

A CRITICAL ANALYSIS OF THE FEASIBILITY OF THE GREEN DEAL: AN EMPIRICAL EXAMINATION OF THE MACROECONOMIC REBOUND EFFECT AND DECOUPLING IN THE EU-27 MEMBER STATES

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ABSTRACT

Current environmental challenges, especially climate change, biodiversity loss, and resource depletion, make it increasingly clear that growth-based economic models are unsustainable. In light of these challenges, a paradigm shift in economic policy thinking is becoming increasingly urgent. Decoupling – the separation of economic growth from environmental pressures – occupies a central place in the theory of sustainable development; although desirable in theory, it faces numerous empirical limitations. This study examines the constraints on the feasibility of decoupling across the 27 Member States of the European Union in light of the macroeconomic rebound effect. The methodology combines comparative analysis and panel econometrics. Relative decoupling is achievable in some cases, but evidence of absolute decoupling remains limited. A further problem is that technological efficiency gains are often offset by the rebound effect, while economic globalization shifts environmental pressures to developing countries. In light of these findings, reconsidering the current economic model and prioritizing strategies aimed at reducing material and energy use in absolute terms are essential to achieving a fairer and more ecologically sustainable future.

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1 INTRODUCTION AND THEORETICAL FRAMEWORK: THE ECOLOGICAL LIMITS OF UNLIMITED GROWTH

Decoupling is a central concept in ecological economics and sustainability thinking. Its importance comes from the fact that conventional economic growth and environmental pressure are closely intertwined: based on historical data, growth in gross domestic product (GDP) is, almost without exception, accompanied by an increase in resource consumption and environmental pollution. The aim of *decoupling* is to break this structural link.

This paradigm shift is made imperative by the planet's finite carrying capacity (*planetary boundaries*). As the capacity of the Earth's ecosystems is finite, unrestricted resource use leads to cumulative environmental crises. Whilst the classical economic paradigm is growth-oriented and largely treats environmental externalities as secondary, ecological economics highlights that infinite physical growth cannot be sustained within a finite system; and, moreover, an increase in material throughput does not automatically result in an increase in social well-being (Meadows et al., 1972). Unrestricted production and consumption, which form the heart of the conventional economic model, thus create a system-level ecological trap that threatens the long-term viability of the natural environment (Jackson, 2009).

Despite all these theoretical limitations, the strategic programmes of the United Nations, the European Union and numerous nation states today are based on the assumption that weakening or eliminating the link between economic growth and environmental pressure will make it possible to maintain the growth paradigm. One of the key policy commitments of the *European Green Deal*, published by the European Commission in December 2019, is precisely that achieving climate protection targets will not entail a halt to economic development (European Commission, 2019). The overarching objective of the initiative is to make the EU climate-neutral by 2050, whilst the medium-term 'Fit for 55' package stipulates an emissions reduction of at least 55 per cent by 2030 compared with the 1990 base year.

The literature reviewed distinguishes between two main types of *decoupling* (Wiedenhofer et al., 2020):

- *Relative* decoupling: The economy continues to grow, but the rate of increase in environmental pressure lags behind the rate of GDP growth.
- *Absolute* decoupling: Whilst GDP grows, the environmental impact decreases in absolute terms.

However, the 'green growth' approach, which dominates policy strategies, has come in for serious criticism (Laurent, 2020; Parrique et al., 2019). On the one

hand, policymakers primarily rely on production-based (territorial) emissions indicators, which, due to outsourced production, are often significantly lower than consumption-based (ecological footprint-type) indicators, thereby painting a false picture of the actual outcomes. Furthermore, this approach rests on the questionable assumption that improvements in technological efficiency alone are sufficient to reduce environmental pressure, without limiting the volume of production and consumption.

2 THE REBOUND EFFECT AS A STRUCTURAL CONSTRAINT ON DECOUPLING

The main theoretical and practical obstacle to the absolute decoupling of economic growth and environmental pressure is the rebound effect (Sorrell, 2007). The roots of this phenomenon go back to the Jevons paradox, described by William Stanley Jevons (1865), which demonstrated that improvements in technological efficiency, by reducing unit production costs, do not lead to a reduction in resource use, but rather encourage the further expansion of consumption and production (Gillingham, 2014; Jarvis-King, 2024).

Modern resource economics (Sorrell, 2009; Font Vivanco et al., 2016) distinguishes between three interrelated and mutually reinforcing levels of the rebound effect:

1. Direct effect: A reduction in the unit cost of a given energy-efficient technology or service directly increases individual demand for that service, in accordance with microeconomic demand theory (through the substitution and income effects).
2. Indirect effect: The monetary savings resulting from increased efficiency (discretionary income freed up for consumers, cost reductions for businesses) are channelled into consumption or investment in other sectors and products that are also potentially resource- and energy-intensive.
3. Macroeconomic impact: System-wide improvements in energy efficiency boost the productivity and competitiveness of the entire national economy. Through implicit price reductions, this reshapes global supply chains, accelerates economic growth, and thereby results in higher aggregate energy and material consumption (Barker et al., 2009).

The existence of the macroeconomic rebound effect fundamentally questions the feasibility of absolute *decoupling* (Antal-van den Bergh, 2016): it highlights that system-level economic feedback loops triggered by efficiency-driven technological progress neutralise engineering-based energy savings (Brockway et al., 2021).

In the context of ecological economics, the rebound effect is therefore not a technical flaw that can be eliminated, but rather an immanent structural consequence of the imperatives of capital accumulation and growth (Hickel–Kallis, 2020).

3 RESEARCH OBJECTIVES, HYPOTHESES AND METHODOLOGICAL FRAMEWORK

The primary aim of this study is to investigate whether technological improvements in energy efficiency, treated as a priority in energy policy strategies, are capable of achieving an absolute reduction in material and energy flows, or whether system-level macroeconomic feedback loops neutralise these engineering-driven savings. To empirically test this theoretical and policy-related tension, we formulate the following main hypothesis:

H1: *In the EU-27 countries, improvements in energy efficiency (a reduction in energy intensity) do not lead to an absolute reduction in environmental pressure, as the absolute increase in energy consumption generated by economic growth offsets the relative efficiency gains (macroeconomic rebound effect).*

To test this hypothesis and identify the driving forces shaping environmental pressure, this study applies the IPAT model, which breaks down environmental pressure (I) into the factors of population (P), social welfare/GDP per capita (A) and technological efficiency (T) (Dietz–Rosa, 1997; Ehrlich–Holdren, 1971).

As the reviewed literature highlights the distorting effects of territorial indicators (Wiedenhofer et al., 2020), our analysis carries out comparative calculations regarding trends in consumption-based and production-based emissions, which represents a novel approach in the literature on this topic. By analysing the temporal emission patterns of Member States' economic sectors, we identify potential structural problems and, by synthesising the results, draw conclusions regarding the realistic feasibility and limitations of *decoupling*.

For the econometric modelling of the rebound effect and decoupling processes (panel regressions, econometric impact analyses), we use the following standardised indicators, which are set out in *Table 1*. Economic growth and income levels are the primary drivers of the rebound effect. Any improvement in energy efficiency result in cost savings for both households and businesses. Rising real income (GDP per capita) boosts aggregate demand for other energy-intensive goods and services /income effect/ (Callen, 2008). Sorrell (2007) emphasises that, without GDP growth, the macroeconomic rebound effect cannot be modelled adequately, as the capital and labour freed up by improvements in technological efficiency

increase GDP. Total per capita GHG emissions help to distinguish between physical energy savings and the actual climate protection outcome (decarbonisation) within national borders (IPCC, 2022). Per capita energy consumption, as defined in the original theoretical definition of the rebound effect (the Jevons paradox), relates directly to trends in primary energy consumption. The absolute increase in energy consumption (backfire) that occurs despite improvements in efficiency, or partial savings, can be measured directly using this indicator (Sorrell, 2007). In developed economies, production-based indicators are often distorted by carbon leakage and the offshoring of energy-intensive industries. It serves to test the illusion of global rebound and decoupling (Peters et al., 2011). The value added by services as a percentage of GDP, driven by the deindustrialisation of the economic structure (a shift from energy-intensive industry to the service sector, which has lower direct energy intensity), can in itself reduce energy and emissions intensity even without technological improvements. Without accounting for (controlling for) this structural shift, the estimated rebound effect would be distorted (Suh, 2006). The share of renewable energy consumption controls the clean transition of the energy mix and its moderating effect on rebound mechanisms (IRENA, 2023). The share of fossil fuels may mean that, alongside a high level of fossil fuel dependence, price reductions resulting from efficiency improvements could trigger stronger demand growth (rebound) due to limited substitutability (Brockway et al., 2021). Primary energy intensity is a key variable in technological efficiency, as when measuring the rebound effect econometrically, technological progress and changes in efficiency can be captured through trends in energy intensity. If an improvement (or reduction) in energy intensity is not accompanied by a proportional reduction in aggregate energy consumption or emissions, this may indicate the presence of the rebound effect (United Nations, 2023; Gillingham–Rapson–Wagner, 2016).

