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Abstract

This paper investigates cost-optimal electricity generation pathways for Europe to achieve carbon neutrality by 2050. Using a pan-European optimization framework developed in the Low Energy Analysis Platform (LEAP) with its NEMO least-cost solver, the study models 35 interconnected countries and incorporates harmonized technology costs, fuel prices and electricity demand projections. The model minimizes total discounted system costs while allowing cross-border trade to capture the effect of transmission on balancing variable renewable energy. Results indicate significant geographical disparities in decarbonization trajectories: by 2050, 14 countries achieve fully renewable electricity systems, while others continue to rely on biomass or nuclear due to capacity and land constraints. Large-scale renewable deployment increases generation costs in several regions, whereas early adopters benefit from long-term fuel savings and export opportunities. Cross-border electricity flows prove essential for system stability and cost efficiency, emphasizing the importance of interconnection and aligned national strategies. Our findings highlight both the feasibility and complexity of a coordinated European energy transition and offer policy recommendations regarding infrastructure investment, decarbonization alignment and targeted support for lagging regions. The study underscores the need for improved spatial and temporal cost datasets to enhance future policy-relevant modelling.

Keywords: Energy; LEAP; Emissions; Least-Cost Optimization; Europe; Sustainable development.

1. Research question and objectives

This study explores how Europe can achieve a resilient and cost-effective pathway to carbon neutrality by 2050 through optimal fuel mixes for electricity generation, when accounting for variations in technology costs, national energy demands and the need to balance variable renewables with firm capacity. The paper's objectives are to (1) construct, based on earlier work by Münster et al. (2024), a pan-European optimization model of its energy system, enabling cross-country analysis, (2) explore a range of scenarios for fuel shares under different cost and demand assumptions to 2050, and (3) provide actionable insights for policymakers to design integrated and robust decarbonization strategies that align with the National Energy and Climate Plans (NECPs) of all Member-States (Koundouri et al., 2025).

2. Literature Review

The transition to a carbon-neutral European electricity system has been widely examined through cost-optimal and scenario-based energy system modelling frameworks. Existing studies highlight the importance of large-scale renewable deployment, sector coupling, and cross-border electricity exchange in minimizing system costs and enhancing security of supply (Brown et al., 2018; Breyer et al., 2023). Long-term modelling consistently suggests that 100% renewable electricity in Europe is technically feasible with sufficient grid reinforcement and resource diversification (Pfenninger et al., 2014; Zappa et al., 2019), although cost and regional variability remain major challenges. Comparative assessments reveal substantial differences in optimal technology mixes across national contexts, driven by demand patterns, land availability, and resource endowments (Breyer et al., 2023). Moreover, shifting from fossil-fuel dependence to renewables requires substantial upfront investment yet yields long-term fuel cost savings (Hesamzadeh and Biggar, 2020; IEA, 2023).

3. Methodology

To capture interactions across renewable technology and country-specific data, we developed a modelling framework that links European-wide technology cost data with the country-specific electricity needs. All countries were connected in a transmission network to allow cross-border electricity flow. 35 countries were modelled, namely the EU27, the Nordic countries, the Balkans, Switzerland and the UK.

This framework was put together using LEAP (Heaps 2022), a scenario-based energy-emissions modelling tool that provides the interface for constructing energy demand and supply scenarios. It's optimization extension, NEMO, is a high-performance linear programming solver, that identifies cost-optimal technology strategies.

The objective of our model is to minimize the total discounted electricity generation system cost for each country when subject to demand, capacity, annual addition, non-negativity and emission constraints. A harmonized cost dataset was applied across Europe, combining literature-based technology costs (capital, fixed and variable operation and maintenance (O&M) costs) with country-specific fuel prices from the IEA, Eurostat, and Diesel Fuel Prices. Representative technology configurations were averaged where multiple options existed, with Solar PV and Onshore Wind modelled for landlocked countries and Offshore Wind included for coastal states. Renewable technologies were grouped to simplify modelling while capturing the main contributions from wind and solar generation across countries.

Although spatial specificity is reduced due to uniform European inputs, the technology-specific granularity still enables a detailed analysis of energy system transitions. The analysis, therefore, aims to find optimal fuel mixes for each European country by 2050 compared to 2025 with cross-border electricity flow.

