# Highlights

**Integrating Spatial Granularity into Climate Policy Analysis: A CGE–GIS Framework for the European Union**

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- Novel CGE-GIS framework enhances EU climate policy analysis with high-resolution NUTS-2 emissions data.
- Fit for 55 analysis reveals divergent regional decarbonization paths, shaped by economic and demographic factors.
- ETS-2 imposes higher carbon prices on buildings/transport, reflecting past mitigation gaps and equity concerns.
- ESR trading creates trade-offs: Eastern EU gains welfare, while wealthier states bear costs, raising equity issues.
- Scalable CGE-GIS tool enables targeted, equitable EU decarbonization by capturing subnational policy impacts.

# Integrating Spatial Granularity into Climate Policy Analysis: A CGE–GIS Framework for the European Union

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**Abstract**

This study introduces a CGE–GIS framework that integrates the GEMINI-E3 model with EU NUTS-2 regional emissions data. It enables spatially refined analysis of climate policies, capturing regional disparities in decarbonization and mitigation costs under the Fit for 55 package. Results identify five distinct regional pathways shaped by demographics, growth, and carbon intensity. ETS-2 shows higher carbon prices than ETS, and emissions trading under the ESR causes uneven welfare effects—gains in Eastern Europe, losses in wealthier states. Despite modest EU-wide costs, regional differences are significant. The framework supports equitable, efficient climate policy tailored to Europe's socio-economic and geographic diversity.

*Keywords:* Computable general equilibrium model, NUTS-2, European climate policy, GIS, Fit for 55 package

## 1. Introduction

Effective climate change mitigation requires not only robust economic modeling but also spatially detailed assessments to ensure both the efficacy and equity of policy interventions. While Computable General Equilibrium (CGE) models have long been employed to evaluate the macroeconomic and sectoral effects of carbon pricing and emissions reduction strategies

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(Babiker, 2005; Böhringer and Löschel, 2006), these models typically operate at a global or national scales. As a result, they often obscure critical sub-national heterogeneity in emissions profiles, economic structures, and vulnerabilities to climate policies. This limitation is particularly salient within the European Union (EU), where substantial environmental and economic disparities across regions necessitate a more disaggregated analytical lens (Lafuente et al., 2020).

This paper is motivated by the need to address key methodological limitations in conventional CGE modeling, particularly when applied to the spatially heterogeneous context of the EU (May et al., 2025). A primary concern is the issue of spatial aggregation bias, wherein national-level CGE models tend to obscure substantial sub-national disparities by averaging outcomes across diverse regions. High-emission industrial zones such as Silesia in Poland, North Rhine-Westphalia in Germany, Lombardy in Italy or Catalonia in Spain, exhibit economic structures and environmental vulnerabilities that differ significantly from those of less industrialized areas (Crippa et al., 2024). However, these distinctions are often lost in aggregate analyses thus the distributional effects of climate policies may be misrepresented, undermining the design of targeted and equitable mitigation strategies.

In addition, traditional CGE models frequently overlook spatial interdependencies, failing to capture the cross-regional spillovers associated with trade flows, labor mobility, and shared infrastructure. These dynamics, which are integral to understanding the full scope of climate policy impacts, can be effectively modeled using Geographic Information Systems (GIS)-based spatial econometric techniques. The integration of CGE modeling with GIS represents a significant methodological advancement, enabling the incorporation of spatially explicit data on emissions, sectoral concentration, and regional disparities in policy outcomes (Dijkstra and Poelman, 2014).

Traditional CGE models are constrained by their reliance on aggregated data, which limits their capacity to capture localized industrial patterns, energy dependencies, and transportation infrastructures that significantly shape emissions trajectories. While detailed sub-national emissions inventories such as EDGAR and Eurostat reveal substantial within-country variation, CGE models commonly apply uniform national emission coefficients, leading to imprecise assessments of regional outcomes. By integrating CGE and GIS approaches, this study aims to enhance the spatial precision of climate policy analysis, enabling a more nuanced evaluation of decarbonization strategies that accounts for the EU's economic and environmental diversity. the proposed integrated framework enhances the granularity and accuracy of economic-environmental assessments, thereby supporting the development of more targeted and equitable climate policies.

The integration focuses on a regional framework of NUTS-2 (Nomenclature of Territorial Units for Statistics, level 2). The NUTS-2 level is particularly advantageous for policy analysis in the EU context, as it offers an optimal compromise between spatial resolution and analytical tractability. Compared to NUTS-1 and NUTS-3, the NUTS-2 regions are sufficiently disaggregated to capture meaningful sub-national variations in economic, social, and environmental indicators—variations that are essential for designing and evaluating targeted policy interventions (Farole et al., 2011). At the same time, they are aggregated enough to ensure data robustness and to mitigate the analytical challenges associated with excessive territorial fragmentation.

NUTS-1 regions, which often correspond to large administrative units such as entire states or provinces, tend to obscure intra-regional disparities and are therefore less suitable for detailed and nuanced policy analysis. In contrast, while NUTS-3 regions offer a finer spatial resolution, they frequently face challenges related to data availability and greater variability, which can compromise the robustness of cross-regional comparisons. Acknowledging these trade-offs, the European Union has adopted the NUTS-2 level as the primary unit for allocating structural and cohesion funds (Medeiros, 2016), given its balance between granularity and data reliability, and its capacity to support coordinated assessments and equitable regional development across Member States (Bachtler and Mendez, 2007).

Against this backdrop, the present paper adopts the NUTS-2 level of analysis to investigate the interplay between regional emissions patterns and climate policy in Europe. The structure of the paper is as follows. Section 2 examines historical emission trends and climate policy developments at the NUTS-2 level, highlighting the heterogeneity of emissions profiles even among regions within the same country. Section 3 details the methodological framework used to integrate the GEMINI-E3-EU computable general equilibrium (CGE) model with NUTS-2 regional data. Section 4 presents an illustrative application involving the construction of baseline and policy scenarios—two fundamental components of CGE modelling—and provides a regionally disaggregated analysis of the results. Finally, Section 5 synthesizes the findings and offers concluding remarks.

## 2. Decarbonizing Europe: Investigating 30 Years of Climate Policy in NUTS-2 Regions

Over the past three decades, European decarbonization has unfolded as a regionally heterogeneous and non-linear process. Despite the EU's overarching commitment to achieving climate neutrality by 2050, the trajectory of GHG emissions reduction has varied markedly across its regions. This variation is shaped by the interplay of demographic trends, economic development, and technological progress.