Table 1**Indicators used for the empirical analysis of the rebound effect**

Name of indicator	Unit of measurement	Explanation	References
Per capita GDP	USD per capita (at current prices)	The per capita GDP is the quotient of gross domestic product and the mid-year population. It is a fundamental indicator of economic development and aggregate macroeconomic output. ²	Callen (2008) Sorrell (2007)
Total GHG emissions per capita	t CO ₂ e / person	A country's total greenhouse gas emissions (excluding LULUCF), per capita. It measures the production-based direct climate impact. ³	(IPCC, 2022)
Per capita energy consumption	kg of crude oil equivalent (koe) per capita	Primary energy consumption per capita, expressed in crude oil equivalents. It shows the trend in aggregate energy demand. ⁴	(Sorrell, 2007)
Consumption-based GHG emissions	tonnes of carbon dioxide equivalent t CO ₂ e / capita	Emissions indicator adjusted for international trade: Consumption-based emissions = Production-based emissions – Emissions related to exports + Emissions related to imports (t) ⁵	(Peters et al., 2011; Parrique et al., 2019)
Value added of services as a	percentage of the GDP	The share of the services sector in gross domestic product (after deduction of intermediate goods). It drives the structural transformation of the economy (deindustrialisation). ⁶	(Suh, 2006)
Share of renewable energy consumption	of total final energy consumption (%)	The share of renewable sources (solar, wind, hydro, biomass) in final energy consumption. It measures the net transition in the energy mix. ⁷	IRENA (2023)

2 <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?end=2023&start=1960&view=chart>

3 <https://data.worldbank.org/indicator/EN.GHG.CO2.PC.CE.AR5?end=2023&start=1960&view=chart>

4 <https://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE?end=2023&start=1960&view=chart>

5 https://ourworldindata.org/grapher/consumption-co2-emissions?tab=table&mapSelect=OWID_EU27~DEU~ITA~FRA~POL~ESP~BEL~NLD~CZE~AUT~ROU~SWE~HUN~FIN~PRT~GRC~IRL~DNK~BGR~SVK~HRV~LTU~SVN~LVA~EST~MLT~LUX~CYP&tableFilter=countries

6 <https://data.worldbank.org/indicator/NV.SRV.TOTL.ZS?end=2023&start=1960&view=chart>

7 <https://data.worldbank.org/indicator/EG.FEC.RNEW.ZS?end=2023&start=1960&view=chart>

Name of indicator	Unit of measurement	Explanation	References
Consumption of fossil fuels	as a proportion of total energy consumption (%)	The share of hydrocarbons and coal in primary energy consumption. It indicates the extent of the carbon-intensive energy mix. ⁸	(Brockway et al., 2021)
Energy intensity of primary energy	MJ/USD (2017 PPP GDP)	The amount of primary energy, in megajoules, used to produce one unit of GDP calculated at purchasing power parity. It is the main indicator of macro-level technological energy efficiency. ⁹	United Nations (2023), Gillingham, Rapson and Wagner (2016).

Source: Compiled by the author

4 ECONOMETRIC TESTING OF THE REBOUND EFFECT

This research seeks to answer why, and through which channels, the relative improvement in energy efficiency (the reduction in energy intensity) resulting from technological modernisation fails to lead to an absolute reduction in environmental impact. Based on the logic of the Jevons paradox, an improvement in efficiency per unit of output results in the freeing up of resources, which, at the macroeconomic level, manifests as growth in real income and a rise in living standards. This expansion in welfare may, through increases in production volume and household consumption partially or entirely offset the technologically guaranteed ecological gains (Brockway et al., 2021).

By eliminating methodological biases in domestic and international policy discourse, the analysis explicitly distinguishes between production-based and consumption-based emission trajectories. This dual approach enables the empirical distinction between carbon leakage mediated by international trade and indirect rebound effects at the macroeconomic level.

To model the transmission mechanisms, we use a bilateral logarithmic (log-log) specification, which allows the estimated coefficients to be interpreted directly as elasticities. The analysis covers 24 years of data (621 observations) from 27 Member States, based on the following variable structure:

⁸ <https://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS?end=2023&start=1960&view=chart>

⁹ <https://data.worldbank.org/indicator/EG.EGY.PRIM.PP.KD?end=2023&start=1960&view=chart>

Dependent variables:

log_ghg_emission: Per capita territorial (production-based) greenhouse gas emissions.

log_consumption_based_emission: Per capita consumption-based carbon dioxide emissions (including the carbon footprint embedded in imported goods).

Explanatory and control variables:

log_E_GDP: Energy intensity; a direct indicator of technological energy efficiency (a decrease in which signals an improvement in efficiency).

log_GDP_per_capita: Real GDP per capita; used to control for economic development and income effects.

log_energy_use_per_capita: Primary energy consumption per capita; to measure scale and volume effects.

log_GVA_services: The share of gross value added (GVA) in the services sector as a percentage of GDP; measures the structural composition effect.

log_CO2_GDP: Carbon dioxide intensity; an indicator of the cleanliness of the energy mix.

log_POP: Demographic control variable (total population).

dummy_paris and *dummy_recession*: Qualitative (dummy) variables to control for the Paris Climate Agreement (post-2015 period) and macroeconomic shocks (the 2008 crisis, COVID-19).

In the analysis, we employed dynamic panel regression, which allows for the simultaneous examination of changes over time and country-specific characteristics.

$$Y_{it} = \beta_0 + \beta_1 X_{it} + \beta_2 X_{it} + \dots + \epsilon_{it} \quad (1)$$

Y_{it} is the dependent variable (per capita CO₂ emissions), relating to the i -th observation unit (27 Member States) and the t -th time period (2000–2023). X_{it} is the vector of explanatory and control variables (GDP per capita, primary energy consumption per capita, energy intensity, carbon intensity, the ratio of value added in the services sector to GDP, population, and dummy variables capturing structural shocks and institutional variables).

4.1 Diagnostic tests: checking for multicollinearity among the explanatory variables

In order to verify the structure of the estimated panel models and the unbiasedness of the standard errors, it is essential to test for multicollinearity amongst the explanatory variables. For this purpose, we used variance inflation factor (VIF) measures for the period under review (*Table 2*).

Table 2
Multicollinearity test for the examined explanatory variables
(based on FMOLS)

Variable	VIF
<i>log_energyuse_per_capita</i>	4.4758
<i>log_GVA_services</i>	19.0931
<i>log_POP</i>	1.8639
<i>log_E_GDP</i>	21.8504
<i>log_CO2_GDP</i>	17.4082
<i>log_GDP_per_capita</i>	7.2488

Source: Compiled by the author using eViews software (tested in an FMOLS model)

Note: *An indicator based on raw data, not adjusted for deviation from the mean. ** As the sample size increases (incorporating more years, months or individual observations into the analysis), the model's estimation error converges to zero as quickly as possible due to cointegration.

Based on the resulting uncentred* VIF values, energy intensity (*log_E_GDP*), the share of the services sector (*log_GVA_services*) and carbon dioxide intensity (*log_CO2_GDP*) exceed the conventionally accepted critical threshold of 10. However, this phenomenon does not constitute a methodological error; the model's results are well-founded due to the following theoretical and econometric characteristics:

System-wide co-movement: The macroeconomic aggregates examined are, by their very nature, closely correlated. Growth in GDP per capita and the structural expansion of the services sector inevitably and simultaneously transform countries' energy efficiency and emissions profiles. The joint inclusion of these variables is theoretically justified (Hickel–Kallis, 2020); omitting them would lead to *omitted variable bias*.

Scale effects and trends: Due to the absolute level of the data and the presence of a constant term, *uncentred* VIF values are, by mathematical necessity, higher in time-series panel data where the variables are presented in logarithmic form, take on exclusively positive values, and follow a distinct long-term trend.

Cointegration and robustness: As long-run cointegration tests (Kao, Pedroni, Johansen–Fisher) have confirmed a persistent equilibrium relationship between the variables, the estimated models possess the property of super-consistency. In practice, this means that when estimating the cointegration vector, OLS-based procedures are asymptotically immune to the distorting effects of multicollinearity. This is empirically demonstrated by the fact that the variances of the coefficients are found to be extremely low (well below 0.001), whilst the resulting coefficients and p-values remain stable, robust and highly significant (Al-Azzam–Fajness, 2018; Kao–Chiang, 2000).

4.2 Econometric estimation methods

In order to distinguish between short- and long-run effects and to examine changes over time and country-specific characteristics together, we employ dynamic, heterogeneous panel econometric models.

Short-run dynamics and static panel specifications

To identify short-run elasticities and immediate shock effects, we use the logarithms of the first derivatives of the variables. We test the robustness of the baseline estimates using three classical methods: Random Effects (RE), Fixed Effects (FE) and Pooled OLS models, with the choice between models guided by the formal criteria of the Hausman test. We test for first-order autocorrelation using the Durbin–Watson statistic, whilst we address panel correlation and heteroscedasticity using robust, period-specific White standard errors.