4. Results

Our scenario finds that in 2025, Germany and the UK lead in renewable deployment, with France relying heavily on nuclear. Overall, a divide appears in the results as Western/Northern Europe (e.g., Denmark, Germany, Sweden) shows high renewable penetration while Eastern/Southeastern Europe (e.g. Poland, Serbia, Bulgaria) still depend on fossil fuels.

By 2050, the cost-optimal scenario indicates that 14 countries can reach 100% renewable electricity, including Greece, Albania, Cyprus, Denmark, Estonia, Germany, Ireland, Latvia, the Netherlands, Norway, Romania, Spain, Sweden, and Switzerland. These countries import only from other fully renewable countries or act as net exporters, demonstrating the feasibility and possible success of building cost-effective and robust grids. Where countries fall short of full renewable penetration, biomass and biofuels play an increasing role, with the UK showing the sharpest increase in reliance by 2050, likely due to capacity constraints limiting further onshore wind and solar expansion. Nuclear generation also persists in countries such as France, Finland and Hungary, reflecting the absence of NECP phase-out targets and its role as a dispatchable low-carbon option in these countries.

Cross-border trade proves vital for system stability. Central and Western Europe (notably Germany, France, and Belgium) act as balancing hubs, while the Nordics and Baltics appear as renewable-rich exporters, highlighting the need for flexible interconnection to manage variability. In Eastern Europe, greater integration (particularly for Poland, Romania, and Hungary) boosts export potential, while Southern Europe (Italy, Spain, Portugal, Greece) shows high renewable capacity but limited transmission, particularly in the Iberian Peninsula. The UK and Ireland also face increasing dependency on continental Europe to balance variable generation, showing the importance of cross-channel trade. In addition, several transmission flows remain stable over time (e.g., Albania to Greece and France to Switzerland/Italy/Spain), potentially signalling grid constraints rather than balance, highlighting the need for infrastructure upgrades.

Cost outcomes vary widely across the continent in the explored cost-optimal scenario. Not surprisingly, large-scale renewable buildouts drive capital and fixed O&M costs up, with 15 countries seeing more than a doubling in generation costs by 2050. These include Portugal, Slovenia, Malta, Lithuania, Hungary, Denmark, Germany and France, where infrastructure expansion or nuclear decommissioning drives substantial cost increases. In contrast, countries such as Belgium, Bosnia, Estonia, Italy, Luxembourg, Sweden and Switzerland achieve lower total costs by 2050 compared to 2025, likely due to early renewable deployment that eliminates fuel costs and reduces variable O&M costs. This is reinforced by Estonia, Sweden and Switzerland showing full renewable penetration in 2050. These outcomes highlight a clear trade-off between short-term capital-intensive transitions and long-term cost savings through reduced fuel dependency.

Policy recommendations can therefore be made. These include aligning national decarbonization timelines to prevent emissions leakage via electricity trade, expanding north–south transmission to support renewable balancing and exports and increased investment in interconnectors by countries nearing 100% renewable penetration. Priority should also be given to any countries lagging in renewables energy shares in 2025 or relying heavily on imported electricity, as early inaction increases the risk of missing long-term climate and energy targets.

Within the study, the lack of country-specific technology cost data and temporal balancing remains a large limitation. Thus, analysis is limited, risking distorting policy insights. For example, industrialized countries often benefit from significantly lower capital costs and thus achieve lower levelized costs of electricity (LCOEs). There is also a need to disaggregate renewables into wind, solar and hydro, for deeper insights, utilized by each country instead of averaging all renewables across Europe as a whole. This would yield additional findings into how the specific mix of renewables impacts both system stability and long-term cost-efficiency per country. Therefore, we highlight the need for deeper technological, economic, and systems-level data to more accurately guide decarbonization strategies.

5. Conclusion

Despite limitations, this modelling exercise, based on cost-minimized electricity generation pathways in LEAP, reveals plausible shifts in national fuel shares by 2050 and highlights strategic transitions toward renewables, biomass, and nuclear across Europe. Crucially, it also underscores the complex cost dynamics associated with this energy transition. The findings underscore the uneven but accelerating pace of Europe's energy transition. A significant share of countries achieves fully renewable electricity by 2050, while others face steep transitional costs or continued reliance on biomass and nuclear. The results demonstrate both the feasibility and the complexity of cost-optimized decarbonization, where system integration, capacity constraints and renewable investment strongly shape national pathways. The tool's ability to assign countries an optimized fuel share provides scientists and economists with a useful basis to start planning more effective ways to meet their NECP goals, considering collaborative solutions, which are currently overlooked.

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