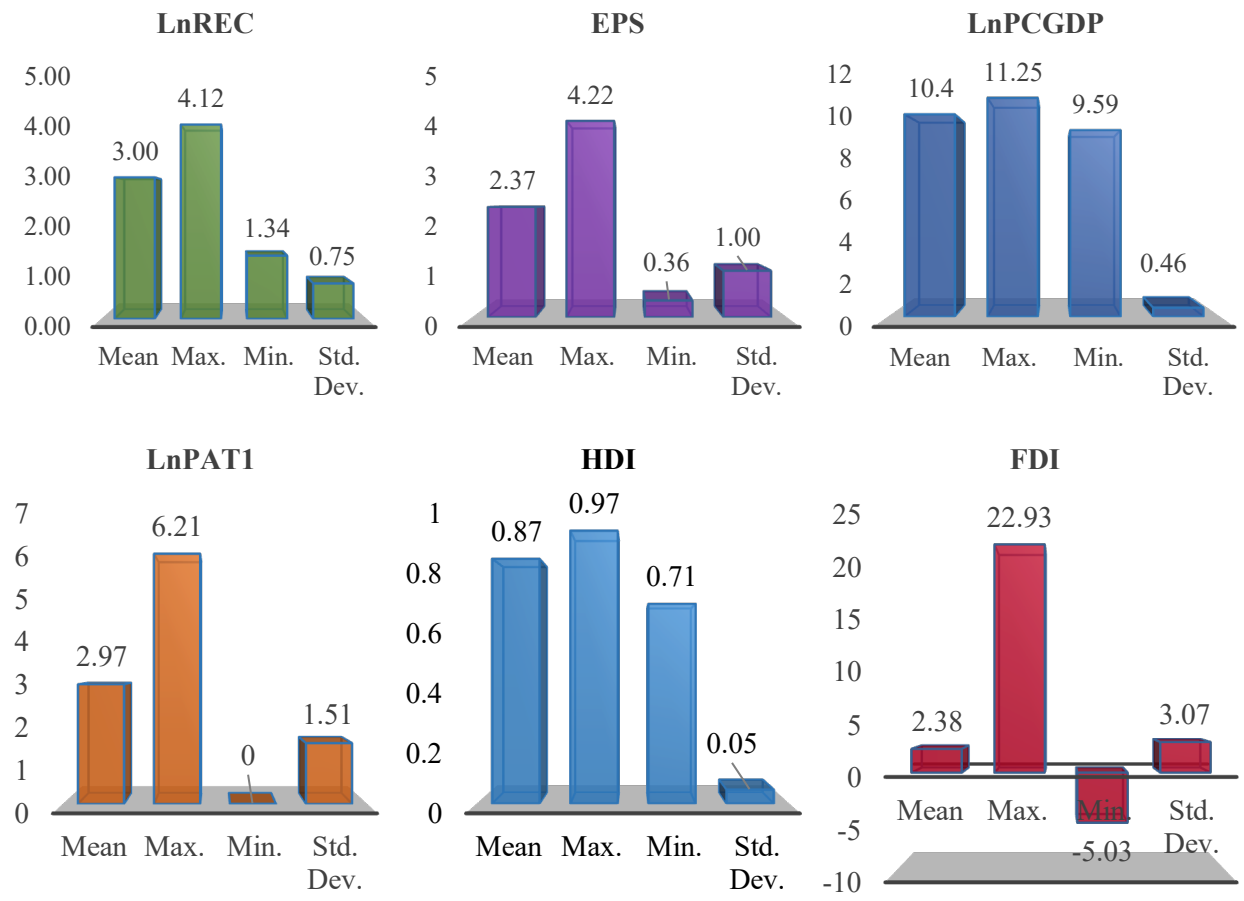


Figure 5. Visualisation of descriptive statistics.
Source: Authors' own presentation

The descriptive statistics of the variables used in the analysis are presented in Figure 5. The

statistics provide values of mean, maximum, minimum, and standard deviation for every variable clearly and comparatively. The results show significant variation across the variables. The mean value of the LnPCGDP is highest with the second-lowest standard deviation. It signifies less variation in the per capita GDP across the panel units. Similarly, HDI shows less variation across the panel units, as its standard deviation is the lowest and the maximum and minimum values are closer to the mean. In contrast, variables such as LnREC, EPS, LnPAT1, and FDI exhibit higher variability, as there are significant differences in their dimensions. These variations are crucial for interpreting their impact on the outcome across econometric models.

