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The Uneven Geography of Carbon Emissions in European Value Chains: A Subnational Analysis of carbon elites-ghettos

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The Uneven Geography of Carbon Emissions in European Value Chains: A Subnational Analysis of carbon elites-ghettos

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Abstract: This paper brings new compelling regional-level evidence on the environmental degradation brought about by intra-European value chains. The paper postulates the presence of pollution havens derived as a consequence of the European production integration. We identify a neat elites-ghettos divide in carbon emission intensity per unit of production across EU regions: while capital-city and Northern regions form a carbon elites club, of contained emissions, Eastern regions converge towards systematically higher intensities. We build the intra-EU emission network, looking at the CO_2 embodied in its backwards linkages to account for the extent to which the divide derives from GVC participation. The flow analysis reveals a steady decline in domestic multipliers, but persistently higher carbon intensity in foreign intermediates, with the Eastern regions dominating the most polluting linkages. The elites-ghettos regions are characterised by opposite emission paths: while the first export CO_2 via the outsourcing of the most-polluting production activities toward the East, the latter import CO_2 via the production of high-emission intermediaries for the West. In fact, convergence clubs display distinct specialisation profiles, with mid-stream manufacturing regions structurally locked into higher emission intensity. Overall, the paper highlights a discarded dimension of GVCs, that is, the environmental lock-in paths for regions embedded into GVCs to serve as pollution havens for the European carbon elite.

Keywords: CO_2 emissions; Global Value Chains; Club convergence; Regional specialisation; Carbon leakage.

JEL Codes: F64; L16; Q56; R11; C23.

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Introduction

The transformation of global production flows via Global Value Chains (GVCs) over recent decades has deeply rearticulated the geography of economic activity at the national and regional levels. New geographies have emerged around the world, and within Europe too. The growing fragmentation of value chains has generated, in fact, new opportunities for regional development and shown progressive gains, particularly for upgrading areas, as in Eastern Europe (Cresti et al., 2023).

Less attention has been devoted to the environmental burden of intra-European production integration, the latter particularly deep after the entry of the Visegrad group. In fact, while the EU region as a whole, when compared to international patterns, has progressively reduced the global share of global greenhouse gas emissions, the relocation of production tasks across regions within the EU has rendered the trajectory of decarbonisation by far more complex. GVC participation might act as a convergence mechanism in carbon efficiency toward lower emission paths, by spreading, via imitation and adoption, better, less-polluting techniques of production. On the contrary, it might entrench new divides in emissions, allowing for strategically locating high-polluting productions beyond domestic borders. Understanding whether new environmental divides are emerging in Europe because of GVC integration is a central question for both economic geography and environmental policy. In fact, this paper postulates the existence of intra-European pollution havens that have been brought about exactly by the process of internal European production integration.

Originally developed for the analysis of international North-South divides, the Pollution Haven Hypothesis (Cole, 2004) posit that polluting activities tend to be relocated by advanced economies to jurisdictions located in the global South with weaker technological or institutional capacity. The PHH well aligns with the stream of literature analysing GVC participation from the perspective of specialisation lock-in in low-value-added and high-emission activities (Capello and Dellisanti 2024; Dosi et al., 2025). The captive nature of GVCs integration for regions lacking the appropriate well-developed capabilities has been highlighted since the earlier studies on regional GVCs, showing how benefits are not automatic but depend on the institutional and organisational capacity of the region (Crescenzi and Rabellotti, 2015; Cainelli et al., 2023).

A powerful empirical design to detect the presence of pollution havens is the analysis of regional convergence, allowing for the identification of regional clubs. In fact, a large body of research has examined the evolution paths of CO_2 emissions across countries and regions, often through the lens of convergence analysis. Early contributions suggested that per capita emissions among industrial economies displayed signs of convergence (Strazicich and List, 2003). However, once emerging economies are taken into account, different clusters of convergence can be spotted (Aldy, 2006; Nguyen Van, 2005). Recent studies confirm that within the EU, divergence persists, often reflecting structural asymmetries between core and peripheral economies (Cialani and Mortazavi, 2021).

No conclusive evidence is, however present in the literature addressing the intra-EU PHH because of GVC integration. This paper intends to fill this gap, by addressing the following research questions: can we identify convergence clubs in carbon emission intensity in Europe?

Are there elites-ghettos types of dynamics emerging? To what extent are these clubs due to the patterns of intra-EU GVC integration? What is the role of regional sectoral specialisation? Overall, is there an environmental cost paid by emerging European countries to obtain economic gains from GVCs participation?

Employing regional-level NUTS-2 data, we combine convergence analysis with multi-regional input–output (MRIO) techniques. The Phillips and Sul (2007) methodology is first applied to identify convergence clubs across European regions. These clusters then serve as the basis for identifying the pollution havens within the EU CO_2 emission network. A neat carbon elites-ghettos divide emerges. We distinguish between domestic and foreign dynamics and employ CO2 multiplier analysis to capture how emissions propagate along value chains. While domestic multipliers display a steady decline over the period, reflecting improvements in carbon efficiency per unit of output, foreign multipliers remain broadly stable, indicating that part of the progress achieved domestically has been offset by persistent carbon intensity in imported linkages. To unpack the drivers of these heterogeneous dynamics, we implement a shift–share decomposition that separates the role of structural change, technological efficiency and specialisation. The results show that the decline in CO_2 multipliers is primarily driven by improvements in carbon efficiency per unit of output, but these gains are offset by the imported components, indicating a relocation of production toward ghettos that raises the carbon content of inputs, leaving total aggregate emissions stable. Finally, we look at sectoral specialisation profiles by clubs, showing that regions locked into mid-stream manufacturing structurally underpin these outcomes, as they capture less value while systematically converging towards higher emission intensities within the broader production geography of the EU. Overall, the paper highlights a discarded dimension of GVCs, that is the environmental lock-in paths for regions embedded into GVCs to serve as pollution havens for the European carbon elite.

The rest of the paper is structured as follows: Section 2 reviews the literature on emissions convergence, GVC integration, and the risk of pollution havens. Section 3 presents the data and methodological framework, including the convergence club analysis and input–output multipliers. Section 4 reports the empirical results on convergence dynamics across EU NUTS 2 regions. Section 5 presents some descriptive statistics on the EU emission network. Section 6 decomposes the changes in emission multipliers through a shift-share analysis. Section 7 proposes an investigation into the specialisation patterns across convergence clubs, while Section 8 concludes.

2. The Role of GVC Integration in EU Emission Patterns

2.1 Emission patterns and convergence in the EU

European regions exhibit markedly divergent trajectories in carbon emissions, a variation driven by the complex interplay of economic structures and technological capacities. Prior to the 2008 financial crisis, a trend of declining carbon intensity in many member states signalled a partial decoupling of economic growth from emissions. However, this progress slowed considerably in the following decade, with several economies exhibiting a renewed coupling of output and carbon, raising concerns about the sustainability of earlier achievements (Naqvi, 2021).

Geographical and sectoral differences underpin this asymmetry. Nations integrated into the EU single market from the post-Soviet bloc maintain high per capita fossil emissions, whereas countries such as Portugal, Malta, and Sweden report much lower levels. Sectoral analysis reinforces this pattern: emissions linked to manufacturing declined steadily, while broader industrial emissions rose until the 1990s before stabilising due to a restructuring of energy supply (Cialani and Mortazavi, 2021). Household carbon footprints are also uneven: Western and Northern regions generate higher mobility- and housing-related emissions, while Eastern and Southern regions remain more carbon-intensive due to their energy sources (Ivanova et al., 2017).

The dynamics of convergence and divergence make clear the difficulty of harmonising emission trajectories. While early research suggested convergence of per capita CO_2 among OECD countries (Strazicich and List, 2003), broader analyses found divergence once emerging economies were included (Aldy, 2006; Nguyen Van, 2005). The emergence of "club convergence" has highlighted that convergence occurs within sub-groups rather than globally, similarly to the findings on the pattern of economic growth (Panopoulou and Pantelidis, 2009). While subsequent works at the sub-national level found similar intra-clustering in China and in the United States across states, provinces and cities (Huang and Meng 2013; Wu et al. 2016; Wang, et al., 2014; Burnett, 2016; Apergis and Payne 2017). Looking at EU member states, Morales-Lage et al. (2019) identified weak convergence into clubs along a core–periphery axis, with Eastern states diverging vis-à-vis the core. Cialani and Mortazavi (2021) find similar clusters and show that convergence speeds differ by sector, pointing to the role of structural composition as a determinant of convergence. However, a regional analysis of convergence dynamics within EU is still missing.

These persistent divides highlight that convergence in emissions is determined by structural and technological conditions. Regions endowed with strong innovation systems and absorptive capacity are better positioned to implement clean technologies, while peripheral economies risk long-term lock-in to carbon-intensive paths (Eitan et al. 2023; Pietrobelli and Rabellotti, 2011). This places technology diffusion and productive specialisation at the centre of the convergence debate.

2.2 The Role of GVCs: Integration, Specialisation, and Leakage

The fragmentation of production over the past four decades has fundamentally transformed the environmental impacts of trade. GVCs have become the dominant mode of organising international commerce, offering new growth and specialisation opportunities but also embedding risks of lock-in into polluting and low-value segments.

If on the one hand GVC participation can foster technology diffusion and provide opportunities for capability building—particularly where domestic innovation systems are sufficiently developed to absorb external knowledge (Pietrobelli and Rabellotti, 2011; Crescenzi and Rabellotti, 2015)—the extent to which such gains are broadly distributed across the economy remains uncertain. A growing body of evidence shows that integration into GVCs is often driven primarily by cost-reducing strategies of lead firms rather than by considerations of long-term development (Taglioni and Winkler, 2016). This mode of GVCs integration creates the risk of wage compression and the entrenchment of regions in middle-income traps, particularly where participation is concentrated in low-value-added segments with limited potential for upgrading (Szymczak, 2022). The smile curve framework illustrates this vulnerability: while value and innovation accumulate at the upstream and downstream ends of the chain, mid-stream manufacturing yields lower returns and greater exposure to competitive pressures (Meng et al., 2021; Riccio et al., 2024). Capello and Dellisanti (2024) further show that, at the European regional level, such functional specialisation is not only associated with limited economic upgrading but also with higher environmental costs, as regions locked in routine production tasks capture less value and remain more exposed to carbon-intensive trajectories.

Indeed, territorial trajectories cannot be disentangled from cross-border processes. Evidence shows that an increasing share of emissions is displaced via trade, complicating assessments based only on domestic emissions (Peters, 2008). The EU Emissions Trading System (ETS) has reduced emissions in regulated sectors, but part of these gains has been offset by rising carbon content in imports—a phenomenon known as carbon leakage (Wang and Kuusi, 2024). For instance, Meng et al. (2018) demonstrate that global value chains reshape not only the geography of value generation but also of embodied emissions, with advanced economies externalising carbon-intensive stages of production. Dosi et al. (2025) extend this analysis, showing that GVC-mediated trade has amplified global CO_2 emissions by reallocating the dirtiest tasks to structurally weaker economies. This demonstrates that apparent territorial reductions may coincide with rising embodied emissions elsewhere, suggesting that EU convergence patterns cannot be understood without accounting for the cross-border displacement of emissions through imported inputs.

These findings are in line with evidence from Almazán-Gómez et al. (2023) and Bolea et al. (2022), who demonstrate that European regions' integration in GVCs is primarily determined by sectoral specialisation, with manufacturing hubs deeply embedded in international production networks while service-oriented regions remain less integrated. Thus, structural risks from a productive and social perspective are mirrored in environmental outcomes: the same specialisation patterns that constrain economic upgrading also correlate with higher carbon intensity. Participation in GVCs, therefore, represents a double-edged sword: it can be a channel of innovation and growth opportunities, but without adequate local capabilities and supportive institutions, it reinforces both developmental and environmental divergence.

