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Energy constraints in the European Union: Macroeconomic implications and the case for a managed degrowth transition

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Foreword

I would like to express my sincere gratitude to my thesis supervisor, Mr. Ruben Olieslagers, for his guidance, feedback and availability throughout the development of this thesis. I am especially grateful that he allowed me to choose a subject that genuinely interested me and gave me the freedom to define the direction of the research. His trust gave me the opportunity to explore this topic in a personal and meaningful way, while his comments and questions helped me improve the clarity and relevance of my work.

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Finally, I am deeply grateful to my parents for their advice, meaningful questions, and support. Their perspective helped me question my results more carefully and reflect more critically on the direction of this thesis.

Abstract

This thesis examines the relationship between energy constraints, monetary Gross Domestic Product (GDP) and physical economic activity in the European Union. While GDP remains the dominant measure of economic performance, it captures monetary output rather than the material and energy flows that keep the production process running. This distinction is central to the decoupling debate, as rising GDP alongside declining energy consumption may be interpreted as evidence of green growth, while potentially hiding stagnation or contraction in the physical economy.

The central research question is the following:

Does the divergence between monetary GDP and physical economic activity in the European Union since 2000 reflect a structural energy constraint, and to what extent does this support a managed degrowth alternative?

The empirical analysis relies on a balanced panel of 26 EU member states over the period 2000–2023. The analysis is built around three steps. Firstly, it compares how strongly energy consumption is linked to GDP and specifically to three physical indicators of economic activity: domestic material consumption, industrial production, and inland freight transport[1]. Secondly, it examines whether these relationships changed after the mid-2000s, when EU energy consumption reached its peak and the global financial crisis occurred. Thirdly, it tests whether countries that depend more heavily on energy show a stronger gap between GDP and physical activity.

The results support the core argument, but with nuance: the EU's apparent decoupling between energy and GDP is, at least partly, a measurement issue, because GDP does not fully reflect what is happening in the physical economy. Physical activity remains closely linked to energy availability, more than monetary GDP. This suggests that GDP can move away from the physical economy beneath it, while production, material use and freight remain more dependent on energy. The structural break and import dependency results are less straightforward than expected, implying that the divergence cannot be explained by one single turning point or by import exposure alone.

[1] The EU-26 sample and the construction of the variables, including inland freight transport, are defined in detail in Part III.

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INTRODUCTION

Context and relevance

Modern economies are built around the expectation of growth. Fiscal decisions, debt sustainability assessments, and social welfare systems all suppose its continuation. The heart of the whole economic and political decision-making process is Gross Domestic Product (GDP), the key aggregate which is used to measure, communicate and manage growth. Yet GDP captures the value of monetary transactions, not the physical flows of matter and energy that provide the basis for economic productivity. This issue has been highlighted by ecologists and economists for decades and has become particularly important now for the European Union (EU).

With over 80% of its natural gas requirements and nearly 90% of its crude oil consumption coming from imports, the EU is still structurally dependent on fossil fuels. The EU faces a longer-term difficulty beyond the geopolitical risk this involves, as shown by the energy crisis in 2022 after Russia invaded Ukraine and the conflict in Iran in 2026. In fact, since its historical peak between 2005 and 2007, overall primary energy consumption has been steadily declining. Supporters of green growth have interpreted this decline as evidence of successful decoupling: an economy growing while consuming less energy. This interpretation is questioned in this thesis. Assuming that energy is not simply a secondary cost but rather the basic prerequisite of production, this phenomenon demands critical investigation and could carry macroeconomic consequences that standard indicators could fail to capture.

Research question, scope and originality

The tension described above has shaped the central research question of this thesis:

Does the divergence between monetary GDP and physical economic activity in the European Union since the year 2000 reflect a structural energy constraint, and to what extent does this support a managed degrowth alternative?

This question is addressed through four parts. The literature review in Part I develops the theoretical foundations, revisiting GDP's limitations in a biophysical context and establishing energy as a fundamental production factor. Part II provides the contextual analysis of EU fossil dependence, declining energy return on investment, and the empirical limits of decoupling claims. After that, Part III constitutes the empirical research: using a balanced panel of 26 EU member states over 2000–2023, it tests whether physical activity indicators (domestic material consumption, industrial production and inland freight) diverge from monetary GDP in a consistent and meaningful way with structural energy constraints. It further examines whether this divergence is amplified in the most import-dependent economies. Finally, Part IV draws out the macroeconomic implications, distinguishing between unmanaged contraction and a deliberate degrowth transition, before a conclusion synthesizes the findings and identifies avenues for further research.

Methodology and key findings

The empirical analysis is built around three econometric models, each of them answering to one hypothesis. The first model begins by comparing elasticities of monetary GDP and physical indicators through fixed-effects regressions, testing whether physical activity is more tightly coupled to energy consumption than monetary output is. The goal of the second model is to try to find a period of time in which a potential change in energy consumption occurred in the EU. Model 2 applies a structural break framework around 2005–2008 to determine whether the *energy–GDP* relationship changed asymmetrically relative to the *energy–physical activity* relationship. Model 3 introduces cross-country variation in energy import dependency to test whether the GDP–physical activity divergence is more pronounced for countries where external energy exposure is the most important.

The results obtained describe a coherent but nuanced picture. Indeed, Model 1 provides as expected the clearest support for the core proposition. Physical activity indicators exhibit energy elasticities close to or above unity, substantially higher than the 0.73 estimated for monetary GDP. This confirms that the physical economy remains more tightly coupled to its energy base than monetary output does. Model 2 is more ambiguous: the structural break around 2008 weakens energy elasticities across all four outcome variables, but not GDP. It seems to contradict the prediction that the break would be concentrated in the monetary dimension. This result, however, is best understood in the context of the 2008 financial crisis, which concurrently reduced both monetary and physical activity before an asymmetric recovery. GDP recovered through growth in both financial and service sectors, while physical throughput did not. Model 3 offers only partial support: import dependency does indeed moderate the energy–industrial output relationship in the predicted direction, but the effect is small in magnitude. Taken together, the evidence supports the central argument with important nuance: the GDP–physical activity divergence is a structural feature of EU data, but it cannot be attributed cleanly to a single break point nor to import dependency only.

PART I. LITERATURE REVIEW

1. Economic growth and GDP

Economic growth, as it is understood and measured, refers to the annual increase in Gross Domestic Product (GDP), the aggregate monetary value of all final goods and services produced within a given economy over a period of time. GDP has become a structural pillar of contemporary governance as well as the main statistical instrument for macroeconomic research since it was institutionalised following World War II. Growth's prominence as a primary goal has been reinforced by the historical correlation between rising output in industrialised economies and improvements in living standards, healthcare, and education (Aghion and Howitt, 2008). GDP expansion is assumed by fiscal frameworks, debt sustainability evaluations, monetary policy goals, and pension plans, turning growth from a performance metric into a systemic necessity (Parrique, 2022).

Yet the scope of what GDP actually captures is considerably narrower than its prominence in public discourse might suggest. By construction, GDP records only activities that generate monetary transactions. Exchange value is measured and on the contrary, use value is not. A forest cleared for commercial development contributes positively to GDP while the volunteer work of those who tried to prevent it does not. Dědeček and Dudzich (2022) note that this focus on marketised output renders GDP per capita a structurally incomplete indicator of economic development, one that conflates the expansion of monetary transactions with genuine improvements in welfare or productive capacity. The metric treats all monetized production as equivalent in accounting terms, regardless of whether it enhances or degrades collective welfare, and it provides no insight into the qualitative dimensions of output that often matter most in sectors such as healthcare or education (Parrique, 2022; Van Leeuwen et al., 2025). More fundamentally, GDP does not record environmental degradation as a cost. Natural capital depletion, biodiversity loss, and ecosystem disruption do not appear as negative entries in national accounts, but they enter only once appropriated and monetized (Brandon et al., 2021). This means that an economy actively liquidating its ecological base can still register robust growth figures, however, predictions of limitless economic growth without concern for environmental degradation are demonstrably erroneous (Maris and Holmes, 2023). Growth is not an abstract monetary phenomenon, but one materially embedded in resource flows and ecological processes (Maris and Holmes, 2023).

The more consequential limitation for the purposes of this study is different. It does not concern what GDP fails to count, but what it counts with no physical counterpart. GDP aggregates the value of monetary transactions, including financial services, asset price appreciation, and the expansion of credit; those are activities that generate measured output without necessarily involving any change in the volume of goods produced, materials extracted, or physical work performed. As Parrique (2022) notes, from a biophysical standpoint economic activity could equally be assessed in kilograms of materials consumed, joules of energy used, or tonnes of freight moved. This creates a conceptual space in which monetary GDP and physical economic throughput can move apart. An economy can expand in monetary terms while the physical substrate sustaining that expansion stagnates or contracts.

An empirical analysis of EU countries finds that the sectoral composition of GDP (specifically the relative weight of industry versus services) significantly shapes the relationship between monetary output and environmental pressures. This finding suggests that GDP growth driven by service-sector expansion carries a materially lighter physical footprint than growth driven by industrial output (Martín-Ortega and González-Sánchez, 2025). However, as Brandon et al. (2021) show through comprehensive wealth accounting, development has historically involved the progressive transformation of natural and material capital into produced and financial capital, meaning that the monetary aggregate grows while the physical foundation it has been based upon is progressively depleted or shifted offshore.

This distinction between monetary and physical measures of economic activity is the conceptual departure point for the empirical analysis developed in Part III. If energy is a structural driver of physical output as the following section argues then the relevant question is not whether GDP continues to grow, but whether the physical economy beneath it does.

2. Energy as production factor

The standard neoclassical production function represents output as a function of capital and labour, with energy either omitted entirely or treated as a marginal intermediate input whose productive weight is approximated by its cost share. This convention has been challenged persistently, and the challenge has become increasingly difficult to dismiss.

Keen et al. (2019) argue that this representation is incorrect. Labour and capital are not independent inputs to production; they are means of converting energy into useful work. A worker without metabolic energy performs no labour, just the same way a machine without a continuous energy flow performs no capital service. Reducing the productive role of energy to its market price share therefore misrepresents the structure of production. It confuses the cost of a factor with its contribution to output. For example, a truck without fuel goes nowhere regardless of how much labour and capital surrounds it, the cost of the diesel is a small fraction of the total operation, but its absence makes the entire operation impossible. Keen et al. (2019) formalise this argument by reformulating the Cobb-Douglas production function so that energy enters as an input to both labour and capital rather than alongside them, yielding a production function in which energy's productive contribution is substantially larger than its cost share implies.

The thermodynamic grounding of this argument goes deeper still. Fagnart and Germain (2015) demonstrate that all economic processes involve the transformation of matter and energy subject to the laws of thermodynamics, meaning that productive capacity cannot in principle be fully dissociated from energy throughput. Efficiency gains can compress the energy required per unit of production, but they do not eliminate dependence. The authors further show that the conditions for sustaining even purely qualitative economic growth (growth in product variety and quality rather than sheer volume) are not fundamentally less demanding in energy terms than those for quantitative growth, an insight with direct implications for the dematerialisation hypothesis discussed in the following section.

An earlier counterpart to this theoretical framing is provided by Pindyck and Rotemberg (1983), who modelled dynamic factor demands and demonstrated that energy, capital and labour function as complements rather than substitutes in aggregate production. Their finding that energy price shocks propagate into investment behaviour, employment and output through capital-energy complementarity established a foundation for treating energy as a structural rather than peripheral input. The macroeconomic transmission of energy constraints works through the entire structure of the economy. When energy availability declines, it is not only energy-intensive sectors that contract, other indicators such as investment and employment fall broadly, since capital and labour lose the energy inputs they require to remain productive. This finding is consistent with the view that energy underpins the productive capacity of the economy as a whole, and it is an argument that has only gained support in subsequent decades.

The aggregate relationship between energy and output has been documented extensively across both cross-sectional and time-series data. Csereklyei et al. (2016), analysing a panel of 99 countries from 1971 to 2010, identify a stable and robust relationship between per capita energy use and per capita income. Their key finding is that while energy intensity (energy consumed per unit of GDP) tends to decline as economies grow richer, total energy consumption continues to rise. In other words, efficiency improvements reduce the energy required per dollar of output, but they do not offset the scale effect of a larger economy. The research also showed that energy intensity does not decline in the absence of economic growth, which is consistent with the view that causality runs at least partly from energy availability to economic performance, not only in the reverse direction (Csereklyei et al., 2016).

