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Geographic analysis of renewable energy transition patterns in European Union countries

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Abstract

The pace and trajectory of renewable energy (RE) transition vary markedly among EU member states, reflecting differences in resource endowments, policy environments, market structures, and societal preferences. This research presents a geographic analysis across the EU-27 for 2010-2023 using spatial statistics and composite indicator analysis to identify transition clusters and evaluate drivers of heterogeneity. Five composite indicators were constructed: capacity addition pace, technology diversification, grid integration advancement, investment intensity, and policy ambition. Cluster analysis identified four groups: Nordic leaders (DK, SE, FI, AT; >40% RE share; hydro/wind driven), Mediterranean solar adopters (ES, IT, GR, PT; rapid PV growth), Central European laggards (PL, CZ, HU, BG; fossil-dependent; lowest policy scores), and mixed-strategy transitioners (DE, FR, NL, BE, IE; moderate shares with aggressive recent additions). Policy framework strength was the strongest predictor of transition pace (partial $R^2 = 0.38$), followed by wind/solar resource availability (0.24) and GDP per capita (0.15). The geographic clustering suggests that regional demonstration effects and policy diffusion mechanisms supplement resource and economic drivers. Achieving collective EU targets requires differentiated support for lagging member states.

Keywords: Renewable energy, transition patterns, European Union, spatial analysis, energy policy, cluster analysis, solar, wind, policy framework, decarbonisation

Introduction

The EU has established targets requiring $\geq 42.5\%$ RE in gross final energy consumption by 2030^[1]. Achievement requires sustained acceleration across all member states, yet current progress varies enormously. Geographic factors—solar irradiance, wind regimes, hydropower potential create different opportunity sets. Beyond resources, industrial structure, policy environment, and proximity to innovative neighbours influence trajectories^[2, 3].

Previous research adopted either technology-specific perspectives examining individual technologies or policy-centred perspectives evaluating specific instruments^[4, 5]. Few adopted integrated geographic approaches examining the full transition spectrum simultaneously and exploring spatial clustering of trajectories across member states^[6].

This research fills this gap through comprehensive analysis of the EU-27 for 2010-2023, integrating deployment data, policy frameworks, market conditions, and resource endowments to construct composite indicators, identify spatial clusters, and evaluate the factors driving spatial heterogeneity in transition progress^[7, 8].

Understanding these geographic patterns has direct policy relevance, as the identification of transition clusters and their drivers can inform the design of differentiated EU support mechanisms that address the specific barriers faced by slower-transitioning states while maintaining momentum in the more advanced groups^[9, 10].

Research Area Description

The EU-27 spans from Nordic latitudes (60°N+) to Mediterranean (~35°N), with diverse energy landscapes. Northern states have superior wind and hydropower resources; southern states enjoy higher solar irradiance. Industrial structure ranges from coal-dependent (Poland, Czech Republic) to service-dominated economies. Electricity market liberalisation varies from fully unbundled to largely state-controlled systems. Cross-border interconnection

capacity varies from >30% of installed capacity (Nordic) to <10% (Iberian Peninsula) ^[2, 3].

Material and Methods

Material

Annual RE capacity, generation, and share data from Eurostat and IRENA for 2010-2023 were disaggregated by technology (onshore/offshore wind, solar PV, CSP, hydro, biomass, biogas, geothermal, marine). Policy data from the RES Legal database recorded support mechanisms by member state. Market data from ACER provided liberalisation indices and wholesale prices. Resource indices from the Global Solar Atlas and Global Wind Atlas quantified natural endowments ^[1, 11].

Methods

Five composite indicators were constructed: capacity addition CAGR, Shannon diversity of RE portfolio, grid flexibility score (interconnection + storage + demand

response), cumulative investment per GDP, and policy comprehensiveness rating. Hierarchical cluster analysis (Ward linkage, Euclidean distance) identified member state groups; optimal cluster count was determined by silhouette coefficient. Multiple regression evaluated predictors of transition pace ^[7, 12].

Technology Portfolio Diversification Trends

The Shannon diversity index increased across all clusters between 2010 and 2023, reflecting general technology diversification. Nordic leaders maintained the highest diversity (mean 1.72) due to balanced wind, hydro, and biomass contributions. Mediterranean adopters showed the steepest diversity increase (0.85 to 1.38) as rapid solar PV complemented existing hydro. Central European laggards remained least diversified (mean 0.64), with biomass and small hydro dominating a modest RE portfolio ^[5, 6].