2.3 Risk of regional pollution havens?

Patterns of convergence and divergence in emissions intensity, together with integration dynamics within the EU production network, help assess whether pollution havens are emerging within the single market. If integration and policy alignment were sufficient to equalise trajectories, regions would gradually converge in emission intensity. Instead, the persistence of divergence and the existence of distinct clubs (Morales-Lage et al., 2019; Cialani and Mortazavi, 2021) indicate that some regions have systematically higher emissions per capita. These regions often coincide with those specialising in the most polluting stages of production, in line with the PHH.

At the global level, the PHH has received extensive empirical attention. The core claim is that profit-seeking firms relocate emission-intensive activities to jurisdictions with lower regulatory standards, thereby externalising pollution. Several studies document that advanced industrial economies reduce their domestic environmental footprint while continuing to consume goods produced through carbon-intensive processes abroad, a dynamic that reinforces ecological unequal exchange. Dietzenbacher and Mukhopadhyay (2007), for instance, show that while India absorbed polluting industries, it gains through inward FDI and technology transfer. In contrast, the so-called "pollution halo hypothesis" suggests that foreign investment may diffuse cleaner technologies, as evidenced in studies of the MENA region (Asghari, 2013) and the Middle East (Al-Mulali and Tang, 2013). The balance between haven and halo dynamics remains debated, yet the global literature consistently shows that emission displacement through trade is central to explaining persistent divergence in carbon intensity across countries.

Within the EU, the emergence of pollution havens is particularly significant because it unfolds inside a common regulatory framework that ostensibly aims at convergence. Firm-level evidence shows that under the EU-ETS, rising carbon costs prompted carbon-inefficient firms, especially in sectors highly exposed to international competition, to relocate investment to countries with weaker environmental constraints rather than adopt costly abatement, consistent with a pollution haven effect (De Beule et al., 2022). Böning et al. (2023) show that declining EU emissions have been offset by rising imports of carbon-intensive goods, pointing to an indirect form of leakage through trade, particularly in the absence of corrective instruments. Dosi et al. (2025) reinforce this finding, showing that the most emission-intensive stages of production tend to be reallocated through GVC backwards linkages to structurally weaker economies, with Eastern Europe playing a disproportionate role in this process. However, there is still a lack of conclusive evidence on the detection of intra-EU regional pollution havens and their direct link with GVC integration.

The persistent divergence documented in convergence studies (Morales-Lage et al., 2019; Cialani and Mortazavi, 2021) can thus be read as an indicator of regional pollution havens within the Union. Unlike global cases where regulatory asymmetries are stark, here the effect arises from the interaction between GVC-driven specialisation and uneven technological capabilities. Regions positioned in mid-stream manufacturing segments accumulate fewer value-added gains but bear the environmental costs, while core economies in Northern and Central Europe maintain lower emission intensities by specialising in upstream or downstream activities (Capello and Dellisanti, 2024).

These outcomes are deeply connected to the dynamics of innovation diffusion and the structure of GVCs. Pietrobelli and Rabellotti (2011) emphasise that learning opportunities from international linkages are conditional on domestic absorptive capacity; without such capacity, GVC participation does not deliver upgrading but locks economies into subordinate positions. In environmental terms, this implies that peripheral regions, what we call the carbon ghettos in this paper, lacking strong innovation systems are unable to internalise cleaner technologies and instead become recipients of polluting tasks from carbon-elite. The persistence of emission divergence across EU regions thus reflects not merely regulatory gaps but the structural logic of fragmented production, where specialisation patterns, technological capacity and the pursuit of cost advantages combine to generate regional pollution havens inside the Union. This is the main research question we will address in the following.

3. Data and Methodology

3.1 Data

The empirical analysis is built upon three primary datasets. The basis of the production network analysis is the European Multi-Regional Input-Output table covering 272 NUTS-2 regions, constructed by Huang and Koutroumpis (2023) for the period 2008–2018. This database fills a gap, as official EU statistical sources do not yet provide consistent, industry-specific trade flow time series at this sub-national level from 2010 onwards. For each region, the tables delineate transactions between 10 economic sectors, classified according to the NACE Rev. 2 classification at the first-digit level, encompassing agriculture, industry, and services. The construction of these tables utilised a hybrid methodology, combining national input-output tables from the OECD with regional economic accounts from Eurostat[1]. This dataset currently represents the most up-to-date representation of the European NUTS-2 production network, making it the most suitable choice for this analysis. Note that these MRIOs focus solely on the intra-EU production network and do not cover flows to or from non-EU regions. This limitation is significant because, as literature shows (e.g., Dosi et al., 2025), EU countries are increasingly offshoring emissions by relocating polluting intermediate production to developing countries outside the EU, primarily in Asia.

The second key dataset comprises CO_2 equivalent (CO_2-eq) emissions from the Emissions Database for Global Atmospheric Research (EDGAR) version 8.0 (Crippa et al., 2023a, 2023b). This source provides high-resolution gridded emissions data, which are aggregated at NUTS-2 level for the European domain. To measure the polluting elements generated in the production process, we use total greenhouse gas emissions expressed in carbon dioxide equivalents. This measure converts emissions of various polluting gases, such as methane and nitrous oxide, into the equivalent amount of CO_2, providing a standardised and comparable metric for total warming impact. The EDGAR database's strength lies in the continuous improvement of its spatial proxies, which downscale national emission totals using global data on point sources (e.g., power plants from the Global Energy Monitor), linear sources (e.g., shipping routes), and area sources (e.g., population density coupled with heating degree days data and built-up areas for non-residential activities) (Crippa et al., 2023). From the initial sample of 272 NUTS-2 regions, we retained 230 after excluding extra-EU territories, the United Kingdom, Albania and a few regions with incomplete or inconsistent data. The full list of regions included in the analysis is reported in Appendix A.

We utilise EDGAR data in two ways. First, we use total NUTS-2 level CO_2-eq emissions to calculate emission factors. Second, we use the sectoral disaggregated NUTS-2 emissions, which are categorised into broad, end-use sectors such as energy production, industrial combustion, buildings, transportation, agriculture, and waste. It is important to note that this sectoral classification is not directly comparable with the production-oriented sectoral classification in the MRIO table. Therefore, the end-use data are treated separately to provide

[1] The validity of this MRIO dataset is supported by its comparison with existing benchmarks. It was directly compared to the previous EUREGIO dataset from the Joint Research Centre (JRC), which covers an earlier period (2000–2010), and demonstrated a high degree of correlation and low relative standard errors (Huang and Koutroumpis, 2023).

insights into the final activities driving energy consumption and emissions, complementing the production-based perspective of the MRIO analysis.

The third dataset consists of regional gross value added (GVA) and gross output statistics for EU NUTS-2 regions, sourced from Eurostat. These data are essential for transforming absolute emissions figures into emission intensities, which express emissions per unit of economic output.

3.2 Methodology

Our empirical strategy proceeds in three steps. We begin with a convergence club analysis, to identify groups of European NUTS-2 regions with similar trajectories of CO_2 intensity over the period under study. These clubs provide the basis for examining how regions are positioned within the EU emission network and whether their relative importance is diminishing or, conversely, becoming more pronounced, allowing for the detection of pollution havens. In the second step, we construct the EU emission network by calculating CO_2 multipliers at the regional level, distinguishing between domestic and foreign components in order to capture how emissions propagate along value chains. Finally, we employ a shift–share decomposition to explain changes in CO_2 multipliers, separating the contributions of technological improvements, structural change, and GVC integration, and complement this with an analysis of the specialisation patterns that characterise the different convergence clubs.

3.2.1 Identifying Convergence Clubs

To test for convergence and identify clubs in CO_2 emission intensity across European regions, this study employs the methodology developed by Phillips and Sul (2007)[2]. This approach allows for models of transitional heterogeneity and identifies convergence clubs endogenously from the data, without relying on assumptions about stationarity or predetermined grouping.

The Phillips and Sul method decomposes the variable of interest, in this case CO_2 emission intensity for region r at time t, denoted K_{rt}, into a common factor (μ_t) and a time-varying idiosyncratic component (δ_{rt}) that captures the region-specific behaviour relative to the common trend: $K_{rt} = \delta_{rt}\,\mu_t$. The focus of the analysis is on the evolution of δ_{rt} over time. To facilitate this, a relative transition parameter (h_{rt}), measuring the transition path for region r relative to the cross-region average:

$$h_{rt} = \frac{K}{N^{-1}\sum_{r=1}^{N} K = \frac{\delta_r}{N^{-1}\sum_{r=1}^{N}\delta_r}} \qquad [1]$$

If all regions converge to the same level, the relative transition paths h_{rt} will converge to 1 for all r as $t \to \infty$ and the cross-sectional variance $H_{rt}=N^{-1}\sum(h_{rt}-1)^2$ will tend to zero**.** The formal test for convergence involves estimating the following *log t* regression[3]:

$$log\left(\frac{H}{H_t}\right) - 2log\big(log(t)\big) = a + \gamma logt + u_t \quad for\ \ t = [sT], [sT]+1, \dots, T \qquad [2]$$

where $L(t)=log(t+1)$ is a slowly varying function and s is a fraction of the sample to be discarded (typically $s=0.3$). The null hypothesis of convergence is $H_0: \gamma \geq 0$. A conventional

[2] This methodology has been applied in innovation studies (Barrios et al., 2019), income inequality (Erfurth, 2023). For a comprehensive technical exposition, refer to the seminal works by Phillips and Sul (2007).
[3]The semiparametric form for the idiosyncratic component is specified as: $\delta_{rt}=\delta_r+\sigma_r\,\xi_{rt}L(t)^{-1}t^{-\alpha}$ where δ_t if fixed, σ_r is an idiosyncratic scale parameter, ξ_{rt} is iid (0,1), L(t) is a slowly varying function (e.g., log(t)), and α denotes the speed of convergence.

one-sided t-test is used, and the null is rejected at the 5% significance level if $t_{\hat{\gamma}} < -1.65$. The coefficient γ is linked to the speed of convergence α by the relation $\gamma = 2\alpha$.

If the null hypothesis of full-panel convergence is rejected, a four-step clustering algorithm is employed to identify subgroups of regions that are converging to their own mean: (1) ordering regions based on the final observation; (2) forming a core group by sequentially applying the *log t test* to the *k* highest-ranked regions to find the largest group for which the *t-statistic* > -*1.65*; (3) sieving potential new members into this core group one-by-one; (4) repeating the procedure for the remaining regions to form subsequent clubs or identify divergent regions. A final step tests for the potential merger of adjacent clubs proposed by Schnurbus et al. (2017).

3.2.2 Construction of CO_2 Multipliers

The core analytical methodology of this paper is based on the input-output framework, which explicitly models the interdependencies between sectors and regions within an economy (Leontief, 1936). The structure of the European production network is represented by its fundamental equation $X = AX - Y$. Where, X is a vector of total output for each sector in each region. Y is a vector of final demand, representing the consumption of goods and services by households, governments, and investors, both within and outside the region of production. A is the matrix of technical coefficients, where each element $a_{(i,r);(j,s)}$ denotes the amount of input from sector i in region r required to produce one unit of output in sector j in region s. To calculate the total inputs required to satisfy a given level of final demand, both directly and indirectly through the entire supply chain, the Leontief inverse matrix is derived $L = (I - A)^{-1}$. Each element $l_{(i,r);(j,s)}$ of this matrix represents the inputs from sector i in region r needed to produce one unit of final output from sector j in region s.