This causality question has led to a large independent research. Mardani et al. (2019), in a systematic review of two decades of empirical work on the energy-growth nexus spanning 1995 to 2017, find that across a wide range of countries and methodologies, energy consumption Granger-causes GDP more frequently than GDP Granger-causes energy[2]. In many contexts, energy availability appears as a driver of growth rather than a passive by-product of it. Aamir and ur Rehman (2024), examining a tri-regional panel of

[2] Granger causality, introduced by Clive Granger (1969), is a statistical concept rather than a test of causality in the philosophical sense. Variable X is said to Granger-cause variable Y if past values of X contain information that helps predict future values of Y, beyond what past values of Y alone can explain. In the energy-growth literature, finding that energy consumption Granger-causes GDP means that changes in energy use systematically precede and predict changes in output.

countries, further confirm a dynamic nexus between fossil fuel use and economic growth, highlighting that dependence on fossil energy is not simply a temporary phase of development but a structural feature of economies that has persisted across decades and geographies.

Taken together, these contributions establish a consistent picture: energy is not a peripheral commodity whose scarcity can be buffered by substitution or efficiency alone, but a structural enabling condition for productive activity. Any sustained reduction in the total energy available to an economy should leave a visible mark on physical output.

3. Decoupling debate

The concept of decoupling, i.e. the idea that economic growth can be dissociated from environmental pressures, occupies a central place in both academic literature and policy frameworks promoting sustainable growth. At its most ambitious, the claim is one of absolute decoupling: that GDP can continue to expand while resource use and environmental impacts decline in absolute terms. The empirical literature examining this claim paints a considerably more ambiguous picture.

The conceptual framework requires precision. Sorman (2023) distinguishes between relative and absolute decoupling, and between decoupling of resource use and decoupling of environmental impacts. Relative decoupling (environmental pressures grow more slowly compared to GDP) is a fundamentally different proposition from absolute decoupling, in which they decline in real terms. The distinction is critical because relative decoupling is entirely consistent with continued environmental degradation, because it simply means degradation is becoming slower relative to output. Most documented cases of decoupling in developed economies are relative rather than absolute and are typically limited to a single indicator such as carbon emissions or energy intensity, while broader measures of material throughput continue to expand (Sorman, 2023). Focusing on a single indicator therefore risks creating a misleading perception of sustainability progress where none of the underlying physical reality supports it.

The global material flow evidence is particularly revealing. Haas et al. (2015), assessing the circularity and material flows of the global economy for 2005, find that only approximately 6% of all processed materials are recycled, a figure that improves only modestly when biomass is included. The volume of physical material injected annually into economic systems continues to outpace recycling efforts by a wide margin, and the vast majority of processed material is either accumulated in built capital, dissipated as waste, or combusted for energy. This finding directly undermines the claim that circular economy strategies can close material loops at a scale sufficient to decouple growth from extraction. As Sorman (2023) notes, drawing on the same evidence, the industrial economy remains thermodynamically entropic far more than it is circular. Standard decoupling analyses, conducted primarily from a statistical or econometric viewpoint, systematically overlook this reality by ignoring the physical laws governing energy and material transformations.

A further structural limitation concerns the role of international trade in generating the appearance of decoupling. Much of the empirical work on decoupling relies on territorial or production-based accounting, which measures only the environmental pressures occurring within a country's borders. For economies that have offshored energy-intensive and materials-intensive manufacturing, this produces a systematic bias. Domestic environmental pressures decline not because the economy has genuinely dematerialised, but because the material-intensive stages of production have been relocated. Sorman (2023) refers to this phenomenon as virtual decoupling, and shows that consumption-based accounting (which attributes to each country the environmental pressures embodied in what it consumes, wherever it was produced) reveals a very different picture.

The implications for the EU context specifically are examined by Sanyé-Mengual et al. (2019), who assess the decoupling of GDP from environmental impacts in the EU-28 between 2005 and 2014. While absolute decoupling appears when using a domestic production perspective, the consumption-based perspective reveals that the environmental burdens of imports increased over the same period, largely offsetting domestic reductions. The authors show that trade components, from both the environmental impacts of imports and those embodied in exports, exhibit larger variations than the domestic component, and that the expansion of imports played a decisive compensating role. What looks like environmental progress within EU borders is partially a geographical transfer of environmental cost to other regions.

Turning to the energy and climate policy literature specifically, Papież et al. (2022) find that EU energy and climate policies have contributed to a relative decoupling of GDP from greenhouse gas emissions across member states, but with considerable heterogeneity and outcomes that fall short of the absolute reductions required for long-term climate commitments. Crucially, this decoupling is concentrated in the carbon dimension of environmental pressure and does not extend consistently to broader measures of resource or energy throughput. This is precisely the methodological shortcoming that Sorman (2023) identifies as the central weakness of the green growth literature, precisely that by connecting decarbonisation with sustainability, it ignores the material and energy dimensions of the economy's ecological footprint.

What the decoupling debate ultimately reveals is a persistent tension between what the monetary surface of the economy registers and what is happening to the physical substrate beneath it. GDP can grow while material consumption stagnates, energy use declines, and the volume of goods physically produced remains flat. Whether that is what has happened in the EU since the mid-2000s is precisely what Part III of this thesis is designed to test. The apparent resilience of EU monetary GDP in the face of declining primary energy consumption is not necessarily a sign of structural transformation toward a lighter economy. It may instead be a sign of divergence between the monetary and physical dimensions of economic activity. That divergence may only become visible when the economy is measured in physical terms rather than monetary terms.

4. Measuring the physical economy

Ripa et al. (2021) analyse the energy metabolism of EU-19 economies through a multi-scale framework[3]. They demonstrate that accounting for embodied energy flows,

[3] Ripa et al. (2021) distinguish three scales of analysis for assessing an economy's energy system. The macroscope captures the overall metabolic pattern of society, examining how economic sectors interact to sustain the system as a whole. The mesoscope assesses the degree of openness of the system (the flows of energy and resources exchanged through international trade). The microscope focuses on the specific production processes taking place inside or outside the economy's borders, linking energy flows to their local environmental impacts.

particularly those rooted in imported goods and energy carriers, reveals a substantially larger picture of energy dependency than conventional territorial energy balances suggest. When externalized energy consumption is included, the total greenhouse gases (GHG) emissions attributable to the EU energy sector rise by approximately 60% on average. This illustrates a general methodological principle, that physical variables measured in units tied to actual material flows are way harder to inflate through financial mechanisms, accounting conventions, or sectoral reclassification than monetary aggregates. They measure what actually happened in the physical economy.

Industrial production indices have historically been used as measures of the physical output of the productive core of the economy precisely because they track the volume of goods manufactured rather than their price. They are structurally less sensitive to financial services expansion, asset price movements, or the growing share of intangible activities in GDP.

What makes these three indicators well-suited to testing the biophysical argument is that they capture distinct and complementary dimensions of physical economic activity: production volume, resource throughput, and logistics. None of them can expand through financial intermediation or service-sector growth. If energy genuinely functions as a structural enabling condition for the economy, all three should remain tightly coupled to energy consumption even if monetary GDP does not. Conversely, the post-2008 divergence between EU energy consumption and GDP may not reflect genuine dematerialisation at all. It may instead reflect a change in what GDP measures, such as a growing share of financial and service value in a stagnant or contracting physical economy, in which case the physical proxies should continue to track energy while monetary GDP drifts above them.

The theoretical and empirical debates reviewed in the literature converge on a tension that remains insufficiently resolved in the existing research. Studies examining decoupling in European economies have consistently found that any absolute reduction in resource use or energy consumption tends to coincide with periods of low economic growth or recession, rather than reflecting a genuine structural loosening of the economy's dependence on physical inputs (Haberl et al., 2020). Yet the existing literature has largely examined this question through the lens of a single environmental indicator (often carbon emissions or equivalent) and has compared it against monetary GDP as the sole measure of economic activity. What has not been systematically tested is whether the divergence observed between energy consumption and monetary GDP in the EU reflects a genuine change in the physical economy, or whether it is an artefact of GDP's growing disconnect from physical throughput. Answering this question requires measuring economic activity in physical rather than monetary terms and testing whether these physical measures remain coupled to energy in ways that monetary GDP no longer does. That is the empirical contribution this thesis makes, in the specific context of the EU over the period 2000–2023, the structural energy conditions of which are examined in detail in Part II.

PART II. EU ENERGY: CONTEXT AND CONSTRAINTS

The decline in EU primary energy consumption raises an important question: is this decline mainly the result of deliberate policy choices, such as energy efficiency and climate policies, or is it also caused by increasing difficulties in accessing energy supplies? To answer this question, it is necessary to look not only at how much energy the EU consumes, but also at where this energy comes from. The following section therefore examines the EU's dependence on imported fossil fuels and the vulnerabilities this dependence creates.

1. Energy consumption in the EU

The European Union is one of the largest energy consumers in the world, and its energy trajectory over the past three decades is central in order to understand the empirical research this thesis investigates. As shown in Appendix 1 (Our World in Data, 2025), EU primary energy use per capita rose steadily from the mid-1960s through the early 2000s, reaching a peak of approximately 44,000 kWh per person around 2005–2006. Since then, it has declined continuously, falling to below 35,000 kWh per capita by 2024, a reduction of roughly 20% from its peak in less than two decades. This is not necessarily a cyclical fluctuation, it is rather a sustained contraction in the energy available to the EU economy per unit of population.

The composition of that energy consumption matters as much as its trajectory. As Appendix 2 (Our World in Data, 2025) illustrates, fossil fuels have accounted for the majority of EU primary energy needs throughout the entire period from 1995 to 2024. While their combined absolute volumes have declined alongside total consumption, they continue to dominate the energy mix. Oil remains the single largest source, followed by natural gas and coal. Renewable energy sources have grown significantly in relative terms and are the only category still expanding in absolute volume, but they remain far from compensating the contraction in fossil fuel supply. In 2024, fossil fuels still accounted for roughly two thirds of EU primary energy consumption. The energy transition is real but incomplete, and the net energy available to the EU economy has continued to decline because the growth of renewables has not offset the fall in fossil fuel use.

This point is important because the thesis does not only ask whether the EU energy mix is becoming cleaner. It asks whether the total amount of energy available to the economy is still sufficient to sustain physical activity. Renewable energy has grown, but not enough to compensate for the decline in fossil fuel consumption. As a result, total primary energy consumption has continued to fall since the mid-2000s. From the perspective developed in Part I, this matters because production, material use and freight depend on energy throughput, whatever the source of energy. A greener energy mix does not automatically remove physical constraints if the total of energy available is shrinking.

2. Fossil fuels and geopolitical exposure

The European Union is a heavily import-dependent regarding its energy use. According to Eurostat data, the EU's overall energy import dependency rate averaged around 55% over the 2000–2023 period. For oil and gas specifically, dependency is considerably higher. As Ripa et al. (2021) demonstrate through a multi-scale accounting of the EU-19 energy sector, this dependency is even stronger when indirect imports are included. Indirect imports refer to the energy used abroad to produce goods or energy commodities that are later imported and consumed within the EU. When both directly and indirectly imported oil are accounted, Ripa et al. (2021) find that the EU-19 average dependency rate on external crude oil is almost 100%. It shows that the EU's physical economy remains deeply exposed to external fossil fuel supply.

This structural exposure creates a vulnerability that goes well beyond price volatility. Fossil fuels are geologically finite resources, and the global supply landscape has been shifting in ways that are directly impacting EU's position. Sorrell et al. (2010), in a comprehensive review of the evidence on global conventional oil[4] depletion, conclude that a peak in conventional oil production before 2030 is plausible, with a significant risk of an earlier peak. Their analysis shows that the cumulative production of conventional oil already exceeded 60% of estimated recoverable reserves at the time of writing, and that a large share of existing production is drawn from mature and declining fields. This

[4] Sorrell et al. (2010) define conventional oil as including crude oil, condensate and natural gas liquids, while excluding liquid fuels derived from oil sands, oil shale, coal, natural gas and biomass. Conventional oil is generally treated separately because non-conventional sources face greater technical, economic and environmental constraints.

matters for import-dependent economies such as the EU, because a decline in conventional oil production would affect global supply volumes and could also reduce the amount of oil available for export. Indeed, as production declines, exporting countries may prioritize their own domestic consumption and export less, which would further tighten international markets. This dynamic would likely increase competition among importing countries for the remaining exportable oil.

