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Designing effective climate policy: Sectoral approaches to energy-related carbon reduction strategies

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Abstract

Aggregate emission reductions can conceal a redistribution of climate-policy burdens across sectors. This study reanalyses published EU27 Kaya indices and sectoral emission shares for 1990-2022 to ask whether economic-environmental decoupling has been accompanied by a shift toward harder-to-abate activities. The extension introduces five complementary indicators: log-change contribution accounting, mitigation-to-growth leverage, decoupling elasticity, a sectoral reallocation index, and concentration and entropy measures. Per-capita GDP increased by 44.6%, while the combined effects of lower energy and carbon intensity outweighed the scale effect by a factor of 2.50. Per-capita CO_2 emissions consequently fell by 42.5%. At the same time, 20 percentage points of the emissions distribution were reallocated among sectors. Transport, residential, and agriculture/waste increased their combined share from 31% to 51%, while the Herfindahl-Hirschman Index fell from 0.289 to 0.237, indicating a more dispersed and institutionally complex mitigation burden. The findings show that successful aggregate decoupling does not eliminate sectoral lock-in. EU climate policy must preserve power-sector momentum while strengthening coordinated, sector-specific instruments for mobility, buildings, industry, and non-CO_2 agricultural emissions.

Keywords: aggregate decoupling, sectoral reallocation, Kaya identity, climate-policy coordination, European Union, hard-to-abate sectors.

1. Introduction

The European Union (EU) has reduced greenhouse gas emissions while expanding economic activity, a development commonly described as absolute decoupling. Yet aggregate success does not imply that every sector follows the same trajectory. Power generation can decarbonize through renewable deployment and fuel substitution, whereas transport, buildings, industry, agriculture, and waste face different infrastructures, investment cycles, behavioural constraints, and non-CO_2 sources. A decline in total emissions may therefore coexist with a redistribution of the remaining burden toward activities that are harder to regulate and technically more difficult to abate.

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This distinction matters for policy design. When emissions are concentrated in a small number of large stationary sources, carbon pricing and technology standards can operate through relatively well-defined regulated entities. As the power sector improves, the residual burden becomes distributed across vehicles, buildings, farms, industrial processes, and local infrastructure. Decarbonization then depends increasingly on coordination among EU institutions, Member States, municipalities, firms, and households. The composition of emissions can therefore become more important than the aggregate trend.

The present study is an explicit extension of Tutar, Štreimikienė, and Kyriakopoulos (2026), who applied sectoral Kaya and Log-Mean Divisia Index decomposition to EU27 emissions over 1990-2022. Their study established the main sectoral trajectories and showed that energy-intensity and fuel-mix improvements were strongest in the power sector, while transport displayed a rebound effect. Rather than repeating that decomposition, this article asks a different question: has aggregate decoupling redistributed the EU emissions burden toward a wider set of harder-to-abate sectors, thereby increasing the coordination demands of climate policy?

The analytical contribution is fivefold. First, the published Kaya indices are transformed into additive log-change contributions, allowing the growth effect to be compared directly with energy- and carbon-intensity effects. Second, a mitigation-to-growth leverage ratio measures how strongly intensity improvements offset economic expansion. Third, a simple decoupling elasticity summarizes the direction and scale of the per-capita response. Fourth, a sectoral reallocation index quantifies the share of emissions that moved among sectors between 1990 and 2022. Fifth, concentration and entropy measures test whether the residual burden became more concentrated or more dispersed. Together, these indicators connect decoupling performance with the institutional complexity of the next stage of EU climate policy.

2. Literature review

2.1. From aggregate decoupling to sectoral reallocation

Absolute decoupling occurs when economic output rises while environmental pressure falls. At aggregate level, this is a desirable outcome, but it provides limited information about where mitigation occurred. A rapid decline in electricity emissions can dominate the total even if transport demand grows or building renovation remains slow. The aggregate indicator therefore combines two analytically different processes: a reduction in emissions intensity and a change in the sectoral distribution of the emissions that remain.

