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The Generalized Jevons Paradox and the Future of Energy

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ABSTRACT: Global energy and materials are essential to the functioning of the economy and have significant implications for macroeconomics and the environment. At the same time, the world is not on track to meet Paris Agreement goals. This paper documents two stylized facts that connect these observations. First, the world economy is characterized by large embedded emissions and materials: different energies and materials are deeply entwined and interdependent. This has historically led to *additive* – rather than *substitution* – dynamics in energy and materials on a global scale. Second, historically there has been a strong positive correlation between efficiency in resource use and total resource use at a global scale. We synthesize these observations by introducing the Generalized Jevons Paradox (GJP). We argue that the GJP reflects the direct and indirect energy/material demand effects of long-term energy and material interdependencies, themselves shaped by market and geoeconomic power, trade arrangements, and financial factors. While future scenarios may diverge from historical data, including because of different population and growth trends, the GJP calls for caution in projecting energy and material flows within the energy transition framework, as it suggests that a declining share of fossil fuels in primary energy consumption can coexist with rising total fossil consumption, and thus rising global emissions – as observed since 2012. The GJP highlights the importance of policies to better allocate energy and material flows across sectors and countries and reduce supply chain vulnerabilities, but raises difficult distributional and political economy questions. Based on the GJP, the paper identifies three areas for research: the detailed analysis of the role of materials in supply chain vulnerabilities; the political economy of material flows; and multidimensional welfare analysis in decarbonization scenarios.

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WORKING PAPERS

The Generalized Jevons Paradox and the Future of Energy

Prepared by William Oman, Etienne Espagne, and Jean-Baptiste Fressoz[1]

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Executive Summary

Global energy and material dynamics are essential from both a macroeconomic and environmental perspective. They matter for countries' energy and resources security (e.g., through higher or lower dependence on imported fuels or other resources), economic growth (as energy and materials are key complements in production), employment (in low-carbon energy and related sectors), balance of payments (including by reducing energy import costs and financing needs), and economic stability (e.g., via lower volatility induced by fossil fuel markets and other commodity markets). In turn, the composition and size of economic activity determine environmental impacts through the burning of fossil fuels, the release of pollution by metals mining and processing, and other channels. This is particularly important at the current juncture, as the world is not on track to meet Paris Agreement goals, and large subsidies prolong reliance on fossil fuels.

The standard framework for thinking about energy and material dynamics rests on two strong assumptions. First, global energies and materials are assumed historically to have been governed by substitution dynamics, where dominant energies and materials would have replaced each other over time, focusing on *market shares*. This assumption is then projected into transition scenarios about the future of energy. Second, energy and material dynamics are assumed to largely mirror technological dynamics, hence implicitly assuming away multiple sources of technological and material interdependence and path dependence. The dominant approaches to climate change mitigation frame the solution as an energy transition: substituting high-carbon energy sources with low-carbon ones, mainly through carbon pricing policies – the instruments that are expected to trigger technological progress and diffusion, and ultimately energy substitution, facilitated by trade, with no need to reduce global energy and material demand.

A more cautious interpretation of the data is possible. Despite numerous technological innovations in the 20th and 21st centuries, the total consumption of all energies and materials has *increased* over time (the only exceptions being sheep wool, asbestos, and mercury). In other words, the evidence suggests that material flows are governed by *additive* – rather than *substitution* – dynamics. This basic observation is critical, because what matters for climate change is the total quantity of greenhouse gases (GHGs) in the atmosphere. In the past, eliminating some sources of energy was never a major policy or societal goal – in contrast to today, arguably. Based on this distinction, the standard framework assumes that replacing fossil electricity production with renewable electricity generation suffices to achieve decarbonization. However, while building renewable energy infrastructure to decarbonize global electricity production would generate a relatively small amount of CO_2, downstream uses (goods, services and infrastructures powered by low-carbon electricity) entail material consumption that depends on fossil fuels and will likely continue to do so. Key examples are heavy industry, transport, food consumption, and the production of biofuels (deforestation). An important element of context is that the rapid growth in emissions in the 20th century occurred in tandem with unprecedented economic and population growth, and it is unclear whether similar increases are replicable given different ongoing demographic and growth trends.

This paper presents evidence and analyzes mechanisms that, taken together, highlight the need for caution about the future evolution of global energy and material dynamics. First, drawing on economic history and more recent empirical evidence, it documents the existence of large and growing *embedded emissions and materials*: energies and materials are deeply intertwined, interdependent, and governed by *additive* dynamics. This results in the accumulation and entwinement of both "clean" and "dirty" technologies and materials at the level of the global economy. Second, the paper finds evidence of a strong positive correlation between efficiency in resource use and total resource use at a global scale. To synthesize these observations, we introduce the Generalized Jevons Paradox (GJP). The latter captures the direct and indirect energy/material demand effects of the long-term energy and material interdependencies (or symbiosis) that accompany significant increases in resource use efficiency. In other words, the GJP underscores the apparent "stickiness" of global fossil and material consumption, notwithstanding the ability of a number of countries (encompassing both middle- and high-income economies) to decarbonize their electricity generation sector. The paper discusses possible drivers of the GJP: market and geoeconomic power, trade arrangements, and financial factors. The GJP therefore extends the classic Jevons Paradox by incorporating macroeconomic, institutional, and technological drivers that reinforce each other and thereby generate systemic rebound effects and material interdependencies. Importantly, the GJP should not be interpreted as an economic "law," but rather as an empirical observation that emphasizes the need for caution in projecting future energy flows.

The GJP calls for caution in applying the Energy Transition (ET) framework, which assumes that technological substitution and efficiency improvements would naturally drive decarbonization. While technological substitution and efficiency improvements do reduce emissions to a small extent, they are not enough to get to zero emissions, as in some (growing) sectors – such as aviation, shipping, iron and steel, cement, plastics, fertilizers, agriculture, construction and arms – no (scalable) substitution with zero-emission technologies is possible in the near term or apparent in the medium term. The need for caution reflects institutional drivers of the GJP – market and geoeconomic power, trade arrangements, and financial factors – which shape investment decisions in a way that further entrenches fossil fuels in the global productive structure. The reason for this entrenchment is that, even with new, low-carbon materials, persistent material interdependencies and the continuous generation of new sources of material demand on a global scale put upward pressure on the total *downstream consumption* of many materials, and thus on emissions.

The analysis highlights some limitations of a technology-centered approach to climate change mitigation. It underscores the need for demand-side policy frameworks that can help better allocate energy and material flows across sectors and countries. This analysis contributes to an ongoing debate on the nature of growth, highlighting its energy, distributional and political economy underpinnings. The paper concludes by outlining avenues for future research: the detailed analysis of the role of materials in countries' supply chain vulnerabilities; the political economy of material flows; and multidimensional welfare analysis in decarbonization scenarios.

Introduction

Global energy and material dynamics are essential from a macroeconomic perspective. Energy and materials are crucial to the functioning of the global economy.[1] They matter for countries' energy and resources security (e.g., through higher or lower dependence on imported fuels or other resources), economic growth (as energy and materials are key complements in production), supply chain resilience, employment (in low-carbon energy and related sectors), balance of payments (including by reducing energy import costs), and economic stability (e.g., via lower volatility induced by fossil fuel markets and other commodity markets).

Energy and material flows also matter for the economy through their impact on the environment. Energy accounts for over 75 percent of global emissions. In turn, climate change can affect countries' macroeconomic and financial stability (Mitra et al. 2025). Other environmental threats magnify these linkages (Gardes-Landolfini et al. 2024). The world is not on track to meet Paris Agreement goals, and large subsidies prolong reliance on fossil fuels (Black et al. 2025). There is evidence that climate change is accelerating, with temperatures and global emission records being broken year after year. In addition, biodiversity is declining at an unprecedented rate, with adverse consequences for ecosystem functioning, water availability and quality, food security and nutrition, human, plant and animal health and resilience to the impacts of climate change (IPBES 2024, NGFS 2023). Climate change and biodiversity are interdependent and have compounding effects on human well-being. These interdependencies are notably reflected in the concept of planetary boundaries, seven of the nine identified boundaries having been crossed (Stockholm Resilience Centre et al. 2025).[2]

Despite these growing environmental threats and the objectives of the Paris Agreement, emissions have continued to rise steadily, driven by increased fossil fuel consumption. To meet the Paris temperature objective of "well below" 2°C of warming, global greenhouse gas (GHG) emissions need to decline by around 5 percent per year over the next decades (and by around 7 percent if one accounts for the evidence of an ongoing sharp decline in carbon sinks – see Carle et al. 2025, Stock 2025, Ke et al. 2024, Pan et al. 2024, Curran and Curran 2025, Sohail et al. 2025). Over the last decades, however, the steady decline in the carbon intensity of the global economy has been accompanied by a significant rise in emissions. An important element of context is that the rapid growth in emissions in the 20th century occurred in tandem with unprecedented economic and population growth, and it is unclear whether similar increases are replicable.

The persistence of fossil fuels in the global economy has implications for countries' energy security and balance of payments. It is widely agreed that a shift away from fossil fuels to renewable energy can bolster energy security by reducing dependence on imported fuels, create jobs in the low-carbon energy and related sectors, and enhance the balance of payments through lower energy import costs, while supporting economic stability via lower volatility induced by fossil fuel markets (IMF 2025a, p. 26). By contrast, many commodities exporting countries depend on the related inflows of foreign exchange to finance their imports of consumption and investment goods, including those needed for low-carbon investments (Moreno et al. 2024).

The simultaneous decrease in global carbon intensity and increase in emissions begs a question: is the conventional understanding of global energy and material dynamics accurate? Large increases in energy demand, driven by the growing world population and rising global GDP per capita, are a key reason why, in recent decades, emissions have continued to rise in tandem with falling carbon intensity. This explanation is insufficient, however, as it does not explain the *level* of carbon intensity. Rather, the "stickiness"

[1] Energy refers to primary, secondary and tertiary energy. Primary energy is found in nature, such as coal. Secondary energy corresponds to carriers of energy obtained by converting primary energy, such as electricity. Tertiary energy is a second conversion of energy, such as converting synthesis gas (itself made by converting coal) into electricity. Materials are elements, constituents, or substances of which something is composed or can be made, such as steel. Dynamics refer to changes in quantities, prices, and global exchanges over time. The rationale for analyzing energy and materials jointly is twofold: they are interdependent (energy is needed to make materials – e.g., coal must be burnt to make steel, and vice versa – e.g., steel is needed to transport oil); and the fossil fuel consumption embedded in material extraction and use is very hard to eliminate.

[2] The planetary boundaries framework identifies nine processes that are "critical for maintaining the stability and resilience of [the] Earth system as a whole" (Richardson et al. 2023). Planetary boundaries are thus environmental thresholds beyond which humanity is no longer in a safe operating space.

of global fossil and material consumption points to the criticality of understanding global dynamics of energy and materials – both the relationships among different forms of energy and the relationship between energy and materials – in *absolute terms*. Independently of the policy objective, having an accurate understanding of the drivers of energy and material flows is essential from a methodological perspective.

The conventional view is that global energy and material dynamics are – and have historically been – largely governed by *substitution* dynamics (see, e.g., Acemoglu et al. 2012, Acemoglu et al. 2023, Aghion et al. 2023), with the relative price dynamics of energy services playing a decisive role in energy "transitions" (from a substitution perspective) in the long run (Fouquet 2016).[3] A key argument to support this view is that the world economy has previously experienced energy and technology transitions. For instance, the International Energy Agency (IEA) argues that "previous transitions" were shaped only by cost or convenience (IEA 2019). Similarly, Vaclav Smil, a leading energy analyst, identifies the "first energy transition" as having occurred in the 19th century (Smil 2024) and describes past "global energy transitions" (Smil 2017). Marchetti (1977) invokes a "history of substitutions" to develop a logistic model of primary energy substitution, which he argues is useful to describe the substitution of other commodities. Grubler (2012) describes two major historical energy transitions: growth in coal-fired steam power, and its "subsequent displacement by oil and electricity-related end-uses and technologies." Fouquet (2016) defines "historical energy transitions" as an increase from 5 to 80 percent of the energy consumption for a service (e.g., power) in a sector.

Our interpretation of the data is different. Economic history and recent developments show that *absolute* energy and material consumption is governed not by *substitution* dynamics but by *accumulation* dynamics (Fressoz 2024). By contrast, the energy transition (ET) framework focuses on substitution dynamics in *relative shares* of energy sources (Fouquet 2016). Two versions of the ET framework should be distinguished. Theoretical economics (e.g., Acemoglu et al. 2012, 2023; Stern 2007) produces models with strong assumptions on the substitutability of low- and high-emission sources of energy. The technical systems approach (e.g., IEA 2024, IPCC 2022) tends to have a solid understanding of technical systems and technical feasibility, but uses models with largely/fully exogenous growth that do not capture systemic rebound effects.[4]

More formally, the ET framework rests on four key assumptions, several of which are implicit:[5] (i) technological and material dynamics mirror each other, such that the deployment of low-carbon technologies (e.g., renewable electricity generation technologies) is expected to induce a commensurate reduction in the consumption of high-carbon materials (e.g., coal and gas); (ii) relative prices (in particular between high- and low-carbon energy technologies) play a crucial role in substituting fossil fuels with low-carbon capital (i.e., low-carbon technologies); (iii) there is a relatively high elasticity of substitution between so-called "clean" and "dirty" technologies; and (iv) increased energy efficiency does not drive, over time, an increase in the demand for energy services (i.e., there is no macro-scale "rebound effect").[6] This justifies an approach to decarbonization centered on policies (mainly carbon pricing, and to a lesser extent subsidies and regulations) that collectively enable substituting fossil fuels with "clean technologies" via technological progress and diffusion, facilitated by trade, with electrification of production and consumption expected to play a key role.

To be sure, the deployment of renewables, or so-called "clean technologies,"[7] is a crucial component of any low-carbon development path or economic trajectory. From this perspective, the significant

[3] For instance, Aghion et al. (2023) develop a model of innovation in which they assume that "While sectors are imperfect substitutes, within each one firms' quality-adjusted offerings are perfect substitutes" (p. 4).

[4] In addition, negative emissions play a major role in net zero scenarios produced by integrated assessment models: 170-900 Gt CO2e need to be stored by 2100 according to the range of scenarios studied in the 2022 IPCC report (IPCC 2022, p. 25).

[5] While these assumptions apply fully to the theoretical economics version of the ET framework, they also largely apply to the technical systems version of the framework, as the latter's exogenous modeling of growth rules out systemic rebound effects.

[6] These assumptions are clearly implicit in the influential framework developed by Acemoglu et al. (2023): "Suppose, following Acemoglu et al. (2012), that there are two substitutable ways of producing energy, dirty and clean, and innovation can be directed either to improving the quality of intermediate goods used in dirty production or clean production" (p. 6). This framework centers on technologies, products, and innovation, and does not consider material flows and interdependencies.

[7] Strictly speaking, no technology is "clean" since material production processes necessarily entail environmental and social impacts.

deployment of renewable energy technologies in recent years is a major development. Yet the ET framework overlooks (or does not sufficiently take into account) key features of global energy and material dynamics, and their interaction with economic forces: the entwinement of materials and resources in production, the absolute size of the global economy, technological interdependencies and path dependence, the broader environmental context, characterized by the crossing of seven critical planetary boundaries, and the institutional drivers of these material processes. Despite all the innovations that took place in the 20th and 21st centuries, no raw material has ever become obsolete. In fact, the consumption of almost all materials has increased significantly in recent decades. This basic but critical fact challenges the ET framework, which rests on the logic of large-sale substitution between so-called "clean" and "dirty" energies, and (absolute) phasing out of the latter.[8]

This paper calls for caution in applying the technology-centered ET framework to the projection of future energy and material flows, for three main reasons. First, the ET framework is anchored in an understanding of the world that focuses relatively narrowly on technological dynamics. Second, it tends to overlook crucial drivers of sectoral linkages that create interdependencies between low-carbon technologies and fossil fuels – notably through hard to abate sectors that underpin modern economies, such as shipping, iron and steel, cement, plastics, fertilizers, construction, and arms. Third, it does not pay significant attention to the institutional drivers of investment dynamics that tend to reinforce carbon-intensive path dependency.

From both an economic and climate perspective, material dynamics matter considerably. The role of population and economic growth in determining global energy consumption does not lessen the need for an accurate understanding of global energy and material dynamics. Yet the ET framework underplays material dynamics. At most, it projects onto material dynamics modes of reasoning (substitution by diffusion of innovation, creative destruction) that are anchored in a narrower, largely ahistorical, approach to the study of technological dynamics.[9] The analysis of material dynamics with respect to environmental issues is not novel, but is arguably a blind spot in energy economics, resource economics, and climate economics. The emissions and materials that are embedded in production and consumption, or what we call energy and material symbioses, are related to the literature on economy-wide material flow analysis and the ecological footprint (e.g., Georgescu-Roegen 1975, Krausmann et al. 2017, Magalhães et al. 2018). However, they remain absent from macroeconomics and the literature on the economics of climate change.

Economics has mainly analyzed materials from the perspective of resource economics, focusing on optimization of extraction, substitutability of resources, and the theory of growth and depletion. Raw materials have been extensively studied in resource economics, notably from a microeconomic perspective (optimal resource extraction theory), to understand the so-called "resource curse," to study supply chain optimization, geoeconomic fragmentation and the criticality of certain materials, and from the perspective of so-called "economic complexity" (the relationship among countries' product complexity, industrial capabilities, trade flows, and growth prospects).[10] Another strand of the literature focuses on substitutability of inputs and technological change (e.g., Acemoglu et al. 2012), and the relationship between natural resources, climate change, and economic growth (Boulding 1966; Daly 1968; Ayres and Kneese 1969; Solow 1971; Nordhaus 1974, 1994; Cline 1992; Stern 2007). There is also a large literature, stemming partly from system dynamics

[8] In a representative example of the dominant ET framework, which is conceptually centered on decarbonization through technological substitution, Fornaro et al. (2025) argue that the recognition for the urgent need for action to limit climate change "has prompted countries worldwide to embrace proposals aimed at promoting a green transition, that is, a structural transformation of our economies away from polluting technologies and towards clean ones."

[9] For instance, the scientific background note for the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2025 awarded to Philippe Aghion, Peter Howitt, and Joel Mokyr, argues that "With a science and technology-focused view [...] social and environmental challenges should set into motion searches for novel techniques to address them, so that the technological process itself may be interpreted as a self-correcting process" (The Royal Swedish Academy of Sciences 2025, p. 38).

[10] In the microeconomics of resource use, the seminal Hotelling rule (Hotelling 1931) defines the net price path of a non-renewable natural resource as a function of time while maximizing economic rent in the time of fully extracting that resource. A burgeoning literature studies the criticality of key materials, focusing on the impact of trade fragmentation on GDP, inflation and decarbonization prospects (e.g., Schwerhoff and Stuermer 2019, Alvarez et al. 2023, Bogmans et al. 2024, IMF 2024a, IMF 2024b, Miranda-Pinto et al. 2024, Bucciarelli et al. 2025). On economic complexity and decarbonization, see, e.g., the Harvard Growth Lab: https://growthlab.app/greenplexity.

research, on non-renewable resources and economic growth (Georgescu-Roegen 1971, 1975; Meadows et al. 1972; Dasgupta and Heal 1974; Solow 1974; Stiglitz 1974; see Neumayer 2025 for an overview).