To integrate emissions into this economic framework, a vector of emission factors, EF is constructed. Each element ef_r represents the CO_2-equivalent emissions per unit of output for region r, calculated by dividing the EDGAR CO_2-eq emissions for that region by its corresponding gross output from Eurostat to ensure comparability across figures[4]. To merge regional emission data with I-O ones, the original Leontief needs to be aggregated at the NUTS2 level, discarding the sectoral dimension. The vector EF is then diagonalised and used to pre-multiply the Leontief matrix to obtain the CO_2 multiplier matrix, which reports the emissions generated throughout the intra-EU supply chain network per unit of final demand.

$$CO = \hat{EF} \cdot L \quad [3]$$

Each element $co_{r,s}$ of the matrix CO indicates the total CO_2-eq emissions from region r that are embodied in one unit of final demand for the production of region s.

The interpretation of this matrix depends on the direction of aggregation. Summing the elements down a column s yields the total carbon footprint per unit of final output for production finalised in that region, representing the emissions generated across the entire value chain to meet its demand, which is the backwards linkages multiplier of the region s.

$$BkwCO_s = CO_2Mult_s = \sum_{r \in s} c_{r,s} \quad [4]$$

[4]Note that, in our knowledge, region-sector databases with classifications comparable to the 1-digit NACE Rev. 2 do not exists. Thus regional emission factor is used aggregating sectors in the Input Output matrix.

Conversely, to compute the forward linkages multipliers of a specific emitting region within the wider EU network, the elements across the r-row are aggregated as a weighted average, using each region's final demand (FD_s) as weights to preserve the fundamental Input-Output properties, as explained by Miller and Blair (2021).

$$\text{FrwCO}_r = \text{CO}_2\text{Mult}_r = \sum_r c_{r,s} \frac{fd_s}{\sum_s fd_s} \quad [5]$$

Similarly, excluding some r region from the computation, we obtain the backward/forward CO_2 multipliers of a specific subset of the EU production network. Thus, for instance, to have only the foreign forward linkages multiplier of – say region w belonging to country c – we select all regions $r: r \notin c$.

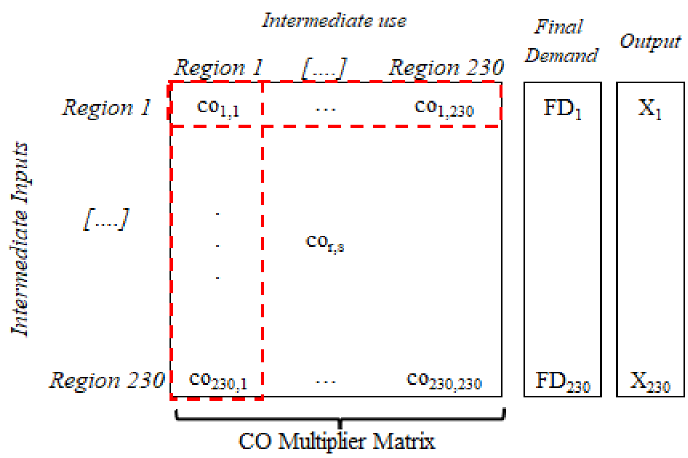

Figure 1. Visual representation of CO_2 Multiplier matrix, demand and output vector.

This study is particularly interested in analysing the backwards linkages of EU regional production chains, following a structural decomposition logic akin to that outlined in Meng et al. (2018). This involves quantifying the origins of emissions embodied in a region's final demand, distinguishing between several segments of the regional production network. In particular domestic, intra- and inter-regional emissions are CO_2 generated in the production of intermediaries within the country where the region is located. While foreign, intra-European emissions are generated in the production process of other EU member states.

4. Pollution Havens within EU? A CO_2 intensity convergence analysis

We applied the convergence framework developed by Phillips and Sul (2007) to CO_2 emission intensity across European NUTS-2 regions in the decades from 2008 and 2018[5]. CO_2 emission intensity accounts for CO_2 equivalent emissions per unit of output an indicator that reflects the production methods prevailing in each territory. Table 1 reports the results of the log-t convergence tests. A t-statistics above -1.65 confirms the significance of the grouping while β coefficient determines if the regions are converging (β>0) or diverging (β<0) within the group. Convergence can be either toward a high-emission or a low-emission equilibrium.

[5]As a robustness check, we conduct two additional analyses. First, we estimate club convergence in CO_2-equivalent intensity for the period 1990–2018 on the available NUTS-2 sample, obtaining results consistent with our baseline. Second, we replicate the analysis using CO_2-equivalent emissions per capita and again find comparable patterns. Ultimately, we focus on CO_2-equivalent emissions per unit of output over 2008–2018, ensuring full consistency between the convergence clubs and the input–output framework.

The results decisively reject the hypothesis of full convergence with a t-statistic of -20.40. This finding aligns with the broader literature on club convergence in emissions, which consistently rejects a single steady state in favour of multiple equilibria in the European context (Morales-Lage et al., 2019). Instead, the analysis endogenously identifies a structure of eight distinct clubs, ordered from the highest (Club 1) to the lowest (Club 8) average emission intensity, alongside a separate group of divergent regions (Club 9) whose members do not conform to any club's trajectory. This outcome, detailed in Table 1, underscores the persistent heterogeneity in the carbon efficiency of regional production systems within the European Union. Notably, the ranking in value added per capita mirrors one-to-one, except for the divergent cluster, the ranking in emission intensity, with an increasing ordering in this case.

In practical terms, the existence of multiple convergence clubs implies that some regions consistently converge towards higher average emission intensities, the so called carbon ghettos, meaning that they systematically pollute more per unit of output; these regions can thus be interpreted as the functional equivalent of pollution havens within the European Union once ascertained that their status as carbon ghettos is due to imported emissions to produce intermediaries for the carbon elite, the regions showing convergence toward low-intensity carbon emission paths. The relative transition paths and within-group heterogeneity for each club are plotted in Figure 2. This figure shows the declining within-group standard deviation (right axis) for all eight clubs, supporting the internal convergence process towards the club-specific mean. Several clubs (Clubs 1, 3, 5, and 6) exhibit positive t-statistics, indicating the existence of within-group convergence.

Club	No. of regions	t-stat	β-coefficient	Avg. CO2 eq. Intensity	Avg. VA per capita
Club 1	14	2.210	0.440	1.438	0.013
Club 2	19	-1.414	-0.381	0.908	0.015
Club 3	34	0.267	0.036	0.599	0.016
Club 4	46	-0.610	-0.063	0.391	0.027
Club 5	52	0.356	0.066	0.266	0.032
Club 6	54	1.930	0.218	0.172	0.039
Club 7	11	-0.566	-0.107	0.106	0.039
Club 8	3	-0.082	-0.047	0.049	0.059
*Club 9**	7	-35.014	-1.000	1.21	0.024

Table 1. Convergence club identified using the Phillips and Sul (2007) methodology for the period 2008-2018.

Notably, Club 1 has a high positive β-coefficient, suggesting a relatively fast speed of convergence towards a high-intensity equilibrium, potentially indicating a 'catching-down' process in emission intensity. Interestingly, these regions are characterised by the lowest value added per person as well. Club 1, therefore, represents a carbon ghetto. In contrast, Clubs 2, 4, 7, and 8 have negative β-coefficients, which suggest a tendency towards weak divergence or a much slower and more fragile convergence process within these groups. These groups are therefore internally more heterogeneous, and no unique pattern can be identified. There are also groups showing convergence toward low-emission paths; this is the case of Clubs 3, 5, 6, which are characterised by heterogeneous levels of productivity, matched with medium-level emission profiles.

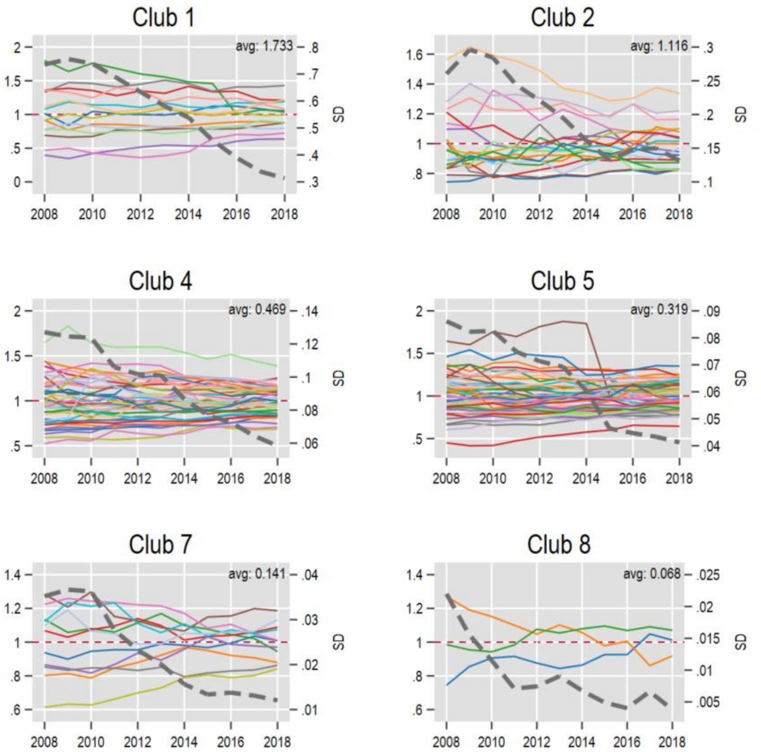

Figure 2. Evolution of Relative Transition Paths (left axis, in colours) and Within-Club Dispersion (bold dotted grey line) measured by internal standard deviation (right axis). See Appendix B for region membership by club.

The composition of these clubs, illustrated in Figure 3, reveals a pronounced spatial and economic stratification, echoing the core-periphery structures identified in studies of national-level EU emissions (Morales-Lage et al., 2019; Cialani and Mortazavi, 2021). A stark geographic divide is evident. Clubs with the highest emission intensities (Clubs 1-3) are predominantly composed of regions in Central and Eastern Europe (e.g., Bulgaria, Poland, Romania, Czech Republic) and Southern Europe (e.g., Greece, Spain), confirming the emergence of a distinct, less carbon-efficient club in the EU's eastern and southern periphery, which we can consider the carbon ghetto-clubs, suggesting the presence of pollution havens within EU. Conversely, clubs with the lowest intensities (Clubs 5-8) are overwhelmingly concentrated in the advanced economies of Western and Northern Europe (e.g., Germany, France, Denmark, Benelux), what we define as the carbon elite-clubs. Notably, capital cities and core economic regions are typically situated in better-performing clubs. A noteworthy illustrative finding is the composition of Club 8, which exhibits the lowest average emission intensity (0.049) but the highest productivity. This club exclusively consists of the capital regions of Austria (Wien), Denmark (Hovedstaden), and France (Île-de-France). This finding strongly supports the hypothesis that the structure of production is a critical determinant of carbon efficiency, as these capital regions are dominated by high-value service sectors rather than carbon-intensive heavy industry.