Sectoral reallocation is defined here as the redistribution of emission shares between activities. It is not automatically beneficial or harmful. A lower concentration can reduce dependence on one sector, but it can also disperse responsibility across many heterogeneous actors. This creates a policy-coordination problem: instruments that work for utilities cannot simply be transferred to households, freight operators, farmers, or energy-intensive manufacturers. The policy portfolio must become broader at precisely the point when the remaining abatement options are more costly and institutionally fragmented.

2.2. Growth pressure and mitigation leverage

The Kaya Identity separates per-capita emissions into GDP per capita, energy use per unit of GDP, and CO_2 per unit of energy. Multiplicative index changes can be expressed additively in logarithms. This makes it possible to compare the positive scale pressure associated with income growth against the negative contributions from energy efficiency and a cleaner energy mix. The mitigation-to-growth leverage ratio introduced below shows whether the combined intensity improvements merely match growth pressure or exceed it by a substantial margin.

2.3. Enabling mechanisms and sector-specific constraints

The transition from concentrated to distributed emissions sources increases the importance of digital coordination, data, and place-based implementation. Smart-city systems and big-data analytics can support infrastructure planning and individualized services (Allam & Dhunny, 2019; Lehrer et al., 2021), while digital innovation can contribute to wider sustainability transitions when it is connected to institutional and organizational change (Mäkitie et al., 2023). Sustainability-oriented digital transformation frameworks likewise emphasize that technology must be assessed together with environmental objectives and decision capabilities (Elia et al., 2020; Martínez-Peláez et al., 2024a, 2024b).

At firm level, decarbonization depends not only on technology adoption but also on viable business-model change. Research on sustainable business models identifies value creation, delivery, and capture mechanisms that can align commercial activity with environmental goals (Evans et al., 2017; Lüdeke-Freund et al., 2018). Studies of Industry 4.0, creative industries, SMEs, and digital entrepreneurship further show that organizational capabilities, resilience, and context condition whether digitalization generates sustainability benefits (Müller et al., 2018; Li, 2020; Grabowska & Saniuk, 2022; Isensee et al., 2023; Hajiheydari et al., 2023; Judijanto, 2025; Scuotto et al., 2021).

Behavioural and knowledge mechanisms are equally important because distributed mitigation requires choices by consumers, managers, and public institutions. Green marketing can shape how environmental value is communicated (Dangelico & Vocalelli, 2017), and evidence on digital marketing links technological diffusion with sustainable-development narratives (Acheampong et al., 2023). Education for sustainability and the integration of sustainability into economics and higher-education curricula can strengthen the competencies needed for implementation, although institutional barriers to digital transformation remain substantial (Brundiers et al., 2020; Ghosh et al., 2023; Noguera-Méndez et al., 2024; Troise et al., 2022).

Agriculture illustrates why sectoral structure matters. The organization and concentration of agricultural production influence investment capacity, bargaining power, technology uptake, and the feasibility of monitoring emissions. Integrated sustainable-development business models can help connect farm-level decisions with broader environmental objectives (Strapchuk, 2023). These sector-specific conditions reinforce the need to interpret aggregate decoupling through the changing composition of emissions.

2.4 Research questions

Based on the literature review, the following research questions are to be addressed:

RQ1: By how much did improvements in energy and carbon intensity offset the emissions pressure associated with EU per-capita income growth between 1990 and 2022?

RQ2: Did the sectoral distribution of emissions become more concentrated or more dispersed, and how much of the emissions share was reallocated?

RQ3: Did the combined share of transport, residential, and agriculture/waste activities increase, indicating a shift toward sectors with distributed sources and complex governance requirements?