Germany, for instance, achieved a 46% emissions cut by 2023, driven by aggressive energy transition policies, such as renewable energy adoption and industrial energy demand reductions (Hartz et al., 2023). In contrast, countries like Cyprus saw rising emissions due to post-accession economic expansion and industrial growth (Watson, 2024). Eastern European countries like Lithuania also report dramatic emissions reductions (Gál, 2021), largely a consequence of deindustrialization and economic restructuring following the collapse of Soviet-era heavy industry (Staddon and Turnock, 2024).

Drawing on historical data,[1] it is evident that the EU has achieved a significant reduction in GHG emissions—approximately 29%. However, this aggregate progress masks substantial regional disparities. From the IPAT framework,[2] it is revealed that regional decarbonization pathways are shaped by three core dimensions. First, population dynamics differ significantly: Western Europe experienced modest growth largely driven by immigration, while many Central and Eastern European regions witnessed demographic decline due to out-migration and low fertility. Second, affluence — measured by GDP per capita — has grown across the EU, but the pace was especially rapid in Eastern Europe as countries like Poland and Romania closed the income gap with Western neighbors. Third, carbon intensity has broadly declined, signaling technological improvement, particularly in former Soviet-bloc regions where outdated infrastructure was replaced or phased out.

[1] Refer to: Annual Regional Database of the European Commission (ARDECO), Eurostat, and Electronic Data Gathering, Analysis, and Retrieval (EDGAR).

[2] The IPAT equation (Impact = Population $\times$ Affluence $\times$ Technology) is a foundational model in environmental studies that describes the multiplicative relationship between human population, economic activity, and technological efficiency in determining environmental impact (Ehrlich and Holdren, 1971; Dietz and Rosa, 1994).

Further identification of those regions based on their regional IPAT trends for 242 NUTS-2 regions with clustering analysis, identifies five distinct decarbonization pathways (Figure 1). Cluster 1 comprises Western and Central European regions with moderate growth and gradual emissions decline (-0.9% annually), suggesting steady or diminishing return of abatement. Cluster 2, by contrast, includes high-population-growth regions (e.g., parts of Spain and Italy) with rising emissions (+0.6% annually), reflecting challenges in offsetting demand-driven emissions through efficiency gains. Cluster 3 encompasses northern and western European leaders, including Denmark and Finland, which achieved the steepest emission cuts (–2.5% annually) and represent policy-driven decarbonization success stories.

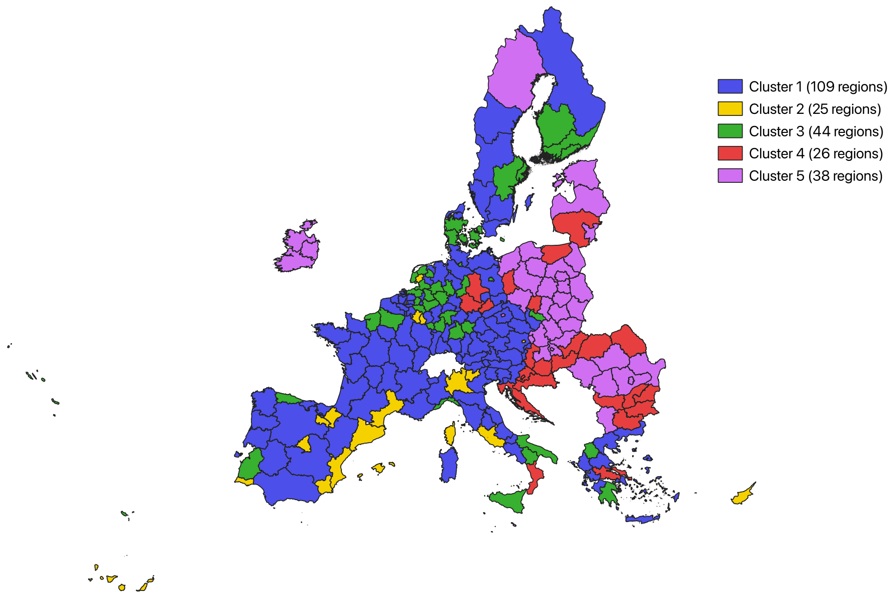


Figure 1: EU NUTS-2 in Clusters - Distinctive Decarbonization Pathway 1995-2023. Source: Authors Estimation as described in the text.

Meanwhile, Cluster 4 includes regions primarily in Southeastern Europe that exhibit economic catch-up but demographic decline, with emissions stagnating due to modest reductions in carbon intensity. Finally, Cluster 5 represents a promising category of rapidly modernizing regions in Central and Eastern Europe. These areas — including parts of Poland, Romania, and the Baltic States — have managed both strong GDP growth (3.7% annually) and significant reductions in carbon intensity (–4.6% annually), achieving net emissions declines (–1.17% annually) despite economic expansion.

The evidence underscores that decarbonization in the EU is not a one-size-fits-all endeavor. Technological advancements and economic modernization have enabled substantial emissions reductions in some regions, while others remain constrained by demographic pressures or structural inertia (Figure 2). The clustering analysis highlights the need for tailored regional strategies that account for specific development contexts and transition capacities (Hermwille et al., 2025). Regions with rising emissions or stagnating progress require targeted policy interventions — such as infrastructure investment, reskilling programs, and support for industrial transformation — to avoid carbon lock-in.

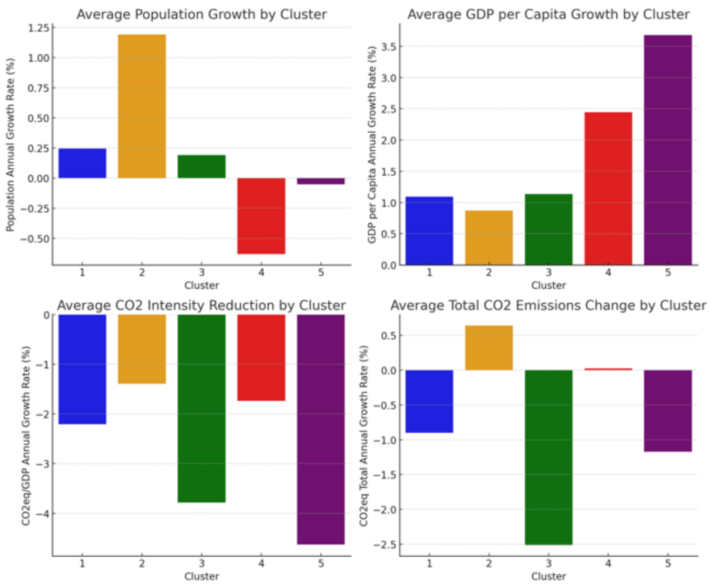


Figure 2: Average Annual Growth Rates (1995–2023) by Cluster. Population, Affluence (GDP per capita), Carbon Intensity ($CO_2$/GDP), and total $CO_2$ emissions growth rates are shown. Source: Authors Estimation as described in the text.