Another dimension of this vulnerability concerns not only the quantity of fossil fuels available, but also their quality as energy sources. The concept of Energy Return on Investment (EROI) measures the ratio between the energy delivered to society and the energy required to obtain it. An economy does not run on gross energy alone, but on the energy that remains after extraction, transformation, transport and infrastructure. Hall et al. (2014) demonstrate a long-term decline in the EROI of fossil fuels, as the easiest reserves are progressively depleted and extraction moves toward more complex resources such as deep offshore oil, tight gas and oil sands. In simple terms, more energy must be invested to obtain the same amount of energy that can actually be used by the economy.

This is directly relevant for the EU's fossil fuel dependency. If imported fossil fuels become harder to access, they cannot simply be replaced by renewables without cost or delay. Renewable energy is essential for decarbonisation, but its expansion requires major investment in grids, storage, electrification, industrial capacity and material extraction. During the transition, part of the available energy, money and materials must therefore be used to build the new energy system itself. Moriarty and Honnery (2019) support this point by arguing that energy systems should be assessed not only by how much energy they produce, but also by how much energy and material input they require. The key issue is therefore not only whether the EU can replace fossil fuel volumes, but whether the transition can provide enough energy to maintain physical economic activity.

For natural gas, the situation is also precarious. The Shift Project (2022), in a risk assessment of EU gas supply based on Rystad Energy data, argues that the EU is exposed to lasting tensions on gas markets. The report estimates that around 70% of EU gas import volumes have historically arrived by pipeline, mainly from Russia, Norway and Algeria.

The sharp decline in Russian supply after the February 2022 invasion of Ukraine therefore revealed a vulnerability that was already present in the European energy system. According to the same report, even if Russian contracts were restored and EU demand declined significantly, unidentified EU gas supply could still reach 25% by 2030 and 50% by 2035. The report should be read as a scenario-based risk assessment rather than a peer-reviewed forecast, but it is useful here because it highlights the EU's exposure to supply uncertainty, LNG competition and dependence on a limited number of external suppliers. Mišík (2022) similarly stresses that EU external energy security has been structurally inadequate for years, with member states' divergent interests and dependence on a small number of suppliers making the Union systemically vulnerable to supply disruptions.

3. From context to research questions

The two observations developed in this section, i.e. the sustained post-2006 decline in EU primary energy consumption and the structural fossil fuel import dependency that constrains the EU's energy supply from outside, directly motivate the three empirical hypotheses tested in Part III.

If energy is a fundamental enabling condition for physical economic activity, as the literature reviewed in Part I argues, then the contraction in EU energy throughput since the mid-2000s should have left a visible mark on the physical economy, and could be reflected on goods produced, materials consumed and freight moved. Yet over much of this same period, monetary GDP has shown relative resilience, recovering after the 2008 financial crisis and resuming a positive trajectory that appears disconnected from the energy trajectory. Whether that disconnection is real or whether it is an artefact of what GDP measures, with the physical economy stagnating beneath a growing monetary surface, is the central question Part III addresses.

Import dependency is another important point. If energy constraints affect the physical economy, this effect should be stronger in countries that are more dependent on imported fossil fuels. In these countries, difficulties in accessing energy are more likely to affect production, transport and material use. Differences in import dependency across EU member states make it possible to test whether import exposure strengthens the gap between monetary GDP and physical economic activity.

PART III. EMPIRICAL RESEARCH

1. Research question & hypotheses

The first two parts of this thesis have shown a central tension. Energy remains necessary for production, while the EU has experienced a decline in primary energy consumption since the mid-2000s. If this decline reflects a real energy constraint, then GDP may no longer give a complete picture of the economy's physical evolution. In other words, monetary GDP may continue to grow even when the material side of the economy stagnates or contracts.

Part III tests this idea empirically using EU data over the period 2000–2023. The following research question and hypotheses examine whether energy is more closely linked to physical indicators of economic activity than to monetary GDP[5].

Does the divergence between monetary GDP and physical economic activity in the European Union reflect a structural energy constraint, rather than genuine dematerialization?

1.1 H1: The physical coupling hypothesis

Energy is not a peripheral input to production but a fundamental enabling condition, we showed that without energy throughput, neither capital nor labour can perform work. This means that indicators measuring the physical output of an economy, such as goods transported, materials processed, or structures built, should remain structurally bound to energy availability. Monetary GDP, however, captures financial transactions and service-sector value that may expand independently of physical output, progressively detaching from the underlying energy base. If this detachment is real, the apparent resilience of EU GDP growth since the mid-2000s would mask a deeper stagnation in material throughput, one that only becomes visible when the economy is measured in physical rather than monetary terms.

H1: Physical activity indicators (freight, DMC, industrial output) are more tightly coupled to primary energy consumption than monetary GDP is, across EU countries over 1995–2022.

[5] The R code used for the empirical analysis is reported in Appendix 8.

1.2 H2: The structural break hypothesis

EU total primary energy consumption reached its historical peak around 2005–2007 (Appendix 1) and has been on a sustained downward slope since then. This turning point coincides with the onset of a period in which monetary GDP, after the interruption of the financial crisis, resumed growth while energy consumption did not recover to its pre-peak levels. If energy really is what drives the economy, a permanent contraction in energy availability should have left a visible change on the GDP trajectory. Yet, by looking at the GDP evolution, it appears to have partially decoupled from it. The question is whether this apparent decoupling reflects a structural transformation of the economy. The way we measure it might be hiding what is really going on with energy and the economy, obscuring a physical contraction that was already underway.

Testing for a structural break around 2005–2008 allows these interpretations to be analysed empirically. If the relationship between energy- and GDP tends to break down while the energy-physical activity does not, it would indicate that the post peak de-coupling is confined to the monetary dimension of the economy and thus does not extend to its material foundation. This would be consistent with the view that apparent GDP rebound post-2007 is driven by sectoral composition shifts and financialization rather than by any fundamental reduction in the economy's reliance on energy throughput.

H2: The relationship between energy consumption and monetary GDP in the EU underwent a significant structural change around 2005–2008, while the relationship between energy consumption and physical activity indicators remained stable across the same break point.

1.3 H3: The import dependency heterogeneity hypothesis

The EU is not a homogeneous energy block. In fact, member differ significantly in how exposed they are to external fossil fuel supply. Countries that rely heavily on imported oil and gas are more directly exposed to both price volatility and volume constraints happening outside their borders. When import-dependent economies face tightening supply or price shocks, the cost of energy inputs rises relative to productive output, compressing physical activity more severely than in countries with greater domestic energy resources or lower fossil fuel dependency. If the GDP-physical activity divergence developed in H1 and H2 is indeed driven by energy constraints rather than by structural economic changes, it should be more pronounced for countries that are the most vulnerable to external supply conditions.

H3: The divergence between GDP and physical activity is more pronounced in countries with higher fossil fuel import dependency.

2. Data & variables

2.1 Sample and time period

The empirical analysis is conducted on a balanced panel of 26 member states of the European Union, observed annually over the period 2000–2023. Malta is excluded from the panel due to the complete absence of inland freight data throughout the study period. The choice of the EU as the unit of analysis is motivated by three considerations. Firstly, the EU constitutes a coherent institutional and policy space, with harmonised statistical reporting through Eurostat, ensuring cross-country comparability of the data. Secondly, as established in Part II, the EU collectively exhibits the structural energy characteristics central to this thesis: high fossil fuel import dependency, a shared trajectory of declining primary energy consumption since the mid-2000s, as well as a common regulatory framework regarding its energy and climate policy. Thirdly, the heterogeneity within its member states (through economic structure, energy mix and import exposure) provides meaningful cross-country variation to test the third hypothesis.

The start of the panel is set for 2000, determined by the availability of Domestic Material Consumption data, the earliest date at which all variables are available for the full set of member states. The end year 2023 reflects the most recent year for which consistent data across all variables had been published at the time of analysis. This window of 24 years places the structural break of interest (the peak and subsequent decline of EU energy consumption around 2005–2008) comfortably within the sample.

2.2 Dependent variables: physical activity proxies

A important methodological choice of this study is the use of physical indicators of economic activity as dependent variables alongside monetary GDP. This choice is theoretically motivated: if energy is a fundamental enabling condition for physical production, then indicators measuring the material output of the economy should remain more tightly bound to energy availability than monetary GDP, which can expand through other means, as explained previously. Three complementary proxies are used, each capturing a distinct dimension of physical economic activity.

Industrial Production Index (IPI)

The first proxy is the index of industrial production, sourced from Eurostat dataset *sts_inpr_a*. It covers the three sectors that constitute the material core of the economy: mining and quarrying, which extracts the raw materials that feed industrial processes; manufacturing, which transforms those materials into goods; and energy supply, which powers the entire production chain. This sectoral coverage corresponds to the NACE Rev. 2 classification used by Eurostat, and together these three sectors represent the part of the economy most directly dependent on physical energy throughput. The index is expressed in calendar-adjusted terms with base year 2015=100 and is available for all EU member states from 1995 onwards. Industrial production is the most direct measure of physical output in the economy, as it tracks the volume of goods actually produced rather than their monetary value.

Domestic Material Consumption (DMC)

The second proxy is Domestic Material Consumption, sourced from Eurostat dataset *env_ac_mfa*. DMC measures the total weight of materials extracted domestically and imported, minus exports. In other words, it concretely measures the material actually used by the economy in a given year, expressed in thousand tonnes. It covers all material categories in aggregate and is available for all EU member states from 2000 onwards. DMC is a particularly relevant proxy for this study because it captures the material scale of the entire economy, not just the industrial sector, and has been used extensively in the decoupling literature (source) as a measure of resource throughput. Crucially, unlike carbon emissions, DMC cannot be reduced through accounting changes or offshoring of production.

Inland Freight Transport (IFT)

The third proxy is road freight transport volume, sourced from Eurostat dataset *road_go_ta_tott*, measured in million tonne-kilometers. It captures total road freight (the aggregate of goods moved by weight and distance) which constitutes one of the most direct observable expressions of physical economic activity. The movement of physical goods requires energy and responds to changes in material throughput across the economy; when production and consumption of physical goods contract, freight volumes follow. Data is available for all EU member states from 1999 onwards. This dataset covers road freight specifically since rail and inland waterway freight are not included, which represents a minor limitation acknowledged in the robustness section.

Together, these three indicators provide a triangulated picture of physical economic activity across production, material use, and logistics. These three dimensions should fluctuate alongside with energy availability if the biophysical argument developed in Part I holds.

2.3 Key independent variable: energy consumption

The key independent variable in all regression models is primary energy consumption, sourced from Eurostat's Complete Energy Balances dataset *nrg_bal_c*, specifically the Primary Energy Consumption indicator as defined under the Energy Efficiency Directive[6]. It is expressed in thousand tons of oil equivalent (ktoe) and is available for all EU member states on an annual basis from 1995 onwards.

Primary energy consumption measures the total amount of energy entering the economy before any transformation or distribution. It captures energy extracted domestically together with net imports, covering all energy carriers including fossil fuels, nuclear, and renewables. It is the broadest and most comprehensive measure of an economy's energy

[6]Primary energy consumption measures the total energy demand of a country. It covers consumption of the energy sector itself, losses during transformation (for example, from oil or gas into electricity) and distribution of energy, and the final consumption by end users. It excludes energy carriers used for non-energy purposes (such as petroleum not used not for combustion but for producing plastics).
Source: Eurostat, "Primary energy consumption - Glossary", available at:
https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Primary_energy_consumption

throughput, and the most theoretically appropriate for this study. The argument developed in Part I establishes that energy is a fundamental enabling condition for all productive activity, not a marginal input: it is the total flow of energy available to the economic system that matters, not the energy reaching a specific end-use sector.

2.4 Control and moderating variables

Real GDP

Real GDP serves a dual role in this study. In the regressions testing H1, it acts as a dependent variable, serving as the monetary comparator against which physical proxies are benchmarked. In the physical proxy regressions, it becomes a control variable, capturing the scale of the economy independently of energy throughput. This second role is necessary because larger economies naturally consume more energy and produce more physical output simultaneously, meaning that including GDP as a control ensures that the energy coefficient captures the genuine energy-activity relationship rather than simply reflecting differences in economic size across countries.

GDP data are sourced from Eurostat dataset *nama_10_gdp*, expressed as chain-linked volumes with base year 2015=100, ensuring comparability with the industrial production index and removing the distorting effects of inflation. This dataset provides complete coverage for all EU member states from 1995 onwards. Expressing GDP and the industrial production index in the same base year also facilitates direct visual comparison in the descriptive analysis.

Country fixed effects

All panel regressions include country fixed effects, which absorb all time-invariant characteristics specific to each member state that could otherwise confound the energy-activity relationship. These include structural factors such as geographic endowments, historical industrial composition, institutional quality, and long-standing energy infrastructure. Without fixed effects, a regression pooling 26 heterogeneous countries would conflate within-country variation over time with between-country differences that have little to do with energy constraints. Fixed effects ensure that identification comes from the temporal dynamics within each country, which is both more appropriate theoretically and more conservative statistically.