3. Methods

This article uses secondary aggregate indicators reported by Tutar et al. (2026): EU27 indexed values for GDP per capita, energy intensity, carbon intensity, and CO_2 per capita, together with sectoral emission shares for 1990 and 2022 (Table 1). The novelty lies in the additional indicators, the sectoral-reallocation research question, and the interpretation of dispersion as a climate-governance challenge. Tutar et al. (2026) should be consulted for the original Eurostat, IEA, and EEA data harmonization, sector definitions, and LMDI procedures.

Table 1
Indicators and trends

Indicator	1990	2022	Use in this study
GDP per capita index	100.0	144.6	Scale contribution and decoupling elasticity
Energy-intensity index	100.0	65.7	Efficiency contribution
Carbon-intensity index	100.0	60.5	Energy-mix contribution
CO_2 per-capita index	100.0	57.5	Observed net decoupling
Five sectoral shares	100%	100%	Reallocation, HHI, entropy, hard-to-abate share

Source: Authors' calculations from the indices and sectoral shares reported by Tutar et al. (2026).

Let y denote CO_2 emissions per capita, g GDP per capita, e energy intensity (energy/GDP), and c carbon intensity (CO_2/energy). The indexed Kaya relation is $y = g \times e \times c$. For endpoints 0 and 1, the change can be written as $\Delta\ln(y) = \Delta\ln(g) + \Delta\ln(e) + \Delta\ln(c)$. Positive values increase emissions; negative values reduce them. Because this is an exact logarithmic identity, the three contributions sum to the observed log change apart from rounding in the published indices.

Mitigation-to-growth leverage is defined as $L = (|\Delta\ln(e)| + |\Delta\ln(c)|)/\Delta\ln(g)$, where $\Delta\ln(g)$ is positive. $L > 1$ means that combined intensity improvements more than offset growth pressure. The relative shares of energy and carbon intensity in total mitigation are computed from their absolute negative log contributions. A complementary endpoint elasticity, ε = percentage change in per-capita CO_2 divided by percentage change in per-capita GDP, indicates absolute decoupling when GDP grows and ε is negative.

For sector i, the share change is $\Delta s_i = s_{i,2022} - s_{i,1990}$. The sectoral reallocation index is $SRI = 0.5\Sigma|\Delta s_i|$. The factor one-half prevents double counting because every gained percentage point must be lost by another sector. Concentration is measured by the Herfindahl-Hirschman Index, $HHI = \Sigma s_i^2$, with shares expressed as proportions. Shannon entropy, $H = -\Sigma s_i \ln(s_i)$, provides a complementary measure in which a higher value indicates a more even distribution. Finally, the hard-to-abate/distributed-source share is operationalized as the combined share of transport, residential, and agriculture/waste emissions. This grouping is transparent but interpretive; it does not imply that every source within these sectors has the same marginal abatement cost.

4. Results

Between 1990 and 2022, the log contribution of per-capita income growth was +0.369. Energy-intensity improvement contributed -0.420, and lower carbon intensity contributed -0.503. The net log change was -0.553, equivalent to the fall in the CO_2 per-capita index from 100 to 57.5. The combined mitigation contribution was therefore 2.50 times the scale contribution. Carbon-intensity improvement accounted for 54.5% of the total downward contribution and energy-intensity improvement for 45.5%.

The endpoint elasticity was -0.95: per-capita emissions fell by approximately 0.95 percentage points for each percentage point increase in per-capita GDP over the full period (Table 2). This is strong absolute decoupling, but it should not be interpreted as a short-run causal elasticity. It is a two-endpoint summary of long-run structural change. A graphical interpretation is provided in Figure 1.