# 3. Coupling CGE and GIS: Case Study of GEMINI-E3 EU and NUTS-2 Regions

## *3.1. CGE Models with Sub-national Resolution: An Overview*

The CGE model is widely employed to assess an economy's response to policy shifts, technological innovation, or other exogenous shocks. Analyses are generally conducted at the national level, reflecting the high-level aggregation of available regional input–output tables (Garcia-Rodriges et al., 2023). Among the few models offering sub-national resolution is RHOMOLO (Christensen, 2022), which has been used to evaluate EU R&D and innovation initiatives as well as the European Cohesion Policy (Barbero et al., 2022). Although RHOMOLO permits NUTS-2-level assessment, its sectoral scope remains limited. The sub-national CGE model for the European Mediterranean countries (Bosello and Standardi, 2018)—itself grounded in the ICES framework (Campagnolo and Davide, 2019) and applied to regional climate-impact studies (Rizzati et al., 2022)—provides greater sectoral detail but covers only a small cohort of EU Member States.

While several regional CGE studies focus on individual countries (e.g. Figus et al. (2018) for Scotland; Rutherford and Törmä (2010) for Finland), our methodology couples a global CGE model of GEMINI-E3 with a dedicated regional information system of NUTS-2, focusing at the EU level. Similar integrative approaches include Joshi et al. (2016) analysis of the economic costs of sea-level rise, Karttunen et al. (2018) assessment of Finnish forest potential, and McDowall et al. (2023) mapping of regional employment vulnerabilities in Europe's energy transition. This coupling strategy effectively overcomes the scarcity of disaggregated regional input–output data.

## *3.2. The GEMINI-E3 model*

GEMINI-E3 is a recursive-dynamic, multi-country, multi-sector general equilibrium model featuring adaptive, backward-looking expectations and full flexibility in macro- and microeconomic markets. Our analysis employs the latest Horizon Europe DIAMOND[3] iteration of GEMINI-E3 EU —adapted per Bernard and Vielle (2008)—anchored on the GTAP-Power v11 database with year 2017 as the baseline (Aguiar et al., 2022).

[3]see `https://climate-diamond.eu/` for a description of the project.

Production demand across sectors aggregates household and government consumption, exports, investment, and intermediate inputs, with final demand allocated between domestic output and imports via the Armington assumption (Armington, 1969). Technologies are captured through nested Constant Elasticity of Substitution (CES) functions, while households make interdependent labor-supply, saving, and consumption decisions—savings and labor supply exogenous, consumption derived from a nested CES utility. Exports emerge endogenously as other regions' imports; sectoral investment derives from anticipated capital demand via CES functions and adaptive expectations. Government balance equals tax and social-contribution revenues minus public consumption and household transfers. Emissions of $CO_2$ and non-$CO_2$ GHGs are mapped to sectors using country policy databases.

The model is designed to analyze climate change mitigation pathways and their socio-economic implications. The model features a detailed geographical coverage that includes the European Union, the United Kingdom, the United States, China, India, and other major global regions. Table 1 gives the countries/regions represented in GEMINI-E3.

Table 1: Geographical coverage of the GEMINI-E3 model

| European Union countries/regions | Non-EU countries/regions |
|---|---|
| Germany (DEU) | United Kingdom (GBR) |
| France (FRA) | United States of America (USA) |
| Italy (ITA) | China (CHI) |
| Spain (SPN) | India (IND) |
| Netherlands (NLD) | Russia (RUS) |
| Sweden (SWE) | Central South and America (CSA) |
| Poland (POL) | Middle East (MID) |
| Belgium (BEL) | Africa (AFR) |
| Croatia, Cyprus, Greece, Portugal, Malta (EU1) | Rest of Asia (ASI) |
| Austria, Luxembourg (EU2) | Rest of the Word (ROW) |
| Czech Rep., Hungary, Slovak Republic (EU3) | |
| Bulgaria, Romania, Slovenia (EU4) | |
| Estonia, Latvia, Lithuania (EU5) | |
| Denmark, Finland, Ireland (EU6) | |

Likewise, model's sectoral architecture captures the complex linkages between economic activity and environmental impacts by distinguishing thirteen primary sectors, each further disaggregated into sub-sectors for greater analytical precision. The energy module comprises coal, crude oil, natural gas, hydrogen and petroleum products, alongside electricity generation—represented by nine generation technologies (coal, oil, natural gas, hydro, nuclear, wind, solar PV, biomass and other plants)—to reflect the full spectrum of fuel sources and power-production methods. The agricultural sector spans the entire gamut of crop and livestock production, enabling detailed evaluation of greenhouse-gas emissions and land-use changes attributable to farming practices. Manufacturing is bifurcated into energy-intensive industries and other industrial activities, facilitating focused analysis of process emissions and the impacts of decarbonization measures on industrial output. Transport is resolved into land, maritime and air segments, thereby permitting nuanced assessment of modal emissions and policy effects across different transport modes. Finally, the services sector captures all non-industrial, non-agricultural activities, ensuring that shifts in tertiary-sector demand and associated environmental outcomes are fully represented.

### *3.3. Regional Module: EDGAR and Additional Database*

The primary regional dataset employed in this study is the 2024 version of the Emissions Database for Global Atmospheric Research (EDGAR), developed jointly by the European Commission's Joint Research Centre (JRC) and the International Energy Agency (IEA). The dataset provides annual estimates of anthropogenic emissions of $CO_2$, $CH_4$, $N_2O$, and fluorinated gases (F-Gases) for the period 1990–2023. Emissions are spatially disaggregated at the NUTS-2 level for European regions using the methodology outlined in Crippa et al. (2024). This study focuses exclusively on the EU-27 Member States.

The dataset covers twelve main anthropogenic emission categories (IEA et al., 2024), of which the following six were selected for analysis: Energy (power generation), Industry (manufacturing and processing, e.g., oil refineries, chemical production), Buildings (residential and commercial energy use), Transport (road, rail, pipeline, off-road), Agriculture (including livestock and crop-related emissions), and Waste (landfills, incineration, wastewater). Emissions from large-scale biomass burning and land use, land-use change, and forestry (LULUCF) are excluded.

