The impacts of low-carbon transition on the competitiveness of European industries and the performance of green energy sectors: A spatial general equilibrium assessment at national and NUTS2 levels

Ioannis Charalampidis, Dimitris Fragkiadakis, Srishti Goyal

Introduction

The European Union's transition toward carbon neutrality presents both structural challenges and new industrial opportunities for European economies. The expansion of renewable electricity, hydrogen, and clean fuels, the electrification of transport, and improvements in energy efficiency across buildings are reshaping production systems and creating new markets for goods and services. At the same time, intensifying international competition, particularly from China in batteries, photovoltaic equipment, and electric vehicles, has heightened concerns about the competitiveness of European industries and the resilience of strategic value chains.

In response, the European Union (EU) has complemented carbon pricing with trade and industrial policy instruments designed to achieve climate neutrality while safeguarding industrial capacity. The Carbon Border Adjustment Mechanism (CBAM) aims to address carbon leakage and ensure a level playing field for emissions-intensive sectors, while the Net-Zero Industry Act (NZIA) promotes domestic manufacturing capacity for key clean technologies. Together, these instruments reflect an integrated climate and industrial strategy.

While the macroeconomic implications of carbon pricing have been widely studied in computable general equilibrium frameworks, the spatial consequences of layered climate and industrial policies remain less explored. Structural adjustment under decarbonisation is inherently regional. Industrial specialisation, agglomeration economies, infrastructure endowments, and historical development trajectories differ markedly across NUTS2 regions. Regional growth dynamics are shaped by structural characteristics and path-dependent processes (Alesina & Rodrik, 1994; Persson & Tabellini, 1994; Agasisti & Bertoletti, 2020), and policy-induced investment shifts may therefore reinforce existing industrial clusters rather than generate convergence.

From a regional science perspective, spatial computable general equilibrium modelling provides a suitable framework to analyse such differentiated adjustment patterns (Karlsson et al., 2015). This paper contributes to that literature by embedding decarbonisation policy, border adjustment, and industrial localisation within a spatially explicit recursive dynamic general equilibrium model that reallocates investment across NUTS2 regions.

By combining macroeconomic decarbonisation pathways with a dynamic regional Attractiveness Index, the study provides new evidence on how the low-carbon transition reshapes competitiveness not only at the national level but also across Europe's economic geography.

Methodology

At the national level, the analysis employs the GEM-E3 model, a recursive dynamic multi-sectoral and multi-regional general equilibrium framework developed by E3Modelling (2017). Firms minimise production costs under nested constant elasticity of substitution functions combining capital, differentiated labour, energy, and intermediate inputs. Households maximise Stone Geary utility subject to income constraints. Trade follows the Armington assumption, allowing imperfect substitution between domestic and imported goods. Markets clear through endogenous price adjustments, ensuring general equilibrium in each period.

The model features detailed representation of the energy system, including thirteen power generation technologies, hydrogen production, biofuels, and electrified transport technologies. Clean technology manufacturing sectors such as batteries, photovoltaic equipment, wind turbines, and electrolysers are explicitly represented. Emissions reduction is achieved through fuel substitution, energy efficiency improvements, and marginal abatement cost curves for non-CO_2 emissions. Revenue recycling from ETS1, ETS2, and CBAM is endogenously modelled, with revenues allocated primarily to building renovation and electric vehicle support.

Four scenarios are examined. The Frozen Policy Pathway (FPP) reflects continuation of pre-2023 policies. The Core Policy Scenario (CPS) implements strengthened carbon pricing consistent with Fit-for-55 targets. The Extended Policy Scenario (EPS) adds CBAM to address carbon leakage in emissions intensive sectors. The Industrial Policy Scenario (IPS) incorporates NZIA domestic manufacturing targets requiring that at least 40 percent of EU deployment needs for selected net-zero technologies be met by domestic production by 2030.