Time fixed effects

Year fixed effects are included alongside country fixed effects, capturing any shocks or trends common to all EU member states in a given year, such as the 2008–2009 financial crisis, the 2020 COVID disruption, or the 2022 energy price shock following the war in Ukraine. Absorbing these common time effects prevents them from being incorrectly attributed to the energy variable, which itself fluctuates in response to these same aggregate shocks.

Energy import dependency

The energy import dependency rate, sourced from Eurostat dataset *nrg_ind_id*, is the moderating variable introduced specifically to test H3. It measures the share of an economy's gross energy consumption that is met by net imports, expressed as a percentage, and is available for all EU member states annually from 1995 onwards. In the H3 specification, it enters the model as an interaction term with energy consumption, allowing the energy-activity relationship to vary across countries depending on their degree of external exposure. A country with high import dependency has limited ability to buffer energy supply constraints through domestic production, making it more vulnerable to the kind of physical contraction the thesis argues is already underway. The interaction term captures whether this vulnerability translates into a measurably stronger GDP-physical activity divergence.

2.5 Data transformations and descriptive statistics

All continuous variables were entered into the models after two transformations. Firstly, in order to make coefficients reflect elasticities, natural logarithms of energy consumption, GDP, and all three proxies were applied. Secondly, all variables were made into per capita by dividing the total amount by the population of a country, since the number of people is a critical factor determining both levels of energy consumption and the size of the economy.

For the descriptive divergence analysis, all series were additionally normalized to the year 2000 as a base year (represented by 100). It simplified visual comparison of tendencies measured in different units. It is important to note that normalization was only used for the graphical presentation of the data and was not used in the regression analysis.

Descriptive statistics for all variables used in the analysis are provided in Appendix 3. The table shows the number of observations, the mean value, standard deviation, minimum, and maximum for each variable for the sample of 26 countries for the period of 2000-2023. Several observations about the data distribution can be made before proceeding to the regression results. Both energy consumption and three physical proxies exhibit a downwards trend from the late 2000s onwards, whereas the real GDP growth shows a less prominent pattern.

For energy consumption and most of the proxies, the deviation from the mean is very significant, which is explained by the fact that some EU countries significantly differ in the size of their economies. For example, Germany and France have the largest economies among the EU members, followed by Poland, significantly surpassing the Baltic states, Slovenia, and other small European states in energy consumption and domestic material consumption (DMC). Finally, for the import dependency, the range between the minimum and maximum is equally significant. For the import dependency, some countries have negative values because they were net exporters of primary energy during the period under review. On average the EU imports more than it exports.

According to the descriptive statistics, the lowest value of import dependency is – 50,62%, whereas the highest is 102,51%. The great dispersion of import values around the mean indicates that there is a significant variation of import dependency levels between EU countries, which is necessary for testing H3. On a theoretical level, this is explained by the fact that several EU members are net exporters of primary energy, and several of them are close to zero energy independence, whereas the majority of EU countries import more than they export. As a result, the dispersion between the minimum and maximum is greater than 150% in most cases.

3. Methodology

3.1 Overall empirical strategy

All three models presented in this section are estimated as two-way fixed effects panel regressions, with both country and year fixed effects included in every specification. The use of fixed effects over random effects is motivated by the Hausman test, results of which are reported in the results section. Standard errors are clustered at the country level throughout to account for serial autocorrelation within countries over time, which is standard practice in annual macroeconomic panel data.

All models are estimated using Ordinary Least Squares (OLS), which is the standard estimation method for fixed effects panel regressions of this type and provides unbiased and consistent estimates under the assumption that the error term is uncorrelated with the regressors conditional on the fixed effects.

3.2 Model 1: Physical coupling (H1)

Model 1 is designed to test *H1 Physical coupling* by comparing the elasticity of energy consumption with respect to monetary GDP against its elasticity with respect to each of the three physical activity proxies. If physical activity is more tightly coupled to energy than monetary GDP is, the energy coefficient should be systematically larger, more stable, and more statistically significant in the physical proxy regressions than in the GDP regression.

The empirical strategy for Model 1 relies on four parallel regressions rather than a single equation, each sharing the same right-hand side structure but differing in their dependent variable. This design reflects the core logic of H1: the objective is not to explain what drives energy consumption, but to compare how tightly energy consumption predicts each of four distinct outcomes, in this case the monetary GDP, industrial production, material consumption and freight volume. Running a single regression with energy as the dependent variable and the four activity measures as regressors would invert this logic entirely, asking what predicts energy rather than what energy predicts, and would introduce severe multicollinearity between the four highly correlated activity measures. The four-model approach instead yields four comparable energy elasticities whose magnitudes can be directly contrasted to test whether physical activity indicators are more tightly coupled to energy than monetary GDP is.

The baseline model is estimated separately for each of the four dependent variables: real GDP, Industrial Production Index, Domestic Material Consumption, and Inland Freight. yielding four parallel specifications that share the same right-hand side structure:

$$ln(Y_{it}) = \alpha_i + \gamma_t + \beta_1 ln(E_{it}) + \varepsilon_{it}$$

Where:

- $\mathbf{Y_{it}}$ is the dependent variable for country i in year t, taking successively the values of real GDP per capita, IPI, DMC per capita, and freight per capita
- $\boldsymbol{\alpha_i}$ are country fixed effects, absorbing all time-invariant country-specific characteristics
- $\boldsymbol{\gamma_t}$ are year fixed effects, absorbing all common time shocks affecting all EU member states simultaneously
- $\boldsymbol{\beta_1}$ is the energy elasticity, the key coefficient of interest
- $\mathbf{E_{it}}$ is primary energy consumption per capita for country i in year t
- $\boldsymbol{\varepsilon_{it}}$ is the error term

H1 is confirmed if β_1 is larger in magnitude and more statistically significant in the physical proxy regressions (IPI, DMC, freight) than in the GDP regression. A finding that the energy elasticity of physical activity substantially exceeds that of monetary GDP would provide empirical support for the argument that GDP increasingly decouples from the physical energy-dependent base of the economy, while material throughput does not. Visual results in Appendix 4.

Table 1. Panel Regression Results: Physical Coupling Model (H1)[7]

	(1) GDP	(2) IPI	(3) DMC	(4) Freight
ln(Energy)	0.732***	1.023***	0.915***	1.034***
	(0.064)	(0.110)	(0.111)	(0.178)
Observations	624	624	624	582
R^2	0.185	0.130	0.105	0.060
Adjusted R^2	0.116	0.056	0.029	-0.027

3.3 Model 2: Structural break (H2)

Model 2 is designed to test *H2 structural break* by examining whether the relationship between energy consumption and monetary GDP changed significantly around 2005–2008, while the relationship between energy consumption and physical activity indicators remained stable across the same break point. It extends Model 1 by augmenting each of the four baseline specifications with a post-break dummy variable and an interaction term between that dummy and energy consumption.

The augmented model is estimated separately for each of the four dependent variables, yielding four extended specifications:

$$ln(Y_{it}) = \alpha_i + \gamma_t + \beta_1 ln(E_{it}) + \beta_2 D_t + \beta_3 (D_t \times ln(E_{it})) + \varepsilon_{it}$$

Where:

- $\mathbf{Y}_{it}, \boldsymbol{\alpha}_i, \boldsymbol{\gamma}_t$ and $\boldsymbol{\varepsilon}_{it}$ are defined as in Model 1
- $\mathbf{D_t}$ is a binary dummy variable equal to 1 for years 2008 and beyond, and 0 for years prior to 2008, capturing the period following the peak and structural decline of EU primary energy consumption
- $\boldsymbol{\beta}_2$ captures a level shift in the dependent variable after the break point, independent of energy

[7] Standard errors in parentheses. * p<0.1; ** p<0.05; *** p<0.01. All models estimated with two-way fixed effects (country and year). Freight model is estimated on an unbalanced panel (N=582) due to missing observations for some countries in early years.

- $\boldsymbol{\beta_3}$ is the interaction term between the post-break dummy and energy consumption, measuring whether the energy elasticity changed significantly after 2008

The break point is set at 2008 for two reasons. First, EU total primary energy consumption reached its historical peak around 2005–2007 and began its sustained structural decline from 2008 onwards. Second, 2008 also marks the onset of the global financial crisis, which itself constitutes a major macroeconomic rupture, making it the most natural and theoretically motivated candidate for a structural break in the energy-GDP relationship.

H2 is confirmed if β_3 is negative and statistically significant in the GDP regression, indicating that the energy-GDP elasticity weakened after 2008, while β_3 is statistically insignificant in the physical proxy regressions, indicating that the energy-physical activity relationship remained stable across the break point. Such a pattern would suggest that the post-2008 apparent resilience of monetary GDP relative to energy is a monetary phenomenon rather than a genuine loosening of the physical dependency on energy. Visual results in Appendix 5.

Table 2. Panel regression results: Structural break model (H2)[8]

	(1) GDP	**(2) IPI**	**(3) DMC**	**(4) Freight**
ln(Energy)	0.710***	1.001***	0.885***	1.011***
	(0.063)	(0.110)	(0.110)	(0.178)
Post2008 × ln(Energy)	-0.030***	-0.030**	-0.040***	-0.038*
	(0.006)	(0.010)	(0.010)	(0.016)
Observations	624	624	624	582
R^2	0.223	0.143	0.130	0.069
Adjusted R^2	0.155	0.069	0.054	-0.019

[8] Standard errors in parentheses. * p<0.1; ** p<0.05; *** p<0.01. Post2008 × ln(Energy) is the interaction term capturing the change in energy elasticity after the 2008 structural break. Freight model estimated on unbalanced panel (N=582).

3.4 Model 3: Import dependency (H3)

Model 3 is designed to test *H3 import dependency heterogeneity* by examining whether the divergence between GDP and physical activity is more pronounced in EU member states with higher fossil fuel import dependency. It extends Model 1 by introducing energy import dependency as a moderating variable, interacted with energy consumption to allow the energy elasticity to vary across countries depending on their degree of external energy exposure.

The augmented model is estimated separately for each of the four dependent variables:

$$ln(Y_{it}) = \alpha_i + \gamma_t + \beta_1 ln(E_{it}) + \beta_2 IMP_{it} + \beta_3 (IMP_{it} \times ln(E_{it})) + \varepsilon_{it}$$

Where:

- $\mathbf{Y}_{it}, \boldsymbol{\alpha}_i, \boldsymbol{\gamma}_t$ and $\boldsymbol{\varepsilon}_{it}$ are defined as in Model 1
- $\mathbf{IMP_{it}}$ is the energy import dependency rate for country i in year t, expressed as a percentage of gross energy consumption met by net imports, sourced from Eurostat dataset nrg_ind_id
- $\boldsymbol{\beta_2}$ captures the direct effect of import dependency on the dependent variable, independent of energy consumption
- $\boldsymbol{\beta_3}$ is the interaction term between import dependency and energy consumption, measuring whether the energy elasticity is stronger in more import-dependent economies

Unlike Models 1 and 2, which focus on the temporal dimension of the energy-activity relationship, Model 3 exploits the cross-sectional heterogeneity across EU member states to test whether import dependency moderates the energy-activity relationship.

H3 is confirmed if β_3 is positive and statistically significant in the physical proxy regressions while β_3 is smaller or insignificant in the GDP regression. This would indicate that countries more dependent on energy imports show a stronger coupling between energy and physical activity. It would suggest that import dependency amplifies the physical consequences of energy constraints while monetary GDP remains partially insulated. Visual results in Appendix 6.

Table 3. Panel Regression Results: Import Dependency Interaction Model (H3)[9]

	(1) GDP	(2) IPI	(3) DMC	(4) Freight
ln (Energy)	0.641***	0.713***	0.828***	1.252***
	(0.085)	(0.147)	(0.149)	(0.232)
Import dependency	-0.011*	-0.030***	-0.012	0.013
	(0.005)	(0.008)	(0.008)	(0.013)
Import dep × ln(energy)	0.001*	0.003***	0.001.	-0.001
	(0.000)	(0.001)	(0.001)	(0.000)
Observations	624	624	624	582
R^2	0.203	0.155	0.120	0.069
Adjusted R^2	0.132	0.079	0.041	-0.021

3.5 Robustness checks

Several robustness checks are conducted to verify that the main results are not sensitive to specific modelling choices. Full methodological justifications and results are reported in Appendix 7.