The regional data for power plant inventory was primarily based on data from Beyond Fossil Fuels dataset (Beyond Fossil Fuels, 2025), for coal and gas power plants. This dataset, provides detailed information on plant name, geolocation, installed capacity, and operational status for coal- and gas-fired power plants across Europe. As the $CO_2$ emissions were available only for coal-fired plants, emissions were estimated using installed capacity for gas-fired plants. It covers facilities with a net capacity exceeding 15 MW, including those within industrial sites, and exclude plants of lower capacity or those used solely for non-electricity purposes. The inventory was further supplemented with additional sources to capture missing plants. In specific cases, such as Cyprus, oil-fired power plants were also included to account for country-specific emissions.

Additionally, regional data on heat production, obtained from the International Energy Agency (IEA), were incorporated to ensure a comprehensive assessment of emissions from the power and heat generation sectors. Analogous to the approach used for the electricity generation sector, an inventory of oil refineries was compiled to incorporate emissions from these facilities into the overall assessment. As the available sources reported only production capacity, without direct GHG emission data, emissions were estimated using capacity-based emission factors, following the same methodology applied to natural gas power plants.

### *3.4. Coupling GEMINI-E3 and the regional module*

Dimensions of the regional module are given in Figure 3. There are nine economic sectors, mostly derived from the EDGAR database, from agriculture, electricity generation, industry, building, to waste. Four GHG emissions are represented as $CO_2$, $CH_4$, $N_2O$ and F-Gases. The EU regions are modeled, corresponding to the 242 NUTS-2 classification. The time period covers the year 2022 to 2050.

The coupling procedure is illustrated by Figure 4, while each emission of our regional module is linked to a GEMINI-E3 driver using equation 1:

$$E^r_{i,t} = \alpha^r_i \cdot X^c_{i,t} \quad \text{where } r \in c \tag{1}$$

Variable $E^r_{i,t}$ represents the GHG emissions from region $r$, sector $i$ and year $t$, while the emissions driver ($X^c_{i,t}$) is derived from GEMINI-E3 for country $c$ to which region $r$ belongs. The coefficient $\alpha^r_i$ is calibrated in Step 1, and regionalization of GHG emissions (under certain scenario - Step 2) is estimated in Step 3. The emission drivers are listed in Table 2.