4.2. Multicollinearity and CSD tests

Before estimating the models, the Variance Inflation Factor (VIF) was used to test the problem of multicollinearity, and Pesaran's (2004) CSD test was employed. The VIF result is presented in Table 2.

Table 2
The VIF test

Variables	VIF	1/VIF
LnPCGDP	3.84	0.26
HDI	7.57	0.13
LnPAT1	2.27	0.43
FDI	1.06	0.94
EPS	3.86	0.26
Mean VIF	3.72	

The mean VIF is less than 4, and the corresponding VIF for all the variables is well below the standard value of 10, which confirms that the variables are sufficiently independent of each other. It confirms that the models do not exhibit multicollinearity and supports the reliability of subsequent regression estimates.

Table 3 presents the outcome of the CSD test. This test examines the existence of residual dependence across the panel units. The test yields a CSD statistic of 1.76, with a p-value of 0.08. It suggests that the null hypothesis of cross-sectional independence cannot be rejected at the significance level of 5%.

Table 3
The Pesaran CSD test

Test	Test statistics	P-value
Pesaran CSD test	1.76	0.08
Off-diagonal elements' average absolute value	0.36	

However, the mean value of the off-diagonal correlation coefficient indicates a moderate pairwise cross-sectional correlation. Thus, the panel does not show strong CSD, supporting the appropriateness of using the Panel ARDL-PMG model. These outcomes also indicate that common shocks across the panel units are limited. This

enables the use of the PMG estimator, which allows short-run heterogeneous dynamics while keeping long-run homogeneous coefficients, to estimate associations among the variables.

4.3. Panel unit root tests

Depending on the cross-sectional dependency of the panel units, two generations of unit root tests can be conducted to test the stationarity of the variables. The first-generation test is employed when there is a complete absence of CSD in the panel data. The second-generation test is used when panel units exhibit cross-sectional dependence (Le & Sarkodie, 2020). In the present study, the Pesaran test rejects the presence of CSD at the 5% level of significance (Table 3). However, considering the group of sample countries, there is likely to be weak CSD in the panel unit. Therefore, we have employed the second-generation CIPS unit root test of (Pesaran, 2007). The results of this test are presented in Table 4. The results indicate that LnPCGDP and LnREC are non-stationary at levels, although both variables become stationary at first difference. The rest of the variables, HDI, FDI, EPS, and LnPAT1, are stationary at the level. Thus, the variables show a mixed order of integration, including I (0) and I (1) variables. These findings support the preconditions to apply a panel ARDL-PMG model to assess short- and long-term associations among the variables.

Table 4
Pesaran CIPS unit root test

Variables	Level t-bar	First difference t-bar	Order of Integration
LnREC	-1.56	-4.31***	I(1)
LnPCGDP	-1.72	-3.38***	I(1)
HDI	-2.51**		I(0)
LnPAT1	-3.10***		I(0)
FDI	-2.84***		I(0)
EPS	-2.78***		I(0)

4.4. Panel ARDL-PMG result analysis

Before estimating the model, the study conducted the Hausman specification test to determine whether the PMG estimator is preferred over the MG estimator. This result has been presented in Table 5. The test, with a p-value of 0.95, shows that the null hypothesis that the PMG and MG coefficients do not differ systematically cannot be rejected at the conventional significance level.

This finding suggests that the PMG estimator is preferred. Accordingly, the analysis is based on the PMG coefficients.

Table 5
Hausman test

Test	Chi-square	P-value	Decision
Hausman MG vs PMG	1.10	0.95	PMG estimation preferred over MG

Table 6 reports the outcome of the panel ARDL-PMG estimator. The coefficients provide significant evidence of a long-run relationship between REC and explanatory variables. The coefficient of the ECT is negative (-0.214) and statistically significant at the 1% level of significance. The estimates suggest a moderate rate of adjustment towards equilibrium, with 21.4% of the short-run deviation from long-run equilibrium being corrected each year. This substantiates the presence of a long-run stable equilibrium relationship among the variables.

In the long run, the EPS with coefficient 0.312 indicates a positive and statistically significant association with REC. This indicates that a one-unit increase in EPS is associated with about a 31.2% increase in the share of renewable energy in total energy consumption, keeping other factors constant. However, this increase does not mean that renewable production has increased by 31.2%. This means total energy supply from RE sources has increased. This suggests that more stringent environmental regulations can boost the consumption of renewable energy, supporting the idea that effective environmental policies contribute to a clean energy transition. In contrast, per capita GDP demonstrates a negative and significant relationship with REC, suggesting that higher economic growth is associated with lower REC in the long run. This result may appear unexpected but is theoretically consistent.