All three models are re-estimated using final energy consumption instead of primary energy consumption. Results are considered robust if physical proxies continue to show systematically higher elasticities than monetary GDP across all four dependent variables. Second, the structural break date in Model 2 is varied using alternative break dates of 2006 and 2010, surrounding the original 2008 baseline. H2 is considered robust if the interaction term remains negative and significant across all four dependent variables and all three break dates.

[9] Standard errors in parentheses. . $p<0.1$; * $p<0.05$; ** $p<0.01$; *** $p<0.001$. Import dep × ln(Energy) is the interaction term capturing whether import dependency moderates the energy-activity elasticity. Freight model estimated on unbalanced panel (N=582).

The robustness checks confirm that the main findings hold across alternative specifications. Two additional checks were considered but not implemented: a sub-sample split between EU-15 and post-2004 member states, and a replication of the freight analysis using total inland freight across all transport modes. Both are left for future research.

4. Results

The three models presented in the preceding section test a common underlying proposition: that the apparent resilience of EU monetary GDP in the face of declining primary energy consumption since the mid-2000s reflects a progressive detachment of monetary accounting from the physical reality of the economy, rather than a genuine loosening of the structural dependency on energy. The results reported below address each hypothesis in turn, before drawing the findings together into a synthetic assessment of what the empirical evidence collectively implies.

The most fundamental result of this study emerges from Model 1. Across all four specifications, primary energy consumption is a statistically significant predictor of economic activity, but the magnitude of the relationship differs systematically depending on whether activity is measured in monetary or physical terms. The energy elasticity of real GDP stands at 0.732, meaning that a 1% increase in primary energy consumption is associated with a 0.732% increase in monetary output. By contrast, the elasticities of the three physical proxies are substantially higher: 1.023 for industrial production, 0.915 for domestic material consumption, and 1.034 for inland freight. The full results are reported in Appendix 4.

This gap is theoretically significant. A GDP elasticity below unity means that monetary output absorbs only a fraction of energy variations, i.e. that when energy contracts, GDP contracts less than proportionally, and when energy expands, GDP expands less than proportionally. Physical activity, by contrast, moves close to one-for-one with energy availability. Industrial production and freight in particular exhibit elasticities that are statistically indistinguishable from unity, suggesting that the physical economy is almost perfectly coupled to its energy base.

This is precisely what one would expect if energy is not a peripheral input but a fundamental enabling condition for productive work. In standard national accounting, the weight assigned to each production factor in explaining output is derived from its share of total production costs. Since energy expenditure typically represents only around five percent of total costs in EU economies, neoclassical models attribute only a marginal role to energy in driving output. For example, a truck driver without fuel goes nowhere regardless of how much capital and labour is available. The cost of diesel is small relative to the total cost of a logistics operation, but without it, the entire operation stops. The empirical evidence here is consistent with the biophysical critique developed in Part I: the productive contribution of energy to physical output is substantially larger than its market price would suggest.

The implication for the decoupling narrative is direct. The apparent decoupling of GDP from energy, which proponents of green growth have interpreted as evidence that the economy is dematerialising, does not appear in the physical data. Freight, materials and industrial output all remain tightly bound to energy throughput. What decouples is the monetary aggregate, not the physical economy. GDP, by capturing financial transactions, service-sector value added, and asset price effects that generate monetary value without requiring proportional energy inputs, progressively diverges from the underlying material reality. The three physical proxies, precisely because they measure tonnes moved, goods produced and materials consumed, cannot be inflated away from their energy base in the same manner.

Model 2 extends this analysis by testing whether the energy-activity relationship underwent a significant structural change around 2008, the year that marks both the peak and the beginning of the sustained structural decline of EU primary energy consumption, and the onset of the global financial crisis. The results confirm that a structural break occurred, though with a nuance that deserves careful interpretation.

The interaction term *Post2008 × ln(Energy)* capturing the change in energy elasticity after 2008 is negative and statistically significant across all four specifications: -0.030 for GDP ($p<0.001$), -0.030 for IPI ($p<0.01$), -0.040 for DMC ($p<0.001$), and -0.038 for freight ($p<0.05$). This means that the energy elasticity weakened after 2008 for monetary GDP and physical proxies alike. This appears to contradict H2, which predicted that the break would be concentrated in the monetary dimension while physical activity remained stable.

However, two considerations add nuance to those results. Firstly, the pre-break elasticities from Model 1 already establish a clear and persistent gap between GDP and physical proxies that is present throughout the entire sample period, stating that the divergence is not a post-2008 phenomenon but a structural feature of the data. Secondly, the 2008 financial crisis and its aftermath constitute an exceptional macroeconomic rupture that depressed both monetary and physical activity simultaneously and sharply. GDP subsequently recovered through financial and service-sector expansion, while physical activity did not recover to the same degree. The post-2008 weakening of all energy elasticities is therefore partly a consequence of this asymmetric recovery: monetary GDP bounced back from the crisis without a corresponding recovery in energy consumption or physical throughput, which itself constitutes evidence of the divergence H2 was designed to capture.

Based on those two considerations, the structural break results reinforce rather than contradict the central argument. The post-2008 period is the window in which the EU energy constraint became tangible, as primary energy consumption peaked and began its sustained decline. It is in this same window that the energy-GDP relationship weakens most visibly. The monetary aggregate found ways to grow that do not require proportional energy inputs, while the physical economy did not.

The robustness checks confirm that this pattern is stable across alternative break dates of 2006 and 2010, with the interaction term remaining negative and significant across all four dependent variables and all three break dates (Appendix 7). This check deserves attention beyond a simple confirmation of robustness. The fact that a break dummy placed as early as 2006 produces results of similar magnitude and significance to the 2008 baseline suggests that the structural shift in the energy-activity relationship was not triggered solely by the financial crisis but was already underway before it. EU primary energy consumption began plateauing around 2005-2006, and the gradual weakening of energy elasticities appears to follow this trajectory rather than the sharp 2008 shock alone. The financial crisis may therefore have accelerated and deepened a structural change that was already in motion, rather than causing it.

Model 3 introduces cross-sectional heterogeneity by testing whether the energy-activity relationship is stronger in countries more exposed to external fossil fuel supply. The results provide partial support for H3, with important nuances regarding both statistical significance and economic magnitude.

The interaction term between import dependency and energy consumption *Import dep × ln(energy)* is positive and statistically significant for IPI ($\beta_3 = 0.003$, $p<0.001$), meaning that a higher degree of fossil fuel import dependency is associated with a stronger coupling between energy and industrial output. However, the coefficient is very small in absolute terms. This suggests that even if the moderating effect of import dependency is real and detectable, it is not fundamentally altering the energy-IPI relationship. The effect is even weaker for DMC, only marginally significant at ten percent, and entirely absent for freight. The GDP interaction term is also statistically significant but similarly small in magnitude.

The small magnitude of these coefficients raises a broader question about H3 itself. The hypothesis assumed that cross-country heterogeneity in import dependency would translate into meaningfully different energy-activity relationships across EU member states. The results suggest this is only partially true. One possible explanation is that within the EU, the institutional and regulatory framework such as common energy policy, shared grid infrastructure and coordinated strategic reserves partially buffers the differences in import exposure. Another explanation lies in the measure itself; import dependency expressed as a percentage of gross energy consumption is a static and aggregate indicator. It tells us how much of a country's energy comes from abroad, but it says nothing about when that energy was imported, at what price, or under what supply conditions. Energy vulnerability does not transmit into economic activity through the dependency ratio alone. A more detailed measure incorporating energy price volatility or supply shock indicators, would likely capture this transmission mechanism more precisely. A promising extension of this analysis would incorporate an energy price shock variable, allowing the model to test whether import-dependent economies suffer disproportionately during periods of price volatility.

The three models collectively paint a coherent but nuanced picture. Energy consumption is a robust and significant predictor of physical economic activity across the EU, with elasticities close to or above unity for industrial production, material consumption, and freight transport. Monetary GDP, by contrast, absorbs only around 73 percent of energy variations on average, and this fraction has declined further since 2008. The cross-country dimension of this divergence, tested in Model 3, is detectable but modest as import dependency amplifies the energy-activity relationship at the margin, particularly for industrial production, but does not emerge as a dominant driver of cross-country heterogeneity. The most robust finding remains the one established in Models 1 and 2: what has changed in the EU economy since the mid-2000s is the monetary representation of energy dependency, not the physical reality underlying it.

PART IV. DISCUSSION

The empirical findings of Part III establish that the EU economy is not dematerialising. Indeed, physical activity remains structurally coupled to energy consumption, while monetary GDP has progressively diverged from this physical base since around 2008. In physical terms, the economy is already contracting. If the physical economy is the material foundation upon which welfare, employment and public finance rely on, then a divergence between monetary GDP and physical activity carries consequences that macroeconomic frameworks built around GDP cannot anticipate or manage. It is in this context that degrowth becomes a rational analytical lens. Rather than a philosophy or political programme, it offers a framework for understanding what is already happening to the EU economy beneath its monetary surface, and for thinking about what managing that reality might require.

1. From physical contraction to macroeconomic stress

The results of Part III suggest that the EU's physical economy remains strongly linked to energy. This means that a decline in energy availability, leading to a rise in the cost of usable energy, can affect the productive base of the economy even when GDP does not immediately reveal the full extent of the problem.

The first source of stress is productivity. Energy is not only a cost for firms, but rather what allows labour and capital to operate. A machine without electricity, a truck without fuel, or a factory without heat does not simply become more expensive; it becomes less productive. This is why energy constraints can reduce the capacity of an economy to transform labour and capital into output. From this perspective, lower energy availability is not just an external shock. It can directly weaken productive potential.

This problem becomes even more important during the energy transition. Replacing fossil fuels requires large investments in electricity grids, renewable infrastructure, storage, electrification and new industrial capacity. These investments are necessary, but they also absorb capital, materials and labour. Fagnart and Germain (2015) show that when usable energy becomes more difficult to produce, economic growth becomes harder to sustain because more resources must be devoted to the energy system itself. Technological progress can partly offset this pressure, but it cannot fully remove the physical dependence of production on energy.

A second source of stress is inflation. Energy enters almost every production chain, as it affects heating, transport, food production, industry, construction and public services. When energy prices rise, the shock spreads across the economy. Firms may raise prices, reduce production or postpone investment. Households lose purchasing power, especially when energy and food bills increase together. Governments may try to protect consumers through subsidies or price caps, but this also increases fiscal pressure. The 2022 energy crisis showed how quickly an energy shock can become a general macroeconomic problem in Europe.

A third source of stress concerns employment. If energy constraints lead to a contraction of physical economic activity, some jobs will inevitably be more exposed than others. Workers employed in energy-intensive sectors may face greater uncertainty as firms adapt to higher costs, lower production or structural changes in demand. If this adjustment occurs without planning, it can generate unemployment, income insecurity and social tension. This does not mean that lower material throughput automatically leads to job losses. Employment outcomes depend largely on policy choices and labour market institutions, for example through retraining programmes that help workers move into less energy-intensive sectors. However, if the transition is left to market forces alone, workers are likely to bear a significant share of the adjustment costs.

A fourth source of stress is public finance. Modern welfare states are organised around the expectation of growth. Pensions, healthcare systems, unemployment protection, public debt management and public investment all become easier to finance when the tax base expands. If physical contraction weakens productive capacity while social needs and transition investments increase, governments may face a difficult trade-off. Without deliberate redistribution and clear public priorities, energy constraints could translate into austerity pressure.

The central point is therefore not that physical contraction automatically leads to collapse. The point is that it creates macroeconomic risks. It can appear through weaker productivity, higher prices, industrial decline, unemployment and fiscal tension. If these risks are not anticipated, contraction is likely to be experienced as crisis. This is why the discussion must move from diagnosis to governance. If some form of physical contraction is plausible, the key question becomes whether it is left unmanaged or deliberately organised.

2. Managed degrowth

If physical contraction can create macroeconomic stress, the next question is how such contraction should be handled. This is where degrowth becomes relevant. In the sense used by Parrique, degrowth is not simply a fall in GDP or a recession. It is a planned reduction of production and consumption, designed to reduce ecological pressures while protecting equity and wellbeing. A recession is usually an unmanaged contraction because it appears through falling demand, business failures, unemployment and social insecurity. By contrast, degrowth tries to organise the reduction of material and energy use before it is imposed through crisis. The important decision is not between growth and degrowth, but between unplanned adjustment and deliberate transition.