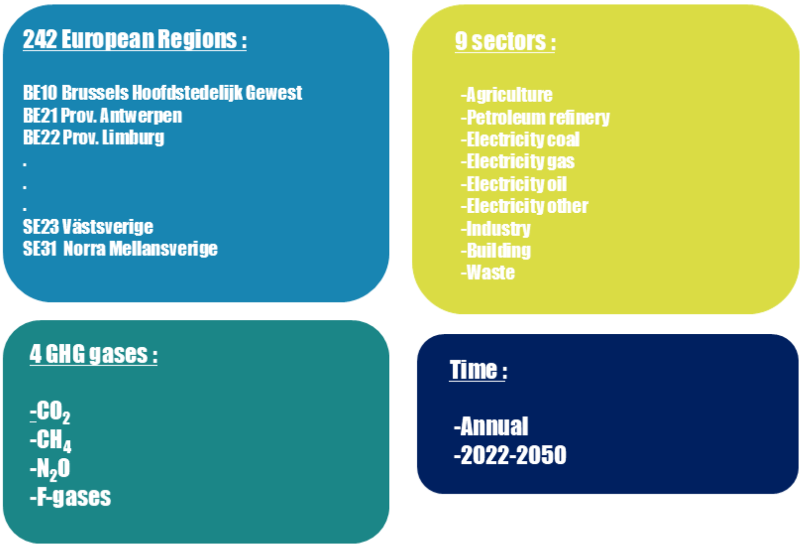


Figure 3: Dimensions of the regional module

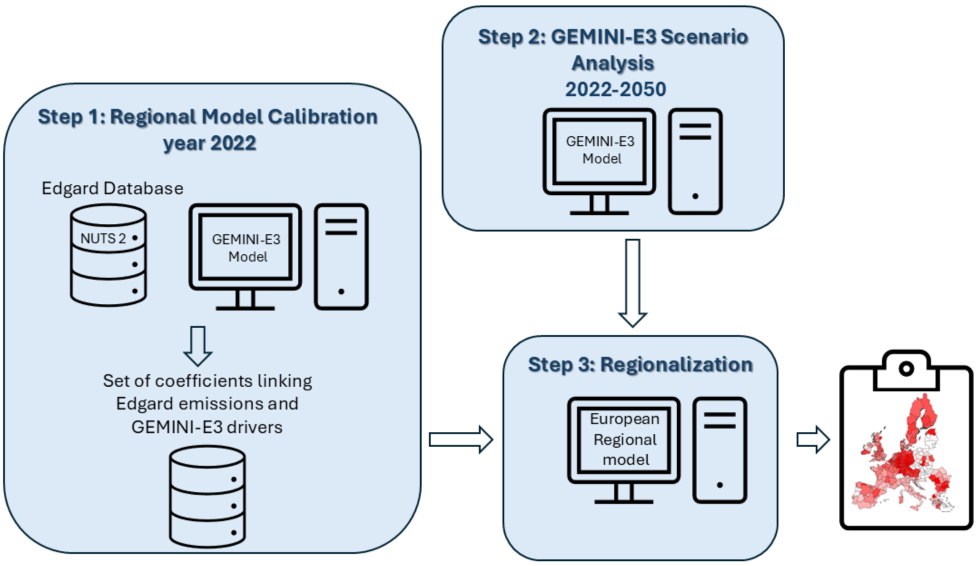


Figure 4: Coupling procedure between GEMINI-E3 and the regional module

Table 2: GEMINI-E3 drivers of regional emissions

| Sector modelled | Gas | GEMINI-E3 driver |
|---|---|---|
| Agriculture | $CO_2$ | $CO_2$ emissions from agriculture |
| Agriculture | $CH_4$ | $CH_4$ emissions from agriculture |
| Agriculture | $N_2O$ | $N_2O$ emissions from agriculture |
| Electricity from coal | $CO_2$ | $CO_2$ emissions from coal power plant |
| Electricity from others | $CO_2$ | $CO_2$ emissions from others power plant |
| Electricity from oil | $CO_2$ | $CO_2$ emissions from oil power plant |
| Electricity from gas | $CO_2$ | $CO_2$ emissions from gas power plant |
| Refinery | $CO_2$ | $CO_2$ emissions from petroleum products sector |
| Energy | $CH_4$ | $CH_4$ emissions from fuel production and transformation and from oil and gas fugitive |
| Energy | $N_2O$ | $N_2O$ emissions from fuel combustion activities |
| Industry | $CO_2$ | $CO_2$ emissions from energy-intensive industries and other manufacturing industries |
| Industry | $CH_4$ | $CH_4$ emissions from industrial combustion |
| Industry | $N_2O$ | $N_2O$ emissions from industrial processes and product use |
| Industry | F-Gas | F-Gas emissions from f-gases |
| Transport | $CO_2$ | $CO_2$ emissions from land transport and households for transportation purposes |
| Transport | $CH_4$ | $CH_4$ emissions from transport |
| Transport | $N_2O$ | $N_2O$ emissions from fuel combustion activities |
| Building | $CO_2$ | $CO_2$ emissions from services and household heating |
| Building | $CH_4$ | $CH_4$ emissions from residential and commercial |
| Building | $N_2O$ | $N_2O$ emissions from fuel combustion activities |
| Waste | $CO_2$ | $CO_2$ emissions from services |
| Waste | $CH_4$ | $CH_4$ emissions from waste |
| Waste | $N_2O$ | $N_2O$ emissions from waste |

## 4. Post-Coupling Illustrative Example: The EU Fit for 55 package and NUTS-2 Mapping

### *4.1. A current policies scenario*

In a CGE model, the baseline scenario also referred to as the reference, business-as-usual, or current policies scenario—projects the economy's trajectory under existing policies, absent major shocks or new interventions. It serves as the counterfactual against which policy scenarios (e.g., carbon taxation or trade reforms) are assessed, enabling the isolation of policy impacts through comparison with expected trends. These terms are used interchangeably in this paper.

The baseline integrates assumptions on key drivers such as population growth, technological change, productivity, and energy prices, aligned with external sources. For this analysis, GDP projections for EU countries follow the 2024 Ageing Report (European Commission, 2024), while projections for the rest of the world and international energy prices follow the Stated Policies Scenario of the World Energy Outlook 2024 (WEO 2024) (International Energy Agency, 2024).

This scenario builds on Paris-Reinforce project's current policies scenario, incorporating climate and energy measures adopted globally. Details on methodology and implications for GHG emissions and temperature outcomes are provided in Giarola et al. (2021) and Sognnaes et al. (2021). For the EU, the scenario reflects *pre-Fit for 55* (Before Fit for 55) policies, including a 40% GHG reduction target by 2030 (relative to 2005), a 43% ETS sector reduction target, and the Effort Sharing Regulation (ESR). National ESR targets are modeled via a domestic GHG tax on non-ETS emissions (see Table 3).

The ETS price is 65 US$ in 2030 (see Table 4), showing that the 40% reduction in ETS emissions could be achieved at a moderate cost.[4] With regard to ESR prices, our simulation shows a wide range of GHG prices, from 0 to 273 US$. The old Member States generally have high ESR prices, with the notable exceptions of Italy and Spain. The averaged ESR price (weighted by country ESR emissions in 2040) is equal to 101 US$.

We now compute the resulting GHG emissions at regional level. Between 2022 and 2030, all NUTS-2 regions included in the analysis exhibit a decline in total greenhouse gas (GHG) emissions, as illustrated in Figure 5.

[4]For comparison, study by Pahle et al. (2025) report 55 € of ETS price in such scenario.

Table 3: European GHG targets before and after the Fit for 55 package - Emissions reductions with respect to 2005 level in percentage

| | Before | After |
|---|---|---|
| EU target* | -40% | -55% |
| EU ETS | -40% | -62% |
| ESR targets | | |
| Germany | -38% | -50% |
| France | -37% | -48% |
| Italy | -33% | -44% |
| Spain | -26% | -38% |
| Netherlands | -36% | -48% |
| Sweden | -40% | -50% |
| Poland | -7% | -18% |
| Belgium | -35% | -47% |
| EU1 | -30% | -39% |
| EU2 | -37% | -48% |
| EU3 | -11% | -23% |
| EU4 | -4% | -16% |
| EU5 | -9% | -20% |
| EU6 | -35% | -47% |
| EU27 | -30% | -41% |

* with respect to 1990 levels

The spatial distribution of reductions reveals a clear north–south gradient, with the most substantial decreases concentrated in Central and Northern Europe. Among the standout cases is Germany, where emission reductions range between approximately –30% and –35% across both coastal (e.g., Lüneburg – DE93, Schleswig-Holstein – DEF0) and inland regions (e.g., Trier – DEB2, Oberfranken – DE24). The sole exception within Germany is Braunschweig (DE91), which records a comparatively lower reduction of –21.6%.

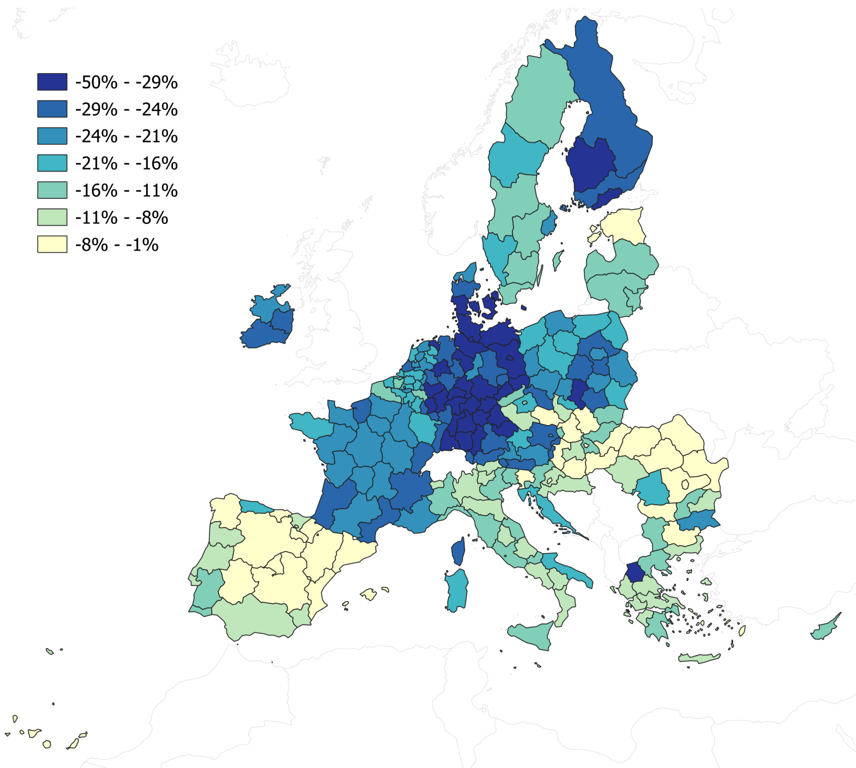


Figure 5: Change in total GHG emissions between 2022 and 2030 for EU-27 NUTS-2 regions - Current policies scenarios. Source: The authors' estimation, as detailed in the main text.