To capture spatial heterogeneity, national results are downscaled to NUTS2 regions using a dynamic regional Attractiveness Index. This index aggregates socio economic indicators including human capital, capital stock, transport infrastructure, vertical integration potential, market size, renewable energy capacity, and the geographical location of strategic industrial facilities. The index influences the allocation of sectoral investment across regions and evolves over time, allowing agglomeration and dispersion forces to shape regional growth trajectories. This approach is consistent with empirical findings that regional development depends on structural characteristics and industrial clustering (Dedominicis, 2014; Panzera and Postiglione, 2022). The modelling framework therefore captures not only macroeconomic adjustment but also endogenous spatial reallocation of production and investment under climate and industrial policies.

Results

Aggregate and Sectoral Effects

Under CPS, strengthened carbon pricing induces moderate but persistent GDP losses relative to the FPP baseline. Higher emissions costs increase production costs in energy intensive and trade exposed sectors, leading to declining exports and a narrowing trade surplus. Investment increases temporarily as capital reallocates toward clean technologies and building renovation but declines in the long term as profitability weakens in carbon intensive sectors. The dominant transmission channel operates through trade competitiveness rather than domestic demand contraction.

The introduction of CBAM under EPS reduces import penetration in ferrous metals and other covered sectors. Trade balances in energy intensive industries improve relative to CPS. However, aggregate GDP and investment do not recover. Higher intermediate input costs increase production costs in downstream sectors, generating crowding out effects. Both exports and imports decline, indicating that CBAM reshapes trade composition but does not stimulate growth.

Under IPS, NZIA reduces import dependence on batteries and photovoltaic equipment by encouraging domestic sourcing. Domestic production increases in these sectors, but exports do not expand proportionally. Aggregate GDP effects remain negligible. NZIA primarily reduces trade intensity and reshapes sectoral composition without fundamentally altering the macroeconomic adjustment path established under carbon pricing.

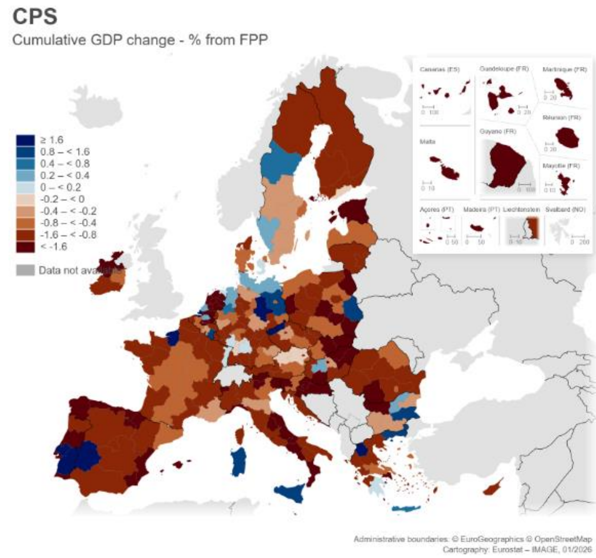
Regional Impacts

The regional dimension of the transition reveals substantial heterogeneity across NUTS2 regions. Figure 1 presents the cumulative percentage change in regional GDP under CPS, EPS, and IPS, each relative to its preceding scenario. The dispersion of impacts confirms that climate and industrial policies generate uneven spatial adjustment patterns across the EU.