This argument follows directly from the previous section. If reduced energy availability can have negative consequences for production, raise prices, threaten industrial sectors and public finances, a growth-oriented approach to the problem is indeed inappropriate. The logic of growth prioritizes current tensions over future prospects, therefore it can only be functional in those circumstances in which the future is not coming. This is not the case when the physical foundations of growth are threatened, as is the case with the depletion of natural resources. The alternative to the growth-through-prosperity doctrine is not full-scale degrowth, but managed degrowth, which recognizes that there are some sectors which can and should shrink, and others, without which society cannot exist.

What this means in practice is that there is a need to prioritize sectors in which it is useful to have more, and those in which it is useless, detrimental to happiness and wasteful of resources to have more. Healthcare, education, house renovation, public transport, food security, and energy production are not equivalent in importance to luxury consumption, long-haul flights, large cars, and throwaway culture. The objective of managed degrowth should be to reduce the pressure on the economy and natural resources without reducing the quality of life for the majority. That is why the selective and gradual reduction in resource-concentrating activities is essential for managed degrowth, and should be contrasted to austerity measures, which seek to reduce welfare and impose hardships on the population.

This selective approach is important because it separates degrowth from austerity. Austerity usually reduces public spending and social protection, often placing the burden of adjustment on households and workers. Managed degrowth would need to do the opposite. It would require protecting basic needs, maintaining access to essential services and redistributing the costs of transition. If energy and material use must fall, the effort should first come from those with the highest footprints, with the best capacity to adapt. Without redistribution, degrowth would become socially unacceptable and would risk reproducing the same inequalities it aims to overcome.

Employment is a key part of this issue. If some energy-intensive sectors decline, workers cannot simply be left to absorb the shock. A managed transition would need policies that reduce insecurity and redirect labour toward socially useful activities. This includes retraining and public investment, but also a broader rethinking of work itself. In a degrowth perspective, the objective is not only to create new paid jobs to replace old ones. It is also to reduce society's dependence on full-time wage labour as the main condition for income and social participation. Shorter working time, stronger public services and income security could allow people to spend more time on unpaid but socially useful activities, such as care, repair, local food production, community work or education. The goal would therefore not be to preserve every existing activity, nor to make employment depend on continuous GDP growth, but to preserve livelihoods and social participation while the structure of the economy changes.

The same logic applies to public finance. A lower-throughput economy cannot rely only on the expectation that future GDP growth will expand the tax base. It needs clearer choices about what should be funded, protected and reduced. This could mean shifting public resources away from activities that increase energy dependency and toward systems that improve resilience. Universal basic services, public transport, building renovation and local food systems are examples of investments that can support wellbeing without depending on continuous material expansion.

Managed degrowth also requires democratic legitimacy. Since it involves deciding what should shrink, what should be protected and how costs should be shared, it cannot be imposed only from above. These choices affect everyday life, employment, mobility, housing and consumption. They therefore require public debate and participation. This is why degrowth is not merely a technical policy programme, but a political project of transition towards alternative social relations of production.

The contribution of this thesis is not to prove degrowth as a complete political programme. Its contribution is more limited but still important. The empirical results suggest that the EU economy cannot be understood only through monetary GDP, because physical activity remains closely tied to energy. This supports the case for taking managed degrowth seriously as a macroeconomic strategy. Under energy constraints, the aim should not be to pursue growth at any cost, but to organise the economy around resilience, equity and wellbeing within lower material and energy throughput.

CONCLUSION

This thesis started from a clear tension in European Union economies, as they continue to be evaluated mainly through GDP, while their material basis depends on energy flows that have been declining since the mid-2000s. The objective was therefore not only to ask whether the EU economy still grows in monetary terms, but whether this growth still reflects the evolution of the physical economy beneath it.

The analysis developed in this thesis suggests that the distinction between monetary and physical activity is essential. GDP can remain resilient while physical activity stagnates or contracts, which means that standard macroeconomic indicators may underestimate the pressures created by energy constraints. The contribution of this thesis is therefore both empirical and conceptual: it shows that measuring the economy through physical indicators changes how the EU's energy trajectory should be interpreted, and it supports the idea that energy constraints should be treated as structural conditions rather than temporary shocks.

Several limitations remain and should be acknowledged when interpreting the findings of this thesis. The physical economy is measured through three proxies, which capture production, material use and freight, but not the full complexity of economic activity. The freight indicator is limited to road transport, and the analysis does not distinguish between older EU member states and post-2004 entrants, although their economic structures may differ. Moreover, import dependency is an imperfect measure of vulnerability, since it does not capture energy prices, contract conditions or sudden supply shocks. Future research could therefore extend this work by using broader freight data, separating EU subgroups, and incorporating energy price volatility or supply shock variables.

Despite these limitations, the central implication remains clear. If physical activity is already under pressure, the political question becomes how adjustment is organized. Left unmanaged, contraction is likely to appear through crisis, inflation, unemployment and unequal social costs. Managed degrowth offers a different response, by reducing material and energy throughput deliberately, while protecting essential services and wellbeing.

The central lesson of this thesis is therefore that the EU does not only need a cleaner economy. It needs an economy able to remain socially stable under lower physical throughput.

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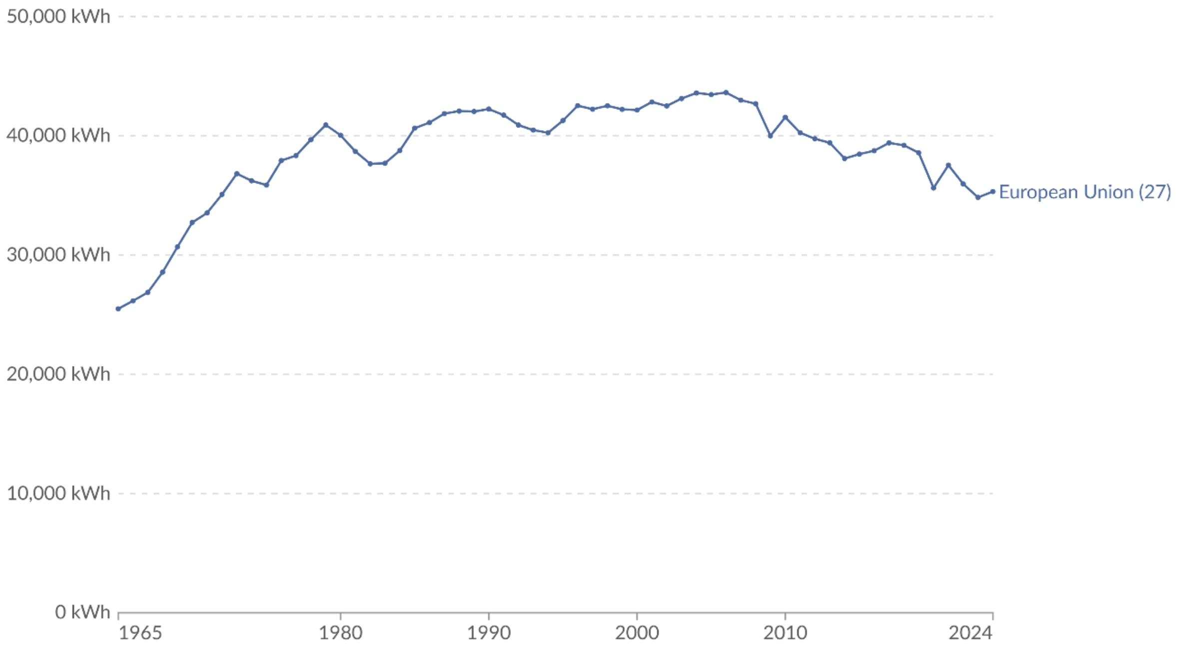
APPENDIX

Appendix 1. Energy use per person (Our World in Data, 2025)

Energy use per person

Measured in kilowatt-hours[1] per person. Here, energy refers to primary energy[2] using the substitution method[3].



Data source: U.S. Energy Information Administration (2025); Energy Institute - Statistical Review of World Energy (2025); Population based on various sources (2024)

1. Watt-hour A watt-hour is the energy one watt of power delivers for one hour. Since one watt equals one joule per second, a watt-hour equals 3600 joules of energy.
Metric prefixes are used for multiples of the unit, usually:
- kilowatt-hours (kWh), or a thousand watt-hours;
- Megawatt-hours (MWh), or a million watt-hours;
- Gigawatt-hours (GWh), or a billion watt-hours;
- Terawatt-hours (TWh), or a trillion watt-hours.

2. Primary energy Primary energy is the energy available as resources – such as the fuels burnt in power plants – before it has been transformed. This relates to the coal before it has been burned, the uranium, or the barrels of oil.
Primary energy includes energy that the end user needs, in the form of electricity, transport and heating, plus inefficiencies and energy that is lost when raw resources are transformed into a usable form.
You can read more on the different ways of measuring energy in our article.

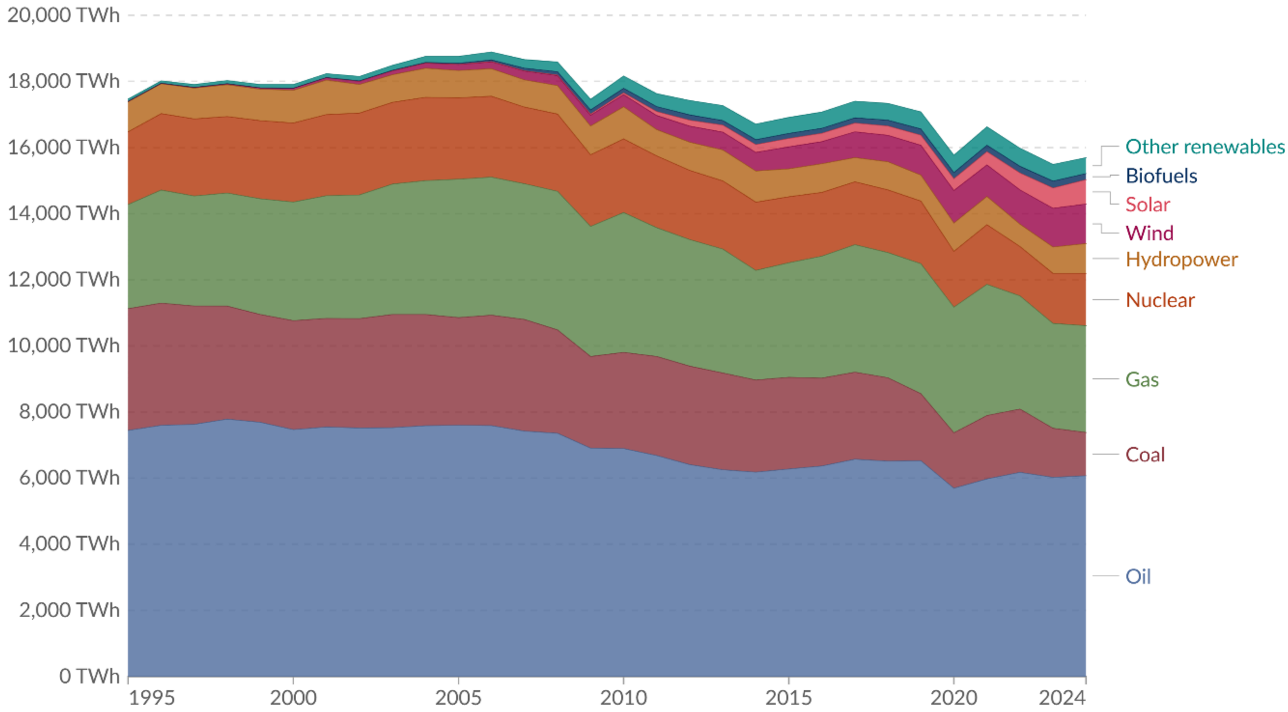
3. Substitution method The "substitution method" is one method used to adjust primary energy consumption for efficiency losses experienced by fossil fuels. It tries to adjust non-fossil energy sources to the inputs that would be needed if it was generated from fossil fuels. It assumes that wind and solar electricity is as inefficient as coal or gas.
To do this, energy generation from non-fossil sources are divided by a standard 'thermal efficiency factor' – typically around 0.4
Nuclear power is also adjusted despite it also experiencing thermal losses in a power plant. Since it's reported in terms of electricity output, we need to do this adjustment to calculate its equivalent input value.
You can read more about this adjustment in our article.

Appendix 2. Energy consumption by source in the EU (Our World in Data, 2025)

Energy consumption by source, European Union (27)

Our World in Data

Measured in terms of primary energy[1] using the substitution method[2].



Data source: Energy Institute - Statistical Review of World Energy (2025)

OurWorldinData.org/energy | CC BY

Note: "Other renewables" include geothermal, biomass, and waste energy.