Long-run equilibrium relationships and cointegration

As macroeconomic time series are often non-stationary processes, we run three state-of-the-art models to quantify long-run structural cointegration vectors, which effectively handle simultaneous biases and endogeneity (an explanatory variable correlates with the model’s error term [the unobserved, omitted factors]), the Fully Modified OLS (FMOLS), Dynamic OLS (DOLS) and Pooled Mean Group (PMG) models. These models make it possible to determine precisely the rate at which, following shocks to the economic system, market mechanisms channel technical savings back into new processes of capital accumulation and consumption.

For the sake of clarity, the modelling results are presented in two separate tables that form a logical whole. Table 3 details the results of the short-run dynamic

panels, as well as the coefficients of the long-run cointegration models and the error-correction PMG model.

Table 3
Short-run dynamic panel regression results for the rebound effect (First-difference level: d_log)

	RE		FE		OLS	
Short run						
Independent variables/explanatory variables	Coefficient	p-value	Coefficient	p-value	Coefficient	p-value
FDependent variable: Consumption-based CO2- emissions (d_log_consumption_based_emission)						
Constant (β_0)	-0.0088	0.0437	-0.0074	0.0018**	-0.0079	0.0003***
Carbon intensity (d_log_CO2_GDP)	0.1536	0.0002***	0.2053	0.0000***	0.1588	0.0000***
Energy intensity (d_log_E_GDP)	-0.2171	0.0033***	-0.3264	0.0000***	-0.2183	0.0005***
Per capita energy consumption (d_log_energy_use_per_capita)	0.3110	0.0009***	0.4095	0.0000***	0.3092	0.0000***
GDP per capita (d_log_GDP_per_capita)	0.1562	0.0143**	0.1497	0.0000***	0.1563	0.0000***
Share of the service sector (d_log_GVA_service)	0.2080	0.0145**	0.0639	0.1832	0.1770	0.0152**
Total population (log_POP_d2)	-0.1215	0.6330	-0.1959	0.2736	-0.0610	0.8548
Dummy variable (dummy_paris)	0.0066	0.1153	0.0073	0.0091	0.0069	0.0087**
Dummy variable (dummy_recession)	-0.0096	0.0701	-0.0048	0.0573*	-0.0098	0.0004***
Model diagnostics						
Durbin-Watson statistic			there is no significant first-order autocorrelation	2.42	there is no significant first-order autocorrelation	2.35
R ²				0.40		0.38
Breusch-Pagan test			We addressed the presence of heteroscedasticity and panel correlation using robust White statistics, ensuring that the standard errors are unbiased.		We addressed the presence of heteroscedasticity and panel correlation using robust White statistics, ensuring that the standard errors are unbiased.	

Hausman test	the model must be rejected	1,000				
F-statistic				10,87		44,72
Akaike information criterion		−4,15				−4,2
	RE		FE		OLS	

Dependent variable: Per capita production-based (territorial) emissions (d_log_ghg_emission)

Independent variables/ explanatory variables	Coefficient	p-value	Coefficient	p-value	Coefficient	p-value
Constant (β_0)	−0.0001	0.8465	−0.0008	0.0103**	0.0003	0.4197
Carbon intensity (d_log_CO2_GDP)	0.3992	0.0000***	0.3975	0.0000***	0.4011	0.0000***
Energy intensity (d_log_E_GDP)	−0.3074	0.0000***	−0.3534	0.0000***	−0.3144	0.0000***
Per capita energy consumption (d_log_energy_use_per_capita)	0.3230	0.0000***	0.3744	0.0000***	0.3300	0.0000***
GDP per capita (d_log_GDP_per_capita)	0.0101	0.3347	0.0047	0.2058	0.0115	0.0856*
Share of the service sector (d_log_GVA_service)	0.0878	0.0020***	0.0486	0.0275**	0.0892	0.0000***
Total population (log_POP_d2)	−0.2105	0.0021***	−0.0610	0.1473	−0.1908	0.0026**
Dummy variable (dummy_paris)	0.0001	0.7535	0.0001	0.5206	0.0001	0.8228
Dummy variable (dummy_recession)	−0.0014	0.1409	−0.0004	0.2636	−0.0011	0.0219**

Model diagnostics

Durbin–Watson statistic		1.63	there is no significant first-order autocorrelation	1.58	there is no significant first-order autocorrelation	1.49
R ²		0.95		0.97		0.95
Breusch–Pagan test			We addressed the presence of heteroscedasticity and panel correlation using robust White statistics, ensuring that the standard errors are unbiased.		We addressed the presence of heteroscedasticity and panel correlation using robust White statistics, ensuring that the standard errors are unbiased.	
Hausman test	the model must be rejected	1.0000				
F-statistic				2413		1284.5

Akaike information criterion	the best-fitting model, which has the smallest value	-7,5				-7,5
Long-run						
	FMOLS		DOLS		PMG	
Independent variables/ explanatory variables	Coefficient	p-value	Coefficient	p-value	Coefficient	p-value
Dependent variable: Consumption-based CO2 emissions (d_log_consumption_based_emission)						
Constant (β_0)					-6.1277	0.0000***
Carbon intensity (log_CO ₂ _GDP)	0.2530	0.0000***	0.4463	0.0007***	0.2157	0.0000***
Energy intensity (log_E_GDP)	-0.5941	0.0000***	-0.5209	0.0028***	-0.5885	0.0000***
Per capita energy consumption (log_energy_use_per_capita)	0.6955	0.0000***	0.3721	0.0095***	0.7433	0.0000***
GDP per capita (log_GDP_per_capita)	0.0411	0.4817	0.1952	0.0804**	0.2829	0.0000***
Share of the services sector (log_GVA_services)	-0.2934	0.0010***	-0.2172	0.1332	-0.5680	0.0000***
Total population (log_POP)	0.3144	0.0100***	-0.1656	0.3018	0.3090	0.0000***
					Short run	
COINTEQ (Error correction factor)					-0.2808	0.0004***
Consumption-based emissions (d_log_consumption_based_emission)					-0.1423	0.0226**
Carbon intensity (d_log_CO ₂ _GDP)					-0.1137	0.3788
Energy intensity (d_log_E_GDP)					-0.1176	0.4981
Per capita energy consumption (d_log_energy_use_per_capita)					0.4658	0.0026***
GDP per capita (d_log_GDP_per_capita)					0.0772	0.0369*

Share of the services sector (d_log_GVA_services)					0.3686	0.0750
Total population (log_POP_d2)					0.4264	0.7808
					1.1278	0.4773

Cointegration tests

Kao Cointegration Test

ADF	-3,4244	0,0003***	There is cointegration			
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Pedroni Residual Cointegration Test

No deterministic trend						
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Group-rho statistic	3.0082	0.9987	There is cointegration			
Group PP statistic	-7.2202	0.0000***				

Group ADF statistic	-1.6814	0.0463	There is cointegration			
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Specification with a deterministic constant (intercept) and trend (Deterministic intercept and trend)

Group-rho statistic	4.4569	1.0000	There is cointegration			
Group PP statistic	-8.3290	0.0000***				

Group ADF statistic	-1.8740	0.0305	There is cointegration			
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Specification with no deterministic intercept and trend (No deterministic intercept and trend)

Group-rho statistic	2.3736	0.9912	There is cointegration			
Group PP statistic	-5.6773	0.0000***				

Group ADF statistic	-0.8322	0.2026	No cointegration			
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Johansen-Fisher Panel Cointegration Test

No cointegration relationship (None max eigen)	717.7	0.0000***	There is cointegration			
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Dependent variable: Per capita production-based (territorial) emissions (d_log_ghg_emission)

Constant (β_0)					-2.7173	0.0035**
Carbon intensity (log_CO ₂ _GDP)	0.4385	0.0000***	0.3526	0.0000***	0.5275	0.0000***

Energy intensity (log_E_GDP)	-0.3950	0.0000***	-0.3673	0.0000***	-1.0472	0.0000***
Per capita energy consumption (log_energy_use_per_capita)	0.3717	0.0000***	0.4079	0.0000***	0.6772	0.0000***
GDP per capita (log_GDP_per_capita)	-0.0181	0.0595**	0.0432	0.2397	-0.1173	0.0382**
Share of the services sector (log_GVA_services)	0.0796	0.0000***	-0.0319	0.5039	0.0613	0.0127**
Total population (log_POP)	-0.2055	0.0000***	-0.1805	0.0013***	0.0776	0.0851**
					Short run	
COINTEQ (Error correction factor)					-0.0039	0.6416
Carbon intensity (d_log_CO2_GDP)					0.3839	0.0000***
Energy intensity (d_log_E_GDP)					-0.3379	0.0000***
Per capita energy consumption (d_log_energy_use_per_capita)					0.3589	0.0000***
GDP per capita (d_log_GDP_per_capita)					-	-
Share of the services sector (d_log_GVA_services)					0.0514	0.0698**
Total population (d_log_POP)					-0.3642	0.0010***