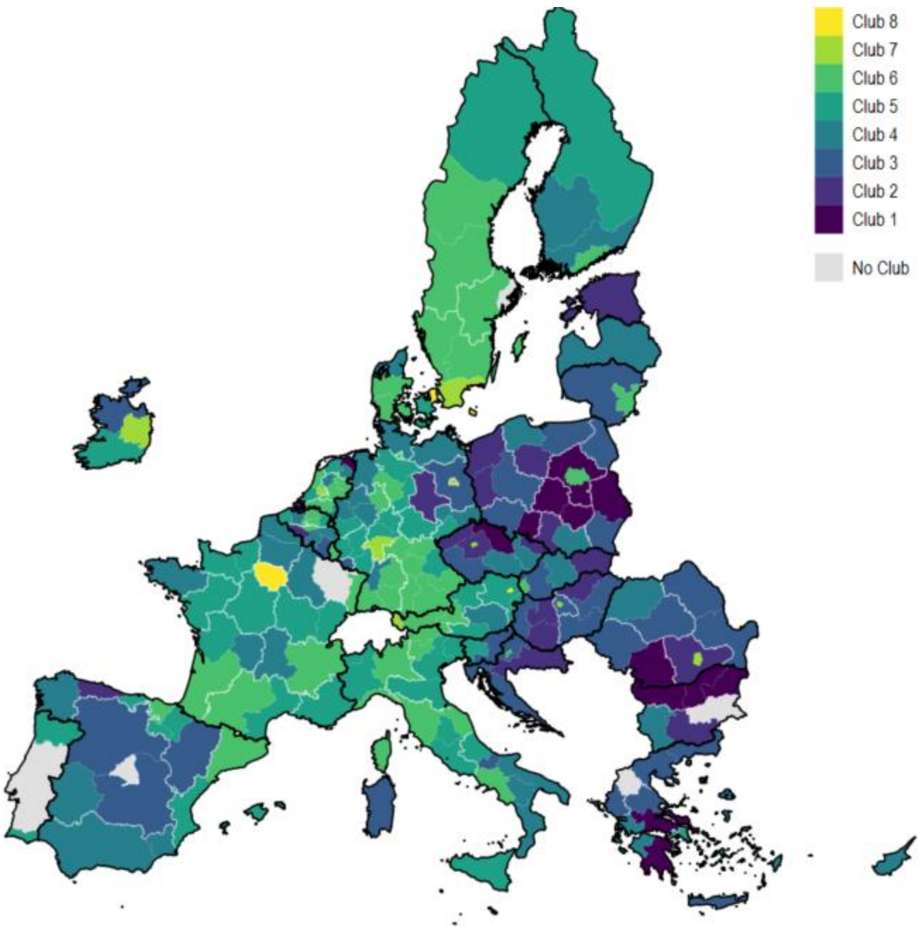

Figure 3: EU convergence clubs. See Appendix B for region membership by club.

5. EU Regional Emission Network: A CO_2 Multipliers Analysis

In this section, the analysis focuses on CO_2 emission multipliers associated with intra-EU intermediate linkages, examining the EU production network as an integrated system. Therefore, we move from the structural analysis of convergence toward a flow analysis. The step is done with the aim of linking the elites-ghettos clubs' dynamics with the patterns of emission flows. In particular, the study assesses the contribution of each NUTS2 region to EU-wide final production, thereby evaluating the carbon content embedded in the forward and backward linkages of regional economies. A key distinction is made between domestic linkages, which occur within the same country, and foreign linkages, which involve cross-border flows of intermediate inputs to pinpoint the role of international trade in shaping production fragmentation and corresponding carbon contents. The analysis starts with EU-wide statistical trends, narrows down to the most and least emitting regions, and finally looks at convergence clubs to elucidate their roles in aggregate emission patterns.

The left panel of Figure 4 indicates an overall decline in intra-EU emissions. However, the recent literature highlights that this reduction may be partially offset by increased emissions embodied in intermediates imported from outside the EU (Dosi et al., 2025), which are beyond the scope of the current analysis. The core evidence is that emissions generated from foreign intra-EU inputs are falling less rapidly than those from domestic linkages. This divergence suggests that GVCs within the EU act as a carrier of emissions, with cross-border production networks retaining a higher carbon intensity compared to domestic production processes. The central panel of Figure 4 provides a direct explanation for this evidence, showing that the CO_2 emission multipliers for foreign linkages have decreased at a slower pace than domestic multipliers. Notably, the absolute level of emissions from foreign EU linkages remained above their baseline value until 2017, while domestic multipliers fell below it earlier. This indicates a persistent carbon intensity in the traded segments of regional production networks.

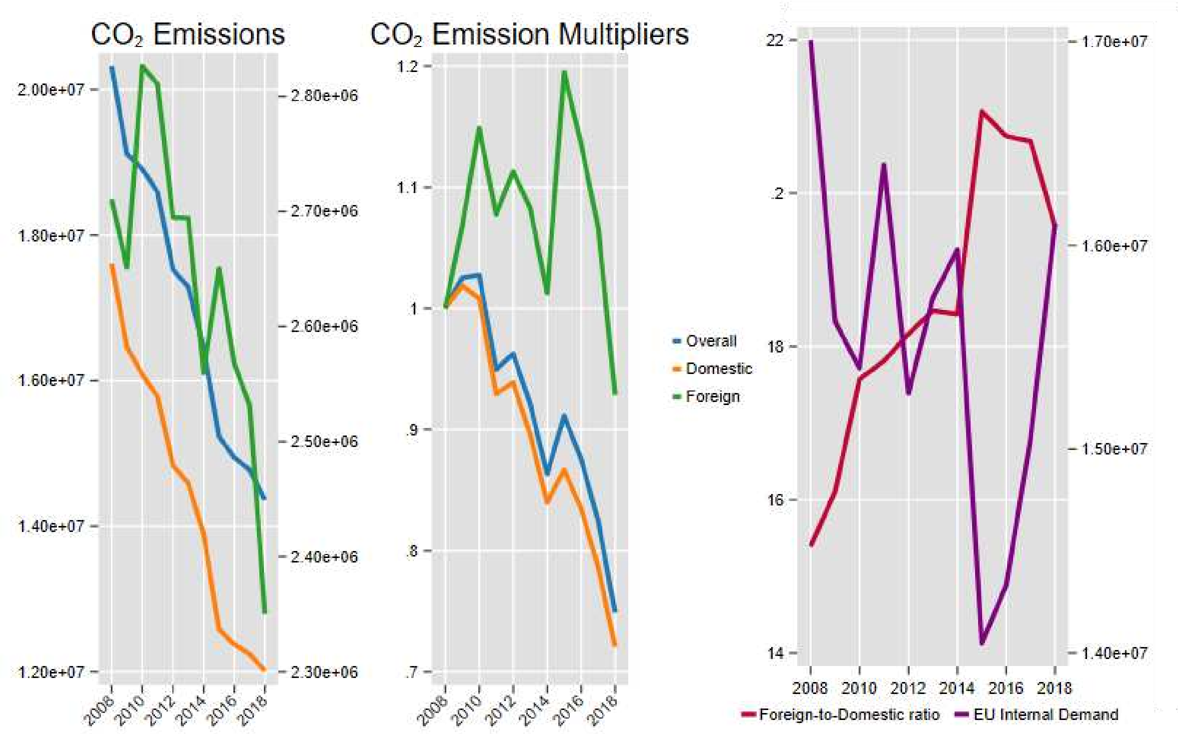

Figure 4. Left panel: Overall, domestic CO_2 emission level (left axis) and foreign ones (right axis). Central panel: Index tracking CO_2 multipliers of overall, domestic and foreign emissions (2008=1). Right Panel: Foreign to domestic CO_2 emission ratio (left-axis), and EU internal demand for EU productions (right-axis)

The left panel of Figure 4 introduces a complementary evidence: the sharp contraction of internal EU demand over the period that contributed to the overall decrease in emissions recorded in the right panel. While the relative dynamics of CO_2 emissions embedded in imported vis-à-vis home country intermediaries, depicted in the foreign-to-domestic emission ratio, rose substantially during the decade. This increasing ratio highlights that the relative importance of foreign intra-EU, carbon-intensive intermediates grew within the EU production network, even as absolute volumes fell.

To zoom in, Table 2 presents the top and bottom emitting regions within the EU production network, ranked by their Balance of Emissions (BOE). This metric is defined as the sum of a region's inward emissions (i.e. foreign backward linkages measuring CO_2 generated abroad and embedded in intermediates used for its production) and its outward emissions (i.e. foreign forward linkages measuring CO_2 generated within the region and embedded in intermediates used for foreign final production), normalised by the corresponding sum of backward and forward gross output values to isolate carbon intensity from scale effects:

$$BOE_r = \frac{BkwCO_r + FrwCO_r}{BkwQ_r + FrwQ_r} \quad [6]$$

This calculation reveals the intrinsic carbon efficiency of a region's participation in intra-EU trade, combining information on input requirements for its own final production and input demand from other EU regions. The results confirm a pronounced and stable core-periphery divide across the continent.

TOP EMITTING							
Rank	**Region**	**Code**	**BOE**	**Δ Rank**	**Share of Forward Emission**	**Share of Backward Emission**	**Club**
1	Opolskie	PL52	2,02	-2	1,480%	0,640%	1
2	Świętokrzyskie	PL72	1,59	-4	1,350%	1,090%	1
3	Severovýchod	CZ05	1,54	-1	1,530%	1,250%	1
4	Severoiztochen	BG33	1,52	3	0,700%	0,190%	1
5	Sud-Vest Oltenia	RO41	1,51	3	1,020%	0,640%	1
6	Severozapaden	BG31	1,48	1	0,510%	0,130%	1
7	Łódzkie	PL71	1,39	-2	1,060%	0,710%	1
8	Severen tsentralen	BG32	1,27	0	0,560%	0,130%	1
9	Peloponnisos	EL65	1,23	-8	0,280%	0,240%	1
10	Észak-Magyarország	HU31	1,14	3	0,430%	0,430%	2
11	Lubelskie	PL81	1,14	0	0,910%	0,440%	1
12	Zachodniopomorskie	PL42	1,07	2	1,190%	1,220%	2
13	Śląskie	PL22	1,04	1	1,530%	2,100%	2
14	Panonska Hrvatska	HR02	1,00	-6	0,190%	0,190%	2
15	Kujawsko-pomorskie	PL61	0,99	-11	0,570%	0,450%	2
BOTTOM EMITTING							
Rank	**Region**	**Code**	**BOE**	**Δ Rank**	**Share of Forward Emission**	**Share of Backward Emission**	**Club**
230	Wien	AT13	0,097	0	0,045%	0,416%	8
229	Ciudad de Melilla	ES64	0,104	0	0,002%	0,003%	7
228	Ciudad de Ceuta	ES63	0,107	0	0,160%	0,001%	6
227	Utrecht	NL31	0,114	2	0,074%	0,106%	7
226	Vorarlberg	AT34	0,119	2	0,281%	0,461%	7
225	Grad Zagreb	HR05	0,128	-1	0,039%	0,032%	6
224	Sydsverige	SE22	0,13	2	0,068%	0,108%	7
223	Bolzano/Bozen	ITH1	0,136	0	0,023%	0,055%	6
222	Hovedstaden	DK01	0,139	2	0,030%	1,972%	8
221	Mittelfranken	DE25	0,149	4	0,072%	0,423%	6
220	Darmstadt	DE71	0,156	4	0,049%	0,600%	7
219	Rhône-Alpes	FRK2	0,157	0	0,018%	0,048%	6
218	Tirol	AT33	0,157	0	0,313%	0,432%	6
217	Västsverige	SE23	0,159	3	0,095%	0,493%	6
216	Berlin	DE30	0,162	21	0,050%	0,366%	7

Table 2. Top and Bottom emitting regions in the EU production network.

The lowest-emitting regions, according to inward and outward emission flows, are predominantly affluent, service-oriented metropolitan areas and highly developed regions in Western and Northern Europe. The large presence of capital cities and major economic hubs such as Wien, Hovedstaden (Copenhagen), Berlin, and Utrecht at the bottom of the ranking underscores that economic structures specialised in high-value services, finance, and public administration are associated with significantly lower carbon intensity in production networks.

The improvement in Berlin's rank (+21 positions) suggests that targeted urban decarbonisation policies can yield substantial results. The inclusion of highly developed non-capital regions like Vorarlberg, Rhône-Alpes, and Sydsverige further emphasises that advanced economic development, rather than capital status alone, correlates with lower emission intensity. The general stability of the rankings points to the persistent nature of these economic structures and their ensuing emission profiles.

Conversely, the top-emitting regions are overwhelmingly concentrated in the manufacturing and energy-intensive industrial hubs of Central and Eastern Europe. A striking geographical clustering is evident, with multiple regions from Poland (e.g., Opolskie, Świętokrzyskie, Łódzkie), Bulgaria (e.g., Severoiztochen, Severozapaden, Severen tsentralen), and Romania (e.g., Sud-Vest Oltenia) dominating the highest ranks. This spatial concentration indicates that high carbon intensity is not an isolated phenomenon but a regional one, deeply embedded in the economic fabric of these areas. Their specialisation in carbon-heavy industries such as mining, metallurgy, and energy production creates a structural lock-in effect, perpetuating high emissions. The stability of their rankings over the decade, with modest changes in rank, further underscores the persistent and path-dependent nature of their carbon-intensive developmental pathways. This East-West divide within the EU production network highlights a fundamental disparity in the carbon intensity of regional economies.

