Socioeconomic and distributional impacts of different energy transformation paths in a regional modelling framework

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Introduction

Achieving climate neutrality requires the decarbonisation of residential heating, the expansion of grid infrastructure for green electricity and the installation of renewable energy sources. This process is primarily determined by the behaviour of private households and regionally differentiated policy measures that take specific local conditions into account. Therefore, it is essential to incorporate a regional perspective on the analysis of the green transition. This contribution examines how the impacts of the energy system transition vary across regions and how these differences can be disclosed and assessed with empirical, model-based methods. Regional disparities in economic structure, labour markets, and institutional conditions shape both the pace of transformation and the distribution of its costs and benefits. Quantifying these effects requires an integrated framework that consistently links the energy system with macroeconomic dynamics while resolving subnational heterogeneity.

Developments in the field of model-based analyses in Germany and Europe.

Earlier economic impact studies on the energy transition focused predominantly on the national level. Central questions concerned the macroeconomic effects of different support instruments and the export potential of technologies – for example, in the expansion of renewables (Lehr et al. 2015; Lutz et al. 2014). With the integration of all sectors under the umbrella of the “Energiewende”, interactions driven by energy efficiency measures and cross-sectoral effects moved further into focus (Lutz et al. 2018; Vrontisi et al. 2020). Numerous nationwide studies conclude that the long-term macroeconomic balance is positive. In particular, when fossil fuel prices are high and export opportunities are realised, the associated benefits outweigh the costs.

Distribution issues within the population are still important: the energy transition should be “affordable” for households and firms. Combining income and cost changes with household expenditure patterns remains complex and is still a key research area (Többen et al. 2023b). In parallel, the potential of the energy transition for regional development has been discussed: the decentralised expansion of renewable energy was identified as an opportunity for rural areas (Hirschl et al. 2010), and the first analyses at the level of the federal states (Bundesländer) emerged (Ulrich et al. 2018; Ulrich 2022; Sievers et al. 2019).

Against the backdrop of national and EU policy on regional cohesion, it is of particular interest whether the energy transition exacerbates regional inequalities or can serve as an opportunity for catching up in disadvantaged regions (Többen et al. 2023a). The debate on a “Just Transition” remains salient in the regional context.

A central focus of further success in energy transformation is knowledge transfer: regional actors are key to implementing climate mitigation measures. Model-based analyses are therefore to be prepared in an interactive information system in a way that is accessible and actionable, enabling regions to align measures, impacts, and funding instruments with their specific conditions. For that reason, the recent study results are going to be published on an online dashboard designed in cooperation with stakeholders.

Modelling framework

Methodologically, economy-wide models face the challenge of consistently representing interactions between the energy system and the economy, as well as among production, prices, labour markets, and household expenditure. For regionalised, empirically grounded modelling, data availability is more limited; at the same time, it is necessary to capture region-specific conditions in detail and to account adequately for interregional linkages. The modelling framework presented here uses a combination of models with varying degrees of regional detail to meet these requirements: the macroeconomic model PANTA RHEI at the national level (Lutz et al. 2021) is coupled with the regional model LÄNDER for the federal states (Ulrich et al. 2022). The results of these dynamic models are generated in an iterative procedure on an annual basis and subsequently passed to the regional input–output model RIMES. RIMES distinguishes 401 districts and 37 product groups and captures regional economic structures on both the demand and supply side, as well as sectoral and interregional division of labour (Ulrich et al. 2025).

Scenario design

Several scenarios were developed for the impact analysis. To demonstrate the capabilities and potential of the approach we choose results for a “heat transition” scenario, benchmarked against a reference scenario (REF). The reference scenario describes the continuation of existing policy instruments and legally fixed targets, with gradual modernisation but without strong acceleration in the diffusion of renewable heating technologies. Annual heat pump installations rise from 193,000 units (2024) to around 500,000 units per year from 2034. This implies average annual investments of EUR 4.1 billion (price-adjusted) through 2045. The district heating share in the residential sector increases from 10.7% (2023) to 17.5% (2045); the fossil share in district heat generation declines from 64% to 29.5%. Average annual investment in district heating amounts to EUR 0.9 billion.

The climate neutrality scenario (CN) describes a highly ambitious transformation pathway compatible with long-term decarbonisation targets. Here, annual heat pump installations accelerate to more than 800,000 units by 2037, requiring average annual investments of EUR 9.1 billion through 2045. The district heating share in the residential sector rises to 20.6%, and the fossil share in district heat generation falls to 19.2%; average annual district heating investments amount to EUR 2.75 billion.

Results: Macroeconomic effects

At the aggregate level, real GDP remains consistently above the reference level in the CN scenario over the entire simulation horizon. The largest deviation occurs in 2030, when GDP in the CN scenario is about 0.2% above the REF scenario. This impulse is primarily driven by higher equipment and construction investment resulting from accelerated heat pump installations and the expansion of district heating, which stimulates domestic demand, value added, and employment, as well as gross wages and disposable household income. After 2030, the investment impulse weakens; by around 2035, the GDP lead of the CN scenario stabilises at roughly 0.1% relative to REF.

Overall employment effects remain positive but vary over time: by 2030, the CN scenario generates about +20,860 additional jobs (+0.05%). As investment dynamics ease, this difference declines to around +5,150 jobs (+0.01%) by 2035. Toward the end of the period, employment gains re-emerge (e.g., +9,100 in 2040, +6,910 in 2045; each +0.02% relative to REF).