Cointegration tests**Kao Cointegration Test**

ADF	-2.93	0.0017***	There is cointegration			
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Pedroni Residual Cointegration Test

Determinisztikus trend hiánya (No deterministic trend)						
Group-rho statistic	3.808	0.9999	There is cointegration			
Group PP statistic	-1.8825	0.0299**				
Group ADF statistic	1.7044	0.9559	No cointegration			

Specification with a deterministic constant (intercept) and trend (Deterministic intercept and trend)					
Group-rho statistic	4.4564	1.0000	There is cointegration		
Group PP statistic	-4.9849	0.0000***			
Group ADF statistic	0.0203	0.5081	No cointegration		
Specification with no deterministic intercept and trend (No deterministic intercept and trend)					
Group-rho statistic	3.3916	0.9997	There is cointegration		
Group PP statistic	-0.2499	0.4013			
Group ADF statistic	3.1025	0.9990	No cointegration		
Johansen-Fisher Panel Cointegration Test					
No cointegration relationship (None max eigen)	665	0.0000***	There is cointegration		

*Note: ***, **, * indicate significance at the 1%, 5% and 10% levels respectively. The short-run static models were run in first-differenced ($\Delta \log$) form. Heteroscedasticity and panel correlation were addressed using robust White-period standard errors. Source: Compiled by the authors using EViews software.*

Based on the results of the econometric estimates, the short-run dynamic panel models (FE, RE, OLS) and the cointegration models exploring long-run equilibrium relationships (FMOLS, DOLS, PMG) reveal a methodologically sound, robust and theoretically consistent causal chain (cause-and-effect relationships). The results of the Hausman tests ($p = 1.000$) for both short-run specifications indicate that the hypotheses of the Random Effects (RE) models must be rejected; consequently, Fixed Effects (FE) models should be regarded as the primary reference when interpreting short-run dynamics. In the case of long-run structures, the ARDL-based PMG (Pooled Mean Group) estimation provides the most reliable results, as it is able to distinguish the country-specific heterogeneity of short-run shocks from the long-run equilibrium path.

The paradox of energy efficiency and the volume effect

The causal relationship between relative improvements in energy efficiency (a decline in energy intensity, $\log_E_GDP$) and absolute energy consumption ($\log_energy_use_per_capita$) plays a central role in the model. The correlations evident from the data *may directly substantiate the theory of the macroeconomic rebound effect*:

Long-run equilibrium (PMG): The significant negative coefficients of energy intensity ($\log_E_GDP$) obtained in the long-run (PMG) model (-0.5885^{***} for the consumption-based emissions model; -1.0472^{***} for the production-based emissions model) appear paradoxical at first glance; however, based on the logic of ecological economics, they provide clear confirmation of the Jevons paradox. In the log-log specification, the negative sign means that a decrease in energy intensity (which signifies an improvement in technological energy efficiency) would lead to an increase in emissions, provided that the other elements of the system (the volume effect) were kept constant. This negative elasticity highlights **that improvements in technical efficiency alone are not capable of achieving absolute emission reductions**, because the mathematical structure of the negative coefficient inherently entails the internal constraint of the rebound effect; that is, an increase in efficiency immediately generates additional energy consumption via the volume effect ($\log_energy_use_per_capita$, $+0.7433^{***}$), which ultimately offsets the relative gains in energy efficiency. The negative sign is therefore not an error, but a mathematical reflection of the Jevons paradox. It shows that improving energy efficiency is, in itself, a trap, because making the system more efficient does not lead to less pollution; rather, by reducing costs, it generates greater, more resource-intensive economic growth, which ultimately completely eats into the technological savings. Mathematically, therefore, the negative sign indicates that an improvement (reduction) in energy intensity paradoxically leads to an increase in CO_2 emissions, as the economy immediately offsets the technological savings through increased production volumes.

The transmission channel (volume effect): Long-run PMG estimates of **primary energy use per capita** ($\log_energy_use_per_capita$) showed the highest positive elasticity coefficients in both models (for consumption-based emissions: $+0.7433^{***}$; for output-based emissions: $+0.6772^{***}$). This result is key to resolving the theoretical paradox observed in energy intensity and may serve as direct evidence for the operation of the macroeconomic rebound effect. The data highlight that, whilst technological modernisation may improve relative efficiency, the internal dynamics of the economic system immediately channelling the freed-up capacity and surplus income back into further production and consumption processes. The variables are logarithmic, and the coefficient can be interpreted directly as elasticity. As the elasticity of emissions with respect to absolute energy volume is extremely high – approaching 0.7 in both the FMOLS and PMG models – in the long run, a 1 per cent increase in energy consumption leads to a rise in associated emissions of nearly 0.7 per cent. This extremely strong, significant positive correlation may support the view that **the increase in energy volume dominates the system and completely offsets the theoretical savings resulting from improvements in technological efficiency**.

Causal mechanism: The results confirm the macroeconomic rebound effect. Although improvements in technological efficiency ($E_GDP\downarrow$) would, in theory, reduce emissions, the resulting economic growth and expansion of capacity increase absolute energy consumption ($energy_use_per_capita$). As the long-run elasticity of the absolute volume effect (+0.67 and +0.74) numerically exceeds the efficiency coefficients (−0.59 and −0.58), the expansion in volume completely offsets the technological savings. This means that as technology advances, energy intensity ($\log_E_GDP$) improves by 1 per cent – that is, 1 per cent less energy is required to produce a unit of GDP – and emissions fall by −0.58 per cent and −0.59 per cent; this would constitute a sustainable saving, whilst all other factors remain unchanged, meaning that the environmental impact would decrease by approximately 0.6 per cent. Conversely, improved efficiency makes production cheaper, which triggers economic growth. According to the model, if, as a result of this growth, absolute energy consumption per capita ($\log_energy_use_per_capita$) increases by 1 per cent, this alone would lead to a 0.67 per cent to 0.74 per cent increase in emissions. This provides empirical evidence of the Jevons paradox: in the long term, more efficient energy use does not lead to a reduction in environmental impact, but rather, through channels of economic growth, to a higher system-level environmental burden. This explanation is crucial from a policy perspective because it highlights that a purely technology-based green transition is doomed to failure on its own if the volume effects of growth are not limited or offset by structural measures.

The asymmetry and indicator dependence of decoupling (GDP per capita)

An analysis of the environmental impacts of economic growth (GDP per capita) reveals critical differences between consumption- and production-based approaches, as shown in *Table 4*, highlighting that the absolute decoupling advocated by mainstream economic policy is, in part, a methodological illusion.

Table 4

The impact of GDP per capita on consumption- and production-based emissions in the short and long term

Time horizon / Model	Consumption-based emissions ($\log_consumption_based$)	Production-based emissions ($\log_ghg$)
Short run (FE)	+0.1497*** (Strongly positive, significant)	+0.0047 (Not significant)
Long run (PMG)	+0.2829*** (Strongly positive, significant)	−0.1173** (Significant, negative)

Source: Compiled by the author

In the short run, economic growth immediately and directly generates consumption-based emissions growth, whilst this effect is not yet significant at the level of production-based emissions. Income growth leads to an immediate increase in imports and a rise in consumption.

In the long run, the negative coefficient (-0.1173) in the production-based model indicates apparent absolute decoupling. At the same time, in the consumption-based model, income elasticity becomes even stronger and positive in the long run ($+0.2829^{***}$).

The causal conclusion is: It cannot be unequivocally stated that decarbonisation has taken place in the EU-27 countries; rather, based on the results, the environmental burden may have been externalised via global supply chains (carbon leakage). Domestic factories may be becoming structurally cleaner (as indicated by the negative production-based coefficient), but the prosperity and consumption of Member States remain closely and persistently linked to global carbon dioxide emissions. In the case of consumption-based emissions, absolute decoupling is completely blocked by the macroeconomic rebound effect.

Structural deindustrialisation and the composition effect (GVA_services)

The share of gross value added in the services sector ($\log_GVA_services$) is intended to measure the transmission mechanism of the economy's structural transformation (composition effect).

In the short run (FE and OLS), the shift towards services has a positive sign with regard to output (OLS for consumption-based output: $+0.1770^{***}$; FE for production-based output: $+0.0486^{***}$). This means that the initial phase of structural change (e.g. digitalisation, the development of data centres, the expansion of logistics networks) entails a temporary increase in energy demand.

In the long run (PMG), the expansion of the service sector leads to a drastic reduction in emissions in the consumption-based emissions model (-0.5680^{***}). This demonstrates that dematerialisation and the knowledge-based economy are capable of mitigating the environmental footprint of consumption in the long run, which is an effective structural tool for partially counteracting structural rebound effects.

4.3 Shock effects and institutional dummies (dummy_paris and dummy_recession)

Paris Climate Agreement (dummy_paris): In the short run, it shows a weak positive effect ($+0.0069$) in the consumption-based OLS model, whilst in the other models (both short- and long-term) it is not significant. In terms of causal relationships, this implies that institutional and international agreements, on their

own and without structural market intervention, were unable to bring about a significant break in the EU's emissions trends during the period under review.