Table 6
PMG estimation results

Long run		Short run	
Variables		**Variables**	**Coef. / Std. Err.**
EPS	0.312***	ECT	-0.214***
	(0.034)		(0.069)
LnPCGDP	-1.752***	ΔEPS	-0.045
	(0.237)		(0.027)
LnPAT1	0.107***	ΔLnPCGDP	-0.314
	(0.036)		(0.202)
FDI	0.028**	ΔLnPAT1	-0.021
	(0.012)		(0.021)

HDI	4.075***	ΔFDI	-0.001
	(1.108)		(0.002)
Constant	3.407***	ΔHDI	0.950
	(1.049)		(1.418)
Number of obs.	240		
Number of groups	8		
Log likelihood	402.557		

Note: Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Further, the estimates of patents related to energy generation, transmission, and distribution (LnPAT1) show a positive and significant association with REC. It indicates that innovation in technology boosts the development and diffusion of clean energy technology. Similarly, FDI exhibits a positive and statistically significant relationship with REC, suggesting that FDI inflows may expedite clean energy adoption through investment, technology transfer, and the expansion of RE infrastructure. Also, the coefficient of HDI reports a strong positive and highly significant relationship with REC. This implies that an enhancement in human development facilitates the clean energy transition.

As expected, the short-run estimates demonstrate limited impacts of independent variables on the REC. The estimates of the changes in the variables EPS, LnPCGDP, HDI, FDI, and LnPAT1 are statistically insignificant. This implies that changes in these variables do not yield statistically noticeable effects on RE in the short period. The contrast between the long- and short-run outcomes underscores the steady nature of the energy transition. Specifically, ECT with a negative and statistically significant coefficient indicates that short-period deviations are corrected over time as the economy approaches the long-run equilibrium path. These outcomes allude to the fact that effects of technological advances, environmental policies, improvements in HDI and FDI boosts on RE usage are realised progressively.

4.5. Robustness check

To validate the findings of the baseline model, the study has employed MG and DFE estimators as robustness verification models. Table 7 presents the results of the MG estimator. Similar to baseline estimates, the ECT coefficient (-0.475) is negative and statistically significant at the 1% level of significance. Further, it also indicates positive effects of EPS on REC. However, the magnitude and level of significance differ for the coefficients. Overall, the estimates of all the

variables are consistent in direction with the coefficients of the PMG model, validating the robustness of the baseline model's findings.

Table 7
MG estimation results

Long run		Short run	
Variables	**Coef. / Std. Err.**	**Variables**	**Coef. / Std. Err.**
EPS	0.100	ECT	-0.475***
	(0.082)		(0.060)
LnPCGDP	-1.392**	ΔEPS	-0.023
	(0.570)		(0.022)
LnPAT1	0.082**	ΔLnPCGDP	-0.318
	(0.038)		(0.215)
FDI	0.031**	ΔLnPAT1	-0.028*
	(0.015)		(0.017)
HDI	5.776***	ΔFDI	-0.009*
	(2.099)		(0.005)
Constant	5.678**	ΔHDI	0.932
	(2.370)		(1.889)
Number of obs.	240		
Number of groups	8		

Note: Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 8 displays the outcomes of the DFE estimator, revalidating the findings of the baseline model. Again, the estimate of the ECT (-0.110) is negative and significant at the 1% level of significance. The EPS indicates positive and significant effects on renewable energy adoption. Every other explanatory variable is also congruent with the findings of the primary model. This congruence of the outcomes from the MG and DFE estimators with the findings of the PMG model boosts confidence in the reliability and validity of the model's outcomes, supporting the idea that the findings are not sensitive to the estimation techniques used.

Table 8
Dynamic fixed-effect estimation results

Long run		Short run	
Variables	**Coef. / Std. Err.**	**Variables**	**Coef. / Std. Err.**
EPS	0.219**	ECT	-0.110***
	(0.104)		(0.025)
LnPCGDP	-1.906***	ΔEPS	0.007
	(0.645)		(0.022)
LnPAT1	0.253***	ΔLnPCGDP	-0.511***
	(0.092)		(0.195)
FDI	0.026	ΔLnPAT1	-0.008

	(0.021)		(0.010)
HDI	4.148	ΔFDI	0.002
	(3.217)		(0.002)
Constant	1.986**	ΔHDI	0.362
	(0.791)		(1.251)
Number of obs.	240		
Number of grou	8		