However, economics has by and large overlooked the relationship between material interdependencies and the functioning and evolution of the world energy system. An emblematic example is the landmark Stern Review on the economics of climate change (Stern 2007), which only mentions materials in a sectoral context, and does not consider their dynamic, economy-wide implications.[11] Similarly, the survey of the literature on the links between macroeconomics and climate change by Bilal and Stock (2025) does not mention materials. The concepts of "rebound effect" and "Jevons Paradox" are not mentioned in either document. The seminal article by Nordhaus (1992) that introduced the influential Dynamic Integrated Climate-Economy (DICE) model mentions neither materials, nor the rebound effect, nor the Jevons Paradox. In the model, firms produce a single final good, which by construction excludes material interdependencies. Gillingham et al. (2016) posit that production occurs by combining energy inputs with non-energy inputs (e.g., capital and labor), with varying degrees of substitutability/complementarity, but do not consider the role of different materials as inputs. Importantly, materials are not modeled as such in the standard production theory, as reflected by the aggregate production function.[12] Sharpe (2023, p. 219) argues decarbonizing energy-intensive industrial sectors requires a combination of electrification/hydrogen, new chemical feedstocks, and carbon capture and storage – a focus on technological change that elides material dependencies. An exception is the literature on economic growth and planetary boundaries, which finds evidence of relative decoupling between GDP growth and material footprint, but no absolute decoupling (see Kallis et al. 2025).

More recently, Aghion et al. (2025) discuss material production, but not from the perspective of economy-wide material flow accounting or material interdependencies. Rather, they oppose "material productivity" and "quality improvements." Their theory assumes that goods and services "act as complementary inputs in the production of final goods" and that "aggregate demand shifts from basic to sophisticated goods," with the latter assumed to have a lower environmental impact, per unit of expenditure, than the former. Their focus is on relative metrics: they argue that, as a society becomes wealthier, environmental damage per dollar spent diminishes. They recognize, however, that "Even though newer technologies typically boast greater environmental friendliness, the expansion of material production inevitably leads to increased emissions."

In this paper, we seek to understand the reasons for vast embedded emissions and materials – effects that we synthesize by introducing the concept of the Generalized Jevons Paradox. We argue that such embeddedness is inherent to any large, complex material-economic system under the constraints posed by key institutional factors. We discuss the implications of the Generalized Jevons Paradox for how to think more rigorously about the challenge of decarbonizing the global economy within the short timeframe left to avoid breaching 2°C of global warming. Building on the Jevons Paradox, the Generalized Jevons Paradox is the notion that increased efficiency in resource use (including energy consumption) is associated with higher, not lower, emissions.[13] It suggests that, absent deep institutional change, the decarbonization potential of technological change that increases the GHG or material efficiency of the global economy is limited by its effects on demand, trade, expected profits, and/or induced technological developments. We identify three key drivers of the GJP: market and geoeconomic power, trade arrangements, and international financial factors. The GJP should not be interpreted as an economic "law," but rather as an empirical observation that calls for caution in projecting future energy flows.

[11] The term "resources" is used throughout the Stern Review, but it mainly refers to natural or financial resources, not to materials in the sense of material flow analysis or material interdependencies.

[12] As noted by Galbraith and Chen (2025), "The technology of the production function is given by the form and the coefficients of the function used. Resources do not figure in the story unless they are subsumed under 'capital.' That, of course, makes it difficult to consider the possible role of a particular resource, such as oil, which accounts directly for only a small share of total expenditure in the economy" (Galbraith and Chen 2025, p. 112). An exception is production functions that add energy, and in some cases materials, as factors of production to capital and labor (KLE or KLEM production functions). However, these production functions do not correspond to any technical reality, since they aggregate extremely heterogeneous energies and materials into a single factor of production, making calibration very difficult (Pottier 2014, p. 66).

[13] The Jevons Paradox is the observation that higher energy efficiency ultimately leads to higher energy demand by lowering the cost of certain energy services (coal, in the Stanley Jevons' original observation – see Jevons 1865).

More formally, our analysis suggests that the history of energy and the functioning of the global energy system support three key assumptions: (i) technological and material dynamics are not equivalent; (ii) the elasticity of substitution between so-called "clean" and "dirty" technologies tends to be relatively low (and in some cases is zero, given a lack of available and/or scalable substitutes); and (iii) there is a rebound effect at the level of the global economy, whereby, in the absence of deep institutional changes, increased energy efficiency tends to drive greater energy demand. Taken together, these assumptions suggest that the global input-output matrix tends structurally to become larger over time, entrenching fossil fuels in the productive structure. This implies "stickiness" in global emissions – and represents a major constraint for decarbonization.

This paper is organized as follows. The first section presents evidence on global energy and material dynamics, examining whether the data support energy transition or energy addition dynamics in the contemporary and historical period, and formulating hypotheses for the future. The second section attempts to make sense of these facts. Based on this empirical evidence, the third section highlights the reasons for caution, based on real-world energy and material dynamics, in applying the energy transition framework. It presents an empirical observation to synthesize these dynamics, the Generalized Jevons Paradox (GJP), as well as some elements of formalization of the GJP. The fourth section draws preliminary implications for economic research. The last section concludes.

Empirics: Energy Transition or Energy Addition?

This section examines global energy and material dynamics. We analyze embedded emissions and materials, resource use, and GHG emissions. Embedded emissions and materials are those associated with a good. For instance, a given amount of coal is embedded in a tonne of steel; various materials and emissions are embedded in manufacturing and shipping a car; emissions and materials (e.g., ammonia, shipping fuel) are embedded in the production and distribution of a kilogram of apples. Embedded emissions and materials matter, as they are linked to supply chain vulnerabilities and drive climate change and other environmental impacts. We divide the analysis into the present (recent decades), the historical period (the 19th century and most of the 20th century), and the future (hypotheses about the next decades based on the evidence). For each period, we consider whether the data are consistent with (A) an energy transition (a substitution between energy sources in absolute terms, reflected in an absolute decline in fossil fuel consumption), or (B) an "energy addition": increasing consumption of all energy sources, reflecting growing embedded emissions and materials.

Present

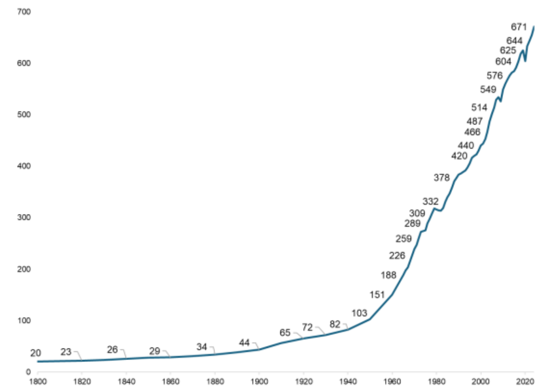
Energy Transition?

The data show an absence of energy transition in absolute terms. Variations in the *shares* of global sources of energy over time mask increasing consumption *levels* for all energies. While there have been large shifts in the *shares* of different energies in the primary energy mix (Figure 1, panel 3) since 1800, in *absolute terms* the consumption of all energies and materials has increased continuously since 1800 (Figure 1, panels 1, 2, and 4). The steady rise in the share of renewables in the energy mix in recent decades has accompanied fossil fuel consumption growth (Figure 1, panel 5). In absolute terms, the *increase* in total, fossil and renewable energy consumption has never been as high as it was in the two decades after 2000 (Figure 1, panel 6).[14]

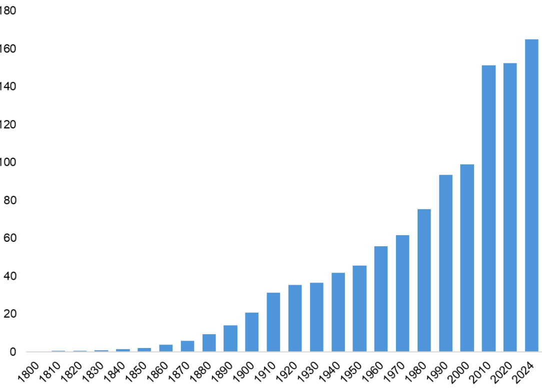
[14] Annex I shows a similar picture by analyzing the change in the mean, median and total energy mix and electricity mix for 117 countries and 120 countries over the period 1971-2023 and 2000-2023, respectively.

Figure 1. No Energy Transition, but an Energy Addition

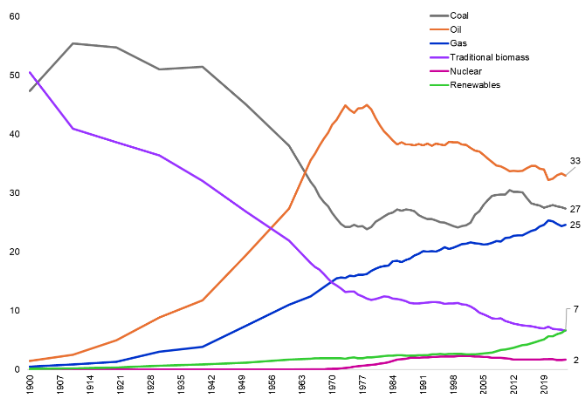
1. Global primary energy consumption from all energy sources (EJ per year): 1800-2024.



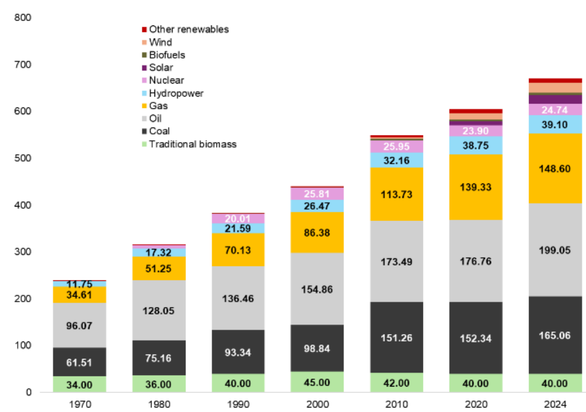
2. Global primary consumption of coal (EJ per year): 1800-2024.



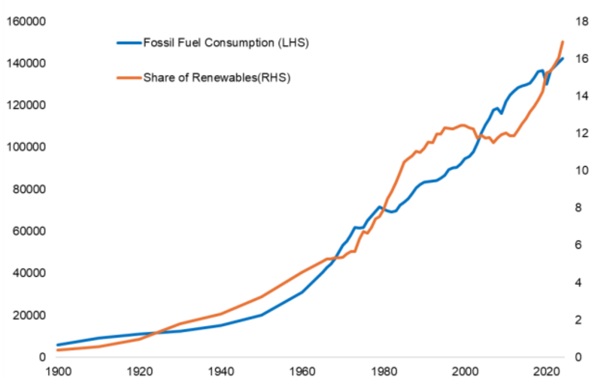
3. Global energy consumption by source (percent of total primary energy mix): 1900-2024.



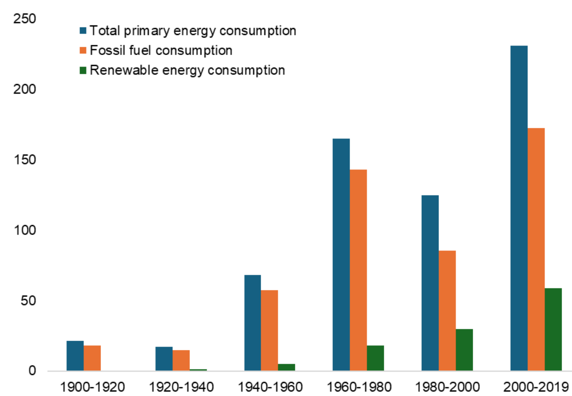
4. Global primary energy consumption (EJ per year): 1970-2024.



5. Share of renewables in primary energy consumption (percent) vs. total fossil fuel consumption (EJ): 1900-2024.



6. Increase in total energy and fossil energy consumption (EJ per twenty-year span): 1800-2019.

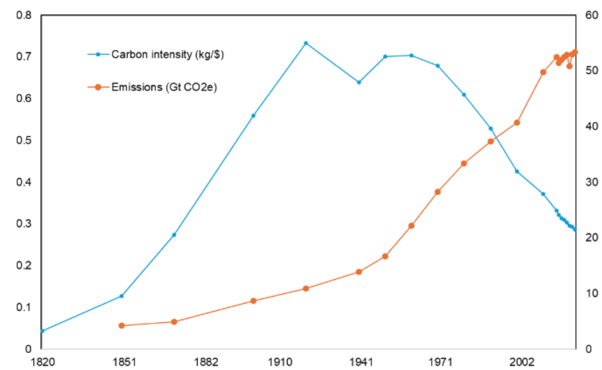


Sources: Our World in Data; and authors' calculations.

Note: In panels 1, 3 and 4, traditional biomass is assumed to be constant since 2015 given the absence of more recent data. In panel 5, renewables correspond to hydropower, solar and wind, fossil fuels correspond to coal, gas and oil, and the share of renewables is calculated as a percentage of total global primary energy consumption. In panel 6, the last twenty-year period stops in 2019 to exclude the impact of the COVID-19 pandemic crisis on global energy

At the same time, rising emissions have occurred in tandem with a steady decline in the carbon intensity of the global economy (Figure 2). Increasing energy efficiency and the rapid deployment of renewable energy in recent decades have co-existed with high levels of investment in fossil fuels (Grubert and Hasting-Simons 2022), as well as a growing role of fossil fuels in key sectors, such as agriculture, construction, and defense. The productive structure of the global economy remains characterized by high-emission production and consumption even as new energy investments are now dominated by renewables (two thirds of global energy investments according to IEA 2024). As of November 2023, governments were still planning to produce, in 2030, over twice the amount of fossil fuels that would be consistent with the median 1.5°C pathway (UNEP 2023).[15] In a single year (2024), China approved close to 67 GW in new coal-fired power capacity, and nearly 98 GW in new or resumed coal power projects – the highest level since 2015 (Qi and Shearer 2025).[16] Thus, in the face of the unprecedented speed of climate change, there are signs of an entrenched "fossil-fueled civilization" (Smil 2022), or what some have called a mid-transition trap (Espagne et al. 2023). It should be noted, however, that the rapid growth in emissions occurred in tandem with unprecedented economic and population growth. It is unclear whether similar increases are replicable.

Figure 2. Declining Carbon Intensity of Global Economy and Rising Emissions: 1820-2022



Source: Our World in Data.
Note: GDP data are in international dollars at 2011 prices.

Energy Addition

Instead of an energy transition, counterintuitively the historical evidence shows a strong positive relation between energy/material energy efficiency and total energy/material footprint. We examine the relationship between energy in resource use and total resource use, at the level of the world economy, for four different indicators in the 20th century: carbon emissions, water use, nitrogen use, and electricity consumption. For all four indicators, we find a very strong positive correlation, since the 1960s-1970s, between efficiency and total consumption or footprint (see also Polimeni et al. 2008).[17] In line with the conventional approach to measuring efficiency, we divide global GDP by total emissions, water or nitrogen used, or electricity consumed, for each year in the sample, using the longest available time series. This pattern matters both for understanding energy and material dynamics and for policies related to environmental objectives. To further analyze the relations between these variables, Annex II presents regression results using three different estimators – OLS, median quantile regression, and the Theil-Sen estimator – the last two being more robust to outliers and non-parametric, and therefore better suited to small samples. The results of this regression analysis confirm the strong correlation between these variables.

The positive correlation between energy efficiency and total GHG emissions, measured at the level of the world economy over the period 1900-2023, is remarkably high. Figure 3 (panel 1) shows data on energy efficiency (measured in international dollars per tonne of CO_2 equivalent emitted) and total emissions

[15] As noted in SEI et al. (2023, p. 19), "The Paris Agreement does not provide a precise definition of what "well below 2°C" means and how these temperature limits should be used in climate policymaking […]. However, it has been interpreted as limiting peak warming to below 2°C with >90% likelihood […], which translates to being "very likely" to limit warming to 2°C in IPCC uncertainty language. This is higher than the 67% probability that the 2°C-consistent scenarios achieve."

[16] To give a sense of scale, this is roughly equivalent to the installed nuclear power capacity of the United States, or to one and a half times the nuclear power capacity of France.

[17] Because the variables considered are not mainly macroeconomic but energy- and environment-related, our focus is not on the correlation between non-trend movements in the time series. In this context, spurious correlation is not a concern.

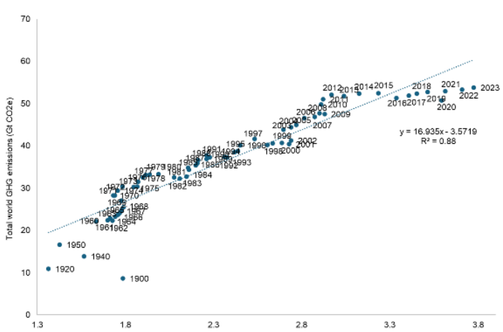
(measured in Gt of CO_2-equivalent, at a decadal frequency over 1900-1950 and at an annual frequency over 1960-2023) at the level of the world economy. The R^2 is 0.88 (sample size of 69). The least squares estimate of the slope coefficient is very high, at 16.9. Counter-intuitively, this means that, over 1900-2023 each dollar of increased energy efficiency at the global level (corresponding to the relationship between global GDP and global GHG emissions) is associated with 16.9 Gt in additional emissions.

There is evidence of the same pattern for two other resources, water and nitrogen, that underpin the world economy and, like emissions, are associated with planetary boundaries. Figure 3 (panels 2 and 3) show the relationship between the efficiency of the use of water and nitrogen (for agriculture), at the level of the world economy (as measured by dollars of GDP per tonne of water and nitrogen, respectively) and total use of water and nitrogen, over the period 1960-2014 and 1961-2023, respectively. The R^2 value is 0.84 and 0.87 with a sample size of 52 and 63, respectively. For nitrogen, the X- and Y-axes are reversed and a polynomial regression is used to represent the data more clearly. The evidence shows a U-shaped relationship between the efficiency of nutrient nitrogen and total world nitrogen use in agriculture over the period 1960-2014, with a steady decrease in efficiency between 1960 and 1984 followed by an increase in efficiency over 1985-2014. The initial decline in efficiency is explained by the surge in nitrogen use in agriculture over that period, by a factor of five (over three times faster than the growth in world GDP over the same period), before growing by only 11 percent over the next decade (against 33 percent for world GDP).

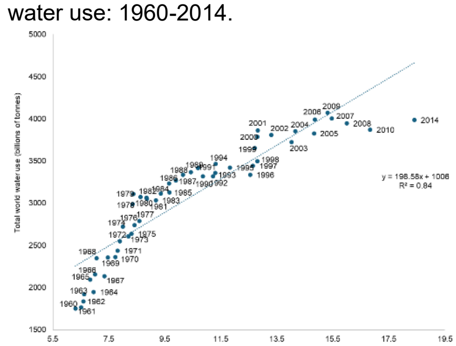
There is also a very strong positive relationship, historically, between electrification of the economy and increased total energy and fossil fuel consumption. The conventional wisdom views electrification, combined with large-scale deployment of low-carbon electricity technologies, as crucial to global decarbonization (IPCC 2022, IEA 2024). However, the significant deployment of low-carbon electricity technologies in recent decades has been accompanied by equally strong (although slightly diminishing) growth in total energy and fossil fuel consumption (Figure 3, panel 4). We find a near perfect correlation between the share of electricity in global final energy consumption and both total energy consumption and total fossil fuel consumption over the last 50 years (the R^2 values are 0.97 and 0.94, respectively, with a sample size of 53).