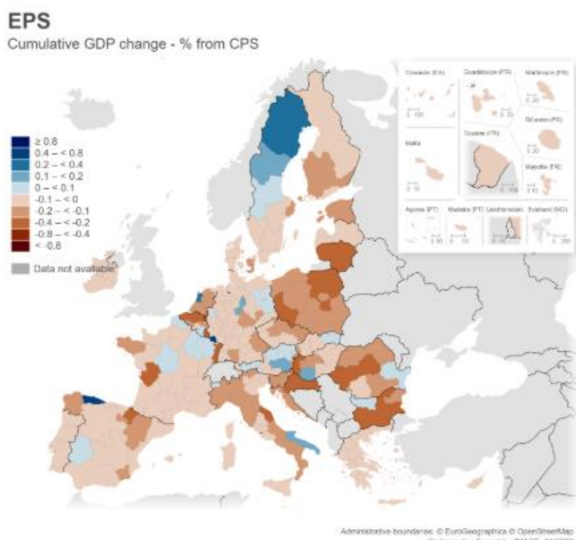
Under carbon pricing alone, as implemented in CPS, most NUTS2 regions experience GDP losses relative to the FPP. These losses are not uniform within countries and depend strongly on regional production structures. Regions with high dependence on carbon-intensive manufacturing and related service activities are more negatively affected due to higher production costs and declining competitiveness in emissions-intensive sectors. In contrast, regions with strong renewable energy potential or emerging clean technology activities display more resilient performance. In several cases, regions with lower exposure to traditional manufacturing but greater potential for renewable electricity, hydrogen production, or clean technology deployment record smaller GDP losses or even marginal gains. These results demonstrate that spatial outcomes are shaped more by regional economic structure than by national averages.

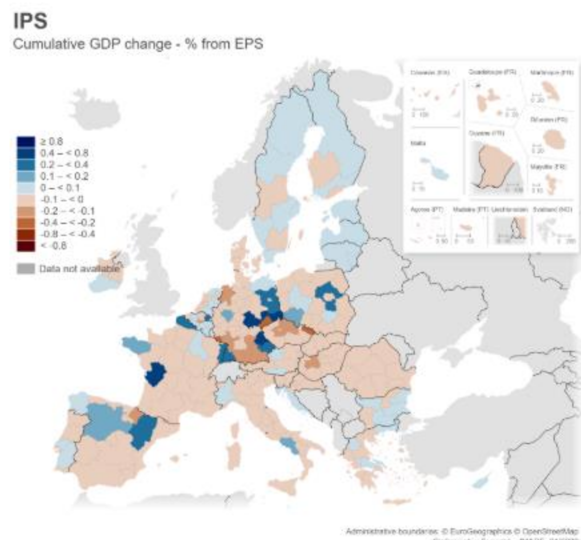
The introduction of CBAM under EPS benefits approximately one-quarter of regions relative to CPS. The gains are concentrated in regions specialised in ferrous metals and other emissions-intensive sectors covered by CBAM. By reducing import penetration and aligning carbon costs between domestic and foreign producers, CBAM improves relative competitiveness in these sectors. However, the magnitude of the gains remains modest and does not fully offset earlier losses relative to the baseline. Moreover, regions heavily dependent on downstream manufacturing or service sectors may experience additional pressure due to higher intermediate input costs. As shown in Figure 1 (b), the spatial pattern under EPS remains heterogeneous, with improvements limited to a subset of industrial regions.

Figure 1: Cumulative percentage change in NUTS2 GDP under CPS, EPS and IPS (relative to preceding scenario)



(a)





(b) (c)

The introduction of NZIA under IPS produces more visible spatial reshuffling. Regions hosting battery production and vertically integrated clean technology clusters benefit from increased investment and localisation of manufacturing activity. However, gains are conditional on overall regional production structures. For example, Střední Čechy benefits from battery production but experiences offsetting losses in other equipment manufacturing and services. Similarly, regions such as Bremen, Chemnitz, and Tübingen experience negative impacts linked to contraction in conventional transport equipment industries. Gains from photovoltaic manufacturing, non-ferrous metals, and biomass production remain insufficient to compensate for losses in larger sectors. As illustrated in Figure 1 (c), IPS concentrates gains in regions already embedded in clean technology value chains, instead of generating widespread regional gains.