This sharp polarisation suggests that integration into European production networks has produced a dual geography of emissions. On the one hand, the least-emitting regions of Western and Northern Europe—particularly capital-city regions such as Vienna, Copenhagen, Berlin, and Utrecht—constitute a *carbon elite*. Their economic structures are dominated by high-value services and knowledge-intensive functions, which secure both economic upgrading and low emission intensity. On the other hand, the most-emitting regions in Central and Eastern Europe operate as *carbon ghettos*, locked into energy- and carbon-intensive manufacturing niches. Their integration into European value chains has largely taken the form of specialisation in polluting industrial segments, particularly through backward linkages in which intermediate goods with high emission intensity are produced in the eastern periphery to meet the demand of affluent western economies.

5.1 Club Analysis

This subsection examines the interaction between the convergence clubs identified previously and the intra-EU fragmentation of production. Figure 5 compares the CO_2 emissions generated in domestic versus foreign stages of production, revealing systematically higher carbon intensity in cross-border value chains. For expository clarity, clubs have been aggregated pairwise, excluding the divergent club.

The analysis reveals a significant disparity in emission efficiency. Although Clubs 1 and 2 contain far fewer regions (33 regions) compared to Clubs 3 and 4 (80 regions) or Clubs 5 and 6 (over 100 regions), their levels of domestic emissions are comparable. This indicates a profoundly higher carbon intensity per region within these clubs. A partially positive finding is the observable decline in domestic emissions across all clubs, suggesting a broad-based, albeit uneven, trend towards decarbonisation in local production processes.

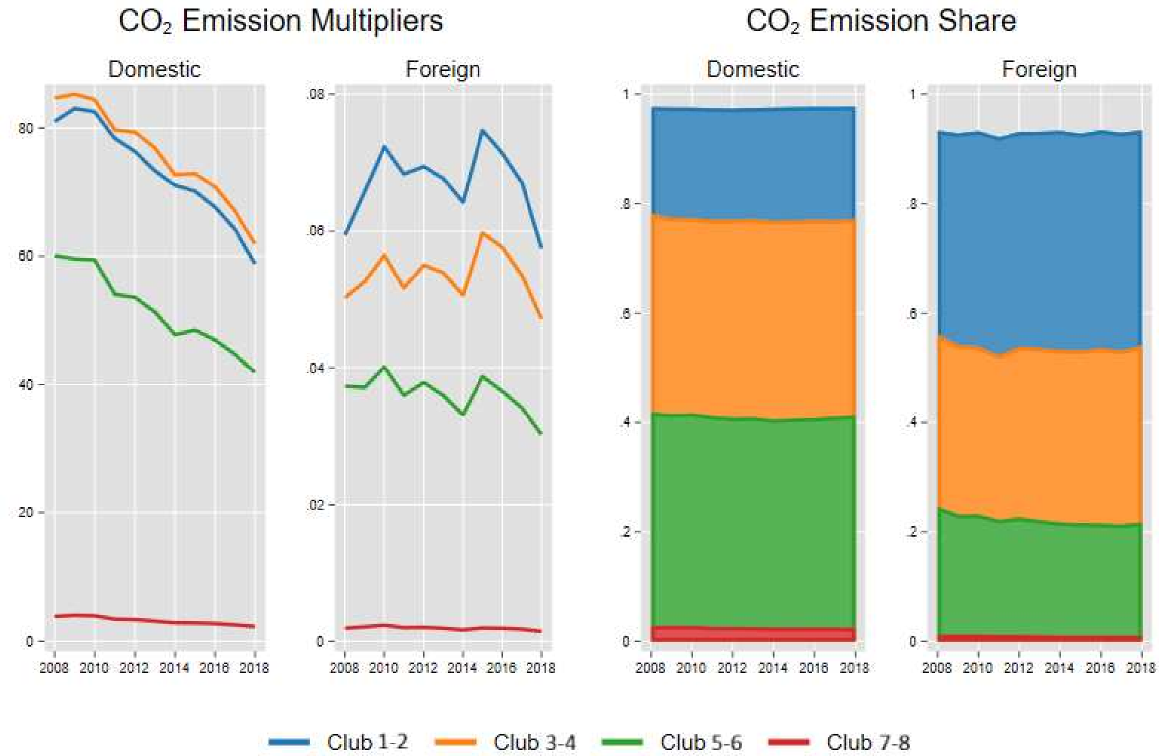

Figure 5. Left panels: domestic and foreign CO_2 multipliers by club. Right panel: share of domestic and foreign CO_2 emissions by club.

The divergence in emission multipliers becomes even more pronounced in the foreign segments of production. Clubs 1 and 2 contribute disproportionately to the total intra-EU emissions embedded in trade, underscoring that their high carbon intensity is particularly exported through cross-border intermediate flows. More concerning is the trend till 2015 as the relative emissions of Clubs 1 and 2 increase within the foreign segment. Their rate of decarbonisation is slower than that of other clubs, meaning their carbon-intensive production processes are becoming even more dominant within the EU's foreign value chains.

This dynamic is further elucidated in the right panel, which plots each club's share of total intra-EU emissions. The figure demonstrates that the most emitting clubs maintain a higher share of emissions originating from foreign rather than domestic linkages. This confirms an emission specialisation within the EU production network, whereby the most carbon-intensive regions are increasingly concentrated in the foreign segments of value chains. Their economic activities are not only more polluting but are also disproportionately oriented towards producing intermediates for other regions' final production. This trend highlights a growing structural dependency of the wider EU economy on carbon-intensive inputs from specific geographic clusters, presenting a substantial obstacle to achieving a uniformly low-carbon European production network. The presence of pollution havens is therefore confirmed by the empirical analysis.

6. Shift Share Analysis

Building upon the documented patterns of emissions embedded in production, this section employs a shift-share analysis to disentangle the drivers behind changes in emission intensity within the intra-European Union production network. The objective is to quantify the contribution of four fundamental components: change in production technologies, changes in input recipes, geographical restructuring of supply chains, and shifts in the composition of final demand. This decomposition allows for a precise identification of whether observed changes in emissions are driven by genuine decarbonisation of production processes or by structural changes in the EU production network that may partially offset such gains (Riccio et al., 2024).

The analysis is conducted on the variation of CO_2 equivalent emission multipliers across the EU's regional production network between 2008 and 2018. The unit of analysis is the NUTS 2 region, and the network encompasses both intra-regional, domestic and inter-regional foreign intermediate linkages. The change in the CO_2 multiplier is decomposed into the following four components:

- Emission Intensity (Technical Change): This component captures pure technological improvements, measuring the change in CO_2 emissions per unit of output for each region, holding the structure of production and demand constant. A decline in this component indicates the adoption of less emission-intensive production technologies within a specific region.
- Technical Coefficients (Input Requirement): This component measures changes in the production 'recipe', namely the efficiency and combination of inputs required to produce a unit of output. It reflects how sectors alter their intermediate consumption (e.g., using less metal or more services), irrespective of the geographical source of those inputs or their emission intensity.
- GVCs Restructuring (Geography of Intermediaries): This component tracks the impact of shifting the geographical source of inputs within the EU internal market. For instance, if a German manufacturer switches its supplier of components from a region in Poland to one in France, and the French region has a different emission profile, the change in overall emissions attributable to this geographical reshuffling is captured here. It is closely associated with the geographical dimension of carbon leakage.
- Final Demand Composition (Geography of consumption): This quantifies how changes in the structure of final demand for goods and services from different regional sectors influence aggregate emissions. For example, an increasing final demand for a less emission-intensive region specialised in service sectors over a more intensive region which produces raw materials would contribute negatively to emission multipliers, indicating a favourable structural transition in consumption patterns.

The formal decomposition of the change in the average CO_2 multiplier is given by:

$$\Delta CO_2Mult_t^{EU} = \Delta \sum_r \frac{fd_s}{fd^{EU}} \sum_{r\epsilon s} l_{r,s} CO_2eff_r = \Delta \sum_r \frac{fd_s}{fd^{EU}} \cdot \sum_s \frac{l_{r,s}}{\sum_{r\epsilon s} l_{r,s} \cdot \sum_{r\epsilon s} l_{r,s}} \; CO_2eff_r =$$

$$= \sum_s \sum_r \Delta \frac{fd_s}{fd^{EU}} \left(\sum_{r\epsilon s} L_s lsh_{r,s} \hat{C}O_2eff_r \right) + \sum_s \sum_r \Delta L_s \left(\frac{fd_s}{fd^{EU}} l\hat{sh}_{r,s} CO_2eff_r \right) + \quad [7]$$

$$+ \sum_s \sum_r \Delta lsh_{r,s} \left(\frac{fd_s}{fd^{EU}} L_s \hat{C}O_2eff_r \right) + \sum_s \sum_r \Delta CO_2eff_s \left(\frac{fd_s}{fd^{EU}} \hat{L}_s lsh_{r,s} \right)$$

The notation *s* refers to GVCs, specifically the NUTS2 region where the final production occurs, while l_r, s represents the inputs coming from region r utilised in the production process of region s. The CO_2 multipliers are initially broken down into region-specific emissions per unit of output (CO_2eff_r), output multipliers ($l_{r,s}$), and then aggregated across the chain using final demand shares of region s in worldwide final demand *($fd_s/fd^{EU}=fd_s/\sum_s fd_s$)*. For each GVC

s, we calculate the total input requirement ($L_s=\sum_r l_{r,s}$) , which is the sum of all inputs needed for the production process of s. Subsequently, we determine the input share of region r in the value chain s by dividing output multipliers by the corresponding total input requirements (L_s). To maintain equality, we multiply by L_s, representing the technical coefficients or requirements needed in production. Note that Δ denotes changes between the initial and final year of the variable, while the hat symbol represents transformations of averages between the initial and final year of the variable. For a detailed mathematical treatment related to the shift-share analysis, please refer to the Appendix C.

The results of this decomposition will first be presented for the entire EU network, distinguishing the contribution of domestic versus foreign (intra-EU) segments. Subsequently, the analysis will utilise the convergence club classification of regions to investigate the heterogeneous role played by clubs with differing economic profiles in driving the aggregate results through each of the four components.

6.1. Aggregate Decomposition of the EU Emission Network

The shift-share analysis confirms a significant decline in the average CO_2 emission multiplier within the EU regional production network between 2008 and 2018. This aggregate trend aligns with broader European decarbonisation established literature on technological improvements within the bloc. The decomposition, however, reveals interesting insights into GVCs' participation and the ensuing geographical dispersion of production, uncovering the countervailing forces that have characterised this period of EU integration. The reduction in the overall CO_2 multiplier is overwhelmingly attributable to improvements in emission intensity, which represents the sole component contributing to a net decrease. This indicates that the primary driver of decarbonisation has been the adoption of less emission-intensive production technologies at the regional sector level. Over the decade, production processes across the EU have progressively incorporated carbon-saving techniques, a trend reflecting the successful diffusion of technology and the impact of stringent environmental regulations.

However, the gains achieved through these technological advancements have been substantially offset by the other three components of the decomposition. Both the technical coefficients (input mix) and GVCs restructuring components exhibit a positive contribution to the emission multiplier, thereby counteracting the progress made via efficiency gains. The positive sign of the input mix component suggests that the evolution of production recipes has favoured more emission-intensive input combinations. Concurrently, the positive contribution of GVCs restructuring indicates that the geographical reorganisation of supply chains within the EU single market has, on aggregate, moved intermediate production towards regions with higher emission intensities, confirming the pollution haven hypothesis. This finding suggests that efficiency gains in most of the regions have been partly offset by a shift toward less emission-efficient regions within the production network.