Note: Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

4.6. PMG model with interaction effect

To understand the long-run differential impact of EPS on REC between the Nordic and the Southern European nations, an interaction term between EPS and the Nordic bloc dummy has been included in the PMG model. Table 9 presents the results of the interaction effect model. The coefficients of every variable are congruent with the findings of the baseline model, including ECT. The coefficient of EPS without interaction is 0.312 ($p < 0.001$) and with interaction is 0.301 ($p < 0.001$). Both estimates are identical, indicating that the baseline estimate is stable. The interaction estimate of 0.225 is positive and statistically significant, suggesting that the impact of EPS is stronger in the Nordic bloc than in Southern European economies. The estimated long-run effect of EPS on the Southern European nation is 0.301, while the total long-run effect on the Nordic economies is obtained by combining the primary and interaction effects, which is about 0.526, providing stronger evidence of regional heterogeneity in the effectiveness of EPS. These findings demonstrate that stricter environmental policies have supported the RE transition in both sets of countries. But the Nordic bloc seems to have converted strict environmental policies into a greater boost in REC, probably because of better energy infrastructure, technological capabilities, and advanced institutional frameworks.

Table 9
Results of the PMG model with interaction effect

Long run		Short run	
Variables		**Variables**	**Coef. / Std. Err.**
EPS	0.301***	ECT	-0.193***
	(0.039)		(0.070)
LnPCGDP	-1.699***	ΔEPS	-0.040
	(0.263)		(0.029)
LnPAT1	0.105***	ΔLnPCGDP	-0.313
	(0.035)		(0.208)
FDI	0.048**	ΔLnPAT1	-0.021

	(0.022)		(0.022)
HDI	4.076***	ΔFDI	-0.003
	(1.182)		(0.003)
EPS_Nord	0.225*	ΔHDI	1.055
	(0.124)		(1.492)
Constant	2.923***		
	(1.042)		
Number of obs.	240		
Number of groups	8		
Log likelihood	401.889		

5. Discussion

All the models of this study yielded significant and theoretically consistent results. The findings offer crucial insights into the factors determining REC across Southern European and Nordic economies. The significant negative ECT (-0.214) validates the presence of a stable long-run equilibrium association among REC, EPS, FDI, HDI, technological innovation, and economic development. The adjustment coefficient reports that about 21.4% of the short-run disequilibrium is corrected in each period, consistent with the previous findings of (Bahl et al., 2026; Şanl et al., 2023). This moderate speed of adjustment implies that the RE transition is a gradual phenomenon, necessitating continuous efforts rather than generating an immediate policy response. The long-run significant positive effect of EPS on REC connotes that stricter environmental policies can play an important role in the clean energy transition. Stronger regulations can increase the cost of carbon-intensive energy sources and encourage industry to adopt cleaner energy technology. Moreover, it motivates private investors and governments to expand clean energy infrastructure. This finding is consistent with the findings of existing studies (Godawska & Wyrobek, 2021; Hassan et al., 2024). However, the insignificant short-run effect indicates that stronger policies do not immediately translate into higher REC, as it takes time for regulatory reform to affect investment decisions and infrastructure development.

The long-run significant negative estimates of per capita GDP indicate an unpopular but literally consistent outcome. Commonly, we expect economic progress to enhance an economy's financial capacity for expanding clean energy infrastructure. However, findings show higher per capita GDP may lead to lower REC, but it does not mean that economic progress suppresses clean energy expansion. It is probably because these economies continue during the period of economic growth; total energy demand could have increased, which could not have been met by clean energy sources.

Basically, economic expansion may increase total energy consumption faster than RE generation, specifically when RE is measured in relative terms to total energy consumption. Previous studies also indicate similar outcomes (Ramadani et al., 2026). Innovation related to energy generation, transmission, and distribution, captured in terms of patent reports, has a significant positive long-run effect, highlighting the importance of innovation. Technological advances in clean energy improve efficiency, reduce cost barriers, and boost RE infrastructure integration. Whereas insignificant short-run outcomes suggest that the advantages of innovation are not realised instantly, as the development, diffusion, and mass adoption of new technology take time. Similar evidence from different scholars validates our results (Onofrei et al., 2024; Radulescu et al., 2025).