Comparable patterns are observed in neighboring Central European countries. In Austria (e.g., Niederösterreich – AT12), France (e.g., Rhône-Alpes – FRK2, Aquitaine – FRI1), and the Netherlands (e.g., Groningen –

NL11, Zuid-Holland – NL33), GHG emissions are projected to decrease by approximately –25%, consistent with the German trend, albeit at slightly lower magnitudes. Further northeast, regions in Poland (e.g., Śląskie – PL22), Denmark (e.g., Syddanmark – DK03), and Finland (e.g., Länsi-Suomi – FI19) also show marked reductions, with some regions matching the upper-bound reduction levels found in Germany.

Notably, the most pronounced reduction occurs in Western Macedonia (EL53) in Greece, where emissions are projected to fall by –49.6%, likely reflecting structural transformations in the regional energy system, including the phasing out of lignite-based power generation.

Conversely, regions across Southern and South-Eastern Europe show more moderate declines. In Italy (e.g., Lombardia – ITC4, Lazio – ITI4), Greece (e.g., Peloponnisos – EL65, Central Macedonia – EL52), and the Balkans (e.g., Panonska Hrvatska – HR02), as well as Portugal, reduction rates generally fall within the –10% to –15% range. Some of the lowest decreases are recorded in Spanish regions (e.g., Castilla-La Mancha – ES42) and in the mid-Danube corridor (e.g., Romania – RO11, RO22; Hungary – HU33), indicating a more gradual pace of decarbonization relative to their northern counterparts.

### *4.2. The fit for 55 scenario*

Our fit for 55 scenario incorporates a major change from previous climate regulations in the form of a new ETS market, the EU ETS-2. The European Union Emissions Trading System-2 (EU ETS-2) is a new carbon pricing mechanism designed to cover emissions from buildings and road transport sectors, complementing the existing EU ETS (European Commission, 2021). Set to become fully operational in 2027, the EU ETS-2 will operate on a 'cap-and-trade' principle, targeting upstream emissions. It aims to reduce emissions in these sectors by 42% by 2030 compared to 2005 levels, by full auction of allowances. To ensure price stability, a mechanism has been incorporated to release additional allowances if prices exceed 45 euro per ton of $CO_2$ during the first three years of operation (Edenhofer et al., 2021; Eden et al., 2023; Günther et al., 2025).

The EU ETS-2 will operate alongside ESR, which assigns binding national emission reduction targets for sectors not covered by the original EU ETS. While ETS-2 introduces a market-based mechanism to support emission reductions, it does not replace the ESR. Member States remain accountable for meeting their national targets and may need to implement additional policies to ensure compliance. The two frameworks are designed to be complementary, with the ETS-2 facilitating cost-effective reductions that contribute to national ESR obligations (Nysten, 2024).

However, the conditional relationship between ETS-2 and the ESR introduces ambiguity regarding how the two mechanisms should be reconciled, particularly with respect to trading provisions. While ETS-2 is grounded in a carbon market framework, the ESR primarily relies on national policies and non-market instruments, such as energy efficiency standards and transport sector reforms. Although the ESR allows limited flexibility through the transfer of Annual Emission Allocations (AEAs) between Member States (European Commission, 2018), this mechanism is not equivalent to a full carbon market and operates through bilateral agreements rather than open trading (Braathen, 2019). This divergence creates uncertainty about the coherence of the EU's climate governance, suggesting the possibility of two divergent trajectories within the Fit for 55 package: one centered on integrated carbon pricing, and another dominated by decentralized, state-led policy action.

This ambiguity gives rise to two plausible implementation scenarios under the Fit for 55 framework. The first, referred to as the *"Without ESR Trade"* scenario, assumes that the ETS-2 target—a 41% reduction in emissions relative to 2005 levels—is applied uniformly across the EU without regard to the differentiated burden-sharing obligations outlined in the ESR. In this case, emissions reductions are achieved solely through the market mechanism, with no explicit consideration of national targets or distributional fairness among Member States. The second scenario, titled *"With ESR Trade"*, presumes that trading is implemented at the country level, with national emission quotas derived from ESR targets (as detailed in Table 3). Under this approach, the ETS-2 system would be reconciled with the ESR by aligning allowance allocations with Member States' differentiated reduction obligations, thereby preserving the burden-sharing logic while introducing a constrained trading framework. These two scenarios reflect fundamentally different approaches to balancing efficiency and equity in the EU's climate governance, and highlight the institutional uncertainty surrounding the integration of ETS-2 and the ESR.

For the purpose of analyzing these illustrative scenarios, we assume that the ETS-2 is implemented in 2025, two years earlier than planned—to align with the temporal resolution of the model. While the ETS-2 is intended to gradually replace certain policy instruments currently used by Member States to meet their ESR targets, particularly for $CO_2$ emissions in the buildings and transport sectors, the ESR framework will continue to govern non-$CO_2$ emissions (such as methane from agriculture) and other residual sources not fully encompassed by the ETS-2. To streamline the analysis, we adopt the simplifying assumption that ETS-2 applies uniformly to both $CO_2$ and non-$CO_2$ emissions within the sectors covered by the new system. This allows for a more consistent comparison between the two scenarios and isolates the implications of trading design and burden-sharing mechanisms on overall emission outcomes.

Table 4 presents the carbon prices estimated by the model for both ETS and ETS-2 systems. By 2030, the ETS price reaches 151 US$ per ton, while the ETS-2 price is notably higher at 244 US$. The ETS price estimated here is slightly below the OECD projection of 177.8 €$_{2020}$ (2020 prices) generated using the ENV-Linkage model (Chateau et al., 2023), but aligns closely with BloombergNEF's forecast, which anticipates an average carbon price of approximately 150 €$_{2020}$ per ton by 2030.[5]. Whereas Pahle et al. (2025) predict an ETS price equal to 180 €. In terms of macroeconomic impact, the GDP cost estimated by the OECD at the EU level is 1%, which exceeds the 0.55% loss calculated by the GEMINI-E3 model used in this study.