Macroeconomic crises (dummy_recession): In the short run, the effect is significantly negative in both models (OLS in the consumption-based emissions model: -0.0098^{***} ; OLS in the production-based emissions model: -0.0011^{***}). This confirms the assumption that the decline in emissions during the examined period was not due to the spread of green technologies, but rather to cyclical downturns in economic activity (the 2008 crisis, shutdowns due to COVID-19).

Empirical quantification and decomposition analysis of the components of the Kaya identity

The primary aim of the analysis is to determine whether improvements in technological energy and carbon efficiency are capable of reducing environmental pressure in absolute terms, or whether the volume impacts of a growth-oriented economic structure offset these efficiency gains. We expect the decomposition analysis to answer the question of whether advances in technological components can simultaneously offset the scale effects of affluence (material well-being) and demographic expansion.

The methodological basis of the research is provided by the logarithmic decomposition of the Kaya identity, which can be interpreted as an extension of the IPAT model proposed by Ehrlich and Holdren (1971). Using this index decomposition method, we compare global aggregate data series with indicators specific to the European Union (EU-27) over the period from 2000 to 2023. In the analysis, we compare the observed data for the period under review with the equilibrium scenarios proposed by the Intergovernmental Panel on Climate Change (IPCC, 2014) as required for the 2C° climate stabilisation pathway (450 ppm)¹⁰.

Global and regional divergences in the decoupling process

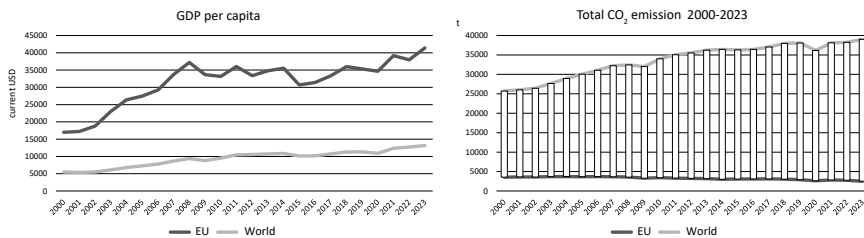
When analysing the relationship between technological advancement and environmental pressure, the first critical step is to compare local (apparent) successes with global biophysical realities. Despite the fact that energy consumption and carbon dioxide intensity have shown relative improvement at the global level, the absolute increase in aggregate environmental pressure has not ceased.

¹⁰ This means that if we take 1 million gas molecules from the Earth's atmosphere, exactly 450 of them are greenhouse gases (mainly carbon dioxide).

According to data from the World Bank (2026) (*Figure 1*), global carbon dioxide emissions rose by approximately 51 per cent¹¹ between 2000 and 2023, whilst global GDP per capita increased by 139.6 per cent in real terms. On a global scale, therefore, there is no evidence of a sustained relative decoupling, let alone an absolute one. In contrast, the macroeconomic trajectory of the European Union (EU-27) appears, at first glance, to show a significant divergence, drawing a structural dividing line between the centre and the global periphery.

Figure 1

The divergence in trends for income per capita (GDP per capita) and total CO₂ emissions in the European Union (EU-27) and globally (2000–2023)



Source: Compiled by the author using World Bank data.^{13 14}

Note: A comparison of the global rising and EU degressive emissions curves in the context of GDP per capita.

In the EU-27 Member States, real GDP per capita rose by 144 per cent¹⁵ between 2000 and 2023, whilst CO₂ emissions per capita fell by 31.2 per cent¹⁶ and total territorial CO₂ emissions fell by 29.5 per cent. Within the framework of neoclassical environmental economics, this trend can be formally interpreted as ‘*absolute decoupling*’, as economic growth is accompanied by an absolute reduction in total emissions. However, this relationship is revealed in a more complex light upon closer examination of rebound effects and international trade flows.

11 <https://data.worldbank.org/indicator/EN.GHG.CO2.MT.CE.AR5>

12 <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD>

13 <https://data.worldbank.org/indicator/EN.GHG.CO2.MT.CE.AR5>

14 <https://data.worldbank.org/indicator/EN.GHG.CO2.LU.OS.MT.CE.AR5>

15 <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD>

16 <https://data.worldbank.org/indicator/EN.GHG.CO2.MT.CE.AR5>

4.3.1. EU-level decomposition results and the tension with IPCC targets

Table 5 summarises the results of the logarithmic decomposition of processes occurring within the European Union between 2000 and 2023 and the equilibrium trajectories required to achieve the normative climate targets.

Table 5

Kaya decomposition matrix and sustainability equilibrium trajectories in the European Union (2000–2023)

Decomposition components (factors)	Observed cumulative change ($\Delta \ln$, 2000–2023)	Observed average annual change	Expected equilibrium trajectory I. (Technology-focused expectation)	Expected equilibrium trajectory II. (Affluency-focused expectation)
Total CO ₂ emissions (I)	–0.171	–0.0078	–0.0503	–0.0503
Per capita GDP ¹⁷ USD/per capita (A)	+0.8920	+0.0405	+0.8920	+0.5712
Population ¹⁸ persons (P)	+0.0443	+0.0020	0.0443	0.0443
Carbon intensity ¹⁹ (CO ₂ /E)	–0.6658	–0.0303	–0.9866	–0.6658
Energy intensity (E/GDP)	–0.4418	–0.0201	–0.4418	–0.4418

Source: Compiled by the author based on World Bank data

The empirical data in the table show that the dominant positive driver of the European Union's emissions dynamics is the rise in living standards (affluence effect: $\Delta \ln A = +0.8920$), whilst demographic pressure remained marginal ($\Delta \ln P = +0.0443$). From a critical perspective, the data refute the optimistic assumption of the Environmental Kuznets Curve (EKC) that a rise in the level of prosperity automatically and sufficiently mitigates environmental pressure (Karsch, 2019; Dinda, 2004; Ekins, 1997; Grossman–Krueger, 1991; Gyamfi et al., 2020).

Although absolute decoupling has formally been achieved, as total emissions have fallen ($\Delta \ln \text{CO}_2 = -0.1710$, corresponding to an annual average rate of -0.78 per cent), this trend falls drastically short of the annual average of -0.0503 log-units (approximately -4.9%) required by the IPCC (2014) to maintain the 2°C stabilisation pathway (450 ppm).

17 <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD>

18 <https://data.worldbank.org/indicator/SP.POP.TOTL>

19 <https://data.worldbank.org/indicator/EN.GHG.CO2.RT.GDP.KD>

Despite some improvement in energy and technological efficiency (energy intensity: -0.4418 ; carbon intensity: -0.6658), a significant proportion of the savings has been absorbed by the growth-oriented economic structure and rising consumption. This is a classic manifestation of the macroeconomic rebound effect (Sorrell, 2007), i.e. the improvement in efficiency failed to achieve a breakthrough because the system immediately channelled the relative gains into volume expansion.

The projected scenarios (columns 3 and 4) highlight the political-economic dilemma: either technological decarbonisation would have had to be radically accelerated to meet climate targets (reducing the cumulative carbon intensity indicator to -0.9866), or, acknowledging technological constraints, the cumulative growth in affluence would have had to be capped at $+0.5712$.

Global-level decomposition results and system-level unsustainability

The decomposition carried out for the global economy as a whole (Table 6) paints an even clearer picture of the conflict between biophysical limits and technical optimisation.

Table 6
Global Kaya decomposition matrix and sustainability equilibrium trajectories (2000–2023)

Decomposition components (factors)	Observed cumulative change ($\Delta \ln$, 2000–2023)	Observed average annual change	Expected equilibrium trajectory I. (Technology-focused expectation)	Expected equilibrium trajectory II. (Affluence-focused expectation)
Total CO ₂ emissions (I)	+0.6260	+0.0284	–0.0503	–0.0503
Per capita GDP ²⁰ USD/per capita (A)	+0.8741	+0.0397	+0.8741	–0.8568
Population ²¹ persons (P)	+0.2687	+0.0122	+0.2688	+0.2688
Carbon intensity ²² (CO ₂ /E)	–0.2291	–0.0104	–2.2495	–0.2291
Energy intensity (E/GDP)	–0.2877	–0.0131	–0.2877	–0.2877
Average annual change in environmental impact	0.028463		–0.0503	–0.0503

Source: Own calculations based on World Bank (2026) databases.

²⁰ <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD>

²¹ <https://data.worldbank.org/indicator/SP.POP.TOTL>

²² <https://data.worldbank.org/indicator/EN.GHG.CO2.RT.GDP.KD>

On a global scale, the cumulative logarithmic growth of the aggregate environmental load was **+0.6260**, representing an annual growth rate of +2.84 per cent. The primary drivers of emissions growth were the cumulative volume effects of global population growth (+0.2688) and rising global affluence (+0.8741).

This combined scale effect completely dominated and overrode the favourable engineering effects resulting from improvements in global energy efficiency ($\Delta \ln(E/GDP) = -0.2877$) and carbon intensity ($\Delta \ln(CO_2/E) = -0.2291$).