Figure 3. Strong Positive Relation Between Efficiency of Resource Use and Global Resource Use

1. Energy efficiency of the world economy vs. total world GHG emissions: 1900-2023.

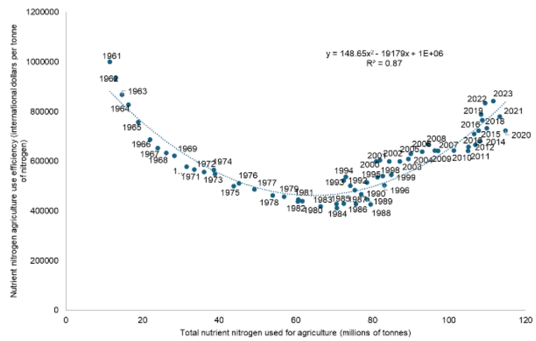


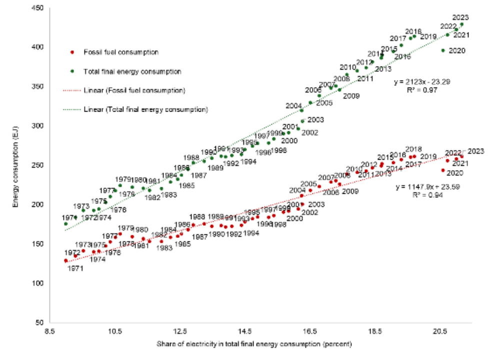
2. Water use efficiency of the world economy vs. total world water use: 1960-2014.



3. Nitrogen use efficiency of the world economy vs. total world nitrogen use for agriculture: 1961-2023.

4. Share of electricity in world final energy consumption / world energy and fossil fuel consumption: 1971-2023.





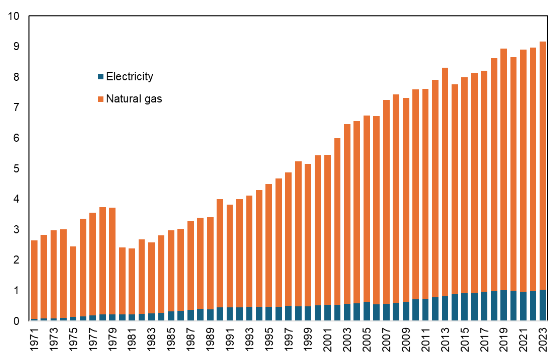
Note: The year corresponding to the data points is indicated next to each data point.

Sources: Global Carbon Project; Our World in Data; FAO; World Bank; IEA; and authors' calculations.

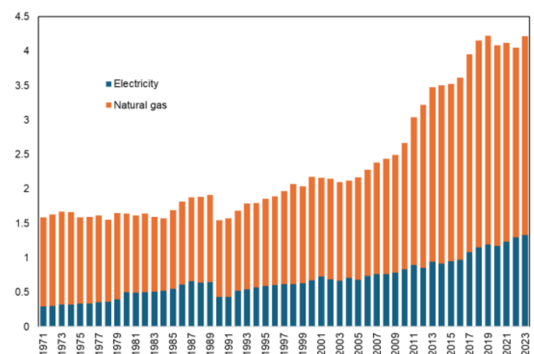
Embedded emissions are apparent in the electricity and gas consumption of oil and gas production. Figure 4 shows the significant embedded emissions and materials in the oil and gas sector through the electricity and gas consumed in oil and gas extraction and oil refining. There are indications that the strong upward trends in Figure 4 accelerated in 2024 and 2025, with strong growth in electricity demand driven by the electrification of oil and gas production and data center construction (Rystad Energy 2025).

Figure 4. Rising Electricity and Gas Consumption in the Oil and Gas Sectors

Electricity and gas consumed in oil and gas extraction: 1971-2023 (MJ).



Electricity and gas consumed in oil refineries: 1971-2023 (MJ).



Sources: IEA World Energy Balances; and authors' calculations.

High embedded emissions also reflect the role of energy as a complement in production. This can be seen in the economic impact of the energy crisis in Europe that followed the early phase of the Russia-Ukraine conflict. The impact was largest for economies that are highly dependent on energy-intensive industrial processes, notably the German economy. As noted by Geerolf (2025), based on macroeconomic models like Baqaee and Farhi (2021), and assuming a 30 percent reduction in the supply of gas, several influential economists estimated (ex-ante) the GDP impact of the sharp reduction in gas supply in Germany at around 0.2-0.3 percent of GDP, up to 3 percent in the most severe scenarios (Bachmann et al. 2024). Instead, Geerolf (2025) notes, German GDP at end-2023 was 6.5 percent lower than the projections of the OECD and several German research institutes at end-2021 – even though the gas supply reduction was around 15-20 percent, compared to the 30 percent assumed in Bachmann et al. (2024). This is consistent with the fact that gas is used both as a primary energy and as an input in a range of sectors: chemicals, metallurgy, glass, ceramic, and paper (Geerolf 2025, p. 49). The size of the economic shock also points to limits – on both the demand and supply sides – to the ability of firms and households to adjust to higher gas prices. The implication is that energy is better conceptualized as a crucial complement in production, rather than as a substitute.

Lifecycle emission analysis shows that embedded emissions and materials are mirrored in the composition of goods and services. Input-output matrices show a complex entwinement of so-called "green" and "brown" sectors (Magacho et al. 2023; Lefèvre 2024). Dirty and semi-clean goods differ in terms of (i) their lifecycle emissions, (ii) the level of energy symbiosis associated with them, and (iii) adverse environmental impacts beyond climate change associated with producing good/services, either upstream or downstream (e.g., water pollution impacts of lithium mining to produce EV batteries).

The criticality of embedded emissions is also reflected in the fact that, so far, partial decarbonization has primarily concerned electricity, which accounts for 40 percent of global emissions, and to a lesser extent heating and land transport. For aviation, shipping, iron and steel, cement, plastics, fertilizers, agriculture, construction and arms, the technological prospects for decarbonization remain highly uncertain. These sectors are described as "hard to abate," a qualifier that may underestimate the difficulty of decarbonizing them.[18]

This is partly because of reliance on high-temperature processes that are very hard to electrify at scale. There is a risk that the boom in renewable energies could electrify an economy that will continue to depend on fossil fuels for large parts of its operations for a long time to come. Indeed, renewables both reduce fossil fuel consumption – for power generation and transport – and have knock-on effects in other areas – materials production. In China, one reason for the lack of CO_2 emission reductions in recent years is the boom in so-called "green" technologies (Lawrie and Stubenberg 2025). These emission embeddedness effects operate via different mechanisms and at different levels. For example, they are larger on energy consumption (e.g., EV production and associated road infrastructure requirements) than on energy production (renewable capacities).

Another major hard to abate sector is global food production (Crippa et al. 2021). Through deforestation, cooking, packaging, preservation, agribusiness, waste management, etc., the food system emits 18 Gt of CO_2 equivalent (one third of global emissions). Half of the warming effect is caused by deforestation and energy production, which could be reduced. The remainder is caused by methane (35 percent), nitrogen oxides – i.e., fertilizers (11 percent), and fluorinated gases (refrigeration) (4 percent), which are much harder to abate.

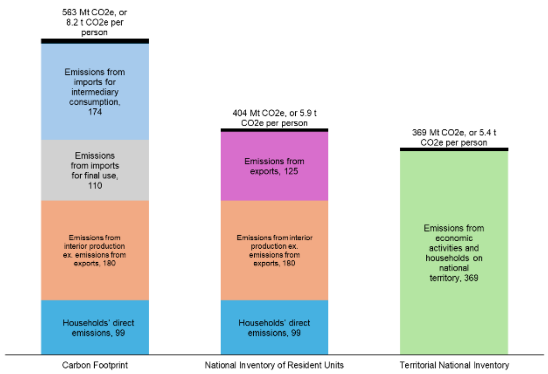
Imports are another way to measure the extent of embedded emissions. Many countries that have decarbonized their power sector import large volumes of more carbon-intensive goods (and sometimes services), revealing high embedded emissions. Figures 5 and 7 show the emissions embodied in international trade for three countries with a low-carbon power sector: France, the UK, and Norway. Figure 6 shows high consumption-based emissions in lower-carbon economies. These data patterns suggest that international trade is one of the main channels through which embedded emissions arise. Assessing embedded emissions and materials therefore requires a deep understanding of the complex material entanglement involved in production and trade. More work is needed to analyze these effects, quantify them, and identify underlying mechanisms.[19] Tubiana et al. (2025) estimate the share of emissions in iron and steel, chemicals, agricultural products and aluminum that are embedded in trade at 34 percent, 45 percent, 24 percent and 50 percent, respectively.

[18] The emission intensity of cement and steel has been broadly flat in recent years (https://www.iea.org/energy-system/industry/).

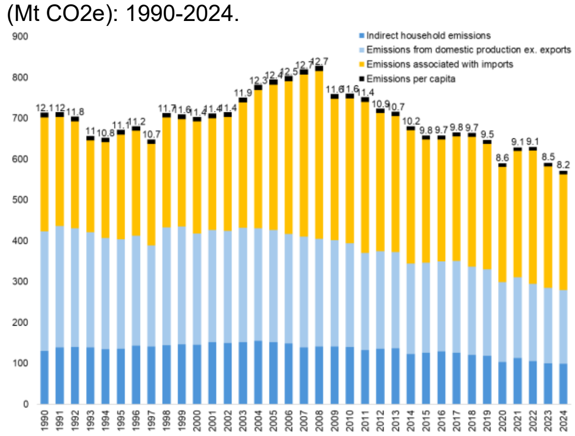
[19] Looking beyond GHG emissions, there is evidence that a considerable amount of resource use and biodiversity-based services are embedded in trade (see, e.g., Silva et al. 2021, Lenzen et al. 2012 and Dasgupta 2021 on the link between growth in global trade and pressures on the biosphere). Similarly, Santos Carneiro et al. (2025) find that a large share of global pressures on planetary boundaries occurs through international value chains and trade patterns among countries (see Annex III).

Figure 5. High Emissions Embodied in International Trade: France, UK, Norway

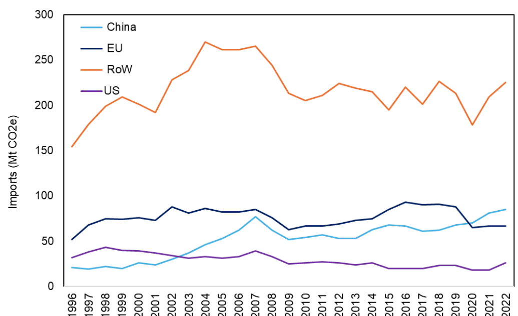
France: Carbon footprint (Mt CO2e): 2024.



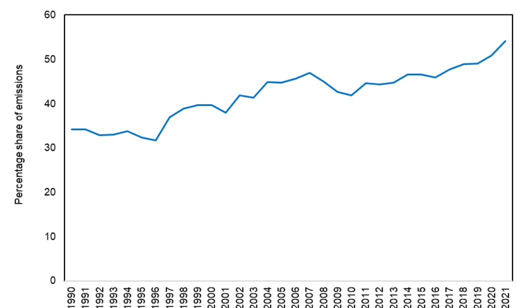
France: evolution of carbon footprint by emission origin (Mt CO2e): 1990-2024.



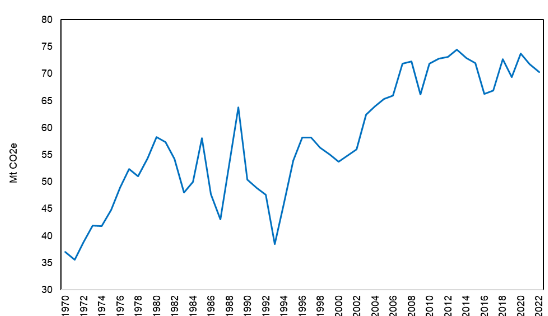
UK: Breakdown of GHG emissions by region of import (Mt CO2e): 1996-2022.



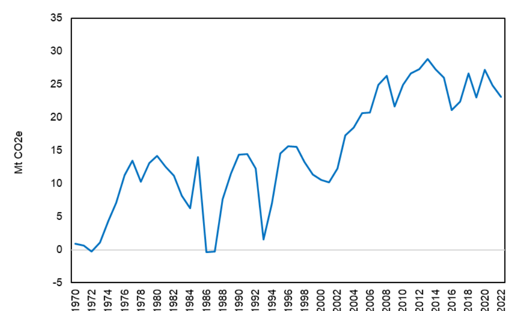
UK: GHG emissions embedded in imports (percent): 1990-2020.



Norway: Consumption-based CO2 emissions (Mt CO2e): 1970-2022.



Norway: Net CO2 emissions in trade (Mt CO2e): 1970-2022.

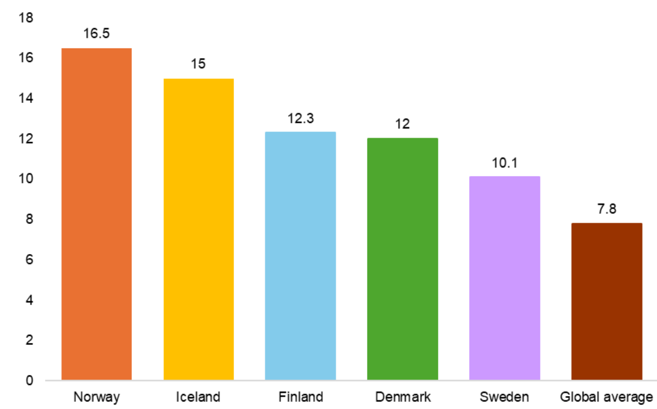


Sources: INSEE-SED; Defra; University of Leeds; CICERO.

Constraints in accessing electricity imply that the large-scale deployment of renewable energies is compatible with the maintenance of large-scale fossil fuel capacities. Even in the field of electricity generation, where commercial decarbonization technologies exist (which is not the case for most hard-to-abate sectors) and are competitive, there is a significant persistence of fossil fuels. For instance, in western China, huge energy parks have recently been inaugurated, which combine solar panels, wind turbines, and thermal power plants. The last of these, which use cheap local coal, compensate for the variability of renewables and make the connections profitable despite particularly high costs, as the electricity is consumed two thousand kilometers to the east. It would appear that 35 to 40 percent of wind and solar capacity recently built in China has been coupled with coal development (Zhang 2023). At COP28 in 2023, the Chinese envoy explained that it was "unrealistic" to completely eliminate the fossil fuels used to maintain grid stability, hence the choice of "transition away" rather than "phasing out" (Stanway 2023). Similarly, the largest drivers of growth in electricity demand in the U.S., which is at its most rapid in several decades (over 3.5 percent per year), are the electrification of oil and gas production and the construction of data centers (Rystad Energy 2025). In turn, the electricity used to supply data centers is mostly supplied by fossil fuels (Murthaugh 2025). By 2024, despite the boom in renewables, emissions from the power sector were still rising globally.[20]

Figure 6. Consumption-Based GHG Emissions Per Capita in Lower-Carbon Economies

Nordic countries: consumption-based GHG emissions per capita (tonnes CO2e per capita): 2023.

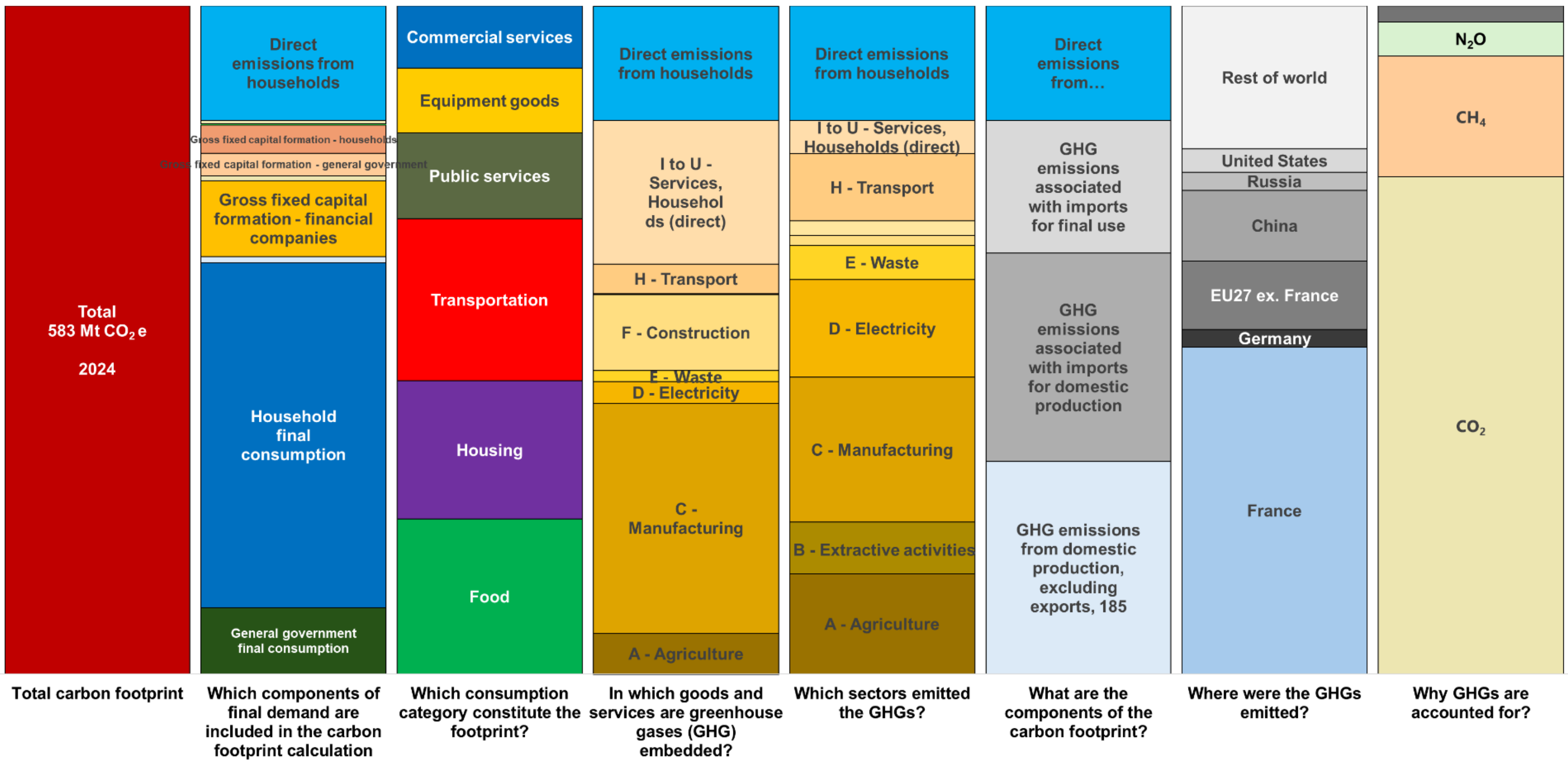


Sources: Eora Global Supply Chain Database.

Finally, there are powerful embedded emissions in pillars of industrial activity: oil, steel, and coal. Oil is pumped by steel machines, transported by steel ships, tank wagons and pipelines, refined in steel factories and finally burned by steel engines driving steel machines. And most of this steel (more than three-quarters) is produced with coal – requiring large quantities of coal for the oil (around one billion tonnes per year globally).

[20] IEA figures. See: https://www.iea.org/fuels-and-technologies/electricity. Since 2000, three times as many coal-fired power plants have been opened worldwide as closed. New capacity: 1.5 TW, closed: 0.45 TW. Calculations based on data from https://globalenergymonitor.org/projects/global-coal-plant-tracker/.

Figure 7. France: GHG Footprint Broken Down by Category: 2024



Source: INSEE-SED.

Note: Emissions broken down by final demand component, consumption category, goods and services, sector, carbon footprint component, country of origin, and type of GHG.

Past

Energy Transition?