When distinguishing between the domestic and foreign segments of production, the decomposition reveals divergent dynamics. The domestic segment, which constitutes the most substantial part of the network, largely mirrors the aggregate trend. The foreign segment, representing intra-EU intermediate imports, tells a different story. While the rate of decline in CO_2 efficiency within foreign inputs is comparable to that of the domestic segment, this positive development is entirely negated by the contributions of the other components. The technical coefficients, GVCs restructuring, and final demand composition all contribute positively to the emission multiplier of foreign inputs.

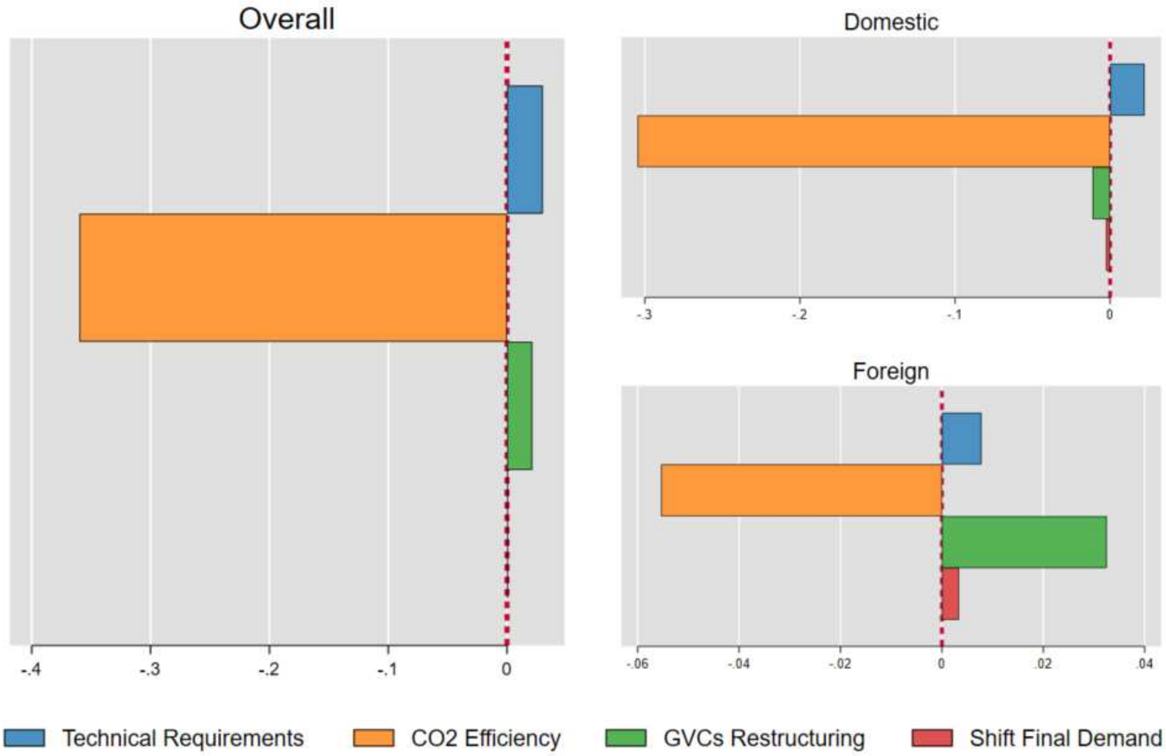

Figure 6. Shift share analysis following Eq. 7 further decompose between domestic and foreign shifts.

Of particular significance is the pronounced positive contribution of GVCs restructuring within the foreign segment. This indicates that the geographical reshuffling of intermediate sourcing between EU NUTS 2 regions has specifically favoured suppliers in higher-emitting locations. This result provides suggestive evidence that, for foreign inputs, the restructuring of value chains has worked against overall decarbonisation goals, potentially reflecting the presence of pollution haven dynamics within the integrated European market. The net effect is that the foreign segment of the production network has acted as a drag on the pace of decarbonisation, with its structural evolution counteracting the technological improvements that have been achieved.

6.2 Club-Based Decomposition of EU Emission Multipliers

The decomposition of emission multipliers by convergence clubs reveals starkly heterogeneous patterns, particularly when distinguishing between domestic and foreign segments of production. This granular analysis moves beyond the aggregate EU trend to uncover the divergent roles played by regions at different stages of economic and environmental development.

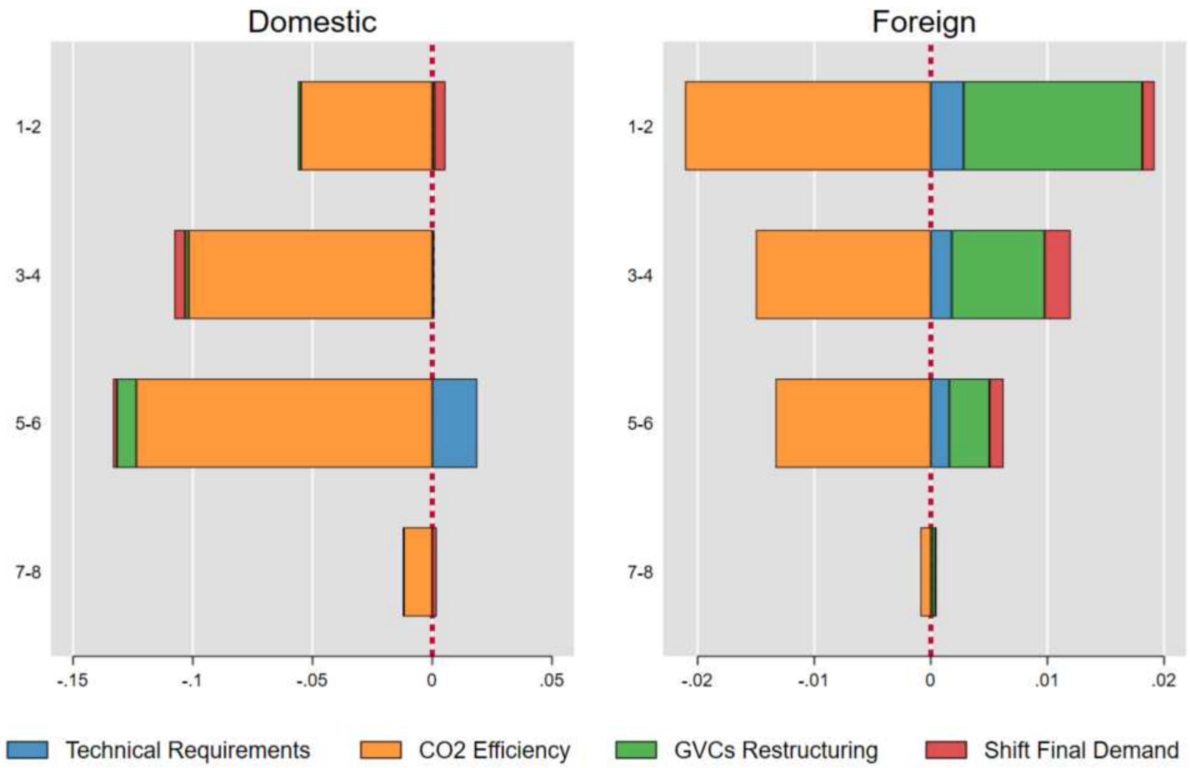

Figure 7: Shift share analysis following Eq. 7 further decompose between domestic and foreign shifts. Regions are divided into 4 groups obtained by pairing consecutive convergence clubs.

For domestic segments, the analysis reveals a ubiquitous decline in emission multipliers across all clubs. This widespread improvement is predominantly led by a substantial and negative contribution from the emission intensity component, indicating that technological advancements and the adoption of cleaner production processes have occurred in all regions, regardless of their initial emission profile. A notable pattern emerges, however, wherein the least emitting clubs exhibit a less pronounced rate of decline. Conversely, the most polluting clubs (Clubs 1-2), despite significant reduction in their domestic emission multipliers, are not the one reducing their contribution the most, confirming the lack of overall convergence spotted in the previous analysis also in the European production network. This suggests that although these higher-emitting regions have been actively engaged in decarbonising their internal production processes, their overall scale of emissions remains well above the EU average.

The dynamics within the foreign segment, presented in the right panel of Figure 7, present a more complex and concerning picture. Here, the reduction in emission multipliers is markedly lower than in domestic segments and is close to zero for most clubs. The decomposition reveals that CO_2 efficiency gains, while present, are completely offset by positive contributions from the other components. The countervailing forces of GVCs restructuring and final demand composition are particularly strong. The significant positive contribution of the GVCs restructuring component indicates that the geographical reorganisation of intermediate sourcing within the EU has systematically favoured more polluting regions. In other words, the input mix has changed in a way that increases the reliance on intermediates from higher-emitting clubs, effectively neutralising the technological gains achieved elsewhere in the network. Furthermore, the positive contribution of final demand composition suggests that consumption patterns have shifted towards the outputs of regions whose production is reliant on more emission-intensive inputs. This signifies a specialisation trajectory where final demand pulls in goods and services that are embedded within higher-carbon production chains. While this effect is less pronounced than that of GVCs restructuring, it nonetheless acts as a second structural force counteracting efficiency gains.

Together, these findings indicate that the structural evolution of the EU's internal market, through its value chains and consumption patterns, has worked against its technological progress in reducing the carbon footprint of foreign intermediate production.

7. Specialisation patterns in the EU Emission network.

This section finally examines how the intersection of carbon emission patterns, regional specialisation, and participation in GVCs contributes to the observed disparities in emission intensity across European regions. First, the analysis examines the sectoral composition of CO_2 equivalent emissions using data from EDGAR v5.0. A Revealed Comparative Advantage (RCA) index is constructed to quantify regional specialisation in emissions-intensive activities. The RCA is defined as:

$$RCA_{i,r} = \frac{\frac{co_{i,r}}{\sum_i co_{i,r}} / \sum_r co_{i,r}}{\sum_r \sum_i \ co_{i,r}} \quad [8]$$

where $co_{i,r}$ denotes emissions from sector i in region r, and. This metric compares the share of a sector in a region's emission portfolio to its share in the EU-wide emission structure.

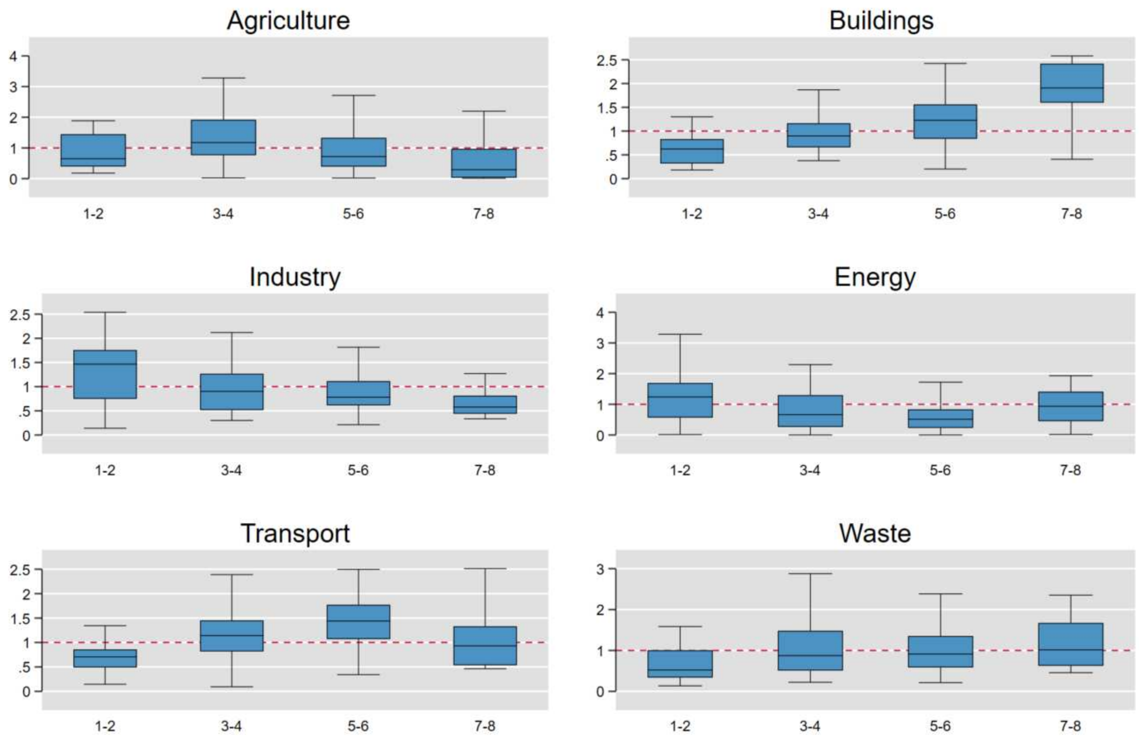

Figure 8: Specialisation patterns in CO_2 emissions across broad end-use sectors. Regions are divided into 4 groups obtained by pairing consecutive convergence clubs.