Results: Regional differences and clustering

At the subnational level, sectoral dynamics and structural heterogeneity lead to differentiated employment impacts. By 2045, 260 of 401 districts record net employment gains in the CN scenario relative to REF. While the relative effects are limited in magnitude (−0.03% to +0.10%), they exhibit systematic spatial patterns.

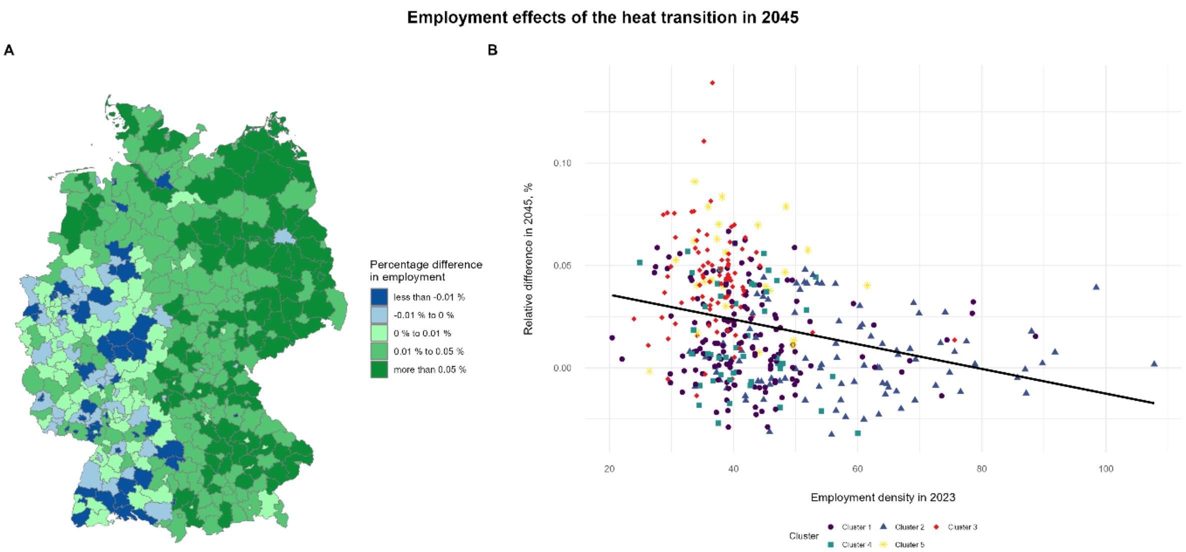
To explain this heterogeneity, five region types (clusters) were constructed that summarise initial conditions for the heat transition (Stöver et al. 2026). Their characteristics differ, among other things, by employment in construction, the prevalence of district heating, the importance of energy-intensive industry, the share of fossil heating systems, and private energy expenditures. This clustering makes divergent transformation pathways and potentials visible.

Key findings for regional impacts include:

- Positive relative employment effects occur more frequently in northern, eastern, and south-eastern districts, which predominantly belong to Cluster 3 (high private energy expenditures, existing stock of fossil heating systems, above-average district heating prevalence) and Cluster 5 (strong renewable generation/storage capacity, high industrial energy demand). Both clusters are predominantly rural and exhibit above-average employment in construction.

- Cluster 1 (average initial conditions), Cluster 2 (urban, with infrastructure challenges), and Cluster 4 (industry-based regions with a high share of energy-intensive production) predominantly show neutral to slightly negative relative effects. In particular, urban and industrialised regions appear constrained in their employment dynamics by structural and infrastructural factors.
- In absolute terms, Clusters 3 and 5 benefit more strongly: taken together, their employment exceeds the REF scenario by around +3,100 employees in 2045. Clusters 1, 2, and 4 together reach about +2,400 additional employees in 2045 compared with REF.

Figure 1: (A) District-level employment changes in Climate Neutrality in 2045 across the 400 German districts (% change from Reference); (B) Relationship between employment density in 2023 and the percentage difference in employment in 2045, with a linear regression line.



Policy implications and equity aspect

The analysis shows clearly that national averages obscure regional differences in impacts. Rural districts with high construction employment and favourable conditions for expanding renewable energy benefit disproportionately from an ambitious climate pathway, whereas urban and industrially shaped regions tend to experience neutral or slightly negative effects. Despite this heterogeneity, there is no evidence of increasing regional economic inequality: the Gini coefficient of gross value added at the district level remains stable, indicating that the ambitious heat transition only marginally redistributes employment without materially changing the spatial distribution of economic activity. This finding underscores the importance of investment-led transformation pathways to avoid spatial polarisation. It also becomes evident that most regions with positive effects are among the less developed or more peripheral areas.

The regionally differentiated results suggest that flanking policies are needed to mitigate transition risks and realise opportunities: examples include skills development, infrastructure investment in urban and industrial areas, targeted support instruments for regions with limited construction capacity, and measures to assist private households with high energy expenditures.

Conclusion

This study operationalises the importance of subnational heterogeneity within a macroeconomically consistent, multi-regional input–output framework (Panta Rhei – LÄNDER – RIMES), thus going beyond purely descriptive typologies. The results confirm that regional initial conditions systematically shape the economic impacts of the heat transition. At the same time, they show that an ambitious heat transition does not, in aggregate, significantly exacerbate regional inequalities, provided that transformation pathways are accompanied by appropriate investment and distributional policies. The implementation of an interactive information system supports regional actors in translating these insights into tailored local strategies.

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