The theoretical trajectories required to meet the IPCC's climate targets (columns 3 and 4) presuppose drastic structural interventions: at a global level, carbon intensity would have had to be reduced to a value of nearly ten times the observed value, to a *cumulative log value* of -2.2495 or, by abandoning the imperative of growth, indicators of material well-being would have had to be reduced in absolute terms ($\Delta \ln A = -0.8568$). This multivariate approach makes it clear that the destabilisation of planetary boundaries cannot be halted at a global level through technocratic fine-tuning.

4.4 An empirical analysis of consumption- and production-based emissions, and emissions from economic sectors

Moving beyond territorial (production-based) data, the research integrates a consumption-based approach (carbon footprint) that reflects international trade flows. This makes it possible to quantify the extent to which the observed reduction in emissions is attributable to genuine efficiency improvements and to what extent it is due to the outsourcing of carbon-intensive production (*carbon leakage*). The chapter also breaks down emission trends between 2000 and 2023 at sectoral level (industry, transport, services, households). Based on structural indicators, we classify EU Member States into three groups of countries, exploring the biophysical constraints of centre-periphery relationships and the presence of macroeconomic *rebound effects*.

The aim and methodological framework of the empirical analysis

Whilst the previous chapter focused on the decomposition of aggregated, territory-based data, this review deconstructs the apparent successes of the EU by incorporating two critical dimensions:

1. *The impact of production relocation (carbon leakage)*: Quantifying the divergence between territorial (production-based) and carbon footprint-based (consumption-based) CO₂ emissions.

2. *Sectoral heterogeneity*: Grouping the EU-27 Member States into three structural country groups based on emission trends across economic sectors (industry, transport, services, households) (2000–2023), revealing direct and indirect macroeconomic *rebound effects*.

The methodological basis of the study is provided by the databases of *Our World in Data* (2024)²³ and of the World Bank (2026). The production-based (territorial) approach favoured by international institutions records only emissions generated within a given country's geographical borders. In contrast, the consumption-based approach adjusts territorial emissions to account for international trade flows. If the consumption-based indicator exceeds the production-based one, the region in question is considered a net carbon importer, which confirms the transnational externalisation of environmental impacts.

4.4.1 Territorial and consumption-based decoupling divergence in the European Union

The current policy of the European Commission targets (2024) – including the 'Fit for 55' legislative package and the proposed 90 per cent net reduction in greenhouse gas emissions by 2040 compared with the 1990 base year – are firmly based on the territorial accounting logic. According to official reports, the EU's total territorial GHG emissions fell by 32.5 per cent by 2022 compared with 1990. At this point, however, narratives of green growth come up against methodological limitations.

Based on historical data sets from *Our World in Data* (2024), between 1990 and 2023 the production-based (territorial) CO₂ emissions index (ΔT) for the EU-27 Member States fell from 3.87 billion tonnes to 2.51 billion tonnes, a reduction of 35.1 per cent:

$$\Delta T = \text{Change in emission}_{\text{production-based}} = \frac{T_{1990} - T_{2023}}{T_{1990}} = \frac{3.87 - 2.57}{3.87} = 0.351 \quad (2)$$

(where T is the production-based /territorial/ CO₂ emissions in billion tonnes).

Consumption-based emissions are calculated by adjusting production-based (territorial) emissions to account for international trade flows; that is, by adding emissions associated with the production of imported goods (which occur abroad) and subtracting emissions embedded in exported products. If a country's consumption-based indicator exceeds its production-based one, that region can

²³ <https://ourworldindata.org/co2-emissions>

be regarded as a net importer of carbon dioxide²⁴. If we take this consumption-based approach as a basis for the EU-27, the 1990 baseline of 4.40 billion tonnes (ΔF) fell to 3.47 billion tonnes by 2022, representing a volume reduction of just **21.1 per cent**:

$$\Delta F = \text{Change in emission}_{\text{consumption-based}} = \frac{F_{1990} - F_{2022}}{F_{1990}} = \frac{4.4 - 3.47}{4.4} = 0.211 \quad (3)$$

(where F is consumption-based CO₂ emissions in billion tonnes)

The results show that the European Union is structurally a net importer of CO₂ as its consumption-based emissions are substantially higher than its production-based emissions.

The structural gap (δ) between the two accounting methods highlights that a significant proportion of the emission reductions reported on a territorial basis is a methodological illusion:

$$\delta = \frac{|\Delta T| - |\Delta F|}{|\Delta T|} = \frac{35.14\% - 21.13\%}{35.14\%} = 39.8\% \quad (4)$$

When applying the consumption-based approach, approximately 35–40 per cent of the emission reductions declared on a territorial basis are negated. This empirical finding confirms that the EU-27 is structurally a net carbon importer. More than a third of domestic successes may stem not from an absolute reduction in global environmental impact, but from the outsourcing of environmentally destructive, carbon-intensive production phases abroad (*carbon leakage*). *The apparent absolute decoupling is thus in reality a geographical and statistical illusion that conceals the transnational rebound effect.*

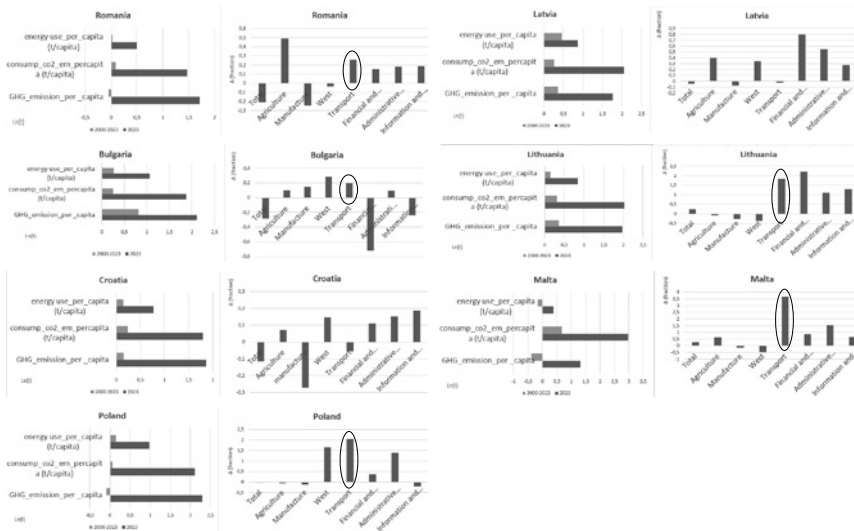
4.4.2 Sectoral decomposition and typology in the EU-27 Member States

In order to understand the unevenness of decarbonisation trajectories, we have classified the EU-27 Member States into three distinct structural groups based on their sectoral and footprint-based trends between 2000 and 2023.

²⁴ https://ourworldindata.org/grapher/consumption-co2-emissions?tab=chart&country=OWID_EU27~OWID_WRL

Figure 2

Trends in economy-structure-based emissions in the context of the rebound effect: empirical observations for country group I (2000–2023)



Source: Compiled by the authors based on World Bank data

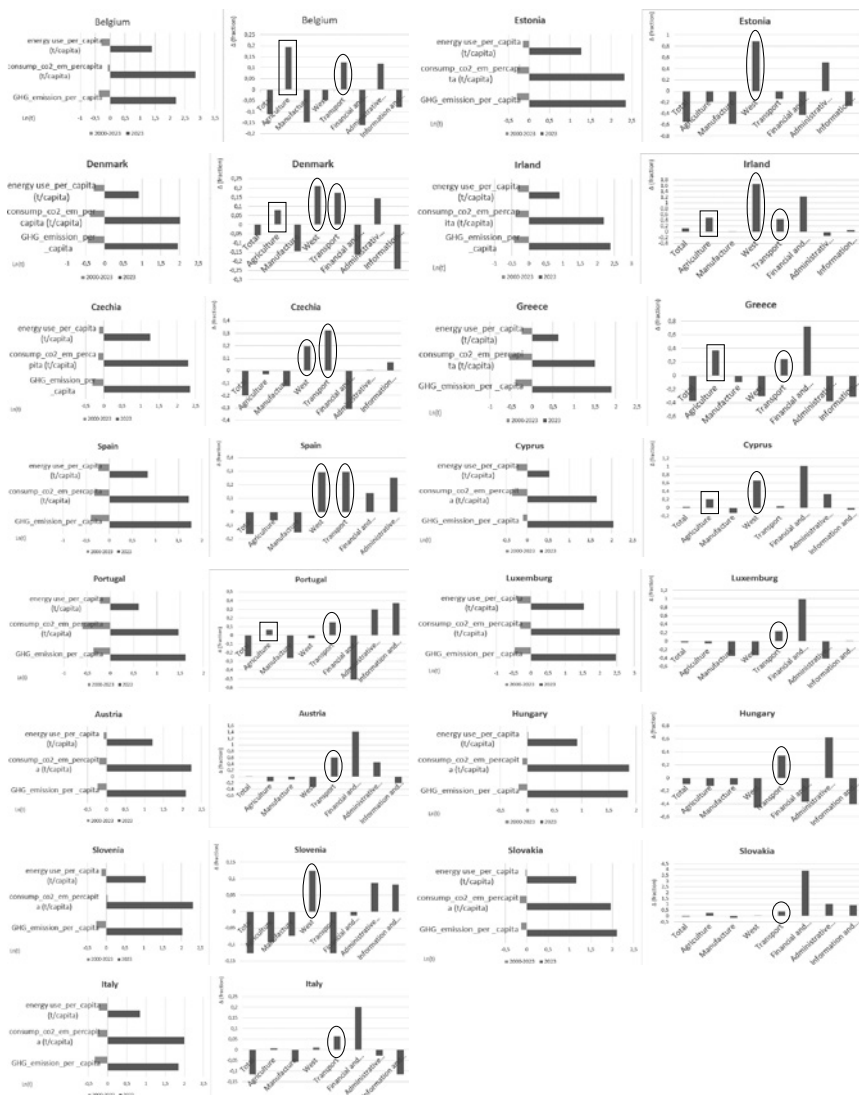
Country Group I (Periphery and catching-up economies)