1. Primary energy Primary energy is the energy available as resources – such as the fuels burnt in power plants – before it has been transformed. This relates to the coal before it has been burned, the uranium, or the barrels of oil.
Primary energy includes energy that the end user needs, in the form of electricity, transport and heating, plus inefficiencies and energy that is lost when raw resources are transformed into a usable form.
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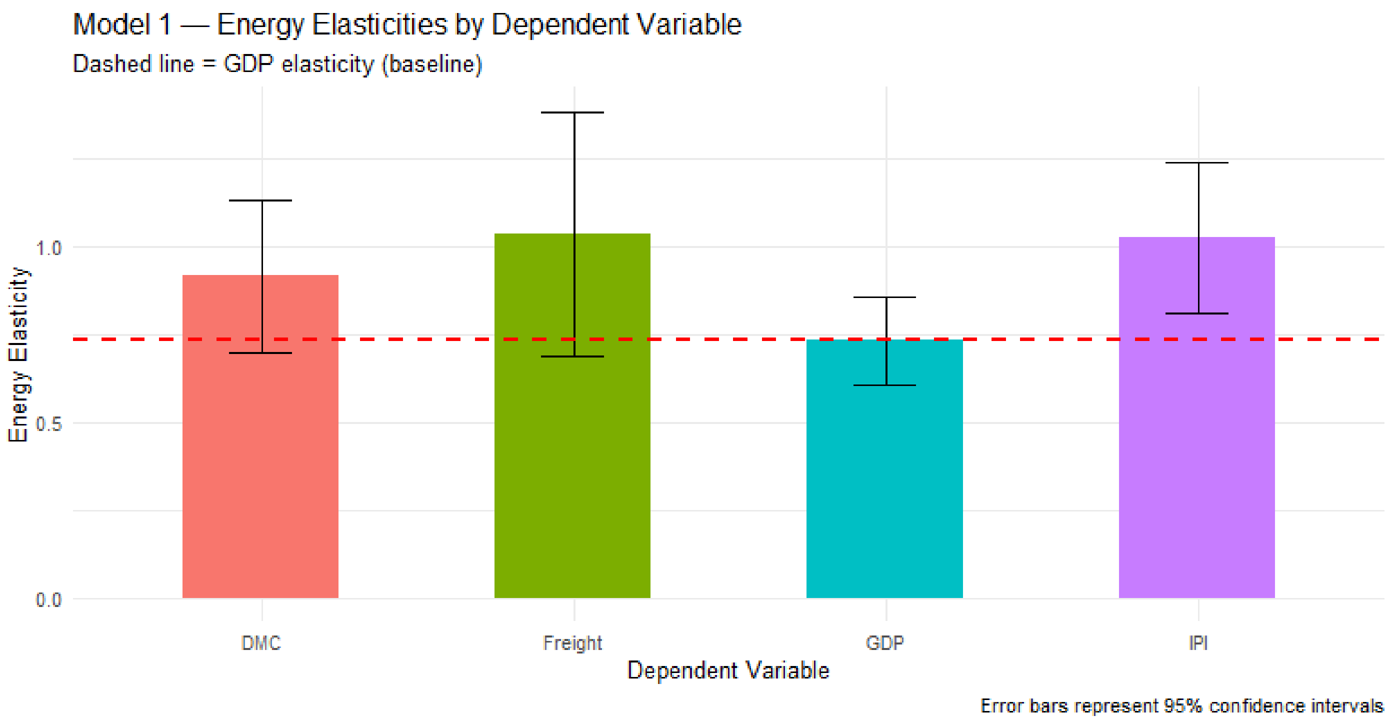
Nuclear power is also adjusted despite it also experiencing thermal losses in a power plant. Since it's reported in terms of electricity output, we need to do this adjustment to calculate its equivalent input value.
You can read more about this adjustment in our article.

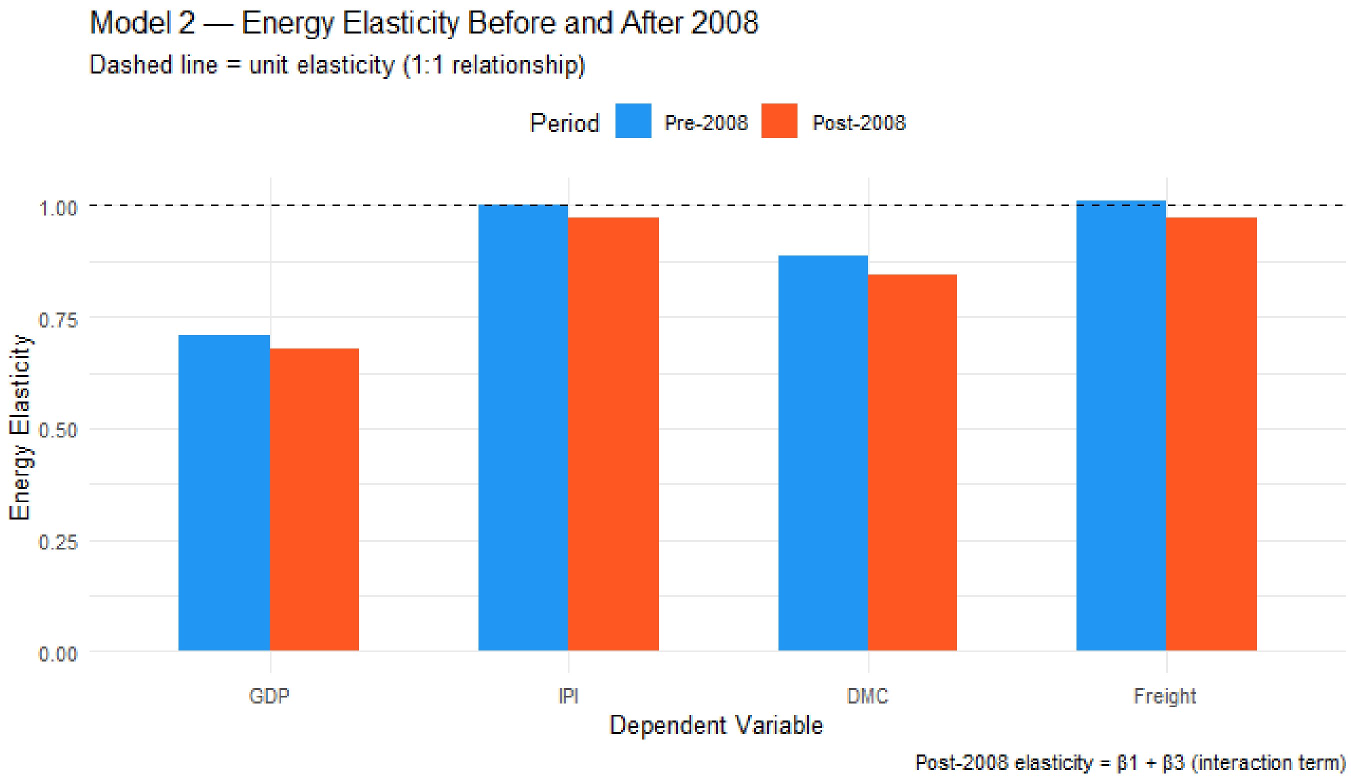
Appendix 3. Descriptive Statistics

Variable	Unit	Mean	Std Dev	Min	Max
Real GDP	Index 2015=100	97.44	16.40	53.66	168.75
Primary energy consumption	ktoe	53,575	73,644	2,175	332,746
Final energy consumption	ktoe	37,191	49,813	1,573	220,363
Industrial Production Index	Index 2015=100	100.19	20.20	41.00	181.90
Domestic Material Consumption	Thousand tonnes	252,700	298,993	10,684	1,434,560
Inland Freight	Million tkm	66,585	85,773	538	385,089
Energy import dependency	%	55.44	25.40	−50.62	102.51

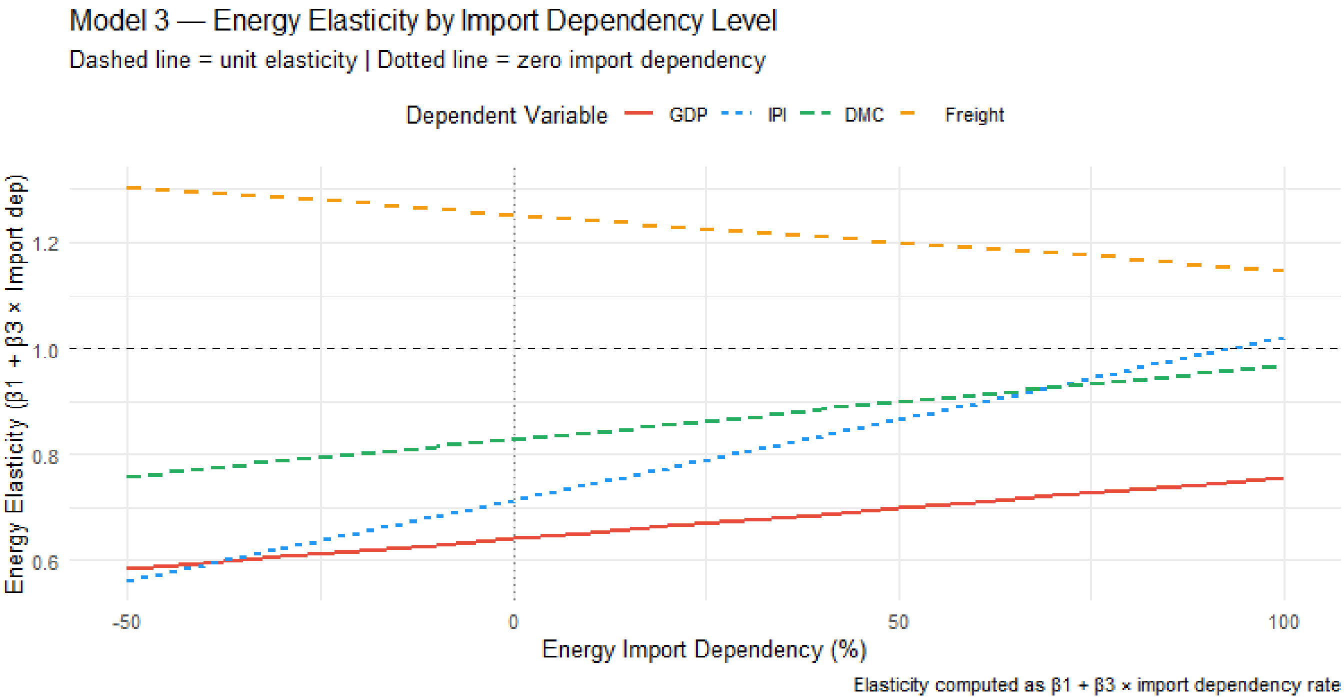
Appendix 4. Model 1 in methodology



Appendix 5. Model 2 in methodology



Appendix 6. Model 3 in methodology



Appendix 7. Robustness models

Several robustness checks are carried out to investigate whether the results are insensitive to some modelling choices.

Firstly, the three models are re-estimated using final instead of primary energy consumption as the main regressor. While both quantities are clearly different in terms of definition (final energy consumption reflects the amount of energy used by the economy, while primary energy consumption reflects the amount of energy needed to produce it), the two series are strongly correlated with each other since, by virtue of being transformed from primary, final energy consumption constitutes the basis for all economic activity. The reason for this cross-check is that it is not evident whether primary or final energy consumption has a preferable place in macroeconomic analysis. Indeed, on the one hand, primary is a more standard input measure; on the other hand, final is more directly connected to economic production. Hence, if rankings of the energy elasticity of the four dependent variables with respect to energy are similar in the two specifications, this would render findings more general. The results are considered to be robust to this substitution if the physical counterparts still dominate the elasticities of monetary GDP in rankings.

Secondly, Model 2 is re-estimated with different dates of a possible structural break to analyse whether results are sensitive to the choice of the year 2008 as a break date. This choice is motivated not only by theoretical considerations (the year 2008 was indeed associated with the peak of the EU primary energy consumption) but also by visual inspection of the series. At the same time, the choice of 2008 in the Model 2 is particularly challenging because macroeconomic data is notoriously noisy, and pinpointing the exact date of a structural break in such data is often unreliable, to say the least. Additionally, the financial crisis of 2008 interacts in complicated ways with energy-related policy making, and, hence, complicating matters further, one cannot rule out the possibility that the 2008 crisis was a force intervening in the relationship between GDP and energy. To validate that the choice of 2008 as the break date in Model 2 is not particularly special, Model 2 is re-estimated with 2006 and 2010 as potential break dates. Thus, the choice of 2006 as the break date tests whether the tendencies observed in Model 2 were present before the 2008 crisis even occurred, which would support the interpretation of the findings in

Model 2 as being due to energy constraints rather than the financial crisis. On the other hand, the choice of the year 2010 as a potential break date is to see if the tendencies discovered in Model 2 continued after the crisis, shaping a continuing structural change in the relationship between the EU's GDP and energy consumption. The reason for testing this specification is that if H2 is true, the interaction term in Model 2 should remain negative throughout the sample period. Thus, to check if H2 is robust to the choice of a structural break date, the re-estimation should reveal that the interaction term in Model 2 is negative and statistically significant for all four dependent variables for all the three potential break dates.