While there were large shifts in the relative shares of different energy sources in the 19th and 20th centuries, there was no energy transition. The standard narrative on past energy transitions focuses on dominant fuels and leading prime movers (Smil 2017, p. 387). This narrative gives the impression that, from the 19th century onward, the world economy experienced a succession of energy transitions (in the sense of substitution with and phasing out of "older" forms of energy). According to this view, there were transitions from wood to coal and from coal to oil, in particular. In absolute terms, however, fuelwood consumption increased in most industrial countries in the 19th and 20th centuries. Second, wood remained fundamental to the energy system of wealthy countries: without wood to prop up the mines, these countries would have had very little coal, and therefore very little steel and very little steam. While props are classified as construction timber, this is a debatable convention as their function was to produce energy. The quantities of mining timber are considerable. At the beginning of the twentieth century, British mines consumed between 3 and 4.5 million cubic meters of pit-props per year. By way of comparison, a century and a half earlier, the UK was burning only 3.6 million cubic meters of firewood.[22] In volume terms, the UK consumed more wood for energy between 1900 and 1950 than in the 1750s. This data pattern holds across countries, as shown in Fressoz (2024).

Energy Addition

Instead of evidence of an energy transition, economic history provides clear evidence of expanding embedded emissions through the "symbiotic" (i.e., interdependent) relationship between oil and coal. In the 1930s, it took around 7 tonnes of coal to make a car – i.e., about as much coal as the oil burned in the lifecycle of a car. An interwar calculation showed that for every tonne of oil consumed in Britain, 2.5 tonnes of coal had to be consumed to build the cars and the infrastructure required throughout its lifecycle (Dalley 1935, p. 17). Historical data patterns on such embedded emissions hold across countries (Fressoz 2024).

Embedded emissions in the production of oil and coal, unlike that between coal and wood, grew stronger in the 20th century. Extracting and transporting oil requires increasing amounts of steel, and therefore more coal. Whereas in 1901, 300 meters of drill pipe were enough to bring oil to Spindletop in Texas, in 2010, the Tiber Prospect off the coast of Mexico pierced the continental shelf ten kilometers below the surface of the ocean. "Oil Country Tubular Goods" (OCTG) statistics provide an incomplete estimate of the mass of steel used by the oil industry.[23] There is an upward trend: the United States consumed around 2 million OCTG in 1950 and 7 million OCTG in 2010 (U.S. Printing Office 1954, p. 1044). At that time, U.S. oil and gas extraction alone consumed as much steel as the entire U.S. economy did at the end of the 19th century.

Hypotheses about the Future

Looking ahead to the next decades, emissions need to fall rapidly (Black et al. 2025) yet there are reasons why embedded emissions of the present and the past could grow. In the case of embedded emissions connecting oil and coal, a key fact that is highly unlikely to change in the next decades is that oil consumption requires road infrastructure, which also consumes enormous quantities of steel, cement and,

[22] Redmayne (1923), p. 44. FAO (1953), Table 15. According to Warde (2007), 3.6 million cubic meters corresponds to the upper range of peak fuelwood consumption in England and Wales in the mid-18th century. Cf. Warde (2007, p. 38).

[23] Incomplete, because there is also a large amount of plate for tanks. A comprehensive 1967 report on material consumption in the US oil industry indicates that OCTG accounted for 69 percent of the steel used in US oil production. Steel accounted for the bulk of metal requirements (2.55 million tons out of 2.6 million in 1967), the remainder being copper, aluminum and nickel. Cf. National Petroleum Council (1967).

indirectly, coal. This implies considerable embedded emissions. Worldwide, cement plants burn mainly coal (70 percent according to the IEA, 90 percent according to cement manufacturers) (IEA 2015).[24] The fortunes of cement are systematically linked to those of roads, and the countries that consume the most cement are those that are building their infrastructures (Zijan et al. 2022). These countries are led by China, which occupies the same position in the world economy as the United States did a century ago from this perspective, consuming around half of the world's cement, half of which is used to build its infrastructures. This trend needs to be reversed to meet Paris Agreement objectives. Although emissions are declining in several large advanced economies and signs are emerging that emissions may have peaked in China, embedded emissions continue to be very large..

At the sectoral level, the limits to the ability of technological progress to drive global emission reductions would need to be overcome, which appears unlikely. Since the 2000s, the carbon intensity of steel production has stagnated. Despite the rapid modernization of cement plants since the 2000s, the carbon intensity of cement has increased by 1.5 percent per year over the last decade. Emissions from cement plants have tripled since 1990, accounting for 8 percent of global emissions. Another example is plastic, which is responsible for 3 to 5 percent of global emissions, and whose production is experiencing very high growth. Production has quadrupled since 1990, and vast markets remain untapped. Finally, nitrogen fertilizers are responsible for 1.5 percent of emissions at the production stage – which could eventually be reduced thanks to "green" hydrogen – but 5 percent if one takes into account their transformation into nitrous oxide by soil bacteria. Thus, in the next decades, if low-carbon electricity powers a productive structure that is broadly characterized by large-scale and growing production and consumption of cars, cement, steel, plastic and industrial agriculture (as is currently the case), global emissions will at best stagnate at a high level, and global warming will at best slow down but not stop. This would be consistent with the historical dynamics of growing embedded emissions and materials.

Third, construction, operation and maintenance of infrastructure – including those aimed at mitigating climate change – would need to decarbonize, which is extremely challenging. Building the infrastructure required to meet countries' mitigation goals, given country strategies' overall reliance on technological change and economic growth rather than lifestyle changes and demand "sufficiency," entails considerable emissions. One study finds that emissions associated with a shift to a low-carbon energy system range from 70 to 395 GtCO2, with an average across scenarios of 195 GtCO2 (Slameršak et al. 2022). In addition to renewable energy, smart grids, batteries, heat pumps and EVs (and the road transportation infrastructure associated with a large and likely growing global vehicle fleet) also require large quantities of cement, steel, metals, glass and plastic. The materials used in these production processes belong to very hard-to-abate sectors. For instance, Yokoi et al. (2022) find that metal production requires enormous amounts of energy for mining, smelting, and refining, which generates approximately 10 percent of global emissions. The case for decarbonizing these sectors is clear given the long-lived nature of the assets involved (Vogt-Schilb et al. 2018). However, the emission impacts described above underscore the importance of the size of the global economy – a factor that is arguably a blind spot of the energy transition framework.

This has implications for the amount of infrastructure that needs to be decarbonized and how much low-carbon infrastructure needs to be built. If this source of emissions is not taken into account in global mitigation strategies, investments that (aim to) lower the carbon intensity of economies could contribute to raising the global level of emissions, at least in the medium term. This is consistent with the pattern observed over 1900-2023 (as shown in Figure 3, panel 1). Furthermore, the emission implications of the investments needed for maintenance are significant. A considerable share of existing and new infrastructure and equipment, including those geared toward mitigation and adaptation, involve hard to abate sectors. Examples include roads, bridges, and energy infrastructure.

Persistent embedded emissions and materials point to two main implications.

[24] See also: https://www.globalcement.com/magazine/articles/974-coal-for-cement-present-and-future-trends.

First, the production and, to an even greater extent, consumption of renewable electricity would need not to depend on materials (steel, cement, silicon, plastics, etc.) that themselves require fossil fuels to be extracted, manufactured, processed, traded, and brought into service. This is a profound challenge. Each of those stages (manufacturing, processing, international trade, putting into service) implies the generation of emissions and in many cases other forms of pollution. According to recent calculations, the construction of a renewable energy production infrastructure on a global scale would ultimately generate a relatively small amount of CO_2, around 50 Gt to manufacture solar panels and wind turbines as well as the materials they are made of — clearly a worthwhile investment from a decarbonization perspective. The issue lies instead with downstream trade and uses (the goods, services and infrastructures powered by low-carbon electricity), whose material composition depends on fossil fuels and will, unless one makes exceptionally heroic assumptions about future technological change that are at odds with sound risk management principles, continue to do so for a long time to come.

Second, there is evidence that embedded emissions and materials could lead to the perpetuation of large energy rents. Tong et al. (2019) find that, if operated as historically, existing fossil fuel energy infrastructure would cumulatively emit about 658 gigatonnes (Gt) of CO_2 (with over half of the emissions expected to come from the electricity sector), and that proposed power plants would emit around a further 188 Gt of CO_2. As of 2019, these combined emissions represented around two-thirds of the remaining carbon budget to limit global warming to less than 2°C. As of 2022, updated estimates of committed CO_2 emissions from existing and proposed energy infrastructures had risen to around 680 Gt and 129 Gt, respectively.[25]

A notable source of energy rents is energy variability, which occurs not only in EMDEs and AEs[26] but also in low- and lower-middle-income countries, where "microgrids" combine solar panels, hydropower, batteries and often diesel generators. Although the share of solar power in total primary energy has risen sharply in recent years, the number of diesel generators in these mini-grids continued to grow between 2018 and 2024. In transport, the electrification of the vehicle fleet includes a significant share of hybrid vehicles, which combine batteries and combustion engines. In China, automobile manufacturer BYD now sells more hybrid cars than pure EVs. Worldwide, sales of hybrid vehicles are almost as high as those of EVs (at 10 and 12 percent of total global sales, respectively).

To be sure, a lower-carbon development path appears to be achievable. The fact that emissions appear to have plateaued over the past 18 months in China is notable (Myllyvirta 2025). It could certainly portend a future in which many developing countries decarbonize their power and other key sectors – with support from FDI in low-carbon sectors from China, as has taken place since 2022 (Xue and Larsen 2025). From a structural standpoint, if China were to become the global economy's new dominant pole, its approach to decarbonization (involving rapid, large-scale deployment of low-carbon technologies) could induce a lower-carbon global growth regime. Against the backdrop of a (possible) earlier-than-expected global population decline, this could lead to a sustained decline in global emissions. However, the emergence of this role would unfold over several decades. Equally important, China's emissions profile should be put into perspective, as the carbon intensity of the economy starts from a very high level today – roughly on par with that of Saudi Arabia.

Interpretation

In this section, we attempt to make sense of the evidence presented in Section 1 from an economic perspective. As in Section 1, we focus on the past, present, and future of embedded emissions and materials.

Past

[25] These updated estimates were shared bilaterally by the corresponding authors.

[26] See the discussion about China on p. 16.

Energy history is dominated by narratives emphasizing relative dynamics; these narratives therefore overlook quantity dynamics that are very different. Energy historians describe industrialization in the 19th century as an energy transition, with wood losing out to coal, which took hold in England in the 18th century and in other industrial countries in the mid-19th century. This way of looking at things is based on a relative view of energies. Indeed, compared to coal, fuelwood seems to be of little importance in most industrial countries at the end of the 19th century.[27]

In line with the focus on relative dynamics, the history of energy is often presented as a series of transitions. Books on the history of energy tend to follow a familiar chronological narrative: early chapters cover muscle power, wood, and water in the pre-industrial era; the 19th century centers on coal and steam; later sections focus on oil, electricity, and nuclear power.[28] This structure reflects a common bias in the history of technology – focusing on what is new in each epoch – that Edgerton (2008) has rightly criticized.

As a result, significant yet less celebrated developments are overlooked: the growth of renewables in the 19th century, the growth of biomass and muscle power into the 20th century, and the rapid expansion of coal since 2000. This transition-centric framework is so deeply embedded that even widely-cited references in energy history, like Kander et al. (2013, pp. 251-256), contain problematic claims. For instance, the book describes oil and electricity as distinct "energy transitions," despite the fact that electricity often increases coal consumption, and oil does not necessarily displace it (Kander et al. 2013). Likewise, Vaclav Smil frequently warns of the immense challenge posed by shifting away from fossil fuels within a few decades. Yet, his historical accounts nonetheless adhere to the conventional narrative of progress through successive energy transitions (see Smil 2010; and Smil 2017, pp. 228, 233, 289, 385-8, 395-7).

Another key historical aspect of energy and materials dynamics is "technological sprawl." The latter is a constant feature of the history of technology. Efficiency gains lead not only to the increased use of a technology (the Jevons paradox) but also to its application to a wide range of other technologies, enabling the development and marketing of new products. For instance, electric motors foreshadowed what took place later with computers. In the early 20th century, electric motors were rapidly diffused throughout the industrial world, as they were much more efficient than steam engines, easier to use, and enabled factory space rationalization. Their low cost and small size led to their diffusion in industries that had never used engines. Their cleanliness facilitated large-scale deployment in households (in electric appliances) in the second half of the 20th century. Their diffusion has recently been supported by more efficient batteries. While there are no statistics on the aggregate number of electric motors globally, it can be estimated in the tens of billions as of 2025. This number is growing very rapidly – some projections put the production of new electric motors at around one billion by 2023 (Associated Press 2018). They accounted for around 45 percent of electricity consumption in 2011 (Waide and Brunner 2011), generating around 6 Gt of CO_2, twice as much as global emissions a century earlier, when manufacturers used (much less efficient) steam engines.

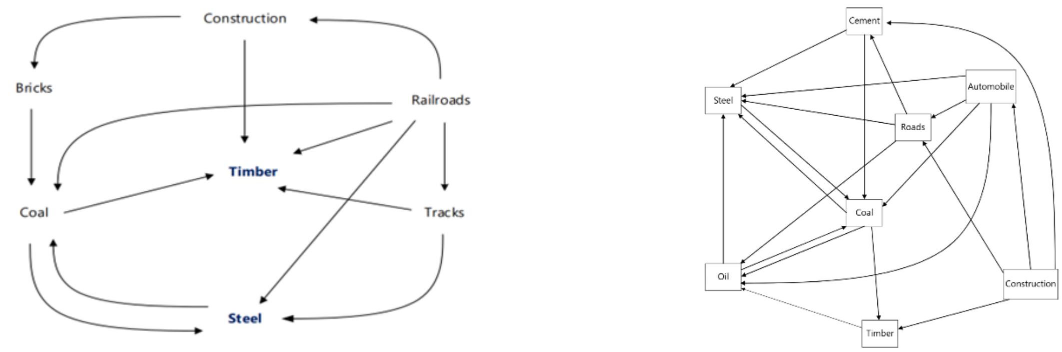
Most historians choose to focus on a single energy source – coal, oil, wood, or renewables – but these "mono-energy" approaches are problematic. They tend to isolate one form of energy from others and from the materials required to harness them. Understanding the history of coal, for example, requires paying attention to timber, which was used for the extraction of coal (Figure 8). Similarly, the rise of oil in the 20th century cannot be understood without considering the critical role played by concrete and steel, and thus coal.

[27] According to data provided by historian Paul Warde, and used by Anthony Wrigley in a well-known chart, wood no longer played any role in the English energy mix from the mid-19th century onwards (Warde 2007, p. 69 and Appendix 2; Wrigley 2011, p. 37).

[28] See for instance: Podobnik (2005); Crosby (2006); Weissenbacher (2009); Sorensen (2012); Deiber et al. (2013); Rhodes (2018); Penna (2021); Black (2022); and Black (2023).

Figure 8. Embedded Emissions and Materials in 1850 and 1930

1. Embedded Emissions and Materials in 1850. 2. Embedded Emissions and Materials in 1930.



Source: Authors.
Note: The direction of the arrows indicates a stimulating effect on demand.

To say that there was no energy transition in the past is not to say that nothing changed, but rather that the change was not the one described in the standard history of energy and industrialization. It is not enough to say that wood "resisted" the advance of coal, or that coal consumption simply added to wood. Wood consumption soared not in spite of coal, but because of it. In 1900, railways in the U.S. consumed around 10 percent of domestic lumber. In the 1950s, in Europe, between 2 and 4 cubic meters of wood were needed per 100 tonnes of coal. In the 1930s, around 7 tonnes of coal were needed to produce a car. This is an important point, as it touches on the interpretation of the material dynamics of industrialization. While industrialization is generally approached from the angle of energy transition, it must instead be understood as a process of amplification, of symbiotic expansion of all materials. In other words, it must be understood as a process of deepening *embeddedness* of emissions and materials in the global economy (see Figure 8).

This history of accumulation and symbiosis begs the question: where did the concept of "energy transition" originate? Until the 1970s, the term was hardly used. Experts expected shifts in the composition of the energy mix and a possible stabilization of total consumption, but not the outright disappearance of entire energy sources. Conservationists, in fact, were more concerned with the long-term depletion of coal reserves than with replacing them. Their time horizons stretched across centuries. In 1915, Herbert Jevons – the son of the economist William Stanley Jevons (the author of *The Coal Question* [1865], to which the Jevons Paradox traces its origins) – predicted that British coal use would peak around 2100 at 400 million tonnes per year, and then stabilize at 300 million tonnes until 2200. The notion of energy transition was foreign to their thinking.

The term "energy transition" itself originally comes from nuclear physics, and was later adopted by advocates of nuclear power, particularly proponents of fast breeder reactors. These reactors offered a vision of boundless energy and a solution to fossil fuel depletion. From this vision emerged the term "energy transition" – a gradual, centuries-long evolution from finite to almost infinite energy. The 1970s energy crisis popularized the term "energy transition" even further. By then, "energy transition" had become a flexible slogan, accommodating a variety of visions: from nuclear technological-fixes to coal revival, solar utopias, steady-state economies, and environmentalist critiques.

Despite the significant differences between these origins and the nature of the challenge posed by climate change, this narrative was repurposed for the climate crisis. Born out of mid-20th-century anxieties about fossil fuel scarcity and technological promise, the energy transition concept proved remarkably malleable in its uses by economists, other social scientists and policymakers. When global warming emerged as a political issue in the late 1970s, the same economists and institutions that had navigated the energy crisis retooled their frameworks to address it.

The continuity is striking, but so is the mismatch. The climate challenge arguably requires an entirely new kind of transformation: not a slow evolution of energy and material systems over centuries, but the rapid and total phaseout of fossil fuels within decades, not driven by scarcity, but by the need to limit atmospheric carbon despite the abundance and relatively low price of fossil fuels. The difference between these two crises – energy scarcity and climate destabilization – is profound, yet the same intellectual compass guides both. Modern climate economics largely harkens back to thinking from the 1970s on the energy crisis. The main policy proposal to stem from climate economics, namely carbon pricing, is specifically designed to simulate the effect of a gradual increase in the scarcity and the price of fossil fuels on the behavior of economic actors.

Present

The assessment of lifecycle emissions contrasts with the clear-cut dichotomy between "green" and "brown" technologies (or between "green" and fossil capitalism) that is conventionally used in the literature on the energy transition (see, e.g., the discussion on "green technologies" and "green energy" in the survey paper by Bilal and Stock 2025, and the discussion of "green products," "green supply chains," "green innovation" and "green sectors" in Weber et al. 2025).

In other words, it is implausible that renewables could competitively produce, on a global scale and by 2050, the "pillars of industrial civilization" (Smil 2022), i.e. steel, cement, plastics and fertilizers, on which contemporary infrastructure, machinery, logistics and agriculture depend. If we consider the current pillars of industrial societies (i.e., steel, cement, plastics, fertilizers) as a given, then renewables are highly unlikely to be able to competitively produce the materials that are foundational to modern economies, on a global scale, by 2050.

Hypotheses about the Future

Building on the facts on energy transition vs. energy addition and growing embedded emissions and materials presented above, we formulate three hypotheses about the future.