When incorporating the scenario with ESR trading among European countries, the impact on ETS prices in both markets remains marginal. The ETS price increases slightly to 152 US$, while the ETS-2 price rises modestly to 246 US$, only a 3 US$ difference compared to the scenario without ESR trading. These minimal changes likely result from the absence of energy efficiency assumptions in our scenario design, which isolates the effects of ESR trading alone, and from the application of more granular, country-specific ESR targets. This outcome contrasts with the findings of Günther et al. (2025), who reports a wider range of projected ETS-2 prices—between 71 and 261 €$_{2022}$ per ton in 2030—depending on the level of energy efficiency improvements. Our results are most consistent with their weak energy efficiency scenario, in which only 30% of ESR targets are assumed to be met across the EU.

The welfare implications of the Fit for 55 package are presented in Table 5, expressed as the percentage change in household consumption. At the aggregate EU level, the welfare cost of additional GHG abatement remains relatively modest, amounting to 0.5%. The implementation of the

[5]https://about.bnef.com/blog/2h-2024-eu-ets-market-outlook-on-tenterhooks-over-supply/

Table 4: GHG prices before and after the Fit for 55 package - year 2030 in US$$_{2017}$ per ton $CO_2$-eq

| | Before | After Fit for 55<br>Without ESR trade | <br>With ESR trade |
|---|---|---|---|
| EU ETS price | 65 | 151 | 152 |
| EU ETS-2 price | na | 244 | 247 |
| ESR prices | | | |
| Germany | 273 | | |
| France | 123 | | |
| Italy | 9 | | |
| Spain | 9 | | |
| Netherlands | 95 | | |
| Sweden | 30 | | |
| Poland | 94 | | |
| Belgium | 57 | | |
| EU1 | 26 | | |
| EU2 | 155 | | |
| EU3 | 0 | | |
| EU4 | 8 | | |
| EU5 | 33 | | |
| EU6 | 320 | | |
| Averaged ESR prices | 101 | 244 | 247 |

ESR does not significantly alter overall EU welfare, as it primarily involves financial transfers among Member States, which balance out at the Union level. However, the national-level distributional impacts are more substantial. In the scenario without ESR trading, welfare effects range from -0.4% to +1.8%, with Eastern European countries—particularly Poland and the EU4 group (Bulgaria, Romania, and Slovenia)—facing the highest welfare losses. In contrast, wealthier Member States such as Germany, France, and the Netherlands experience relatively minor impacts, situated at the lower end of the cost spectrum.

Table 5: Welfare change in % of household consumption in 2030 - Fit for 55 scenario

| | Without ESR Trade | With ESR Trade |
|---|---|---|
| Germany | -0.5% | -1.6% |
| France | -0.4% | -1.0% |
| Italy | -0.7% | -0.2% |
| Spain | -0.1% | 0.6% |
| Netherlands | -0.1% | -0.7% |
| Sweden | -0.3% | -0.3% |
| Poland | -1.8% | 0.5% |
| Belgium | -0.4% | -0.9% |
| EU1 | -0.1% | 0.8% |
| EU2 | -0.5% | -1.1% |
| EU3 | -0.6% | 3.8% |
| EU4 | -0.8% | 2.2% |
| EU5 | 0.4% | 2.6% |
| EU6 | -0.3% | -1.8% |
| EU27 | -0.5% | -0.5% |

Introducing a trading system based on ESR targets calibrated to GDP per capita fundamentally shifts the distribution of welfare effects (Vielle, 2020). Under this scenario, the welfare cost range widens considerably, from -1.8% to +3.8%, reflecting a redistribution of the economic burden across Member States. Several Central and Eastern European countries—notably the EU3 (Czech Republic, Hungary, Slovak Republic), EU4, and EU5 (Estonia, Latvia, Lithuania)—realize welfare gains through the trading mechanism. Conversely, the welfare burden increases for wealthier countries such as Germany, France, and the EU6 group (Denmark, Finland, and Ireland), which assume a greater share of the adjustment costs. This highlights the equity-efficiency trade-offs embedded in the design of burden-sharing mechanisms within the Fit for 55 framework.

Figure 6 illustrates the volume and distribution of ESR allowance trading across Member States in 2030. A total of 117 Mt $CO_2$-eq are exchanged, corresponding to approximately 6.7% of the total ESR allowances, with a financial value estimated at 29 billion US$. The majority of purchases are concentrated among a few high-income Member States—Germany (61 Mt), France (21 Mt), and the EU6 group (20 Mt)—which together account for 86% of total demand. On the supply side, the main sellers are the EU3 (29 Mt), Poland (22 Mt), and the EU4 group (18 Mt), collectively responsible for 60% of the allowances supplied to the market. When measured relative to national ESR allocations, the most significant trading activity occurs in the EU3 group, where traded allowances represent 24% of their total ESR cap.

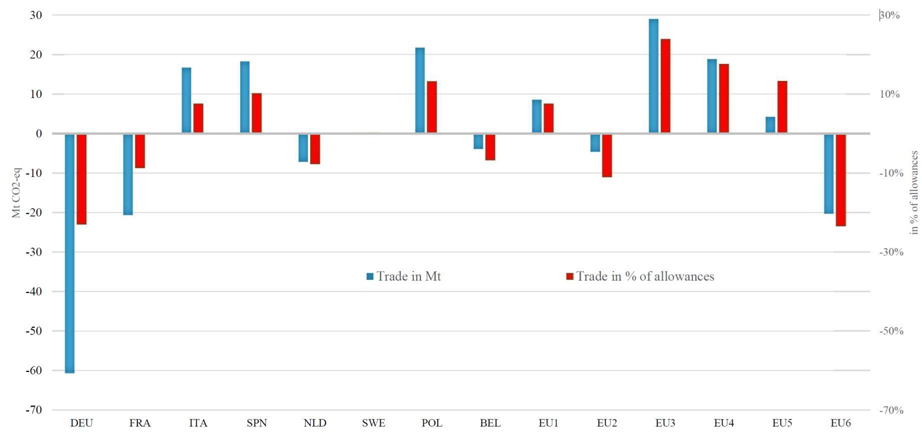


Figure 6: Trade in ESR allowances in Mt $CO_2$-eq and in % of allowances - Year 2030 - (positive number means selling, negative one buying)

On the other hand, there are insignificant differences for GHG emissions for both ETS-2 trading scenarios. Relative to the baseline, all NUTS-2 regions considered,[6] show a further decline in total GHG emissions, with an average reduction of -20.3% The spatial distribution illustrated in Figure 7 shows a clear trend among European macro-regions: Eastern Europe together with the southern European countries show the most pronounced decreases, while the smallest values are visible in the Nordic and Western countries.