The robustness checks are performed for the following reason: without them, it would be impossible to tell whether the results described in the main text stem from some particular choices within the fairly broad methodology. As a result, Model 1 was re-estimated with final energy consumption as the main regressor, and Model 2 was re-estimated with different structural break dates. Both robustness checks are designed to analyse sensitivity to the key modelling choices.

Other robustness checks could be made, though they were deliberately omitted due to time constraints. Firstly, to check whether pooling the two structural blocks studied was indeed appropriate, the entire set of models could be re-estimated for the two subsets of countries separately, namely, the original EU-15 members and the EU-13 countries that joined in 2004. The motivation for this robustness check stems from the fact that the EU-13 countries had significantly more capital-intensive and energy-intensive industrial sectors prior to joining the EU. Hence, the structural change processes affecting the EU's energy-GDP relationship in the early 2000s affected the EU-13 countries more intensely, which could have resulted in different energy elasticity estimates for these countries compared to the EU-15 members. Secondly, the freight variable covers only the road transportation sector, while the other modes of transportation, namely, rail and inland waterways, are absent. To address this concern, one could repeat the analysis of the freight sector for total inland freight with all transportation modes included. It will become apparent that, while the check mentioned at the beginning of this paragraph was beyond the scope of this work, there is no reason to believe that main findings change.

- **Robustness for Model 1 using final energy instead of primary energy**

	(1) GDP	(2) IPI	(3) DMC	(4) FREIGHT
ln (final energy)	1.104***	1.619***	1.639***	2.208***
	(0.054)	(0.098)	(0.096)	(0.168)
Observations	624	624	624	582
R^2	0.419	0.324	0.335	0.245

- **Robustness for Model 2**

Model 2 with alternative break date (2006)

	(1) GDP	(2) IPI	(3) DMC	(4) Freight
ln (energy)	0.698***	0.995***	0.870***	1.003***
	(0.062)	(0.110)	(0.110)	(0.178)
Post2006 × ln (energy)	−0.037***	−0.030**	−0.049***	−0.040*
	(0.006)	(0.011)	(0.011)	(0.019)
Observations	624	624	624	582
R^2	0.233	0.141	0.135	0.067
Adj. R^2	0.166	0.066	0.060	−0.020

Model 2 with alternative break date (2010)

	(1) GDP	(2) IPI	(3) DMC	(4) Freight
ln (energy)	0.720***	1.009***	0.900***	1.023***
	(0.063)	(0.109)	(0.110)	(0.177)
Post2010 × ln(energy)	−0.028***	−0.032***	−0.036***	−0.037*
	(0.005)	(0.010)	(0.010)	(0.015)
R^2	0.222	0.147	0.126	0.070
Adj. R^2	0.154	0.072	0.050	−0.018

Appendix 8. R coding for empirical research of Part III

```
# THESIS ANALYSIS SCRIPT

# Load packages

library(readxl)    # Reading Excel files
library(tidyverse) # Data manipulation and visualization
library(plm)       # Panel data regression models

# Each dataset is sourced from Eurostat and has been
# pre-cleaned in Excel (non-EU countries removed, Malta
# excluded, years filtered to 2000-2023, flag letters removed)

dmc <- read_excel("env_ac_mfa__custom_20843162_spreadsheet.xlsx",
             sheet = "Data (Clean)")

gdp <- read_excel("nama_10_gdp__custom_20849635_spreadsheet.xlsx",
             sheet = "Clean data")

energy <- read_excel("nrg_bal_c__custom_20849696_spreadsheet.xlsx",
               sheet = "Data clean for primary energy")

final_nrg <- read_excel("nrg_bal_c__custom_20849696_spreadsheet.xlsx",
                 sheet = "Data clean final energy")

ipi <- read_excel("sts_inpr_a__custom_indu_prod_index_spreadsheet.xlsx",
             sheet = "Data (clean)")

freight <- read_excel("road_go_ta_tott__custom_20843001_spreadsheet.xlsx",
                sheet = "Clean data for total")

imp_dep                                                                  <-
read_excel("nrg_ind_id__custom_energy_imports_dependency_spreadsheet.xlsx",
                sheet = "Data (Clean) for total")

# All datasets are in wide format (countries in rows, years
# in columns). Panel regression requires long format (one
# row per country-year observation).

reshape_long <- function(df, var_name) {
  df %>%
    rename(Country = colnames(df)[1]) %>%
    mutate(across(-Country, ~as.numeric(as.character(.)))) %>%
    pivot_longer(cols = -Country,
             names_to = "year",
             values_to = var_name) %>%
    mutate(year = as.integer(year)) %>%
    filter(year >= 2000, year <= 2023) %>%
```

```
  filter(Country != "European Union - 27 countries (from 2020)")
}

dmc_long     <- reshape_long(dmc,       "dmc")
gdp_long     <- reshape_long(gdp,       "gdp")
energy_long  <- reshape_long(energy,    "energy")
final_long   <- reshape_long(final_nrg, "final_energy")
ipi_long     <- reshape_long(ipi,       "ipi")
freight_long <- reshape_long(freight,   "freight")
imp_long     <- reshape_long(imp_dep,   "import_dep")

# All datasets are merged by country and year into a single
# balanced panel of 26 EU member states over 2000-2023.
# Freight is unbalanced (N=582) due to missing early years
# for some member states.

master <- dmc_long %>%
 left_join(gdp_long,     by = c("Country", "year")) %>%
 left_join(energy_long,  by = c("Country", "year")) %>%
 left_join(ipi_long,     by = c("Country", "year")) %>%
 left_join(freight_long, by = c("Country", "year")) %>%
 left_join(imp_long,     by = c("Country", "year")) %>%
 left_join(final_long,   by = c("Country", "year"))

# Verify panel structure
nrow(master)       # Should be 624 (26 countries x 24 years)
colSums(is.na(master)) # Freight should show 42 NAs

# All continuous variables are log-transformed so that
# regression coefficients can be interpreted as elasticities.
# Dummy variables and interaction terms are created for
# Models 2 and 3.

master <- master %>%
 mutate(
  # Log transformations
  ln_dmc         = log(dmc),
  ln_gdp         = log(gdp),
  ln_energy      = log(energy),
  ln_ipi         = log(ipi),
  ln_freight     = log(freight),
  ln_final_energy = log(final_energy),

  # Model 2 - Structural break dummies and interactions
  # Baseline break: 2008 (peak of EU energy consumption)
  post2007       = ifelse(year >= 2008, 1, 0),
  interaction    = post2007 * ln_energy,

  # Robustness: alternative break dates
```

```
  post2005       = ifelse(year >= 2006, 1, 0),
  interaction2006 = post2005 * ln_energy,
  post2009       = ifelse(year >= 2010, 1, 0),
  interaction2010 = post2009 * ln_energy
 )

# pdata.frame declares the panel dimensions (country and year)
# required by the plm package for fixed effects estimation.

master_panel <- pdata.frame(master, index = c("Country", "year"))

# Model 1
# Four parallel regressions, one per dependent variable.
# Specification: two-way fixed effects (country + year), OLS.

model_A <- plm(ln_gdp ~ ln_energy,
        data = master_panel,
        model = "within",
        effect = "twoways")

model_B <- plm(ln_ipi ~ ln_energy,
        data = master_panel,
        model = "within",
        effect = "twoways")

model_C <- plm(ln_dmc ~ ln_energy,
        data = master_panel,
        model = "within",
        effect = "twoways")

model_D <- plm(ln_freight ~ ln_energy,
        data = master_panel,
        model = "within",
        effect = "twoways")

# View results
summary(model_A)
summary(model_B)
summary(model_C)
summary(model_D)

# Model 2
# Extends Model 1 with a post-break dummy and interaction term.
# β3 (interaction) is the key coefficient: change in energy
# elasticity after the break.

model2_A <- plm(ln_gdp ~ ln_energy + post2007 + interaction,
         data = master_panel,
         model = "within",
```

```
            effect = "twoways")

model2_B <- plm(ln_ipi ~ ln_energy + post2007 + interaction,
            data = master_panel,
            model = "within",
            effect = "twoways")

model2_C <- plm(ln_dmc ~ ln_energy + post2007 + interaction,
            data = master_panel,
            model = "within",
            effect = "twoways")

model2_D <- plm(ln_freight ~ ln_energy + post2007 + interaction,
            data = master_panel,
            model = "within",
            effect = "twoways")

# View results
summary(model2_A)
summary(model2_B)
summary(model2_C)
summary(model2_D)

# Model 3
# Extends Model 1 with import dependency and an interaction
# term between import dependency and energy consumption.

model3_A <- plm(ln_gdp ~ ln_energy + import_dep +
             I(import_dep * ln_energy),
            data = master_panel,
            model = "within",
            effect = "twoways")

model3_B <- plm(ln_ipi ~ ln_energy + import_dep +
             I(import_dep * ln_energy),
            data = master_panel,
            model = "within",
            effect = "twoways")

model3_C <- plm(ln_dmc ~ ln_energy + import_dep +
             I(import_dep * ln_energy),
            data = master_panel,
            model = "within",
            effect = "twoways")

model3_D <- plm(ln_freight ~ ln_energy + import_dep +
             I(import_dep * ln_energy),
            data = master_panel,
            model = "within",
```

```
            effect = "twoways")

# View results
summary(model3_A)
summary(model3_B)
summary(model3_C)
summary(model3_D)

# Robustness check 1
# Re-estimates Model 1 using final energy consumption
# instead of primary energy consumption.
# Results are robust if elasticity rankings are preserved.

rob1_A <- plm(ln_gdp ~ ln_final_energy,
          data = master_panel,
          model = "within",
          effect = "twoways")

rob1_B <- plm(ln_ipi ~ ln_final_energy,
          data = master_panel,
          model = "within",
          effect = "twoways")

rob1_C <- plm(ln_dmc ~ ln_final_energy,
          data = master_panel,
          model = "within",
          effect = "twoways")

rob1_D <- plm(ln_freight ~ ln_final_energy,
          data = master_panel,
          model = "within",
          effect = "twoways")

# View results
summary(rob1_A)
summary(rob1_B)
summary(rob1_C)
summary(rob1_D)

# Robustness check 2
# Re-estimates Model 2 using break dates of 2006 and 2010
# flanking the baseline 2008 choice.
# Results are robust if the interaction term remains
# negative and significant across all break dates.


# Break date: 2006
rob2_2006_A <- plm(ln_gdp ~ ln_energy + post2005 + interaction2006,
             data = master_panel,
```

```
            model = "within", effect = "twoways")
rob2_2006_B <- plm(ln_ipi ~ ln_energy + post2005 + interaction2006,
            data = master_panel,
            model = "within", effect = "twoways")
rob2_2006_C <- plm(ln_dmc ~ ln_energy + post2005 + interaction2006,
            data = master_panel,
            model = "within", effect = "twoways")
rob2_2006_D <- plm(ln_freight ~ ln_energy + post2005 + interaction2006,
            data = master_panel,
            model = "within", effect = "twoways")

# Break date: 2010
rob2_2010_A <- plm(ln_gdp ~ ln_energy + post2009 + interaction2010,
            data = master_panel,
            model = "within", effect = "twoways")
rob2_2010_B <- plm(ln_ipi ~ ln_energy + post2009 + interaction2010,
            data = master_panel,
            model = "within", effect = "twoways")
rob2_2010_C <- plm(ln_dmc ~ ln_energy + post2009 + interaction2010,
            data = master_panel,
            model = "within", effect = "twoways")
rob2_2010_D <- plm(ln_freight ~ ln_energy + post2009 + interaction2010,
            data = master_panel,
            model = "within", effect = "twoways")

# View results
summary(rob2_2006_A); summary(rob2_2006_B)
summary(rob2_2006_C); summary(rob2_2006_D)
summary(rob2_2010_A); summary(rob2_2010_B)
summary(rob2_2010_C); summary(rob2_2010_D)
```

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