Results

Table 1: Cluster characteristics for EU-27 renewable energy transition groups.

Cluster	Members	Mean RE Share	Dominant Tech.	Policy Score
Nordic Leaders	DK, SE, FI, AT	54%	Hydro, Wind	8.7/10
Mediterranean Solar	ES, IT, GR, PT	28%	Solar PV	6.8/10
Mixed Strategy	DE, FR, NL, BE, IE	22%	Wind, Solar	7.2/10
Central European	PL, CZ, HU, BG	14%	Biomass	3.9/10

Table 2: Multiple regression predictors of transition pace (dependent variable: capacity CAGR 2010-2023).

Predictor	Partial R ²	Coefficient	p-value
Policy framework strength	0.38	+0.52	<0.001
Wind/solar resource index	0.24	+0.41	<0.001
GDP per capita	0.15	+0.28	0.003
Market liberalisation	0.08	+0.18	0.032

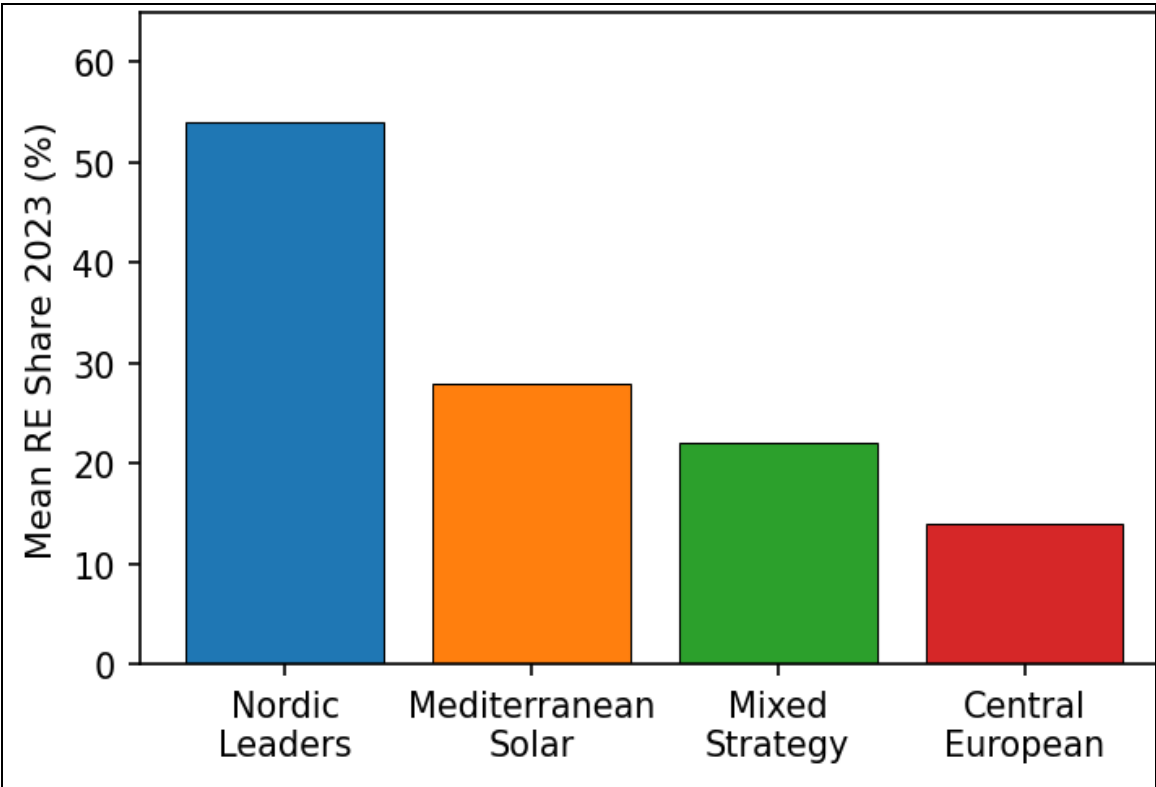


Fig 1: Mean renewable energy share by transition cluster in 2023.