First, "technological sprawl" is likely to persist. As discussed above, and as documented by Fix (2024), improvements in technical efficiency – including energy efficiency – have overwhelmingly been used, since the industrial revolution, to generate "technological sprawl" rather than conservation of materials and energy. Fix provides evidence concerning computing power: instead of enormous efficiency gains in computers being used for resource conservation, they were almost entirely used to catalyze technological sprawl – that is, to enable the diffusion of a wide range of technologies in consumption patterns, including a surge in the per-capita number of smartphones, tablets and other smart appliances, at least in high-income economies. Technological sprawl can be seen as a kind of "horizontal Jevons Paradox" effect – similarly to the standard distinction between horizontal (or structural) industrial policies, which apply to all sectors/firms, and vertical industrial policies, which target specific sectors/firms. There are indications that this horizontal Jevons Paradox effect will persist. For instance, in 2025, rapid growth in artificial intelligence induced sharp growth in data centers. Combined with growing power demand from electrification across transportation, manufacturing and households, this led to strong growth in gas demand, a shortage in gas turbines, and a switch to coal for power generation in many countries (Stapczynski et al. 2025).[29]

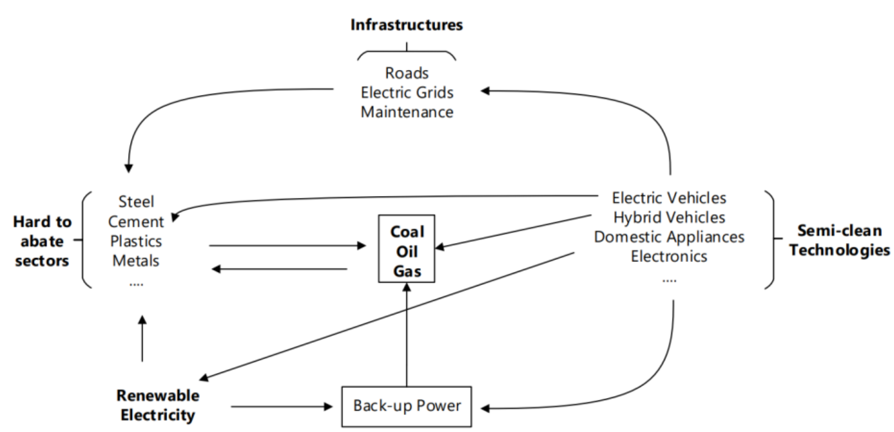
[29] There is preliminary evidence that partial decarbonization itself could paradoxically strengthen the GJP through economy-nature feedback effects. Specifically, some studies find that reduced sulfur dioxide emissions from ships, by reducing cooling from clouds, generates additional global warming of 0.2C per decade (Hansen et al. 2023). More evidence on this phenomenon is needed, however. Similarly, there is evidence that reduced sulfate emissions from decarbonization of land transportation (given co-emissions of anthropogenic aerosols and GHGs) adds to global warming (Samset et al. 2018). As action to decarbonize the economy grows, the induced reduction in sulfur emissions (mainly in the transport, industrial, energy and agriculture sectors) could increase solar radiation absorption, thereby strengthening the impact of the GJP on global warming by indirectly generating additional warming through partial decarbonization of some sectors.

Second, there will likely be upward pressure on global emissions from many highly carbon intensive adaptation investments. For instance, sea walls and irrigation systems require large quantities of concrete, air conditioning requires considerable energy and generates large amounts of powerful GHGs in the form of refrigerants (estimated at 3 percent of global emissions and 7 percent of global electricity consumption in 2024[30]). Likewise, the production of insulating building materials continues to generate significant emissions (see Grazieschi et al. 2021), and desalination of water is characterized by large energy needs and adverse environmental impacts that contribute to global warming.[31] There are also potentially adverse implications for emissions from the land-use changes required for adaptation (including reduced land areas for carbon sinks and emissions from land conversion). According to the IEA, the impacts of climate change contributed about half of the increase in global energy demand in 2024 (IEA 2025a), with space cooling being one of the leading drivers of rising electricity demand in buildings and of generation capacity additions to meet peak power demand. With environmental constraints on economic activity tightening, positive feedback loops between climate change and emissions are set to become stronger. Climate change itself will thus stymie global decarbonization.

Third, political economy factors are likely to continue to constrain climate change mitigation. A relatively slow pace of decarbonization, partly as a result of the GJP, reinforces channels (or creates new ones) that entrench fossil fuel production and consumption by supporting powerful vested interests. Of particular relevance are large corporations (e.g., ICE-centered automobile companies, fertilizer producers, state-owned and international fossil fuel companies).

Embedded emissions and materials can therefore be expected still to be very large in 2050. Figure 9 depicts the main drivers of embedded emissions and materials at a 2050 horizon, focusing on the energy and productive system and abstracting from climate change adaptation. As the diagram shows, it is easy to see how powerful feedback loops between so-called low- and high-carbon technologies and sectors could persist.

Figure 9. Embedded Emissions and Materials in 2050



Source: Authors.
Note: The direction of the arrows indicates a stimulating effect on demand.

[30] See Ritchie (2024). The IEA expects power demand to grow at 4 percent per year through 2027 (IEA 2025b).

[31] For instance, toxic brine generated by desalination adversely impacts marine habitats' ability to act as a carbon sink.

Theory: Energy Transition Framework vs. Generalized Jevons Paradox

Sections 1 and 2 presented contemporary and historical evidence on embedded emissions and the energy and material dynamics of the global economy, and on that basis it formulated hypotheses about the future. In this section, we first discuss implications of energy and material dynamics for the energy transition framework. We then connect the evidence from Sections 1 and 2 to the Jevons Paradox, augmenting it to introduce the concepts of energy symbiosis and Generalized Jevons Paradox. Finally, we provide some elements of formalization in climate and energy economics.

Limits of the Energy Transition Framework

We begin by identifying key implicit assumptions of the Energy Transition (ET) framework. Then, building on the evidence presented in Sections 1 and 2, we argue that these assumptions are not consistent with the data. The main takeaway is that evidence on the indirect and macro-scale impacts of technological change reveals a crucial difference between *technological* and *material* dynamics, which is not reflected in the ET framework.

An axiom of the ET theory is that energy and material dynamics are governed by *substitution* through the *diffusion of innovations*. In their survey of the economics literature on macroeconomic frameworks to analyze climate mitigation policies, Bilal and Stock (2025) identify three key strands of research: carbon pricing frameworks, innovation and technical progress, and factor market reallocation. A common theme across all strands is the assumption, modeling results or empirical evidence that emphasize the role of substitution from “dirty” to “green” energy in achieving mitigation. The authors note that “These estimates highlight the importance of substitution through technology, but also trade” (Bilal and Stock 2025, p. 16). Consistent with this analytical framework, the IEA’s influential *World Energy Outlook* argues that “deploying cost competitive clean energy technologies represents a lasting solution [...] for bringing down emissions” (IEA 2024, p. 3). This premise does not correspond to key features of energy and material dynamics. This is a fundamental problem because, as emphasized by Perrings (1987, pp. 8-9), a correspondence between axioms and key features of the real world is needed for theories based on deductive inference to yield practically relevant results.

The fact that there has never been an attempt to eliminate sources of energy does not mean it is impossible, but it calls for caution regarding societies’ ability to do so given complex interdependencies among energies and materials. Similarly, while the invention of, and large-scale substitution with, low-carbon materials is a theoretical possibility, the evidence and framework presented in this paper suggest that it is not a reliable pathway to decarbonization. For instance, even if commercially scalable low-carbon steel were invented, the complementarity between steel and carbon-intensive inputs (e.g., plastics in cars, new goods) would spur demand for materials, and thus fossil fuel consumption (e.g., to produce plastics, in this example). One possible outcome would feature new technologies that generally require less emission intensive inputs, which would help put global emissions on a downward trend but would not in and of itself generate rapid decarbonization.

While history does not provide analogies for decarbonization, industrial firms have sought to reduce fossil fuel use for over a hundred years. Before now, policies have never sought to induce a transition away from primary energy sources. However, although 20th-century industrial firms did not seek to reduce CO_2 emissions, they constantly sought to economize on fossil fuels, which represented very large costs in railroads, cement works, steelworks, and electricity production. In some cases, achievements were rapid. For example, high coal prices during World War I and advances in industrial electrification induced rapid efficiency gains between 1915 and 1930. In the U.S., rail freight reduced emissions per ton-kilometer by 30 percent, blast furnaces reduced the carbon intensity per ton of steel by 22 percent, and cement plants reduced the carbon intensity per ton of cement by 27 percent. The most significant progress was made in power plants, which divided carbon intensity per kWh by five between 1915 and 1930 (Yaworski 1938, Polakov 1933, Du Boff

1967). Replacing steam engines with electric motors drastically reduced the carbon intensity of industrial power. As a result, U.S. coal consumption fell after World War I. More generally, between 1900 and 1950, the power of all available machines in the U.S. was multiplied by 70, while CO_2 emissions were multiplied by only four (Historical Statistics of the United States, Colonial Times to 1957, Chapter S: Power).

The assumption that substitution dynamics are central is linked to another assumption: that *technological dynamics* drive changes in the consumption of materials. Another implicit assumption of the ET framework is that, just as the spread of the steam engine led coal to replace wood, so will the diffusion of renewable energy technologies lead to a substitution of fossil fuels with renewable energies. This can be seen in key papers on the economics of climate change mitigation, which implicitly or explicitly adopt the ET framework. In an influential paper, Acemoglu et al. (2012) distinguish between goods produced from "dirty" and "clean inputs," and find that with sufficient substitutability of inputs, "sustainable growth can be achieved with temporary taxes/subsidies that redirect innovation toward clean inputs."[32] Grubb (2013, p. 316) argues that "studies of historical transitions in energy emphasize that diffusion itself takes far more [time] still." He also argues that the "'Schumpeterian wave' that established the oil age, like other major energy system transitions, took around three-quarters of a century." Building on the Dynamic Integrated Climate-Economy model of Barrage and Nordhaus (2024), Fernández-Villaverde et al. (2025) argue that structural Integrated Assessment Models provide insights into "managing the green transition."[33] Similarly, Aghion et al. (2021, p. 173) view the challenge of decarbonizing the economy as that of designing a "transition to clean energies."[34]

Consistent with these assumptions, the economics literature on climate change mitigation assumes the existence of a clear-cut dichotomy between so-called "green" and "brown" technologies and "low-carbon" and "high-carbon" sectors. While to our knowledge there is no consensus on the definition of "green" technologies, Rodrik (2014) defines them as "production techniques that economize on exhaustible resources and emit fewer greenhouse gases." Other papers do not define the term: Juhász et al. (2024) simply mention "green technologies," while Hallegatte et al. (2013) mention "green sectors" and "green technologies."

The implicit assumptions on the role of substitution dynamics in global energy and material flows are not consistent with the evidence. As documented in Sections 1 and 2, energy and material dynamics exhibit growing *embeddedness* (and thus consumption) of emissions and materials, rather than energy and material *substitution* through technological diffusion (which would imply a decline, in absolute terms, in the consumption of key energies and materials). The global economy is characterized by an extension of embedded emissions and materials (Figures 3, 4, 5, 7). As a result, emissions have increased continuously since 1800, and higher energy efficiency (as measured by more dollars of output per kilogram of global emissions) has resulted in rising, not falling, emissions (Figures 1 and 2). The growing embeddedness of emissions and materials can be explained by the fact that, at the level of the world economy, different primary energies do not exhibit substitution dynamics but are instead deeply intertwined and interdependent. This ultimately results in an accumulation of primary energies and materials over time, in absolute terms, at the level of the world economy.

Likewise, the clear-cut dichotomy between "green" and "brown" technologies is not supported by material production and consumption patterns. As shown in Figure 10, while a simple and meaningful distinction can be made between high- and low-carbon industries in terms of final demand, high-carbon industries are nonetheless involved as inputs in the intermediate consumption stage. This pervasive entwinement of materials in the production of technologies challenges the clear-cut dichotomy between "green"

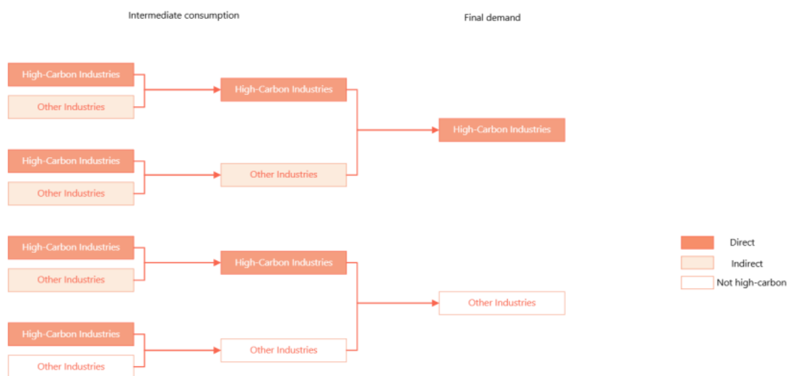
[32] Crucially, in their two-sector model of directed technical change, they assume a high degree of substitutability between two sectors that are defined based on whether they are "clean" or "dirty." One sector uses "dirty" machines and creates environmental degradation; in the other sector, profit-maximizing researchers build on previous innovations and direct their research to improving the quality of machines. Pottier et al. (2014) criticized this framework as an illustration of the "pitfalls of incorporeal visions of the economy."

[33] They use a model that produces gross output using a Cobb-Douglas technology with capital, total factor productivity, and labor, where capital is defined using an aggregate measure of capital is used – thereby making technology exogenous.

[34] These authors argue that state intervention is needed to "redirect firms to innovate in green technologies," and describe electric vehicles as a "nonpolluting good" (p. 182), despite EVs' non-trivial lifecycle emissions (especially taking into account related infrastructure needs) and broader ecological footprint.

and "brown" technologies. An example is electric vehicles, whose production requires the consumption of fossil fuels embodied in steel, plastic and other key materials.

Figure 10. Direct and Indirect Industry Linkages Challenge the Green/Brown Industry Dichotomy



Source: Authors; adapted from Magacho et al. (2023).

Key Concepts

Given the limitations of the ET framework and the dichotomy between "green"/"brown" technologies highlighted above, we propose an alternative framework for understanding global energy and material dynamics.

Our starting point is that energy and material dynamics encompass an uncertainty paradigm. Drawing on Weitzman (2009, 2011), we take it as axiomatic that economic dynamics face deep structural uncertainty over the "unknown unknowns" of environmental phenomena, as well as their feedback effects on the economy. This deep uncertainty implies that there is "unlimited downside liability on planetary damages" (Weitzman 2011). In contrast, the ET framework focuses on risks. For instance, Bilal and Stock (2025) define climate change as encompassing a series of risks, including sea level rise. However, as noted by Weitzman (2009), the probability of climate damages causing a disastrous collapse in planetary welfare is not objectively knowable. In our view, this justifies using an uncertainty paradigm in developing economic concepts to understand the dynamics of energy and material flows. Given unlimited planetary downside entailed by deep uncertainty, the precautionary principle points to an important ethical reason for the need to decarbonize the economy as fast as possible to avert catastrophic planetary outcomes. It also highlights the need to better understand interactions between the economy and biophysical factors.

Placing our analysis within an uncertainty paradigm, we introduce two core concepts: energy symbiosis and the Generalized Jevons Paradox, which builds on the Jevons Paradox.

Jevons Paradox

In *The Coal Question* (Jevons 1865), Stanley Jevons observed that the technological developments that had led to greater efficiency in coal use had counterintuitively increased rather than decreased coal use across a range of sectors. The conclusion Jevons drew was that technological development is not a reliable strategy for reducing natural resource use. He instead posited a causal link between increased energy efficiency of a technology and higher demand for, and consumption of, the services rendered by that technology, and thus higher investment in the (relatively) lower energy intensive good or service. Another causal channel that the literature identifies is an income effect that operates through aggregate demand: higher efficiency generally reduces the cost of some goods or services and therefore increases real incomes, which raises demand and thus economic growth, and ultimately increases process-induced resource use given the carbon content of existing goods and services.

The Jevons Paradox is the paradoxical observation that saving energy ultimately leads to more energy consumption (Khazzoom 1980). In the Jevons Paradox, more technological efficiency lowers the price of an energy source – in the historical case, coal. This initially lowers demand for coal, but ultimately increases it through direct effects (more investment/consumption in sectors that benefit from energy savings) and indirect effects (external output effects, such as higher demand for iron, steel and coal, higher demand for capital and labor; and substitution effects: higher demand for energy-intensive goods and services, relative decrease in the demand for non-commercial energy goods and services, such as sailing ships) (Madureira 2012).

There is empirical support for this causal chain, which is also known as the energy efficiency paradox. Rausch and Schwerin (2018) document a strong rebound effect in the US economy between 1960 and 2011 (see also Sorrell et al. 2009, Magee and Devezas 2017, Brockway et al. 2021).[35] The economic channels behind the Jevons Paradox relate to prices: higher energy efficiency lowers both energy prices, which raises profitability in energy-intensive industries, leading to reallocation of capital to those industries, and consumer prices, which raises aggregate demand and therefore energy demand (Madureira 2012, p. 407). This is consistent with Fouquet (2014), who finds for the United Kingdom that income elasticities over the last two centuries generally followed an inverse U-shape curve, and price elasticities generally followed a U-shape curve. He concludes that, at least for the next few decades, market forces and long-run trends associated with population and economic growth, price and income elasticities, and energy transitions are likely to push global energy service demand and energy consumption upward, implying rising emissions.

Energy Symbiosis

Energy symbiosis is different from the classic rebound effect (and thus from the Jevons Paradox). The energy symbiosis effect describes the network of material interdependencies that exist among technologies. In other words, energy symbiosis corresponds to emissions and materials that are embedded in a product or material. In the widely studied case of insulation, the rebound effect means that the reduction in energy consumption to heat homes will be smaller than that which could have been expected given the gains in efficiency. The symbiotic effect describes the growth in demand for the materials needed to produce insulation: resins, glass wool, polyurethane foam and, ultimately, fossil fuels.

Energy symbiosis corresponds to the interdependencies in the energy and material structure of the economy, observed over the long period, driven by the persistence and addition of energy and material inputs into technologies. We argue that the energy transition is slowed or even prevented by the sum and combination of rebound effects and symbiotic effects. For a more detailed representation of the economic channels involved in energy symbiosis, see Annex Figure AIV.1.

Generalized Jevons Paradox

The positive relation between global energy/material efficiency and total consumption is an apparent paradox that is different from the Jevons Paradox and energy symbiosis. Indeed, the Jevons paradox is a microeconomic concept, even though some of the indirect effects related to the Jevons Paradox can occur at the macroeconomic level. Similarly, energy symbiosis occurs upstream of investment decisions, and therefore cannot explain on its own why there would be such a high correlation between energy/material efficiency and total energy/material use. We argue that the macroeconomic pattern that we document (see Figure 3) is explained by a broader, encompassing, phenomenon, which we call the Generalized Jevons Paradox.

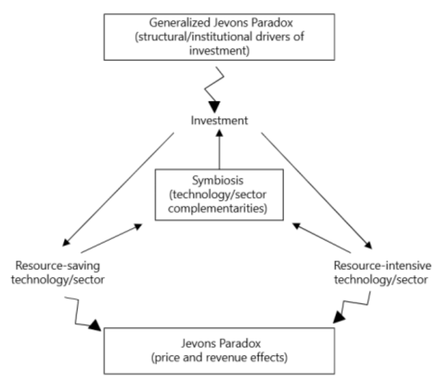
The Generalized Jevons Paradox (GJP) encompasses the direct and indirect energy/material demand effects of long-term energy and material interdependencies (or symbiosis), explained by institutional, economic and technical change causes. It adds a macroeconomic and long-term dimension to the Jevons Paradox, and it adds institutional and economic mechanisms to energy symbiosis. The GJP extends the Jevons Paradox by broadening the scope from a single industry to the global economy. The GJP synthesizes these effects. It expresses the fact that, historically, lower global carbon and material intensity has ultimately

[35] Heun et al. (2025) note that the concept of rebound effect appears to have been first introduced by Williams (1840).

led to more – or, at a minimum, not significantly lower – global emissions and material use. Another way of describing the GJP is the following: technical change that increases the GHG or material efficiency of the global economy (measured in dollars per tCO2e or kilogram) tends ultimately to lead to higher global GHG emissions and a greater material footprint – or, in any case, a decline in the former at a pace that is too slow to meet international environmental goals. This argument was also made by Polimeni et al. (2008).