Table 2. Growth pressure, mitigation contributions, and decoupling indicators

Measure	Value	Direction	Interpretation
Income-scale log contribution	+0.369	Upward	Economic growth increased potential emissions
Energy-intensity log contribution	-0.420	Downward	45.5% of combined mitigation contribution
Carbon-intensity log contribution	-0.503	Downward	54.5% of combined mitigation contribution
Net per-capita CO_2 log change	-0.553	Downward	Index declined from 100 to 57.5
Mitigation-to-growth leverage	2.50	Above 1	Intensity gains more than offset growth
Endpoint decoupling elasticity	-0.95	Negative	Absolute decoupling over 1990-2022

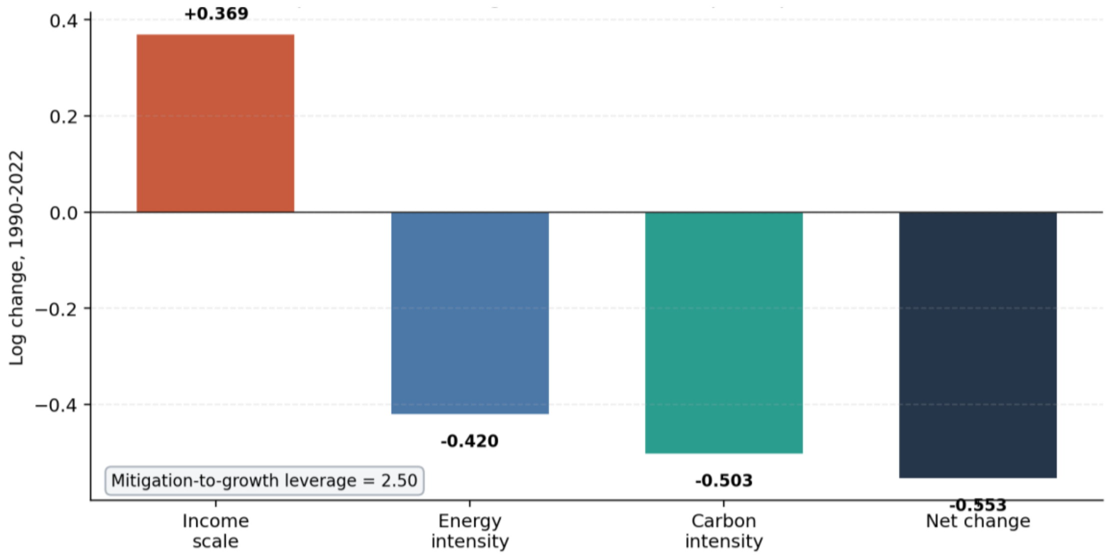

Fig. 1. Growth pressure and mitigation effects in EU per-capita CO_2 emissions, 1990-2022.

Note: Exact log changes calculated from the endpoint indices reported by Tutar et al. (2026). The net value differs slightly from the sum of displayed components because the published indices are rounded.

The sectoral reallocation index equals 20 percentage points. Energy lost 17 points of total emissions share and industry lost three (Table 3). Transport gained 13 points, residential sources gained three, and agriculture/waste gained four. The change is not simply a decline in one leading sector: it is a redistribution toward several activities with different technologies and responsible actors. Figure 2 summarizes these results.

Table 3
Sectoral share reallocation between 1990 and 2022

Sector	1990 share	2022 share	Change (pp)	Policy implication
Energy	41%	24%	-17	Power-sector success reduces its dominance but must be maintained
Industry	28%	25%	-3	Moderate decline; deep-process technologies remain necessary
Transport	18%	31%	+13	Largest increase; activity growth offsets efficiency gains
Residential	9%	12%	+3	Distributed assets require renovation and heating transition
Agriculture/Waste	4%	8%	+4	Non-CO_2 mitigation and sink governance become more prominent