The spatial distribution of gains and losses indicates that the low-carbon transition does not automatically generate regional convergence. Instead, localisation incentives tend to reinforce existing industrial clusters. Regions that already host manufacturing capacity, skilled labour pools, supplier networks, and infrastructure for clean technologies are better positioned to attract additional investment. Peripheral or service-oriented regions with limited manufacturing bases capture fewer benefits and remain exposed to contraction in traditional sectors.

This dynamic can be understood through the concept of structural path dependence. Regional development often follows historical trajectories shaped by past industrial specialisation, accumulated skills, infrastructure, and firm networks. When new policy incentives are introduced, such as domestic manufacturing requirements under NZIA, investment tends to flow toward regions that already possess the capabilities to respond effectively. As a result, industrial policy may strengthen regions that are already industrially strong while offering limited opportunities for structurally weaker regions. Without complementary intervention, this process can reinforce pre-existing economic patterns rather than transform them.

Because green industrial policy tends to favour regions that are already industrially advanced, European cohesion policy plays a critical role in ensuring balanced development. Targeted, place-based measures aimed at skills upgrading, infrastructure investment, diversification strategies, and support for emerging clusters are essential to prevent widening regional disparities. A coordinated approach that integrates climate policy, industrial policy, and regional cohesion instruments is therefore necessary to ensure that the benefits of the transition are distributed more evenly across European regions.

Conclusions

The EU's low-carbon transition reshapes competitiveness and industrial geography through three interacting mechanisms. Carbon pricing under CPS drives economy-wide structural reallocation and affects trade competitiveness in energy-intensive sectors. CBAM under EPS mitigates carbon leakage and partially stabilises emissions-intensive industries but does not restore aggregate growth. NZIA under IPS alters the spatial distribution of production by encouraging domestic sourcing of clean technologies, thereby reducing import dependence while concentrating manufacturing activity in selected regions.

From a regional science perspective, the transition functions less as a spatial equaliser and more as a cluster-amplifying mechanism. Regions with established industrial ecosystems, vertically integrated value chains, and skilled labour pools are better positioned to capture localisation gains under industrial policy. In contrast, peripheral or service-oriented regions remain more exposed to contraction in traditional sectors and benefit less from new clean technology deployment.

These findings suggest that achieving climate neutrality while maintaining industrial competitiveness does not automatically ensure territorial cohesion. Industrial policy instruments designed to strengthen European value chains may reinforce structural path dependence unless complemented by place-based strategies that expand capabilities in lagging regions. Coordinated integration of climate policy, trade instruments, and regional development measures is therefore essential to align competitiveness objectives with cohesion goals.

By embedding carbon pricing, border adjustment, and industrial localisation within a spatial recursive dynamic general equilibrium framework, this study shows that the green transition is not only an environmental transformation, but also a strategic reconfiguration of Europe's industrial and regional landscape.

References

Alesina, A., & Rodrik, D. (1994). Distributive politics and economic growth. *The Quarterly Journal of Economics, 109*(2), 465–490. https://doi.org/10.2307/2118470

Agasisti, T., & Bertoletti, A. (2020). Higher education and economic growth: A longitudinal study of European regions 2000–2017. *Socio-Economic Planning Sciences, 71*, 100823. https://doi.org/10.1016/j.seps.2020.100940

Dedominicis, L. (2014). Inequality and growth in European regions: Towards a place-based approach. *Spatial Economic Analysis, 9*(2), 120–141.

E3Modelling. (2017). *GEM-E3 model documentation*. E3Modelling S.A.

Karlsson, C., Andersson, M., & Norman, T. (Eds.). (2015). *Handbook of research methods and applications in economic geography*. Edward Elgar Publishing.

Panzera, D., & Postiglione, P. (2021). The impact of regional inequality on economic growth: A spatial econometric approach. *Regional Studies, 56*(5), 687–702. https://doi.org/10.1080/00343404.2021.1910228

Persson, T., & Tabellini, G. (1994). Is inequality harmful for growth? *The American Economic Review, 84*(3), 600–621.