Further, the long-run coefficient of FDI shows a significant positive relationship with REC. This implies that foreign capital flows facilitate host economies directing FDI toward the clean energy transition. This is because FDI enables technology transfer, offers investment resources, and provides better access to international expertise. However, insignificant short-run effects demonstrate that foreign investments do not necessarily generate RE immediately. Even long-run effects depend on numerous factors, such as the ability of host economies to direct FDI towards clean energy infrastructure and the sectoral composition of capital flow. Therefore, FDI policies and regulations that prioritise investment in environmentally friendly technology can support the expansion of renewable energy. Some recent studies also indicate a positive relationship between FDI and REC (J. Zhao, 2025). The long-run estimate of HDI reports a strong positive and significant association with REC. This suggests that improvements in human development can facilitate the adoption of renewable energy. Higher HDI advances the economic abilities of the people, improves education, generates awareness related to environmental issues, and boosts institutional capacities that encourage RE adoption. Further, developed nations possess better governance and greater technical and financial capacity to introduce cleaner energy policies effectively. Nevertheless, insignificant short-run coefficients indicate that an increase in HDI does not immediately affect the energy transition; rather, it does so through cumulative and structural changes. This finding is consistent with a study that examines the relationship between the top ten HDI nations and REC (Kaewnern et al., 2023). The study reports that HDI facilitates clean energy consumption. Another study based on 126 economies of the world finds positive effects of HDI on REC (Adekoya et al., 2021).

In short, the analysis suggests that the RE transition is shaped by continuous endeavour in the form of financial support, technological innovation, and institutional and developmental support, rather than a short-run response.

6. Conclusion and policy implications

This study examines the effects of EPS, technological innovation, and macroeconomic variables on renewable energy consumption, especially focusing on the Nordic and Southern European economies. We used data from 1990 to 2020 to conduct panel ARDL-PMG estimation to understand the short-run and long-run dynamics. Our empirical analysis is based on all the appropriate tests required, such as the variance inflation factor (VIF), Pesaran's cross-sectional dependency (CSD); the second-generation CIPS unit root test; and the Hausman specification test (Hausman, 1978; Pesaran, 2007). Further, findings of the baseline model have been validated by the MG estimator and DFE estimation analysis, suggesting findings are relevant regardless of the model. First, the result of VIF confirms the absence of the issue of multicollinearity in the data. Second, the CSD test did not report strong cross-dependence, supporting the use of the Panel ARDL-PMG model. Third, the CIPS unit root test demonstrated that all the variables used in the current study are stationary. Fourth, the Hausman specification test clearly indicated the preference for the PMG estimator.

Fifth, overall, the analysis of the baseline model reveals a clear distinction between long-run and short-run dynamics. While the long-run estimates are statistically significant, short-run coefficients are insignificant. The long-run coefficients of environmental policy stringency suggest positive effects on renewable energy consumption. The effects of EPS interaction estimation suggested a higher marginal effect of EPS on REC in the Nordic economies relative to the Southern European nations, highlighting the importance of stricter environmental regulations. Other variables like patent activity, foreign direct investment, and human development also exhibit positive effects on REC. While per capita GDP reported a negative sign, which does not necessarily mean GDP growth lowers REC, especially when it has been measured as a share of total energy consumption. Most importantly, the significant and negative ECT indicates that deviations from the long-run equilibrium gradually correct themselves over time. Finally, these findings are validated by our robustness check models, where every coefficient's direction is

consistent with the findings of the primary model. Our analysis offers valuable policy implications for policymakers, regulators, and government bodies.

- Coordinated long-term policy strategy: The ECT indicates that deviations from long-run equilibrium are gradually getting corrected, and estimates of explanatory variables are significant in the long run. Therefore, to achieve a renewable energy transition, it would be beneficial to implement coordinated long-term policy strategies that integrate environmental policies with innovation, investment mobilisation towards clean energy, and human development.
- Strict implementation of environmental regulation: The findings demonstrated significant positive effects of EPS that suggest that policymakers and government bodies should continuously maintain progressive environmental regulation, including carbon pricing, fossil fuel regulations, and emission standards, which should be strengthened and monitored. Further, the stronger marginal effect of EPS in the Nordic bloc implies that stricter policy translates more effectively when supported by better technology, strong institutions, better financial markets, and renewable energy infrastructure. Therefore, these elements must be used in an integrated way.
- Technological innovation and improved human development: Patent activities and HDI indicate a positive effect on REC, suggesting that the clean energy transition should be considered as a part of a broader developmental strategy. More investment in research and development, education, health, green innovation, and industry-university partnerships can boost the capability of families and businesses to adopt clean energy equipment and sources. Therefore, policies should look beyond increasing access to clean energy and focus more on green innovation and development of human capital.

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