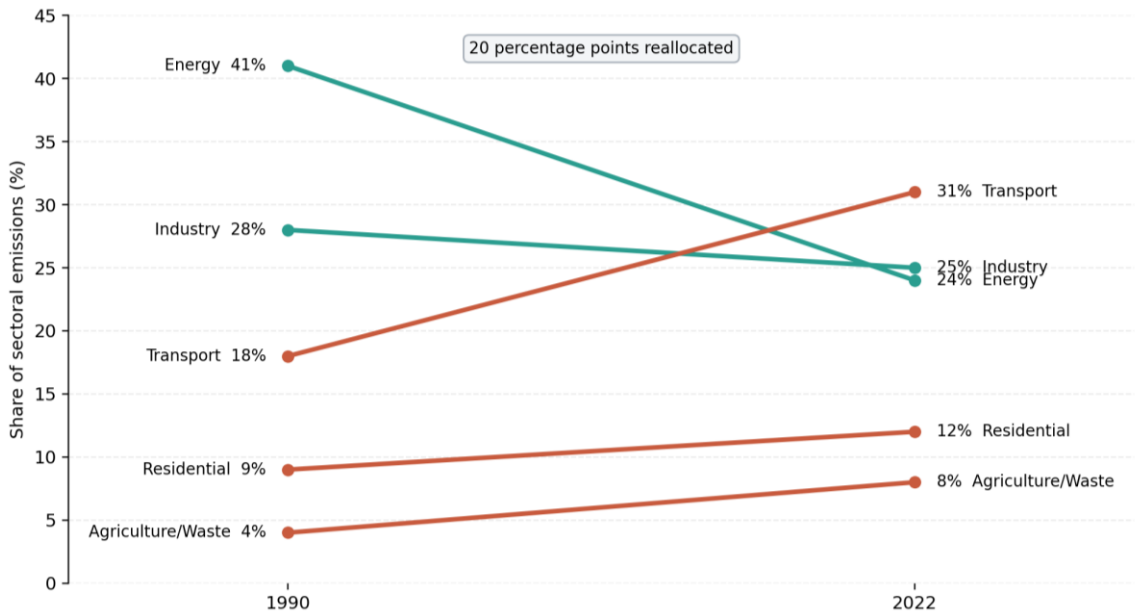

Figure 2. Reallocation of the EU emissions burden across sectors, 1990-2022. Source: Authors' calculations from sectoral shares reported by Tutar et al. (2026). Percentage-point changes refer to composition and should not be read as percentage changes in absolute emissions.

The HHI declined from 0.2886 to 0.2370, a reduction of -17.9% (Table 4). Shannon entropy increased from 1.376 to 1.509. Both measures show that emissions became more evenly distributed across the five sectors. At the same time, the combined share of transport, residential, and agriculture/waste rose from 31% to

51%. Thus, the remaining burden is both less concentrated and more heavily located in sectors characterized by distributed sources, heterogeneous decision makers, or non-CO_2 processes.

Table 4
Indicators of sectoral dispersion and policy complexity

Indicator	1990	2022	Change/meaning
Herfindahl-Hirschman Index	0.2886	0.2370	-17.9%: lower concentration
Shannon entropy	1.376	1.509	+0.133: greater dispersion
Transport + residential + agriculture/waste	31%	51%	+20 pp: larger distributed-source burden
Sectoral reallocation index	-	20 pp	One-fifth of total share redistributed

5. Discussion

The findings change the interpretation of EU decoupling in an important way. The aggregate result is strong: reductions in energy and carbon intensity together exceeded income-related scale pressure by a factor of 2.50. Yet this success was accompanied by a major compositional shift. Power generation ceased to dominate emissions to the same extent, while transport became the largest sector and the combined share of distributed-source sectors exceeded one-half. Aggregate decoupling therefore marks progress, but it also changes the governance problem.

The lower HHI and higher entropy should not be read as deteriorating environmental performance. They show that responsibility is spread more evenly across sectors. This dispersion makes a single-instrument strategy less credible. Emissions trading remains important for electricity and large industry, but it cannot by itself accelerate building renovation, restructure urban mobility, manage aviation demand, change fertilizer use, or strengthen carbon sinks. These tasks require distinct financing arrangements, standards, infrastructure, information, and implementation capacities.

The results also clarify why continued power-sector progress is necessary but no longer sufficient. Electrification transfers energy demand from vehicles, heating, and some industrial processes to the electricity system. Its climate benefit depends on keeping electricity carbon intensity on a downward path while expanding grids, storage, and flexibility. A slowdown in power-sector decarbonization would weaken mitigation in every end-use sector. Conversely, clean electricity alone will not overcome rebound effects, slow asset replacement, or behavioural and institutional barriers.