The Generalized Jevons Paradox augments the Jevons Paradox and energy symbiosis by capturing political economy mechanisms that account for systemic rebound effects. The Jevons Paradox focuses on the microeconomic and macroeconomic effects resulting from efficiency gains through investments. Energy and material symbiosis focuses on the path dependency and technological complementarities arising in the long run in energy and material systems. However, describing how efficiency gains might lead to further resource intensive investments because of different technological (symbiosis) or economic (Jevons Paradox) reasons does not yield insights into the underlying mechanisms at play, nor does it explain structural or institutional bias towards resource intensive investments. This matters, as the historically observed technological complementarities that characterize energy symbiosis have their origins in investment dynamics. Similarly, the Jevons Paradox does not originate when a resource saving activity starts, but more upstream when the related investment decision is made. The Generalized Jevons Paradox focuses on the drivers of investment – i.e., their political economy. Figure 11 shows the articulation of these concepts.[36]

Figure 11. Articulation of Jevons Paradox, Symbiosis and Generalized Jevons Paradox



Sources: Authors.

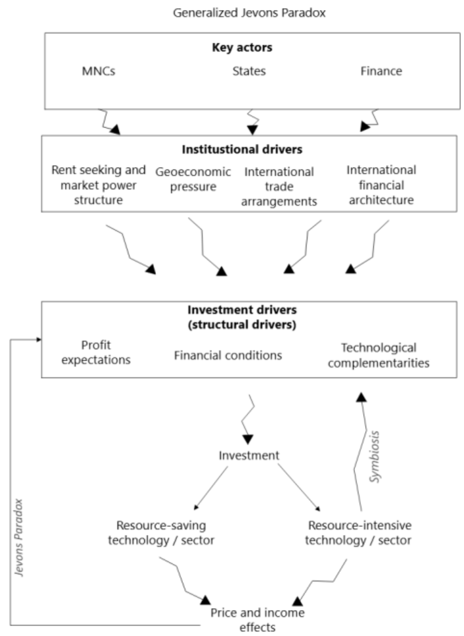
The Generalized Jevons Paradox focuses on the drivers of investment. Investment is crucial in determining economic dynamics and the resulting productive structure of the economy, and the latter has major implications for total energy and material consumption. Indeed, investment decisions shape the evolution of the productive structure over the long term through well-known mechanisms, notably path dependence and technological, infrastructure or policy lock-in, which itself largely results from switching costs, network effects, and institutional inertia.

We attempt to endogenize the GJP by identifying a political economy composed of three main actors: large companies/multinational corporations, states, and large financial actors (which we subsume under the "finance" heading). We hypothesize that, collectively, these actors influence institutional factors that underpin the GJP: (1) relative expected sectoral profitability, rent seeking, and market power; (2) geoeconomic pressures (i.e., political and geopolitical power); (3) international trade arrangements; and (4) the international financial architecture (Figure 12). More direct, structural, drivers of investment such as profit expectations, financing conditions and technological complementarities, are essentially determined by the institutional forms

[36] The charts presented in Figure 3, which form the empirical basis for the GJP, do not make any assumptions about the behavior of economic agents or social groups, which are evolving, have evolved in the past, and are likely to evolve in the future. The GJP framework describes institutional patterns that provide a frame for these possible future developments. This framework rejects the Lucas critique in the sense that, in the framework, the driving force behind economic dynamics is institutional, but it anchors the dynamics of symbiosis at the meso level.

taken by these four factors. While we discuss these actors separately for greater clarity, there is some overlap among them regarding their role in driving the GJP.[37]

Figure 12. Generalized Jevons Paradox: Key Actors and Institutional/Structural Drivers of Investment



Sources: Authors.

Multinational Corporations (MNCs)

One of the key objectives and powers of MNCs is to maintain high levels of profitability. In turn, expected profitability plays a key role in shaping investment decisions. Low levels of investment in renewable energy technologies in developed economies are in part attributed to relatively low expected profitability in these sectors.[38] The high levels of investment in some countries (e.g., China) are to a large extent associated with significant subsidies, which forced the diffusion and adoption of these technologies and allowed for a significant cost reduction (see Christophers 2023). However, large investment costs in these sectors and the relatively long-term profile of returns induce a lower profitability relative to fossil equivalents. This, in turn, reduces the commercial attractiveness of several low-carbon technologies even when these technologies have lower costs than their fossil-based equivalent (Box 1). A driver of the GJP is thus an asymmetry in the relative profitability of sectors that is negatively related to their potential role in decarbonization. These differences are partly due to market structure and business models.

There is also a qualitative reason for asymmetry in expected sectoral profitability: differences in terms of scarcity of resources and the inherent profitability of sectors. A key feature of a range of sectors that are crucial for decarbonization (renewable energy, shared and active mobility, new ways of providing services that are less resource intensive) is that they are not linked to raw materials or other resources that are scarce and can thus generate rents. Indeed, the supply of sunlight and of kinetic energy of wind is infinite, and the

[37] It could be argued that another key actor is consumers. Rising inequality puts pressure on consumption levels, which may become hard to sustain. This can induce risky lending to maintain firms' profitability. Ultimately, states may provide guarantees for such risky lending practices in the form of bailouts. We do not include consumers as part of the key actors, however, as their role is arguably secondary compared to the influence of large firms/multinational corporations, states, and large financial actors.

[38] Christophers (2023, p. 212) reports a range of estimates that indicate that, in recent years and in most countries, internal rates of returns for solar and wind energy have been low (around 5 to 8.5 percent) and volatile. By contrast, profitability in the oil and gas sector is relatively higher (Christophers 2023, p. 216-18), and median corporate profitability has been around 10 percent in most regions since 2015 (IMF 2025b, p. 9).

(human) energy needed for active mobility is vast. The profitability of sectors involved in shared or active mobility (e.g., public transit, cycling) is also limited by virtue of the nature of the activity (e.g., walking) and/or structure of the industry (e.g., bicycles).[39] Likewise, many innovations that can reduce the resource intensity of a good, service or system (such as "frugal innovation") have an inherently limited ability to generate profits, since they entail doing more with less thanks largely to new, ingenious ways of producing and consuming that are not patentable and more generally not conducive to the creation of new property rights.

Box 1. Expected Profitability and Investment in the Solar Industry

The solar industry has low barriers to entry and is thus highly competitive – making expected profitability relatively low and uncertain. Its business model – developing and operating solar plants – features the upfront sale of infrastructure (for developing solar plants), highly volatile spot electricity prices – with negative electricity prices being mainly associated with renewables – and therefore low expected profitability.[1]

By contrast, the oil and gas industry features high barriers to entry and is oligopolistic, its business model involves continued sales of scarce raw materials, and it is highly profitable (Christophers 2023, p. 218). The relative profitability of high- versus low-carbon energies is also affected by policy interest rates because low-carbon technologies have a much higher ratio of capital expenditure to operational expenditure than fossil fuels, and hence much greater sensitivity to the cost of capital.

This differential is amplified by the fact that the oil and gas industry has accumulated very large profits in recent years, partly because of the energy crisis of 2022-2023, and therefore relies relatively little on external financing.

The objective of maintaining capital accumulation at a minimum rate – firms' profitability imperative – plays an important role in both financing and investment decisions in countries of all income levels. This generates capital accumulation pressures across sectors and countries. There is evidence that expected profitability plays a more important role than costs in determining investment in renewable energy, constraining its deployment (Christophers 2023, pp. 212-13).

[1] Christophers (2023), p. 223-226. Christophers notes that there is a paradoxical "cannibalization effect" in electricity markets whereby renewable electricity generators "undermine the conditions of their own future viability and growth precisely by virtue of their own success in displacing more expensive, conventional generating technologies and thereby reducing the price of electricity." The low and uncertain profitability of the solar industry is reflected in the actions taken by the Chinese government in September 2025 to address a surge in losses in the industry (White et al. 2025).

A large-scale sign of the relevance of sectoral profitability for decarbonization is the economic features of the two planetary boundaries that have not been breached. Out of nine planetary boundaries beyond which humanity is no longer in a safe operating space, only two have not been breached: increased atmospheric aerosol loading and stratospheric ozone depletion (Stockholm Resilience Centre 2025). A distinctive feature of these boundaries is that they are the only ones for which there existed profitable alternatives to the technologies that were driving the move toward breaching a planetary boundary. In the case of aerosol loading, profitable alternative technologies emerged gradually over the last 40 years and are only now driving improvements in the global trend – with a likely warming effect on the global climate, however, as discussed below. In the case of ozone depletion, the gases that drive it were used in a small number of industries (air conditioning, refrigeration, propellants), and profitable substitution products were available in the

[39] According to IPCC (2022), "demand-side mitigation encompasses changes in infrastructure use, end-use technology adoption, and socio-cultural and behavioural change. Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end use sectors by 40-70% by 2050 compared to baseline scenarios [...]. Demand side mitigation response options are consistent with improving basic wellbeing for all."

1980s, limiting substitution costs.[40] At an aggregate (planetary) level, these patterns are consistent with the hypothesis that expected profitability is a key determinant of the ability to limit global environmental impacts through large-scale technological substitution.

One way for companies to orient the profitability of investments is through rent seeking and market power. Rent seeking is exerted when a company or financial institution is able to impose revenue extraction beyond the levels it would reach in a competitive environment (or the marginal return on capital). Rent seeking is not always problematic; in some cases it can incentivize innovation by raising the expected profits stemming from this innovation. But when the innovation is successful, the rent-seeking behavior can morph into very large market power. The market concentration of a given sector is a good indication of undue profits. The supply of coal, oil and gas is concentrated among a small number of producers, in terms of both countries (Kim et al. 2025) and firms (Draghi 2024, p. 39). The top three producing countries account for about 65 percent, 50 percent, and 70 percent of the global production of agriculture, energy, and minerals (IMF 2023, p. 74). While the prices of minerals could increase significantly in global decarbonization scenarios because of concentrated supply and supply chains and geoeconomic fragmentation (IMF 2023, p. 83), the near-universal availability of sunlight and kinetic wind energy creates a structural constraint for the profitability of renewable energy.

In the local political economy of EMDEs, large importing companies often constitute the most powerful vested interests against decarbonizing the productive structure, as the goods and services that they import (e.g., internal combustion engine vehicles, gasoline, agricultural products) have large – and very hard or, in some cases, impossible to abate – carbon/emission footprints.

States

States play an important role in shaping the institutional drivers of the GJP. Governments are increasingly resorting to geoeconomic pressures to keep the profitability of their domestic and foreign investments. Geoeconomics has been defined as "an area of study of economics and political science that focuses on how governments use their country's economic strength to exert influence on foreign entities" (Clayton et al. 2025). A related phenomenon is geoeconomic fragmentation, which has been defined as "a policy-driven reversal of global economic integration, guided by strategic considerations such as national security, sovereignty, autonomy, or economic rivalry" (Weber et al. 2025). By resorting to geoeconomic pressures, governments tend to play a decisive role in the profitability of their domestic and multinational companies. Some smaller countries can also benefit from these fragmentation trends by playing the role of gates between geopolitically opposed blocks. For instance, Xue and Larsen (2025) report that, since 2022, China's low-carbon technology foreign direct investments (in batteries, solar, wind, new energy vehicles, green hydrogen) have amounted to over US$220 billion in 54 countries.

Military spending is a further source of profits across a range of sectors, and a potential (partial) solution to overproduction. Military spending more than doubled between 2000 and 2021, rising from around US$1 trillion to US$2.1 trillion per year. It grew by close to 30 percent between 2021 and 2024, reaching $US 2.7 trillion in 2024 (Liang et al. 2025). The EU's ReArm Europe program, launched in March 2025, implies an increase in military spending of around $US765 billion by 2029. So-called military Keynesianism is a potential source of aggregate demand in the face of slowing growth. At the same time, military institutions have historically been a major contributor to military and civilian technology, both of which have been carbon intensive (Edgerton 2008, Crawford 2022). If it were a country, the defense industry would be the fourth largest global emitter. Geopolitical competition could thus, through military dynamism, increase the emission intensity of structural economic change. This is another GJP driver, especially to the extent that military spending crowds out spending that has a lower environmental footprint, such as social spending.

Private corporations have access to powerful, state-backed legal instruments to entrench their interests, or what Pistor (2025) calls "legal subsidies." As noted by Pistor (2025 p. 2), the law – with the

[40] See Pottier (2020) for a discussion of the main factors behind the large-scale substitution that enabled the phasing out of chlorofluorocarbons, in turn driving the reversal of stratospheric ozone depletion.

backing of powerful states – has prioritized private interests in three ways: by giving the power to private actors to shape the law; by giving them access to centralized means of coercion to enforce their rights; and by "tolerating legal arbitrage as an expression of autonomy even when this comes at the expense of the rights of others." Specific legal instruments that help entrench private interests include regional and bilateral investment treaties, as well as various legal modules – mainly property rights and collateral, contract, trust, corporate and bankruptcy law (Pistor 2019). An example is the Investor State Dispute Settlement system, a legally binding international treaty that allows foreign investors to bring a case for damages against a host state to protect investments. This can expose governments to legal action for breach of protection when they seek to implement regulatory measures. These legal instruments provide ways to entrench private interests, and can thus reinforce the GJP by helping secure the profitability of emission-intensive investments.

Power relations inherent in international trade also contribute to shaping the investment strategies of firms and countries. The trade position of a country quite often influences its own internal political economy, with key exporting sectors in a position to lobby the government to keep their exporting profits, and the government unwilling to embark in the unpopular move to substitute for the imports (Olson 1965, Frieden and Rogowski 1996, Rodrik 2018).[41] For most world trade, the predictability and stability generated by the multilateral trading system is fading because of political and geopolitical developments (Wolff 2025). This has resulted in the proliferation of ad hoc bilateral trade arrangements that reflect power relations between countries. Environmental considerations have been absent from trade agreements, except for the EU Carbon Border Adjustment Mechanism (Magacho et al. 2023). In fact, the guiding principle behind trade rules has tended to be economic efficiency, contributing to a large negative environmental bias of trade policy.[42] Profits are often secured against the will of countries to strengthen domestic environmental policies, with the ISDS being a key legal enforcement mechanism. It should be noted that the contribution of global trade to crossing planetary boundaries goes well beyond narrow environmental indicators of trade's footprint (see Annex III).

Finance

Finance plays a key role in determining investment decisions. Financial power affects investment through the creation, trading and enforcement of financial claims (Braun and Kodenbrock 2023). Banks play a crucial role through their role as creators of the majority of money in the modern economy (McLeay et al. 2014), and the non-bank financial sector also uses leverage power extensively (BIS 2024). Under bailout expectations, firms may engage in correlated behavior and large investment in carbon-intensive sectors (Stern and Stiglitz 2021), as discussed below. For instance, the short-term profit expectations of financial institutions supported investment in oil and gas and reduced investment in renewables in the 2022 energy crisis (Christophers 2022).

The interplay between states and financial actors thus affects investment choices. Financial conditions, which matter for investment choices, are affected by monetary policy, prudential policies, financial regulation and oversight by central banks, financial supervisors and central governments, exchange rate dynamics and policies, and the international monetary and financial architecture. Central banks and financial supervision and regulation frameworks were designed in periods of history when reducing fossil fuel use and addressing climate-related financial stability issues were not part of these institutions' and frameworks' mandate and objectives, respectively. While some central bank mandates exhibit a certain degree of plasticity (Scialom 2022), this institutional history contributes to shaping investment choices. As financial supervisors, central banks are in charge of ensuring adequate risk management by the institutions they supervise. As a result, considering their potential role in shifting profit expectations with respect to the emission intensity of economic activities is not part of their mandate. Some central banks have started indirectly to take the carbon intensity of assets into account. For instance, the ECB has taken steps to incorporate climate risks into its collateral

[41] One framework, building on the so-called specific factors (or Ricardo-Viner) approach, suggests that it is not a country's factor endowments but the specificity of a given industry's human and physical capital, and its position in world trade and payments, that predicts the likely pressure for or against trade liberalization (Frieden and Rogowski 1996, p. 38).

[42] Copeland et al. (2022) and Shapiro (2021) identify five stylized facts on the relationship between trade and the environment: (i) polluting industries are more exposed to trade; (ii) there is a negative environmental bias in trade policy; (iii) polluting industries tend to be located upstream in value chains; (iv) carbon emissions embedded in products that are internationally traded account for a fourth to a third of global emissions; (v) advanced economies are increasingly outsourcing greenhouse gas emissions.

framework (ECB 2025) (Schnabel 2020, see also NGFS 2024a, FSB 2025). However, regulators generally remain guarded in assessing their own impact on investment.[43]

Relatedly, central bank actions influence the relative expected profitability of different industries – especially during financial crises. Major central bank asset purchases to support the economy during crises operate through price and signaling channels. This can shift the structure of market prices across jurisdictions by supporting firms' debt. Some actions in the recent past have consisted in acting as a price-insensitive buyer and supporting companies with low creditworthiness (see Blinder 2022 on central bank purchases of high-yield corporate bonds in the secondary market in 2020). While not geared toward fossil fuel producers or carbon-intensive firms, central bank asset purchases targeting firms whose Scope 1, 2 or 3 emissions are high (i.e., most firms, reflecting the carbon-intensive nature of the real economy) that lost creditworthiness sends a signal to financial markets that indirectly supports high-carbon economic activities. While preliminary, some estimates (Espagne et al. 2023) suggest that the implied global temperature rise of purchases made under crisis-era asset purchase programs of two major central banks during the COVID-19 crisis stood at 2.3°C to 3.1°C, indicating a high degree of carbon intensity. Finance, interacting with the state, thus drives the GJP by shaping the relative profitability expectations in favor of the existing productive structure.

Finance also affects investment through its influence on corporate governance. Since the 1980s, firms in developed countries have established strict investment project selection criteria influenced by financial norms that have raised profitability requirements (Lazonick and O'Sullivan 2000). There is also evidence that financialization has caused an increase in the cost of financial capital because of increased profitability requirements (Cordonnier et al. 2019). Moreover, there is a connection, across advanced economies, between financial systems, the characteristics of industries, and the growth and investment of industries (Carlin and Mayer 2003). Taken together, these findings point to how finance also drives the GJP by shaping expected profitability, thereby supporting investment in carbon-intensive but relatively more profitable sectors.

Policies can – and often should – play a central role in shaping and/or changing the institutional drivers of the GJP. As a result, interdependencies can evolve over time for reasons that go beyond technological innovations. In other words, at least to a certain extent, policies can contribute to determining the boundary between the ET and GJP as the framework of reference.

Elements of Formalization

We provide preliminary elements of formalization to incorporate the Generalized Jevons Paradox (GJP) into climate, energy and resource economics.[44] The empirical evidence presented in Section 1, of which we attempted to make sense in Section 2 and through the GJP concept developed in this section, challenges key assumptions in the standard approach to modeling interactions between technical change, growth, and environmental constraints. We focus on one such key assumption: the relatively high substitutability among inputs. We consider the model developed in Acemoglu et al. (2012), as it is widely cited and highly influential in the economics literature on the link between technological change, economic growth, and climate change.