The pronounced core-periphery divide in emission intensity reflects deeper structural differences in regional economic profiles and innovation capacities. Figure 8 shows that regions belonging to the high emission clusters, predominantly located in Central and Eastern Europe, are often specialised in carbon-intensive industrial and energy sectors. Their economic structures are characterised by a reliance on traditional manufacturing and primary commodity production, which locks them into high-emission developmental pathways. Conversely, low-emitting regions (Club 5,6,7,8) often affluent capital cities and service-oriented hubs in Western and Northern Europe, benefit from economic structures centred on high-value services characterised by very low emissions that emerge in their extreme specialisation in emissions from buildings.

A second perspective, presented in Figure 9, analyses productive specialisation within GVCs, distinguishing between domestic and foreign linkages. The sectoral classification from the MRIO data is aggregated into six broad sectors for tractability. The RCA metric is adapted to evaluate specialisation in value-added terms across these segments.

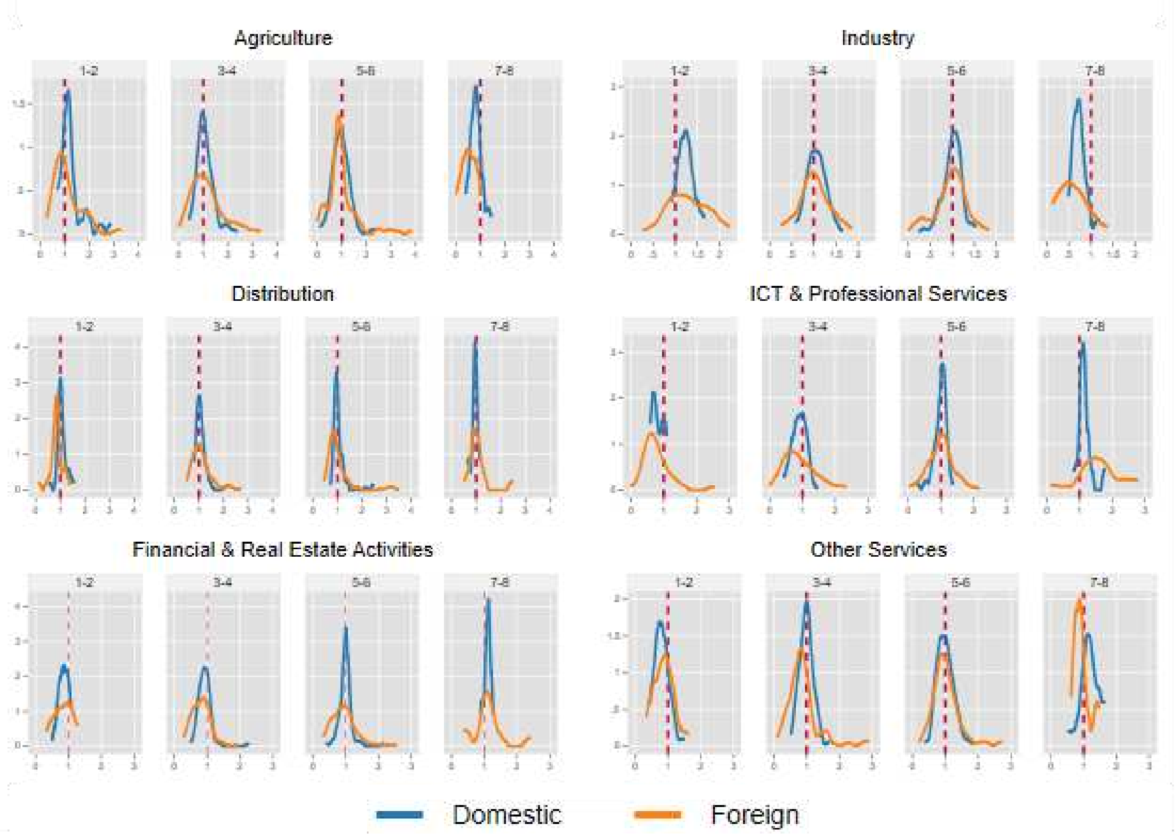

Figure 9. Specialisation patterns in the EU GVCs across broad sectors, distinguishing between domestic and foreign flows. Regions are divided into 4 groups obtained by pairing consecutive convergence clubs.

The integration of regions into GVCs plays a critical role in either reinforcing or mitigating emission intensity distribution in the EU production network. GVCs can serve as conduits for knowledge transfer, technological upgrading, and innovation, but their impact is highly contingent on regional innovation systems and governance patterns (Pietrobelli and Rabellotti, 2011). For high-emitting regions, participation in GVCs often occurs through captive or hierarchical governance modes, where lead firms dictate production standards but offer limited opportunities for technological learning and innovation. This can perpetuate a dependency on carbon-intensive activities, as seen in regions specialised in industrial and agricultural exports in Figure 8. The limited absorptive capacity of these regions, coupled with fragmented innovation systems, hinders their ability to leverage GVCs for upgrading and decarbonisation. The foreign segments exhibit even stronger concentration in these sectors than domestic activities, indicating that cross-border value chains amplify existing specialisation patterns.

In contrast, the less emitting, more developed regions—including capital cities—display a clear comparative advantage in high-tech services, finance, real estate, and distribution. These regions can exploit GVCs to access global knowledge, adapt technologies, and diversify into less emission-intensive sectors. The case of Berlin, which improved its rank significantly (+21), exemplifies how targeted innovation policies and urban decarbonisation strategies can enhance regional competitiveness within GVCs while reducing carbon intensity. These sectors, characterised by lower carbon intensity, are the predominant specialisation in both domestic and foreign value chains in these regions. However, the foreign specialisation is again more pronounced, highlighting that the integration of high-emitting clubs into GVCs is particularly skewed towards carbon-intensive industrial and agricultural exports.

8. Conclusions

This paper has contributed to a new theoretical and empirical understanding of the relationships between value chain production networks and environmental burden, measured via emission intensity, of European regions. Merging structural information from carbon intensity in the European region, which allows for the identification of clubs, or geographical clusters, with input-output interlinkages at the European level, we have shown that the patterns of integration of EU eastern regions have come at the cost of becoming the pollution havens of carbon elites regions.

The striking results of the persistent of different heterogeneous clubs in emission intensity, is accompanied by the verification that intra-EU emissions, although overall decreasing, have experienced an increasing pattern because of the fragmentation of productions, with eastern territories first assuming the role importing countries of low-value added production stages, and then the role of exporters of low-value added and low-paid intermediate productions, accompanied by emissions contents disproportionately higher when compared to the affluent North and Central Europe. As such, these findings contribute to ongoing debates on the developmental and environmental implications of GVC integration. They highlight a fundamental trade-off: while GVC participation may foster innovation diffusion and create growth opportunities, it simultaneously risks reinforcing environmental divergence and developmental asymmetries across Europe.

The analysis shows how convergence methods and production network approaches can be combined to uncover persistent spatial inequalities in emissions. In addition, the consistency between emission-based and production-based RCA analyses confirms that the disparities in carbon efficiency are structurally embedded in regional economic specialisation. The higher reactivity of foreign linkages to these patterns underscores the role of intra-EU trade in reinforcing spatial inequalities in carbon efficiency. The concentration of high-emitting regions in industrial and agricultural exports within GVCs suggests that efforts to reduce the carbon footprint of the EU production network must address these sectors directly. The retrograding trajectory, where regions experience declining capabilities and worsening emission profiles, underscores the risks associated with footloose GVCs and external competitive threats (Lema et al., 2018). While regions with strong innovation systems are better positioned to engage in GVCs upgrading, ultimately leading to a decrease in emissions intensity. Indeed, the benefits of GVC participation are not automatic; they require deliberate efforts to build technological capabilities and strengthen local innovation ecosystems (De Marchi et al., 2018). In conclusion, the spatial clustering of emission intensity in the EU production network is deeply intertwined with regional specialisation, innovation capacities, and GVC integration.

Our findings bear substantial policy implications: setting EU-level emission targets, without accounting for the emergence of pollution havens in peripheral regions, some of which are candidate member states, as Serbia or Turkey, risks missing the objective of a cohesive environmental and climate policy able to exert benefits for all. At the current stage, the patterns of integration into EU value chains seem to bring economic benefits in the short run for accessing regions/countries. The question is what happens in the long run, and who pay for the cost of environmental pollution. In addition, this long-run perspective, given the global climate emergence, will be shorter than expected. We have shown that production-based rather than consumption-based perspectives are more appropriate to identify which plant/sector pollutes, to what extent and how this environmental harm impinges upon the pattern of regional labour markets and how it is linked to territorial specialisation (Bez and Virgillito, 2024). Such a type of geographical mapping is quite important to design EU-level policies that target territories according to a principle of selective redistribution, that is, giving more to areas more deprived, looking however at the content of regional specialisation and emission profiles. At this stage, EU cohesion policies are missing the target of equalisation, while they are rather directly or indirectly influencing the patterns of regional asymmetries. Rethinking the implication of regional specialisation in high-emission production stages will imply considering not only targets but also restrictions on emission contents, but also environmental stringency requirements for headquarters. The lock-out from a carbon-intensive energy mix is the first strategy to undertake to decarbonise the EU. Efforts in such directions are timid vis-à-vis the urgency of the climate crisis.

Limitations of our findings include the limited time horizon and the lack of data availability connecting regional and industry-level value chains. Future studies should go in such directions to commonly track both dimensions. In addition, proxies for actual carbon-saving technological upgrading, constructing regional-level measures of diffusion of environmental technologies, would represent a new avenue of research, connecting regional and plant-level dimensions. The implications of the existence of pollution havens for the overall regional productive system still need to be assessed, and the role of interlinkages with China might trigger a reshuffling of the position of the peripheries in the coming years. Certainly, geopolitical pressures are by far more relevant in affecting the future paths of regional specialisation, particularly in the energy mix, than in the period analysed in this paper. New advancements should attempt to fill such shortcomings.