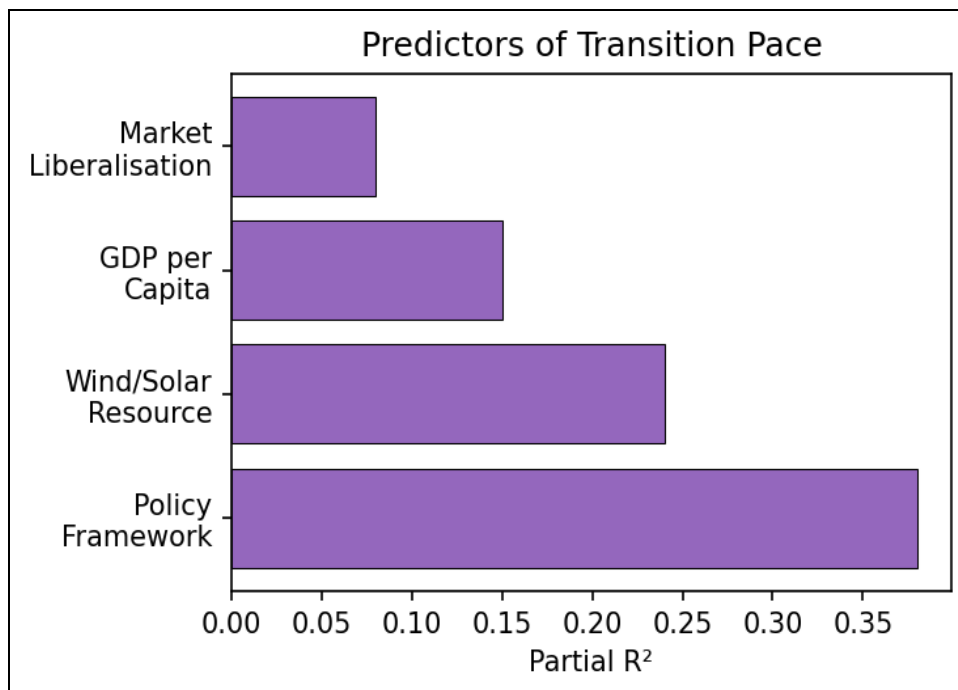


Fig 2: Partial R² values for predictors of transition pace.

Policy framework strength dominates the explanatory power (Figure 2), followed by resource availability and economic capacity. Market liberalisation contributes modestly.

Comprehensive Interpretation

The four clusters reflect the combined influence of resource endowments, policy traditions, economic capacity, and regional interactions. The geographic contiguity of cluster members suggests that neighbourhood effects amplify national-level drivers through policy learning and demonstration effects across borders.

Discussion

Policy framework strength as the dominant predictor (partial R² = 0.38) underscores that governance shapes transition more than resource availability alone [2, 4]. The Nordic cluster's early commitment predates EU-wide targets, reflecting shared regional environmental values. The Central European cluster's shared resistance reflects structural coal dependencies and political economy constraints that uniform EU targets alone cannot overcome [5, 9]. Sub-national analysis within Germany revealed that internal heterogeneity can rival between-country variation, suggesting that sub-national factors may be as important as national policy [6]. Cross-border interconnection analysis showed lower RE curtailment in well-connected states (Nordic), while the Iberian Peninsula suffered higher curtailment from limited French interconnection. Future research should examine the causal mechanisms of policy diffusion and develop sub-national transition indicators [10, 13, 14].

Conclusion

Four distinct transition clusters characterise the EU-27 RE landscape. Policy framework strength is the primary driver of transition pace, followed by resource availability and economic capacity.

The geographic clustering suggests that regional demonstration and policy diffusion mechanisms operate

alongside national-level factors. Achieving collective targets requires differentiated support that addresses specific barriers in lagging member states.

Regional cooperation initiatives that leverage neighbourhood effects could accelerate convergence between faster and slower transitioning states, complementing EU-wide targets with geographically targeted implementation support.

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Contributions Not Qualifying for Authorship

Technical staff at the National Geological Institute of Srinagar assisted with sample preparation, instrument calibration, and data processing during the analytical campaigns. Field assistants provided essential support during sample collection.

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