A key implication of our paper is that the GJP does not depend on the evolution of the cost of individual energy sources or technologies, or on the carbon intensity of the economy. In fact, declines in the cost of low-carbon technologies (notably solar and wind) often lead to greater use of high-carbon energies (such as oil) by contributing to lower energy costs and therefore supporting aggregate demand, and by increasing the flexibility of technological systems. As noted in Section 1 (Figure 2), the evidence shows that low-carbon and high-carbon energies have grown in tandem at the level of the world energy system.

In economic terms, the GJP is thus reflected in an elasticity of substitution between so-called "clean" and "dirty" energies that is close to zero at the level of the world energy system. This can be illustrated

[43] See Oman et al. (2024) for an overview of these policy debates.

[44] Annex V provides additional elements of formalization from the perspective of the Kaya identity.

using the framework developed in Acemoglu et al. (2012), where there is a single final good, produced competitively using “clean” and “dirty” inputs, Y_c and Y_d, according to the aggregate production function:

$$Y_t = (Y_{ct}^{(\varepsilon-1)/\varepsilon} + Y_{dt}^{(\varepsilon-1)/\varepsilon})^{\varepsilon/(\varepsilon-1)}$$

where $\varepsilon \in (0, +\infty)$ is the elasticity of substitution between the two sectors.

The GJP implies that the two sectors are complements, and therefore that $\varepsilon < 1$. This contrasts with the key elasticity assumption made by Acemoglu et al. (2012), who argue that “the case of substitutes $\varepsilon > 1$ (in fact, an elasticity of substitution significantly greater than 1) appears as the more empirically relevant benchmark, since we would expect successful clean technologies to substitute for the functions of dirty technologies.”

Crucially, the evidence does not support the claim in Acemoglu et al. (2012) that an elasticity of substitution significantly greater than 1 is more empirically relevant. In fact, there is strong empirical support for a *low* elasticity of substitution. The meta-analysis conducted by Labandeira et al. (2017) finds that, on average, the literature has estimated short- and long-term price elasticities of energy demand of −0.21 (ranging from −0.29 to −0.02) and −0.61 (ranging from −0.77 to −0.19), respectively. This is likely clearer if calculating elasticities using market size in physical terms (i.e., EJ of primary energy consumption) rather than market share. Meta-analyses by Espey (1998) and Goodwin et al. (2004) find that the price elasticity of gasoline is between –0.6 and –0.3, implying that $\varepsilon < 1$ (Pottier 2014, p. 65). It is noteworthy that, in the framework developed by Acemoglu et al. (2012), two sectors are (gross) complements when $\varepsilon < 1$, and that when the two sectors are complementary, the only way to avoid an environmental disaster is to stop long-run economic growth (Acemoglu et al. 2012, pp. 135, 144).

Two caveats should be noted. First, as stressed by Pottier et al. (2014), aggregating quantities of primary energy depending on their “clean” or “dirty” nature and studying the elasticity of substitution between them, as done in Acemoglu et al. (2012), is hardly meaningful from a technical perspective. Indeed, there is significant heterogeneity in the efficiency of transformation channels between primary and final energy and in energy accounting conventions to build energy balances. Frondel and Schmidt (2002) also highlight the difficulty of obtaining meaningful estimates of elasticities of substitution between energies and other factors of production. This work also raises fundamental questions on the aggregate production itself, as argued among others by Galbraith and Chen (see footnote 12, p. 8). Second, food-system and biofuel emissions are very hard to abate yet often ignored or not explicitly modeled in economic models.[45]

These insights add a new dimension to the strong sustainability paradigm, or non-substitutability paradigm (Neumayer 2025; Godin et al. 2022). This paradigm takes a cautious view on large-scale substitution among different resources. This view is summarized by Ayres (2007), who reviews the literature and concludes that there is more support for strong sustainability than (near-) unlimited substitution. The empirical evidence on embedded emissions and materials and the Generalized Jevons Paradox add a new dimension to the strong sustainability paradigm by extending the limited substitutability hypothesis through material interdependencies.

Summing up this section’s arguments, there are key differences in how the ET framework and the GJP conceptualize energy and material dynamics. Tables 1 and 2 summarize these differences along technical, institutional and ethical dimensions. Although we do not discuss this, some elements in these dimensions reflect differences in the worldviews and values that underpin each framework.

[45] However, there is a global research community working on improving the representation of agriculture-related emissions in economic models (see https://agmip.org/).

Table 1. Main Differences Between the Energy Transition Framework and Generalized Jevons Paradox

Dimension	**Energy Transition Framework**	**Generalized Jevons Paradox**
Technical	Energy transition via substitution; clean vs. dirty technology; risk paradigm	Energy symbiosis with additive dynamics; dirty vs. semi-clean technology; uncertainty paradigm
Institutional	Net-zero goals via technology diffusion and carbon pricing	Emphasis on global/sectoral/groups energy and material demand, role of institutions in investment choices, welfare trade-offs
Ethical	Optimism about technological breakthroughs	Precautionary principle emphasizing uncertainty and equity

Source: Authors.

Table 2. Key Features of the Energy Transition Framework and Generalized Jevons Paradox

Dimension	Feature	Energy Transition Framework	Generalized Jevons Paradox
Technical	**Dynamic governing the energy system**	Energy transition: long phases of dominance of a primary energy source (wood, coal and oil in the 18th, 19th and 20th centuries, respectively) resulting in energy transitions in relative terms (measured by the share of primary energy in the global energy mix)	Energy symbiosis: economy-wide entwinement and interdependence among primary energy and materials, resulting in continuous energy additions in absolute terms (measured by global energy consumption); reflected in steadily rising consumption of virtually all materials
	Classification of technologies and sectors/industries	Clean vs. dirty; green vs. brown (measured by direct use emissions)	Dirty vs. semi-clean (measured by lifecycle emissions, ecological footprint)
	Implicit relationship between high- and low-carbon sectors	High elasticity of substitution (weak sustainability paradigm)	Complementarity (strong sustainability paradigm)
	Scope of environmental analysis	Climate change	Planetary boundaries (climate change and other planetary boundaries); feedback loops within Earth system; nexus of environmental challenges (IPBES 2024)
	Risk vs. uncertainty paradigm	Risk paradigm; optimization; interaction of the economy with other factors can be precisely identified and optimized (cf. Integrated Assessment Models, Social Cost of Carbon)	Deep uncertainty; fat-tailed uncertainty (Weitzman 2011); complex interactions of the economy with other key factors that cannot be (fully) modeled; biophysical and chemical thresholds / tipping points imply non-linear effects and associated impacts (planetary boundaries)
	Implicit view on the possibility of decoupling economic growth and emissions	Emphasis on evidence of relative decoupling (decline in material or carbon intensity of GDP at the country level), taken as evidence that rapid absolute decoupling is possible	Emphasis on absence of evidence of sustained, sufficiently rapid absolute decoupling (absolute decline, at a relatively rapid pace, of resource use, as GDP increases, measured at the level of the world economy), justifying caution on the assumption regarding the possibility of absolute decoupling
	Role of global energy demand in decarbonization	Variable	Central

Institutional	**Overarching goal of climate change mitigation strategy**	Net zero emissions (e.g., in 2050, 2060, 2070)	Development model anchored in economic and environmental planning to achieve fundamental rights (health, education, etc.) within planetary boundaries; technological discernment (political agreement, grounded in scientific evidence and democratic deliberation, on legitimacy/prioritization of different technological end-uses) (in line with the Paris Agreement)
	Emission abatement mechanism	Technological diffusion and progress driving (i) substitution of high-carbon with low-carbon energy sources coupled with electrification, and (ii) higher energy efficiency	Management of global demand for energy and materials (primarily) Technological diffusion and progress coupled with electrification, as well as higher energy efficiency (secondarily)
	Key economic mechanisms in climate change mitigation strategy	Change in relative prices (notably through carbon pricing) exploiting the full range of mitigation responses and achieving emission abatement at the lowest cost (by equating the cost of the last tonne reduced across responses and sectors)	Global energy and material demand management, based on the definition of a set of values on which societies can agree (related to human needs and end-uses of technologies), changes in relative prices
	Implicit underlying view of relationship between technological change and emissions	Technological change may or may not support decarbonization depending on policies	Uncontrolled innovation dynamic, where capital accumulation pressures generate tendency to generate new end-uses and increased production, resulting in carbon and environmental bias of technological change
	Key hurdle faced by climate change mitigation strategy	**Policy focus:** design of appropriate policy packages (emphasis on economic and environmental efficacy, political acceptability / durability)	**Institutional focus:** democratic deliberation on implementing fundamental rights/SDGs within planetary boundaries; end-uses of technologies and resources; welfare trade-offs in the allocation of hard-to-abate emissions and material uses across and within countries; aim of constructing desirable societal horizon
Ethical	**Ethical perspective on role of potential technological breakthroughs in decarbonization strategy**	Possibility of future technological breakthroughs viewed as justification for emphasis on technological progress, substitution effects, and support for R&D investment Significant role for technological breakthroughs in decarbonization strategy	Precautionary principle: given scientific consensus on catastrophic impacts of climate change >2C (dismal theorem) and of crossing biophysical tipping points, and radical uncertainty around future technological breakthroughs, ethically problematic to give large role to technological breakthroughs in decarbonization strategy

Source: Authors.

Implications for Economic Research

In Sections 1 and 2, we presented evidence on global energy and material dynamics and on embedded emissions and materials. This evidence points to a need for caution regarding key assumptions made in the energy transition framework. In Section 3, we connected this evidence to the Jevons Paradox and introduced a concept to understand energy and material dynamics: the Generalized Jevons Paradox (GJP). We explored some preliminary implications for economic modeling. In this section, we discuss the implications of these insights for economic research. We identify three priority research areas, guided by the topics and issues covered in Table 2: (1) a detailed analysis of the role of materials in supply chains, and associated economic vulnerabilities; (2) the political economy of material flows; and (3) the multidimensional welfare analysis of scenarios.

In interpretating the findings of this paper and identifying avenues for future research and policy implications, as discussed in Section 3 it is important to note that policies can – and often should – play a central role in shaping and/or changing the institutional drivers of the GJP. Indeed, a critical point is that interdependencies can evolve over time for reasons that go beyond technological innovations.

Detailed Analysis of the Role of Materials in Supply Chain Vulnerabilities

The GJP reveals the existence of a systemic nexus between materials, energies and emissions. The evidence we present and the concept that we develop in this paper connect the scientific and historical literature on the interdependence of energies and materials with the economic literature on production, consumption, spillovers, and emissions. The systemic nexus that we identify highlights the macroeconomic criticality of complex interdependencies among materials and energies. In turn, the supply chain vulnerabilities and the higher trajectory of emissions (relative to rapid decarbonization scenarios) that these interdependencies imply suggest an amplification of both physical and economic/financial shocks in the future.

Larger and more frequent shocks call for detailed input-output analysis of countries' supply chain vulnerabilities. Intensifying climate change and persistent energy and material interdependencies create significant supply chain vulnerabilities. A key variable that will be affected is prices. Climate change will raise prices through a range of channels, including supply shortages from damaged agricultural and industrial production and trade disruptions (Mitra et al. 2025, NGFS 2024b, Beirne et al. 2021, Kotz et al. 2023). The 2022 energy crisis showed how fossil fuel dependence can impact on inflation. Alvarez and Kroen (2025) find that energy price shocks have a large effect on inflation through sectoral channels, and that energy dependence plays a critical role in inflation passthrough. Crucially, large physical shocks (stemming from climate, ecosystems, energy, materials) would lead to large supply constraints. The ability of price signals to enable economic adjustment would be limited. These effects could be magnified by demand constraints linked to green budgeting and green planning. Repeated or simultaneous shocks would compound shocks. Finally, borrowing costs and debt levels could increase (because of lower growth prospects, weaker fiscal positions, bailout costs). This environment would make it more challenging for central banks to meet their price stability objective. It is thus critical to understand the uses of materials (e.g., sulfur monoxide, oil, ammonia) throughout the economy, and associated vulnerabilities. Input-output analysis is a promising tool for this.

A detailed understanding of supply chain vulnerabilities would inform industrial policies. Since 2020 and the supply chain disruptions caused by the COVID-19 pandemic, as well as heightened geopolitical tensions, many large economies increased their use of industrial policies to enhance the resilience of their supply chains (Huang et al. 2025). One objective is to target public support to specific firms and sectors to develop strategic industries, notably to reduce reliance on energy imports (IMF 2025c). So-called green industrial policy, in particular, would benefit from a detailed understanding of countries' supply chain vulnerabilities, as it would allow countries to identify interdependencies between key materials and energies, as well as strategies to change countries' productive structure so as to reduce their vulnerabilities.

Input-output analysis would also help envisage more realistic, technologically-constrained pathways. The GJP points to the need for technological realism to understand the global energy and material dynamics and their interactions with economic forces. Technological realism should be informed by an understanding of the interconnected drivers of global economic, technological, energy and material dynamics. This approach would make it possible to assess the implications of constrained technological pathways for sectoral change and the distribution of resources, both within and across countries. Analysis related to decarbonization strategies should include independent assessments of industrial R&D claims. Structured dialogue between academia and private innovators should be institutionalized to evaluate what technological options are feasible or plausible by 2050. This would help policymakers move beyond generic tools like carbon pricing, which are often assumed – without sufficient evidence – to drive “green innovation” (see for example Lilliestam et al. 2020, who review the literature and find little evidence of the effectiveness of carbon pricing in stimulating innovation and zero-carbon investment).

Political Economy of Material Flows

There is a need for political economy analysis on the coalitions that support particular institutional arrangements that relate to the GJP drivers identified in Section 3.3 – rent seeking and market power, geoeconomic pressure, international trade dynamics, and international financial architecture. Research should seek to understand how vested interests are formed and organized, and how the pursuit of the accumulation of political power shapes the emergence of strategic interests of states – and thus, directly and indirectly, the entrenchment of carbon-intensive material flows. This includes the role of vested interests, sociopolitical groups and political actors in establishing rules, organizational forms and distributive principles that shape the productive structure, with implications for material flows.

Economic and social change implies changes in political power that have been largely underestimated by the climate economics community. As demography affects the number of political agents in a sociopolitical group, economic dynamics support the emergence of some sectors over others, increasing the economic weight of some sociopolitical groups (Amable and Palombarini 2024, p. 62). Similarly, as technical change affects hierarchies within the productive system, countries’ social contract can be affected in different ways by the large-scale structural transformations (Combet and Pottier 2024).

The aim should be to articulate material flow analysis and the political economy of institutional architecture. An important issue is the differential effects that states have on different political and economic strategies, advantaging some actors to the detriment of others (see, e.g., Jessop 2016, Aglietta and Espagne 2024, Amable and Palombarini 2024). The notion of “historical viability regimes” (Aglietta and Espagne 2024) analyzes how institutions and social groups have throughout history shaped energy and materials flows and related environmental impacts, how these flows were distributed and reallocated to serve the reproduction of these social groups and the preservation of these institutions. This concept could serve to better understand the institutional sources of the GJP, and potential reforms and opportunities for alternative future scenarios. Structural models that endogenize the impact of large-scale policy and regulatory changes are also needed.

Multidimensional Welfare Analysis of Scenarios

The GJP implies that fossil fuels are likely to persist in the energy system, and hence a “stickiness” of emissions. One of the key implications of the GJP is that rebound effects in energy and material flows generate “stickiness” in global emissions. Indeed, the GJP means that there is considerably more inertia in the global energy system than is recognized by the conventional literature, which generally operates within the energy transition framework. So-called hard-to-abate emissions (cement, steel, other heavy industries) are crucial for development (for building housing, roads, renewable energy), but the absence of affordable or profitable zero emission technologies in those sectors may require careful consumption distribution, with low-income countries having priority. This raises difficult distributional questions across and within countries (Semieniuk et al. 2021).

Given the likely stronger persistence of fossil fuels in the global energy system implied by the GJP, research is needed on the differential utility of fossil fuels across economic sectors. Current economic models may not be suitable for capturing the nuanced impacts of declining activity in “hard-to-abate” sectors. Policymakers require tools to quantify sector-specific effects of decarbonization and assess the broader resilience of the economy to the potential downsizing of certain sectors. Moreover, there is a need for research on incorporating non-monetary evaluations of CO_2 utility, grounded in welfare economics, to better reflect societal well-being.[46] Currently, the few IAMs that explore scenarios with significant energy demand shifts operate at highly aggregated levels, which limits their usefulness for designing targeted, effective policy interventions.

Models that enable sophisticated distributional analysis of decarbonization scenarios should be developed. Most net-zero scenarios and climate-economic frameworks are based on Pareto optimality assumptions, constraining the scope for distributional considerations. Models should be developed to analyze scenarios for material and emissions transfers between and within countries, across income groups. Such models could help guide the evaluation of fairness in the distribution of decarbonization efforts and outcomes both within and across countries.

Conclusion

This paper introduces a new concept to understand global energy and material flows and their relationship with the macroeconomy. We present evidence of what we call the “Generalized Jevons Paradox”: at the level of the world economy, higher energy efficiency (and higher efficiency in the use of other materials) leads to higher – rather than lower – total energy use (and total use of other materials). Counter-intuitively, this implies that lower carbon intensity of the world economy, measured by emissions per unit of GDP, is likely to lead, in a central scenario, to higher (or, at a minimum, persistently high) global emissions.

The Generalized Jevons Paradox (GJP) is closely related to two other phenomena: the Jevons Paradox and embedded emissions and materials. The Jevons Paradox corresponds to the fact that saving energy tends to lead to more energy consumption. Emission and material embeddedness describes the network of material interdependencies that exist among technologies. The GJP results from direct and indirect energy/material demand effects of the long-term energy and material interdependencies (or symbiosis), explained by institutional, economic and technical change causes. The GJP augments the Jevons Paradox and energy symbiosis by capturing structural and institutional mechanisms that account for systemic rebound effects. The Jevons Paradox focuses on the micro and macro effects resulting from efficiency gains through investments. Emission and material embeddedness focuses on the path dependency and technological complementarities arising in the long run in energy and material systems. The Generalized Jevons Paradox focuses on the root causes of these dynamics within the institutional drivers of investment.

The GJP informs assessments of the future evolution of global energy and material dynamics. The energy transition framework entails two core notions: (1) the world energy system is governed by substitution dynamics, whereby some forms of energy substitute for others, driven by technological diffusion; (2) there is a broad equivalence between technological change and material change, such that the deployment of low-carbon technologies implies a commensurate decrease in fossil fuel consumption. Consistent with these assumptions, the standard framework sees the history of energy as “stagist”: a succession of long phases of dominance – in relative terms – of specific sources of primary energy (wood, coal, oil, etc.). By contrast, the GJP is emphasizes two stylized facts: (1) the world energy system is governed by additive dynamics and energy symbiosis, whereby different forms of energy pile up on top of one another as a result of material interdependencies; (2) technological and material dynamics can, and typically do, differ significantly, such that the rapid deployment of low-carbon technologies is compatible with continued (or even increased) consumption of fossil fuels.

[46] Examples of research that explore distributional aspects of decarbonization include Denning et al. (2015), de Palma et al. (2024), and Fleurbaey et al. (2014).

Consistent with the GJP, the history of energy is characterized by an accumulation – in absolute terms – of different energies and other materials.

The GJP is related to, but broader than, the macroeconomic and economy-wide rebound effects that have been documented in the literature (see Brockway et al. 2021 for an overview). Whereas macroeconomic rebound effects capture a range of mechanisms, their scope is narrower in that they do not capture the dynamic interactions among technologies, energy, materials, and institutions. In other words, these effects do not capture how the deployment of "clean" technologies simultaneously increases the energy efficiency of the global economy and generates, through the entwined relationships among energies and materials, significant inertia in the emissions generated by the global economy's productive structure, notably by contributing to the generation of new economic "needs" (and therefore sources of demand).