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Appendix

A. List of Regions Covered.

NUTS	Description	NUTS	Description	NUTS	Description
AT11	Burgenland	EL42	Notio Aigaio	ITF1	Abruzzo
AT12	Niederösterreich	EL43	Kriti	ITF2	Molise
AT13	Wien	EL51	Anatoliki Makedonia	ITF3	Campania
AT21	Kärnten	EL52	Kentriki Makedonia	ITF4	Puglia
AT22	Steiermark	EL53	Dytiki Makedonia	ITF5	Basilicata
AT31	Oberösterreich	EL54	Ipeiros	ITF6	Calabria
AT32	Salzburg	EL61	Thessalia	ITG1	Sicilia
AT33	Tirol	EL62	Ionia Nisia	ITG2	Sardegna
AT34	Vorarlberg	EL63	Dytiki Elláda	ITH1	Provincia Aut. di Bolzano
BE10	Bruxelles-Capitale	EL64	Sterea Elláda	ITH2	Provincia Aut. di Trento
BE21	Prov. Antwerpen	EL65	Peloponnisos	ITH3	Veneto
BE22	Prov. Limburg (BE)	ES11	Galicia	ITH4	Friuli-Venezia Giulia
BE23	Prov. Oost-Vlaanderen	ES12	Principado de Asturias	ITH5	Emilia-Romagna
BE24	Prov. Vlaams-Brabant	ES13	Cantabria	ITI1	Toscana
BE25	Prov. West-Vlaanderen	ES21	País Vasco	ITI2	Umbria
BE31	Prov. Brabant Wallon	ES22	Comunidad de Navarra	ITI3	Marche
BE32	Prov. Hainaut	ES23	La Rioja	ITI4	Lazio
BE33	Prov. Liège	ES24	Aragón	LT01	Sostinės regionas
BE34	Prov. Luxembourg (BE)	ES30	Comunidad de Madrid	LT02	Vidurio ir vakarų Lietuvos
BE35	Prov. Namur	ES41	Castilla y León	LU00	Luxembourg
BG31	Severozapaden	ES42	Castilla-La Mancha	LV00	Latvija
BG32	Severen tsentralen	ES43	Extremadura	MT00	Malta
BG33	Severoiztochen	ES51	Cataluña	NL11	Groningen
BG34	Yugoiztochen	ES52	Comunitat Valenciana	NL12	Friesland (NL)
BG41	Yugozapaden	ES53	Illes Balears	NL13	Drenthe
BG42	Yuzhen tsentralen	ES61	Andalucía	NL21	Overijssel
CY00	Kýpros	ES62	Región de Murcia	NL22	Gelderland
CZ01	Praha	ES63	Ciudad de Ceuta	NL23	Flevoland
CZ02	Střední Čechy	ES64	Ciudad de Melilla	NL31	Utrecht
CZ03	Jihozápad	ES70	Canarias	NL32	Noord-Holland
CZ04	Severozápad	FI19	Länsi-Suomi	NL33	Zuid-Holland
CZ05	Severovýchod	FI1B	Helsinki-Uusimaa	NL34	Zeeland
CZ06	Jihovýchod	FI1C	Etelä-Suomi	NL41	Noord-Brabant
CZ07	Střední Morava	FI1D	Pohjois- ja Itä-Suomi	NL42	Limburg (NL)
CZ08	Moravskoslezsko	FI20	Aland	PL21	Małopolskie
DE11	Stuttgart	FR10	Ile-de-France	PL22	Śląskie
DE12	Karlsruhe	FRB0	Centre — Val de Loire	PL41	Wielkopolskie
DE13	Freiburg	FRC1	Bourgogne	PL42	Zachodniopomorskie
DE14	Tübingen	FRC2	Franche-Comté	PL43	Lubuskie

DE21	Oberbayern	FRD1	Basse-Normandie	PL51	Dolnośląskie
DE22	Niederbayern	FRD2	Haute-Normandie	PL52	Opolskie
DE23	Oberpfalz	FRE1	Nord-Pas de Calais	PL61	Kujawsko-pomorskie
DE24	Oberfranken	FRE2	Picardie	PL62	Warmińsko-mazurskie
DE25	Mittelfranken	FRF1	Alsace	PL63	Pomorskie
DE26	Unterfranken	FRF2	Champagne-Ardenne	PL71	Łódzkie
DE27	Schwaben	FRF3	Lorraine	PL72	Świętokrzyskie
DE30	Berlin	FRG0	Pays de la Loire	PL81	Lubelskie
DE40	Brandenburg	FRH0	Bretagne	PL82	Podkarpackie
DE50	Bremen	FRI1	Aquitaine	PL84	Podlaskie
DE60	Hamburg	FRI2	Limousin	PL91	Warszawski stołeczny
DE71	Darmstadt	FRI3	Poitou-Charentes	PL92	Mazowiecki regionalny
DE72	Gießen	FRJ1	Languedoc-Roussillon	PT11	Norte
DE73	Kassel	FRJ2	Midi-Pyrénées	PT15	Algarve
DE80	Mecklenburg-Vorpommern	FRK1	Auvergne	PT16	Centro (PT)
DE91	Braunschweig	FRK2	Rhône-Alpes	PT17	Área Metrop. de Lisboa
DE92	Hannover	FRL0	Provence-Côte d'Azur	PT18	Alentejo
DE93	Lüneburg	FRM0	Corse	PT20	Região Aut. dos Açores
DE94	Weser-Ems	FRY1	Guadeloupe	PT30	Região Aut. da Madeira
DEA1	Düsseldorf	FRY2	Martinique	RO11	Nord-Vest
DEA2	Köln	FRY3	Guyane	RO12	Centru
DEA3	Münster	FRY4	La Réunion	RO21	Nord-Est
DEA4	Detmold	FRY5	Mayotte	RO22	Sud-Est
DEA5	Arnsberg	HR02	Panonska Hrvatska	RO31	Sud-Muntenia
DEB1	Koblenz	HR03	Jadranska Hrvatska	RO32	Bucureşti-Ilfov
DEB2	Trier	HR05	Grad Zagreb	RO41	Sud-Vest Oltenia
DEB3	Rheinhessen-Pfalz	HR06	Sjeverna Hrvatska	RO42	Vest
DEC0	Saarland	HU11	Budapest	SE11	Stockholm
DED2	Dresden	HU12	Pest	SE12	Östra Mellansverige
DED4	Chemnitz	HU21	Közép-Dunántúl	SE21	Småland med öarna
DED5	Leipzig	HU22	Nyugat-Dunántúl	SE22	Sydsverige
DEE0	Sachsen-Anhalt	HU23	Dél-Dunántúl	SE23	Västsverige
DEF0	Schleswig-Holstein	HU31	Észak-Magyarország	SE31	Norra Mellansverige
DEG0	Thüringen	HU32	Észak-Alföld	SE32	Mellersta Norrland
DK01	Hovedstaden	HU33	Dél-Alföld	SE33	Övre Norrland
DK02	Sjælland	IE04	Northern and Western	SI03	Vzhodna Slovenija
DK03	Syddanmark	IE05	Southern	SI04	Zahodna Slovenija
DK04	Midtjylland	IE06	Eastern and Midland	SK01	Bratislavský kraj
DK05	Nordjylland	ITC1	Piemonte	SK02	Západné Slovensko
EE00	Eesti	ITC2	Valle d'Aosta	SK03	Stredné Slovensko
EL30	Attiki	ITC3	Liguria	SK04	Východné Slovensko
EL41	Voreio Aigaio	ITC4	Lombardia		

B. Club Convergence

Club1: BG31, BG32, BG33, CZ05, EL64, EL65, NL11, PL52, PL71, PL72, PL81, PL92, PT16, RO41.

Club 2: BE32, BG42, CZ02, CZ04, CZ08, DEE0, EE00, ES12, HR02, HU21, HU23, HU31, NL34, PL22, PL42, PL43, PL61, RO31, SK04.

Club 3: BE34, CZ03, DE40, DEC0, EL43, EL51, EL52, EL54, EL61, ES24, ES41, ES42, HR03, HR06, HU12, HU22, HU32, HU33, IE04, ITF2, ITG2, LT02, PL41, PL51, PL62, PL82, PL84, PT17, RO12, RO21, RO22, RO42, SI03, SK02.

Club 4: AT22, BE23, BE33, BE35, BG41, CY00, CZ06, CZ07, DE12, DE50, DE80, DE94, DEA1, DEA3, DEA5, DED2, DED5, DEF0, DK05, EL41, EL42, EL62, EL63, ES11, ES43, ES61, ES62, FI19, FI1C, FRE1, FRE2, FRF2, FRH0, FRI2, FRK1, ITF4, ITF5, ITF6, LV00, NL13, NL23, NL42, PL21, PL63, RO11, SK03.

Club 5: AT11, AT12, AT21, AT31, BE22, BE25, DE23, DE72, DE73, DE91, DE93, DEA2, DEB1, DEB2, DEB3, DED4, DEG0, DK02, EL30, ES13, ES22, ES23, ES52, ES53, ES70, FI1D, FRB0, FRC1, FRC2, FRD1, FRD2, FRG0, FRI3, FRJ1, FRL0, IE05, ITC1, ITC2, ITF1, ITG1, ITH3, ITH4, ITH5, ITI2, ITI4, NL12, NL33, PT11, PT15, PT20, SE33, SI04.

Club 6: AT32, AT33, BE21, BE24, BE31, DE11, DE13, DE14, DE21, DE22, DE24, DE25, DE26, DE27, DE60, DE92, DEA4, DK03, DK04, ES21, ES51, ES63, FI1B, FRF1, FRI1, FRJ2, FRK2, FRM0, FRY1, FRY2, FRY3, FRY4, HR05, ITC3, ITC4, ITF3, ITH1, ITH2, ITI1, ITI3, LT01, LU00, MT00, NL21, NL22, NL32, NL41, PL91, SE12, SE21, SE23, SE31, SE32, SK01.

Club 7: AT34, CZ01, DE30, DE71, ES64, HU11, IE06, NL31, PT30, RO32, SE22.

Club 8: AT13, DK01, FR10.

C. Shift Share Analysis

To understand the drivers behind the evolution of CO_2 multipliers within the intra-EU production network, we employ a shift-share analysis (SSA). This method decomposes the total change in a variable into the contributions of its constituent factors.

A standard two-factor decomposition distinguishes between changes within sectors (holding weights constant) and changes between sectors (holding within-sector values constant). Our case requires a more granular, four-factor decomposition of the change in the CO_2 multiplier. In what follows, we use the following notation:

- fd and l refer to final demand and input shares, respectively.
- L refers to the total input requirements.
- c refers to the CO_2 emission factor.
- A prime symbol $'$ denotes a value from the final period.

Since the aggregate decomposition for the intra-EU network is the sum of all individual input-output cell decompositions, the formula below holds for each input (i,j) used in the production process of (h,k).

$$\Delta CO2Mult = CO2Mult' - CO2Mult = (fd'l'L'c') - (fdlLc) =$$

$$(fd' - fd)\frac{1}{4}\left[\frac{(c'l'L') + (clL)}{2} + \frac{(c'L') + (cL)}{2}\frac{(l' + l)}{2} + 2\left(\frac{(l' + l)}{2}\frac{(L' + L)}{2}\frac{(c' + c)}{2}\right)\right] +$$

$$+(c' - c)\frac{1}{4}\left[\frac{(fd'l'L') + (fdlL)}{2} + \frac{(l'fd') + (lfd)}{2}\frac{(L' + L)}{2} + 2\left(\frac{(l' + l)}{2}\frac{(L' + L)}{2}\frac{(fd' + fd)}{2}\right)\right] +$$

$$+(l' - l)\frac{1}{4}\left[\frac{(c'fd'L') + (cfdL)}{2} + \frac{(c'L') + (cL)}{2}\frac{(fd' + fd)}{2} + 2\left(\frac{(fd' + fd)}{2}\frac{(L' + L)}{2}\frac{(c' + c)}{2}\right)\right] +$$

$$+(L' - L)\frac{1}{4}\left[\frac{(c'l'fd') + (clfd)}{2} + \frac{(l'fd') + (lfd)}{2}\frac{(c' + c)}{2} + 2\left(\frac{(l' + l)}{2}\frac{(fd' + fd)}{2}\frac{(c' + c)}{2}\right)\right].$$

Note that the scope of this appendix is not to derive the whole shift-share decomposition but just to deliver the full formula.