This group includes *Latvia, Lithuania, Romania, Bulgaria, Croatia, Malta and Poland*. The transitional macroeconomic trajectory of these countries is characterised by the clear dominance of economies of scale. Based on the empirical data, per capita energy consumption and production-based (territorial) CO₂ emissions have either increased or stagnated in parallel. At the same time, consumption-based emissions systematically exceed production-based emissions, particularly in the case of Poland and Romania.

This phenomenon indirectly qualifies the findings of Wiedmann et al. (2020): whilst the deindustrialisation of core countries leads to emissions outsourcing, the position of catching-up peripheral countries is subject to a double burden. In these countries, GDP growth is driven simultaneously by the expansion of domestic production and the import of carbon-intensive goods. At the sectoral level, emissions from agriculture, transport and services linked to household consumption have risen. Although direct emissions from the tertiary sectors are lower, they generate significant indirect environmental pressure through their global supply chains (Ivanova et al., 2016). In this group, neither absolute nor relative decoupling can be identified.

Figure 3

Trends in economy-structure-based emissions in the context of the rebound effect: empirical observations for country group II (2000–2023)



Source: Compiled by the authors based on World Bank data

Note: Heterogeneous sectoral shifts and an increase in consumption-based emissions alongside stagnant territorial data..

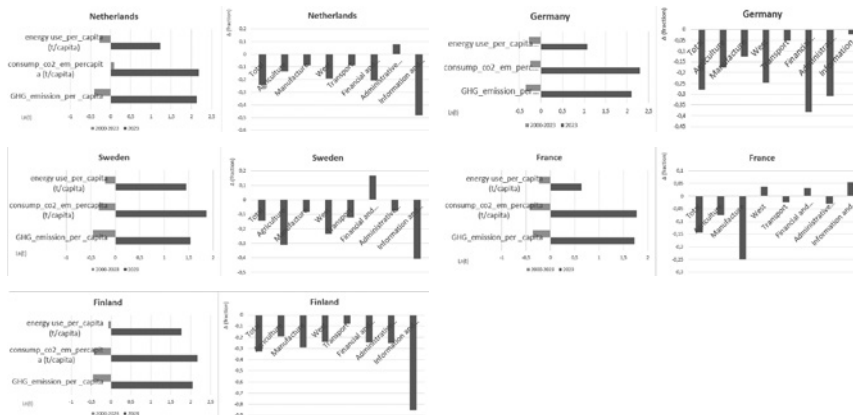
Country Group II (Countries with transitional and fluctuating decarbonisation)

Countries in the second group: In the case of *Luxembourg, Belgium, Ireland, Austria, Estonia, Cyprus and Greece*, per capita energy consumption and territorial emissions show a decline or stagnation, whilst consumption-based indicators point to a drastic increase or persistently high levels. In Ireland and Cyprus in particular, the divergence between the consumption footprint and domestic production data is striking.

A sectoral breakdown highlights that, whilst efficiency in the industrial and energy sectors has improved, emissions from transport, logistics and direct household consumption have risen. This is a textbook example of the direct and indirect rebound effect (Sorrell, 2009), whereby economic actors channelled the financial resources freed up by industrial energy efficiency into increased mobility, more extensive digital services and imported consumer goods. In this group, the decoupling is only partial, and on the consumption side it disappears entirely.

Figure 4

Trends in structure-based economic output in the context of the rebound effect: empirical observations for Country Group III (2000–2023)



Source: Compiled by the authors based on World Bank data

Note: Structural decarbonisation in core countries and persistently high household carbon footprints

Group III countries (the developed core countries of the EU)

The Netherlands, Germany, France, Sweden and Finland are often cited in policy discussions as global role models for sustainable green growth and absolute decoupling (EEA, 2023). However, a closer look at the sector-specific data also

reveals biophysical constraints here. Although consumption-based emissions in Sweden and France are also showing a downward trend alongside growth in real GDP, their primary energy consumption has fallen only marginally. This demonstrates that the results achieved are not due to absolute dematerialisation, but to the decarbonisation of the energy mix (the penetration of nuclear and renewable energy).

In the case of Germany and the Netherlands, the reduction in consumption-based emissions lags significantly behind that of production-based emissions, reinforcing the thesis of 'green outsourcing' (Wiedmann et al., 2020). Almost everywhere, the decline in direct emissions from the industrial sector is offset by the implicit energy demand arising from the transnational supply chains of the growing digital and service sectors (e.g. data centres, e-commerce), which demonstrates the marked presence of indirect rebound effects (Giampietro and Mayumi, 2018).

DISCUSSION AND CONCLUSIONS

An integrated analysis of consumption-based and sectoral data provides a critical rebuttal of technology-focused theories of green growth.

The data may confirm that, regardless of economic development (centre-periphery location), improvements in technological efficiency alone are incapable of curbing environmental pressure and import dependency. Group I (periphery) is unable to decouple due to economies of scale, whilst the apparent successes of Group III (centre) may be underpinned by the transnational outsourcing of carbon-intensive phases and net carbon dioxide imports.

The methodological break of approximately 40 per cent (39.8 per cent to be precise) observed at EU-27 level between production- and consumption-based data may serve as empirical evidence that the macroeconomic rebound effect and carbon leakage (*carbon leakage*) offset the relative efficiency gains. The realisation of green growth is questionable, as local efficiency savings generate further consumption and hidden sectoral emissions shifts at the global level due to growth pressures and material affluence (Victor, 2019).

The theoretical and practical limitations of the sustainability transition therefore lie not in the underdevelopment of technology, but in the growth-oriented macroeconomic structure. Genuine absolute decoupling within a globally closed system cannot be achieved through technocratic fine-tuning based on the results; it requires the conscious, structural restriction of consumption patterns, income distribution and economic output.

According to the Kaya decomposition data, the rate of improvement in technological efficiency ($\Delta \ln(E/GDP) = -0.2877$; $\Delta \ln(CO_2/E) = -0.2291$) lagged far behind economic economies of scale. Based on Fixed Effects (FE) models, an increase in the share of renewable energy sources significantly reduces import dependency ($\beta = -0.6647$), whilst an expansion in final energy consumption generates drastic import pressure ($\beta = 9.0823$). Improvements in energy productivity showed a significant positive coefficient for import dependency ($\beta = 6.2086$), confirming that a reduction in unit costs leads to extra economic activity and higher energy imports. Based on the results, we can conclude that improvements in technological efficiency alone are unable to curb environmental pressure and import exposure.

Based on the results of the econometric analysis, we can conclude the following: In the Member States of the European Union, technology-driven improvements in energy efficiency are unable to reduce the absolute environmental burden in the long term. Based on data from cointegration PMG models, the relative savings accompanying improvements in energy intensity (E_GDP) are channelled by the economic system's internal growth imperative into an increase in absolute energy consumption ($energy_use_per_capita$), which may neutralise the environmental benefits of technical efficiency. Whilst territorial (production-based) indicators suggest an apparent absolute decoupling in the long run (GDP per capita) (PMG): -0.11^{***} , the consumption-based emissions model demonstrates that economic growth continues to increase emissions (GDP per capita) (PMG) closely and significantly in the long term: $+0.28^{***}$. This confirms that the EU-27 countries have not decoupled themselves from environmental constraints, but have merely externalised their environmental impact via import agents. The error correction term in the PMG model ($COINTEQ = -0.2808^{***}$) may serve as evidence that, in a consumption-based emissions system, following short-term shocks or green policy interventions, the system corrects back towards its long-term, growth-oriented equilibrium trajectory extremely rapidly, at a rate of 28 per cent per annum. This figure may highlight that the rebound effect is not a random phenomenon, but rather a systemic feature of how the market operates. If we intervene in the system with a green technology, market mechanisms (prices, the pursuit of profit, demand) immediately begin to work to transform this saving into growth and pull the economy back onto its familiar, high-emission trajectory. As a result, short-term political successes are eroded in the long run. Whilst the expansion of the service sector causes structural frictions and a temporary rise in emissions in the short term, in the long run this is the only structural macroeconomic variable capable of substantially and radically reducing consumption-based emissions (elasticity: -0.56^{***}); dematerialisation is therefore a key tool for partially mitigating the rebound effect. If the share of services in the economy (in terms of value added) increases by 1 per cent, this reduces the population's total global

consumption footprint (consumption-based emissions) by nearly 0.57 per cent. This is a strong, statistically significant effect. *The real key to the green transition is not making heavy industry more efficient (because the market compensates for this through growth), but rather structurally shifting the engine of the economy from material production to services.* Based on the models, this may be the only long-term strategy that is truly capable of reducing society's global consumption footprint.