The evidence presented in this paper suggests a need for caution in applying the energy transition framework. It highlights the likely long-term persistence of fossil fuels in the global economy and the importance of reducing energy demand to achieve significant and sustained decarbonization over the next decades. A sustained decline in global emissions driven by a major economy (see Myllyvirta 2025 and Xue and Larsen 2025 on China's emissions profile since 2024 and its very high FDI in low-carbon sectors since 2022, respectively) is certainly possible, especially if the global population declines sooner than currently expected. However, this hypothesis rests on strong assumptions, as China's carbon intensity remains very high, and such a global dynamic would probably unfold over several decades.

More specifically, our analysis highlights the fragility of implicit assumptions of the ET framework. The evidence we present suggests that technological and material dynamics are not equivalent, that the elasticity of substitution between so-called "clean" and "dirty" technologies is relatively low (and in some cases zero), and that – in the absence of binding constraints on energy consumption – there is a macro-scale rebound effect associated with increased energy efficiency. The stylized facts are thus inconsistent with the implicit assumptions on which the ET framework rests. Taken together, they suggest that the global productive structure tends to become larger and more complex over time, entrenching fossil fuels. This points to "stickiness" in global emissions because of the GJP – an overlooked constraint on decarbonization. In line with Bolton et al. (2020), the concept we develop underscores the need to adopt an uncertainty paradigm. Importantly, the GJP should not be seen as an economic "law" but an empirical observation.

We discuss possible key drivers of the GJP, as well as its consequences. Technological complementarities that characterized embedded emissions and materials (or symbiosis) have their origins in the dynamics of investment. Similarly, the Jevons Paradox originates upstream, when the investment choices are made. This requires an understanding of the factors that determine these investment decisions – that is, the political economy of the GJP. We describe this political economy as having four drivers: (1) rent seeking and market power; (2) geoeconomic pressures; and (3) international trade arrangements; and (4) financial flows. In turn, we identify three key sets of actors that shape these drivers: large companies and multinational corporations; states; and large financial actors. We evaluate the implications of the GJP for the future of energy and materials. We highlight different likely impacts: the perpetuation of large energy rents; a persistence of "technological sprawl" – that is, the continued diffusion of a wide range of technologies in consumption patterns; large emissions tied to construction, operation and maintenance of infrastructure, including for climate change adaptation and mitigation; and continued political economy constraints to climate change mitigation.

Finally, we outline three main avenues for economic research. First, the GJP implies a need for detailed analysis on the role of various materials in creating vulnerabilities in countries' supply chains. Given the deep entwinement between energies and materials documented in this paper, and the ongoing intensification of physical sources of economic shocks, it is essential to enhance tools to conduct detailed analysis of the link between materials and countries' supply chain vulnerabilities. Second, the political economy of material flows. This would help identify political coalitions that support particular institutional arrangements that relate to GJP drivers, and hence contribute to particular orientations of material flows in the global economy. Third, multidimensional welfare analysis of scenarios. The likely persistence of fossil fuels in the global energy system implied by the GJP calls for research on the differential usefulness of fossil fuels across economic sectors.

Annex I. Evolution of Global Energy Mix and Electricity Generation Mix

Table AI.1 Global Energy Mix

Global Energy Mix				
	Energy supply		Share in the energy mix	
	Fossil Fuels	Renewable Energy	Fossil Fuels	Renewable Energy
	Change (percent): 2000-2023		Change (percentage points): 2000-2023	
Mean	121	323	0.3	-0.9
Median	61	80	-0.4	0.3
Total	52	84	-0.4	2.5

Source: IEA World Energy Balances; and authors' calculations.
Note: The data cover 145 countries, including all advanced economies and most emerging market and developing economies, accounting for 98 percent of 2024 global GDP in current prices. Calculations are made until 2023, as this is the most recent year for which data are available for all countries. The total (last row) is obtained by aggregating the energy supply of all countries in the sample in 2000 and 2023 and calculating its growth rate over this period (first two columns – "Energy supply"), and likewise by calculating the change, over this period, in the share of fossil fuels and renewable energy in the aggregate global energy mix (last two columns – "Share in the energy mix"). The mean and median (first two rows) show the mean and median, respectively, for these indicators (change in energy supply, in percent, between 2000 and 2023; change in the share in the energy mix, in percentage points, between 2000 and 2023) for all 145 countries. For some countries (Bahrain, Brunei Darussalam, Gibraltar, Malta, Oman), the data indicate a renewable energy supply of zero in 2000, hence these countries were excluded from calculations to obtain the mean and median for the energy supply growth.

Table AI.2 Electricity Generation Mix

Electricity Generation Mix				
	Energy supply		Share in the electricity mix	
	Fossil Fuels	Renewable Energy	Fossil Fuels	Renewable Energy
	Change (percent): 2000-2023		Change (percentage points): 2000-2023	
Mean	468	966	-6.5	7.1
Median	71	167	-3.1	4.0
Total	84	215	-4.0	11.4

Source: Ember Global Electricity Review 2025; and authors' calculations.
Note: The underlying dataset used for the analysis covers 124 countries, including all advanced economies and most emerging market and developing economies, accounting for 96 percent of 2024 global GDP in current prices. Calculations are made until 2023, as this is the most recent year for which data are available for all countries. The total (last row) is obtained by aggregating the energy supply of all countries in the sample in 2000 and 2023 and calculating its growth rate over this period (first two columns – "Energy supply"), and likewise by calculating the change, over this period, in the share of fossil fuels and renewable energy in the aggregate global energy mix (last two columns – "Share in the energy mix"). The mean and median (first two rows) show the mean and median, respectively, for these indicators (change in energy supply, in percent, between 2000 and 2023; change in the share in the energy mix, in percentage points, between 2000 and 2023) for all 124 countries.

Annex II. Empirical Relationship Between Energy Efficiency and Total Resource Use

In this annex, we present regression analysis results on the relationship between the efficiency of the use of certain resources (or flows) that are critical for the functioning of the world economy (energy, water, nitrogen, and electricity) and the total use of raw materials/environmental footprints (emissions, water use, nitrogen use, energy use). The regressions use three different estimators: OLS (consistent with the regression lines shown in Figure 3), and two nonparametric estimators that are more robust to small samples (median quantile regression and Theil-Sen estimator).

The results show a statistically significant positive relationship between efficiency in resource use and total resource use, which is counterintuitive yet consistent with the Generalized Jevons Paradox. Indeed, the regression coefficients are large and statistically significant, and the estimates are similar across all three regression methods. In line with Figure 3, the regression analyses cover the following periods: 1900-2023 for energy efficiency and total world GHG emissions, 1960-2014 for water use efficiency and total world water use, and 1971-2023 for the share of electricity in world final energy consumption / world energy and fossil fuel consumption. For nitrogen use efficiency and total world nitrogen use for agriculture, the sample is restricted to 1985-2023 to account for the U-shaped relationship between these variables over 1960-2014 (explained by the decline in efficiency that followed the surge in nitrogen use in agriculture over 1960-1984, as noted in Section 1). Data on emissions are taken from the Global Carbon Project and Our World in Data. Data on nitrogen are taken from the FAO. Data on water are taken from World Bank. Data on energy are taken from the IEA.

Table AII.1 OLS and Median Quantile Regressions: Energy Efficiency and Total Emissions

Dependent variable	Total emissions (Gt CO2e)	
	(1)	(2)
	OLS	Quantile regression
Energy efficiency (international dollars per kilogram of emissions)	16.94***	16.13***
	(0.766)	(0.887)
Constant	-3.572*	-0.436
	(1.889)	(2.187)
N	68	68
R^2	0.881	

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table AII.2 Theil-Sen Estimator: Energy Efficiency and Total Emissions

Parameter	Estimate	95% CI Lower	95% CI Upper
Slope	17.265	15.808	19.168
Intercept	-1.902		

Table AII.3 OLS and Median Quantile Regressions: Water Use Efficiency and Total Water Use

Dependent variable	Total water use (billions of tonnes)	
	(1)	(2)
	OLS	Quantile regression
Water use efficiency (international dollars per tonne of water)	198.6***	193.9***
	(12.42)	(18.17)
Constant	1,006***	1,107***
	(134.9)	(197.3)
N	52	52
R^2	0.836	

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table AII.4 Theil-Sen Estimator: Water Use Efficiency and Total Water Use

Parameter	Estimate	95% CI Lower	95% CI Upper
Slope	221.015	187.555	259.193
Intercept	1046.28		

Table AII.5 OLS and Median Quantile Regressions: Total Nitrogen Used for Agriculture and Agriculture Nitrogen Use Efficiency

Dependent variable	Agriculture nitrogen use efficiency (international dollars per tonne of nitrogen)	
	(1)	(2)
	OLS	Quantile regression
Total nitrogen used for agriculture (millions of tonnes of nitrogen)	7,473***	7,175***
	(536.2)	(844.6)
Constant	-76,229	-50,204
	(49,700)	(78,288)
N	39	39
R^2	0.84	

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table AII.6 Theil-Sen Estimator: Total Nitrogen Used for Agriculture and Agriculture Nitrogen Use Efficiency

Parameter	Estimate	95% CI Lower	95% CI Upper
Slope	7420.703	6164.207	8752.042
Intercept	-54185.703		

Table AII.7 OLS and Median Quantile Regressions: Share of Electricity in Total Final Energy Consumption and Total Energy (or Fossil Fuel) Consumption

Dependent variable	Total energy consumption (EJ)		Fossil fuel consumption (EJ)	
	(1)	(2)	(3)	(4)
	OLS	Quantile regression	OLS	Quantile regression
Share of electricity in final energy consumption	2,123***	2,092***	1,148***	1,135***
	(50.95)	(92.35)	(39.38)	(71.40)
Constant	-23.30***	-17.39	23.60***	26.88**
	(7.816)	(14.17)	(6.042)	(10.95)
N	53	53	53	53
R^2	0.971		0.943	

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table AII.8 Theil-Sen Estimator: Share of Electricity in Total Final Energy Consumption and Total Energy (or Fossil Fuel) Consumption

Effect 1: Electricity share → Total Final Energy

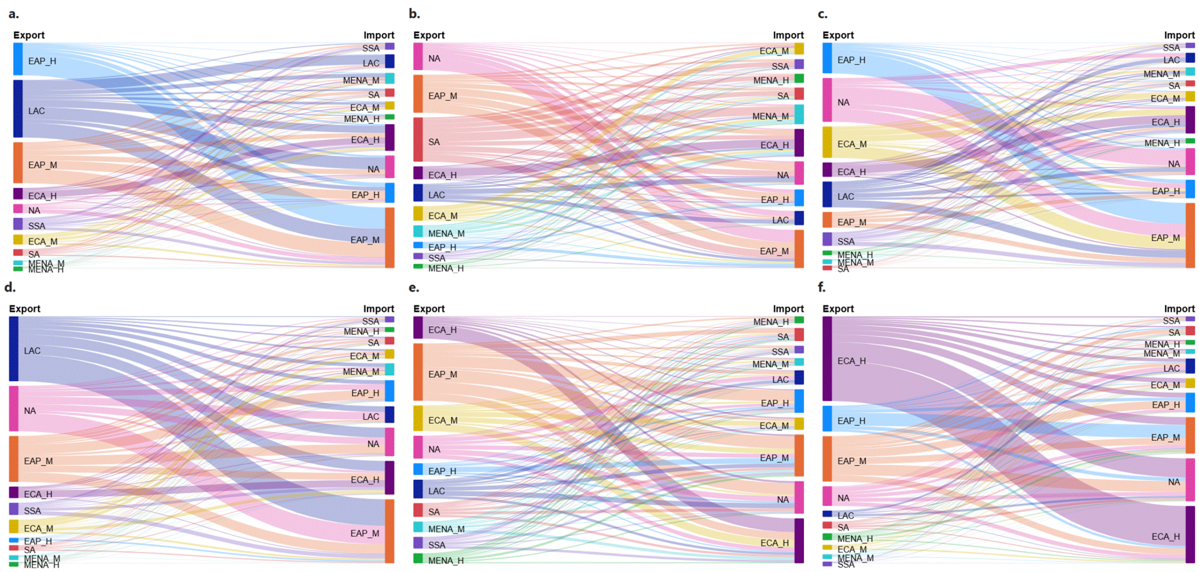
Parameter	Estimate	95% CI Lower	95% CI Upper
Slope	2129.455	1993.782	2238.717
Intercept	-39.242		

Effect 2: Electricity share → Fossil Fuel Consumption

Parameter	Estimate	95% CI Lower	95% CI Upper
Slope	1158.363	1055.637	1241.488
Intercept	11.418		

Annex III. Environmental Footprints Embedded in International Trade

Figure AIII.1. Global Trade Flows and Ecological Pressures Across Six Planetary Boundaries



a. Biosphere integrity, b. Freshwater change in terms of blue water consumption, c. Land use change, d. Biogeochemical flows, e. Climate change, f. Novel entities

Source: Reproduced with permission from Santos Carneiro et al. (2025).

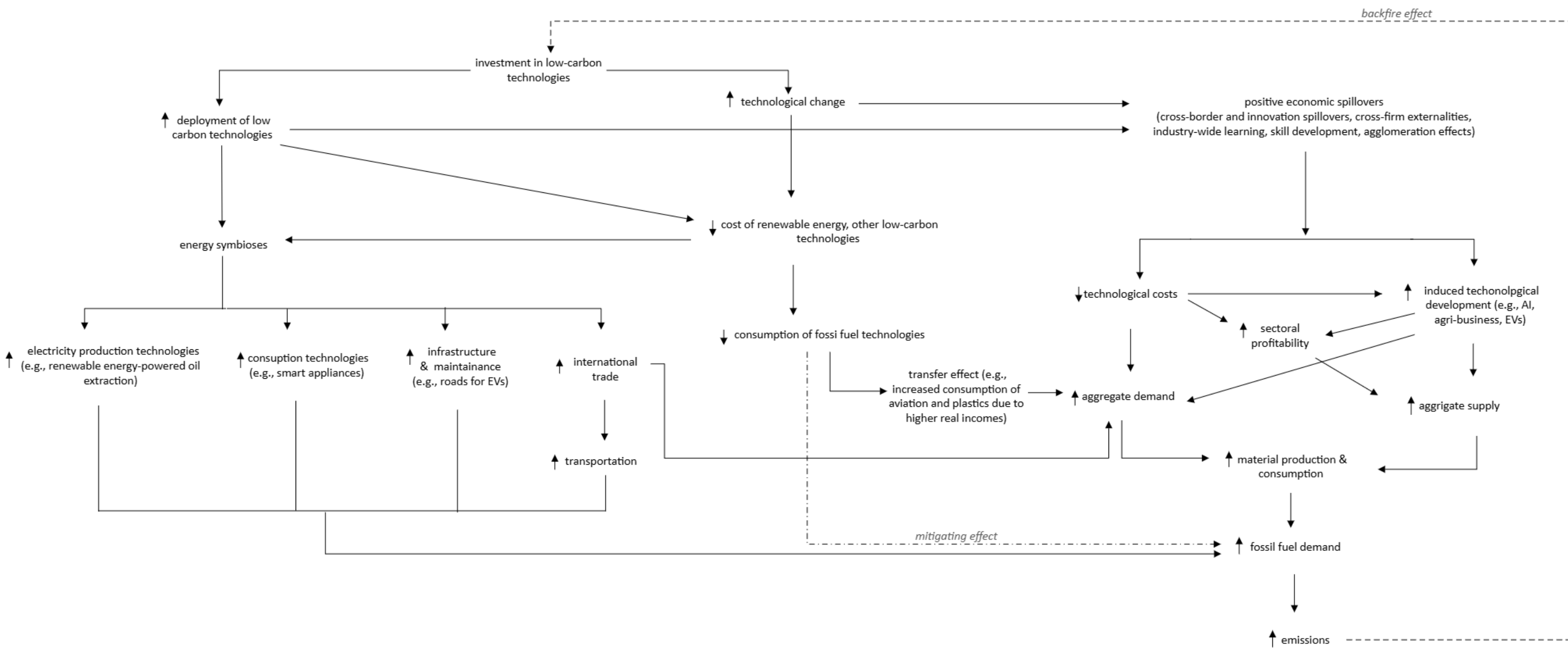
Figure AII.1 presents a set of Sankey diagrams that illustrate how global trade flows between exporting and importing regions contribute to ecological pressures across six planetary boundaries, mainly biosphere integrity, freshwater change in terms of blue water consumption, land use change, biochemical flows, climate change, and novel entities. These visual representations show that high- and middle-income countries are the main drivers of import consumption pressure, meaning that they demand goods and services whose production exerts pressure on planetary boundaries elsewhere. The flows typically originate in middle- and low-income regions – especially in Latin America and the Caribbean, and East Asia and the Pacific – and terminate in high-income regions such as Europe, North America, and high-income Asian countries, although with important nuances depending on the planetary boundary considered.

Across the different planetary boundaries (such as biosphere integrity, land system change, freshwater use, climate change, and biogeochemical flows), the Sankey flows highlight recurring imbalances: many lower-income regions export significantly more ecological pressure than they import. In regions such as Latin America, the export-to-import pressure ratio is particularly high. For example, Latin America exports over four times more pressures than it imports for the biosphere integrity boundary. In contrast, high-income regions show the opposite pattern, importing much more pressure than they export.

Overall, Figure AII.1 visually underscores how global trade contributes to the stickiness of the GJP: wealthy countries' consumption offloads part of their environmental degradation elsewhere, creating an illusion of transition in the same countries that would normally have to reduce their footprint the most. In a mirror image, the ecological pressure is often exerted in less wealthy, resource-exporting regions, where this source of revenue is often vital to maintain a certain level of macroeconomic stability and social cohesion.

Annex IV. Embedded Emissions and Materials (Energy Symbiosis) Channels

Figure AIV.1. Illustration of Some of the Key Economic Channels of Embedded Emissions and Materials (Energy Symbiosis)



Source: Authors.

Annex V. Elements of Formalization: Kaya Identity

The GJP can also be formalized using the Kaya identity, which decomposes emissions. It can be useful to compare analyses that perform such decompositions on the model runs used for planning future decarbonization (e.g., CMCC 2014) versus using these for analyzing historical emissions (e.g, Damania et al. 2025, p. 27). The main difference between future scenarios and historical emissions is that future scenarios have exogenous GDP growth, therefore they cannot capture the correlation between energy efficiency and GDP growth – i.e., what we capture through the concept of the Generalized Jevons Paradox.

Using the following equation, where CO_2 is total CO_2 emissions, *pop* is the total population, TPES is the total primary energy supply, and *s* is the sectors of the economy:

$$CO_2 = pop \times \frac{GDP}{pop} \times \sum_s \left(\frac{GDP_s}{GDP} \times \frac{TPES_s}{GDP_s} \times \frac{CO_{2_s}}{TPES_s} \right)$$

the Generalized Jevons Paradox (GJP) can be conceptualized as follows.

The conventional Energy Transition framework assumes that a combination of TPES/GPD (i.e., energy efficiency) and CO2/TPES can bring the world economy relatively close to zero emissions. This hypothesis does not hold, as there are correlations and complex relationships among the components of this equation, which stem from embedded emissions and materials (i.e., synergies among sources of energy, and among energy and materials). For instance, GDP is correlated with TPES/GDP (energy efficiency), through the mechanisms of the GJP. In addition, with current technologies, CO2/TPES cannot go to zero in every sector (notably construction of housing and infrastructure). As a result, there is a need to act on the size of GDP, or at least the size of some sectors in global GDP. This likely requires more intentionality regarding the distribution of some of these activities between high-income and low-income individuals and countries.

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