The carbon-intensity contribution was slightly larger than the energy-intensity contribution in the endpoint accounting. This suggests that fuel switching and renewable deployment played at least as important a role as using less energy per unit of output. Policy should not infer that efficiency has become secondary. Efficiency reduces the scale of the clean-energy system that must be built, lowers infrastructure costs, and helps protect households from energy-price exposure. The two strategies are complementary, as their combined leverage is what produced absolute decoupling.

An effective EU policy architecture should combine a common direction with differentiated implementation. For power and large industry, carbon pricing, contracts for difference, permitting reform, and infrastructure investment can reduce technology and market risk. For road transport, standards and charging networks need to be reinforced by public transport, urban planning, and measures that address total mobility demand. For buildings, long-term renovation finance, minimum performance standards, heat-pump deployment, and protection for vulnerable households must operate together. Agriculture requires verified methane and nitrous oxide mitigation, improved manure and fertilizer management, and stronger incentives for soil and ecosystem carbon. Waste policy should continue methane capture while prioritizing prevention and circular material flows, for which digitalization can provide important enabling infrastructure (Antikainen, 2018).

The sectoral reallocation index can serve as a compact monitoring indicator. A continued fall in total emissions accompanied by further reallocation toward difficult sectors would signal the need to shift administrative capacity and investment support. It should be reported together with absolute emissions because share changes alone can be misleading. Concentration and entropy measures can similarly help policymakers anticipate whether mitigation is becoming more dependent on a narrow set of regulated entities or more dispersed across households, firms, and local authorities.

This study does not present the Kaya decomposition, sectoral dataset, or 1990-2022 endpoints as new evidence. Those elements originate from Tutar et al. (2026). The present contribution is a transparent secondary extension: it reformulates the endpoint indices as additive log contributions, introduces leverage and elasticity metrics, quantifies sectoral reallocation, and evaluates changes in concentration, entropy, and the combined share of distributed-source sectors. It also develops a distinct interpretation centred on the changing coordination demands of EU climate policy. This explicit relationship avoids treating previously published results as an independent empirical study.

6. Conclusions

The EU achieved strong aggregate decoupling between 1990 and 2022: energy- and carbon-intensity improvements jointly outweighed per-capita income growth by a factor of 2.50, and per-capita CO_2 emissions fell substantially. However, the structure of the remaining emissions changed. Twenty percentage points of sectoral share were reallocated, concentration declined, and transport, residential, and agriculture/waste activities increased their combined share from 31% to 51%.

This creates a new phase of climate policy. Earlier reductions were driven heavily by power-sector transformation; future progress depends increasingly on coordinating multiple instruments across mobile sources, buildings, industrial processes, agriculture, waste, and land use. Effective policy must therefore be differentiated by sector but integrated across governance levels. Aggregate targets remain essential, yet they should be accompanied by indicators that reveal where the residual burden is moving and whether institutions and investment are moving with it.

The analysis uses two endpoint years for the sectoral-distribution measures and therefore cannot identify the timing of reallocation or distinguish cyclical shocks from persistent changes. The published indices are rounded, creating a small identity residual. Sectoral shares describe composition rather than absolute emission changes. The hard-to-abate grouping is an operational classification and conceals substantial variation within sectors. Finally, the indicators are descriptive and do not establish causal effects of individual EU policies.

Future research should calculate the reallocation, concentration, and leverage measures annually and by Member State. Linking them to policy implementation, investment, energy prices, technology adoption, and distributional outcomes would permit dynamic panel or quasi-experimental analysis. Consumption-based emissions should also be incorporated to test whether declining domestic concentration reflects genuine mitigation or relocation of carbon-intensive production. A sector-country panel would make it possible to identify which governance combinations prevent aggregate progress from stalling as the residual burden becomes more dispersed.

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