[6] with an exception for Zeeland (DK02, +0.7%)

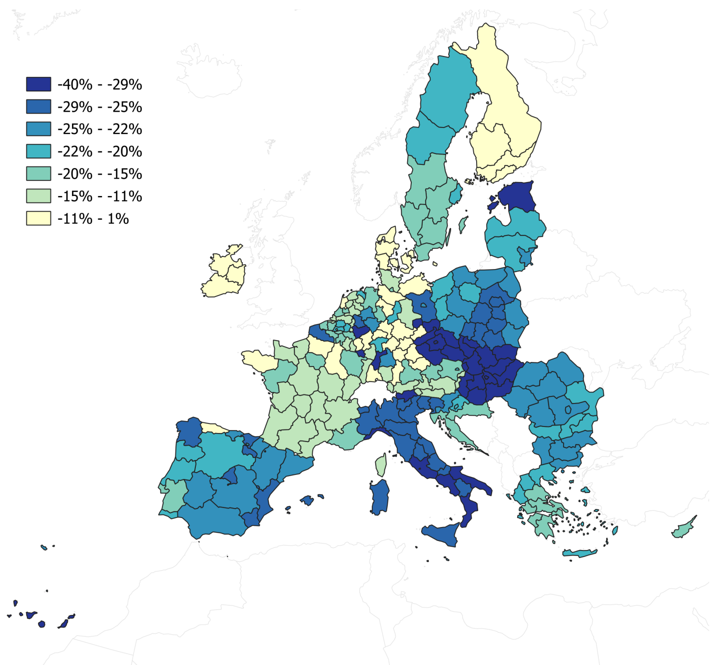


Figure 7: Difference in total GHG emissions between the "Fit for 55" (ETS-2 Trading Scenario) and the Baseline for 2030 for EU-27 NUTS-2 regions. Source: The authors' estimation, as detailed in the main text.

In Hungary, the Czech Republic and Slovakia, regions such as Közép-Magyarország (HU11, -39.9%), Praha (CZ01, -38.0%) and Stredné Slovensko (SK03, -34.2%) show the most pronounced cuts. In Poland, Bulgaria and Romania, the rates are on average lower around -25% (e.g. -26.2% in Mazowiecki regionalny PL92, -25.0% in Sud-Vest Oltenia RO41, -24.2% in Yugoiztochen BG34). On the Italian peninsula, Lazio (-34.2%, ITI4) and Campania (-30.7%, ITF3) are among the regions with the highest reduction rates. In Spain, the average reduction is close to -25%, with peaks exceeding -31% in the Canary Islands (ES70); Portugal, Croatia and Greece follow a similar trend, although stopping around -20% on average.

For Western Europe, the Fit for 55 scenario leads to additional reductions that are more moderate than for southern and eastern Europe. In Germany, the average values are around -16.5%, but show great heterogeneity within national borders: from peaks of more than -30% in the regions of North Rhine Westphalia (e.g. Köln DEA2) to smaller decreases below -10%

in more central regions (e.g. Thüringen DEG0). In Belgium, the average decrease is slightly above -18%, with provinces such as Antwerpen (BE 21) exceeding -20%. Austria, France and the Netherlands show more homogeneous behaviour between regions with even more moderate averages of -15.4%, -14.7%, -14.2% respectively (e.g. -16.9% for Niederösterreich AT12, -13.4% for Rhône-Alpes FRK2, -15.6% for Zuid-Holland NL33).

Finally, with the exception of the Swedish regions, which follow a trend similar to Central European countries (e.g. -18.2% for Västsverige SE23), in the rest of the Nordic countries and in Ireland, the effect of the F55 scenario shows much more limited results: Southern and Eastern Ireland (IE05, IE06) fall back on average by -2.6%, in Denmark the average is -2.2% with even one region showing a slight increase (+0.7% in Zeeland DK02), while in Finland values remain around -5%. Therefore, Western and Nordic Europe confirm a less pronounced additional impact, ideally closing the picture that sees the most pronounced cuts concentrated in Southern and Eastern Europe.

## 5. Conclusion

This study introduces a novel methodology that couples a Computable General Equilibrium model with spatially disaggregated data to regionalize GHG emissions at the NUTS-2 level across the European Union. By enhancing the spatial granularity of emissions modeling, we provide a robust framework for assessing both the effectiveness and the equity of climate policy interventions. The approach is applied to evaluate the implications of the EU's Fit for 55 package, offering insights into how its dual emissions trading systems—ETS and the newly established ETS-2—reshape regional decarbonization trajectories.

Our findings confirm that the Fit for 55 package leads to a substantial strengthening of GHG abatement within the original EU ETS. The estimated ETS carbon price of approximately 150 US$ per ton by 2030 reflects decades-long structural decarbonization, particularly within the power sector, and suggests that these reductions are achievable at a moderate macroeconomic cost. The relatively low welfare loss and regionally homogenous reductions in ETS emissions underscore the maturity of this market mechanism.

In contrast, the introduction of the ETS-2 for buildings and transport represents a pivotal shift in EU climate policy. With modeled prices nearing 252 US$ per ton, ETS-2 imposes a significantly higher marginal abatement cost than ETS, reflecting the limited historical decarbonization in these sectors. This raises complex questions regarding the interaction between ETS-2 and the ESR, particularly concerning overlapping governance structures, trading design, and national compliance obligations. The analysis reveals notable distributional effects, with potential welfare gains in several Eastern European regions under ESR trading, juxtaposed against increased burdens in wealthier Member States. Such disparities highlight the urgent need for further research into the redistributive consequences of carbon pricing on countries, regions, and households.

Overall, our integrated CGE–GIS framework provides a scalable and policy-relevant tool for assessing climate policy impacts with sub-national precision. It enables a more differentiated understanding of the spatial dynamics of decarbonization, and offers a pathway to design climate strategies that are both environmentally effective and socially just.

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