REFERENCES

- Al-Azzam, M. – Fajness, M. (2018): On the Estimation of the CO₂ Emission, Economic Growth and Energy Consumption Nexus Using Dynamic OLS in the Presence of Multicollinearity. *Sustainability*, 10(5), 1315. <https://doi.org/10.3390/su10051315>.
- Antal, M. – van den Bergh, J. C. J. M. (2016): Re-spending rebound: A macro-level assessment for OECD countries and emerging economies. *Energy Policy*, 95, 140–150. <https://doi.org/10.1016/j.enpol.2016.04.018>.
- Barker, T. – Dagoumas, A. – Rubin, J. (2009): The macroeconomic rebound effect and the world economy. *Energy efficiency*, 2(4), 411–427. <https://doi.org/10.1007/s12053-009-9053-y>.
- Brockway, P. E. – Sorrell, S. – Semieniuk, G. – Heun, M. K. – Jackson, T. (2021): Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. *Renewable and Sustainable Energy Reviews*, 141, 110781. <https://doi.org/10.1016/j.rser.2021.110781>.
- Callen, T. (2012): Gross domestic product: An economy's all. *International Monetary Fund: Washington, DC, USA*.
- Dietz, T. – Rosa, E. A. (1997): Effects of population and affluence on CO₂ emissions. *Proceedings of the national academy of sciences*, 94(1), 175–179.
- Dinda, S. (2004): Environmental Kuznets Curve hypothesis: A survey. *Ecological Economics*, 49(4), 431–455.
- Ehrlich, P. R. – Holdren, J. P. (1971): Impact of Population Growth: Complacency concerning this component of man's predicament is unjustified and counterproductive. *Science*, 171(3977), 1212–1217. <https://doi.org/10.1126/science.171.3977.1212>.
- Ekins, P. (1997): The Kuznets curve for the environment and economic growth: examining the evidence. *Environment and planning a*, 29(5), 805–830.
- European Environment Agency (2023): Trends and projections in Europe 2023: Tracking progress towards Europe's climate and energy targets (EEA Report No. 07/2023). *Publications Office of the European Union*. <https://data.europa.eu/doi/10.2800/181515>.
- European Commission. (2019): The European Green Deal. Brussels, 11 December 2019. COM(2019) 640 final. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640>.
- Font Vivanco, D. – Kemp, R. – van der Voet, E. (2016): How to deal with the rebound effect? A policy-oriented approach. *Energy Policy*, 94, 114–125. <https://doi.org/10.1016/j.enpol.2016.03.054>.
- Giampietro, M. – Mayumi, K. (2018): Unraveling the complexity of the Jevons Paradox: The link between innovation, efficiency, and sustainability. *Frontiers in Energy Research*, 6, 349753. <https://doi.org/10.3389/fenrg.2018.00026>.
- Gillingham, K. (2014): Rebound effects. *The New Palgrave Dictionary of Economics*.
- Gillingham, K. – Rapson, D. – Wagner, G. (2016): The rebound effect and energy efficiency policy. *Review of environmental economics and policy*.

- Grossman, G. M. – Krueger, A. B. (1991): Environmental Impacts of a North American Free Trade Agreement. *National Bureau of Economic Research Working Paper* No. 3914.
- Gyamfi, B. A. – Bein, M. A. – Ozturk, I. – Bekun, F. V. (2020): The moderating role of employment in an environmental Kuznets curve framework revisited in G7 countries. *Indonesian Journal of Sustainability Accounting and Management*, 4(2), 241â–248. <https://www.resourcepanel.org/global-material-flows-database>.
- Hickel, J. – Kallis, G. (2020): Is green growth possible? *New Political Economy*, 25(4), 469–486. <https://doi.org/10.1080/13563467.2019.1598964>.
- International Energy Agency (2016): Energy Efficiency Market Report 2016. *OECD/IEA*. <https://www.iea.org/reports/energy-efficiency-market-report-2016>.
- International Energy Agency (2022): Energy Efficiency 2022. *Paris: IEA*. <https://www.iea.org/reports/energy-efficiency-2022>.
- International Energy Agency (2023): Energy Efficiency 2023. *IEA*.
- IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.), *IPCC*, Geneva, Switzerland, 151. <https://www.ipcc.ch/report/ar5/syr/>.
- IPCC (2022) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report. *Cambridge University Press*.
- IPCC (2014) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change.
- IRENA (2023): Renewable Energy Statistics 2023. *International Renewable Energy Agency*, Abu Dhabi.
- Ivanova, D. – Barrett, J. – Wiedenhofer, D. – Macura, B. – Callaghan, M. W. – Creutzig, F. (2020): Quantifying the potential for climate change mitigation from consumption. *Environmental Research Letters*, 15(9), 093001. <https://doi.org/10.1088/1748-9326/ab8589>.
- Jackson, T. (2009): Prosperity Without Growth: Economics for a Finite Planet. *Earthscan*.
- Jevons, W. S. (1865): The coal question: An inquiry concerning the progress of the nation and the probable exhaustion of our coal-mines. *Macmillan*.
- Jarvis, A. – King, C. W. (2024): Economy-wide rebound and the returns on investment in energy efficiency. *Energy efficiency*, 17(6), 60. <https://doi.org/10.1007/s12053-024-10236-7>.
- Kao, C. – Chiang, M.-H. (2000): On the estimation and inference of a cointegrated regression in panel data. In *Advances in Econometrics*, 15, 179–222.
- Karsch, N. M. (2019): Examining the validity of the environmental Kuznets curve. *Consilience*, (21), 32–50.
- Laurent, É. (2020): The European Green Deal: from growth strategy to social-ecological transition. *Social policy in the European Union: state of play*, 97–111.
- Meadows, D. H. – Meadows, D. L. – Randers, J. – Behrens, W. W. (1972): The limits to. *Growth*, 102, 27.
- OECD (2002): Indicators to measure decoupling of environmental pressure from economic growth. <https://doi.org/10.4236/ajibm.2022.126061>.
- Parrique, T. – Barth, J. – Briens, F., Kerschner, C. – Kraus-Polk, A., Kuokkanen, A. – Spangenberg, J. H. (2019): Decoupling debunked. Evidence and arguments against green growth as a sole strategy for sustainability. A study edited by the *European Environment Bureau EEB*, 3.
- Peters, G. P. – Minx, J. C. – Weber, C. L. – Edenhofer, O. (2011): Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences (PNAS)*, 108(21), 8903–8908. <https://doi.org/10.1073/pnas.1006388108>.

- Sorrell, S. (October, 2007): The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. <https://ukerc.ac.uk/publications/the-rebound-effect-an-assessment-of-the-evidence-for-economy-wide-energy-savings-from-improved-energy-efficiency/>.
- Sorrell, S. (2009): Jevons' paradox revisited: The evidence for backfire from improved energy efficiency. *Energy Policy*, 37(4), 1456–1469. <https://doi.org/10.1016/j.enpol.2008.12.003>.
- Suh, S. (2006): Are services better for climate change? *Environmental Science & Technology*, 40(21), 6555–6560. <https://doi.org/10.1021/es0609351>.
- United Nations Environment Programme (UNEP, 2011): Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication. Nairobi: *United Nations Environment Programme*. https://www.unep.org/resources/report/towards-green-economy-pathways-sustainable-development-and-poverty-eradication-10?utm_source=chatgpt.com.
- United Nations (2023): Global Sustainable Development Indicators Database: SDG Indicator 7.3.1 - Energy intensity measured in terms of primary energy and GDP [Data set]. *UN Statistics Division*. <https://unstats.un.org/sdgs/dataportal/>.
- Victor, P. A. (2008): Managing without growth: Slower by design, not disaster. In *Managing Without Growth*. Edward Elgar Publishing.
- Wiedenhofer, D. – Virág, D. – Kalt, G. – Plank, B. – Streeck, J. – Pichler, M. – Haberl, H. (2020): A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping. *Environmental research letters*, 15(6), 063002. <https://doi.org/10.1088/1748-9326/ab842a>.
- Wiedmann, T. – Lenzen, M. – Keyßer, L. T. – Steinberger, J. K. (2020): Scientists' warning on affluence. *Nature Communications*, 11(1), 3107. <https://doi.org/10.1038/s41467-020-16941-y>.