

Club Convergence and Complex Causality in Europe's Energy Transition: Pollution–Footprint–Recycling Linkages, Equifinality, and Necessary Conditions

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Extended Abstract

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Abstract Summary

This study examines whether Europe's energy transition (EnT) converges along a single pathway or within distinct regimes, and whether these regimes imply different causal, configurational, and constraint structures linking recycling (RECY), ecological footprint of production (EFP), and CO₂ emissions (POLL). Using annual data for 24 European countries (1997–2021), EnT is measured as the ratio of renewable to fossil-fuel energy consumption and subsequently transformed into its natural logarithm (lnEnT) for empirical analysis. The Phillips–Sul tests reject the null of global convergence and identify two clubs: a high-transition Nordic club (Denmark, Finland, and Sweden) and a larger club of 21 countries converging to a lower transition path. JKS panel Granger tests reveal club-specific predictive patterns (i.e., temporal precedence rather than structural causality): in the larger club, RECY significantly predicts EnT (and also predicts EFP and POLL), while EnT predicts RECY; in the Nordic club, POLL and EFP predict EnT, with limited predictive relevance for RECY. Fuzzy-set QCA indicates equifinality, with multiple sufficient configurations for high and low EnT that differ across clubs, and permutation tests provide robustness checks. Necessary Condition Analysis shows that in the Nordic club, RECY and EFP impose binding threshold constraints for very high EnT, whereas no single bottleneck emerges in the larger club. These results suggest that energy-transition policies may be tailored to regime-specific drivers, configurations, and constraints.

Presenting Author Biography

Zakir Khan is a Ph.D. candidate and researcher in environmental economics. His work focuses on climate change, energy economics, and sustainable development. He holds a Master's degree from National Yunlin University of Science and Technology, Taiwan, and has expertise in advanced econometric modelling. He lives in Taiwan and is actively engaged in research and teaching.