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Reducing GHG emissions and raw materials embodied in imports: assessing a cross-sectoral sufficiency-oriented national climate strategy in France

Antoine Teixeira¹ · Fanny Vicard¹

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Abstract

European climate policies largely target territorial emissions, overlooking greenhouse gas (GHG) emissions and raw materials embodied in international trade. This study quantifies the potential and limitations of a sufficiency-oriented national strategy to reduce these impacts from a consumption-based perspective. Using the MatMat Environmentally Extended Input–Output (EEIO) model, we assess France’s transition pathways toward Net Zero Emissions (NZE) by 2050 under two scenarios: an Efficiency-driven (Eff.) and a Sufficiency-oriented (Suff.) one. Results show that sufficiency systematically outperforms efficiency by reducing both GHG emissions (−44% vs. −31%) and raw material extraction (−24% vs −4%). Its outperformance stems from its stronger ability to reduce import dependency and to shift demand towards less material-intensive production. Housing, mobility, and food drive most reductions, while final services remain a persistent blind spot. In 2050, about two-thirds of France’s consumption-based impacts remain embodied in imports, 75% of which originate outside the EU, limiting the leverage of European decarbonization policies. These findings highlight the upstream mitigation potential of sufficiency and the need to extend NZE strategies beyond territorial scopes. Two key implications emerge. First, extending sufficiency to service provision is crucial to limit rebound effects and address the growing role of services in ageing societies. Second, integrating sufficiency into coordinated EU-level trade, industrial, and resource policies is essential to tackle imported pressures and strengthen the resilience of low-carbon transitions.

Keywords Sufficiency · Consumption-based GHG emissions and raw materials · Net-Zero emissions strategies · Scenarios analysis · Input-Output analysis · Industrial ecology

1 Introduction

Despite their ambition, current European climate policies, such as the European Green Deal (2019) and the Fit for 55 legislative package (2021), aim to achieve Net-Zero territorial GHG Emissions (NZE) by 2050, primarily through reductions in direct territorial emissions across sectors including energy supply, buildings, transport, agriculture, and industry (Tsiropoulos et al., 2020). These strategies rely predominantly on technological improvements and energy efficiency to drive domestic decarbonization. However, this

territorial and efficiency-centered approach largely overlooks the indirect GHG emissions and resource use embodied in international trade (Grubb et al., 2022). Recent estimates suggest that such imported emissions represent roughly one-third of Europe’s consumption-based GHG emissions, primarily concentrated in manufactured goods (Wood et al., 2020). By improving energy efficiency without questioning consumption levels, these strategies remain ineffective at tackling the emissions embedded in imported manufactured goods, particularly those associated with material production along global supply chains (Teixeira & Lefèvre, 2025). Moreover, they often inadvertently increase demand for materials, thereby amplifying upstream emissions and resource extraction abroad (Krausmann et al., 2020; Müller et al., 2013; Wei et al., 2021). Beyond climate concerns, this pattern also exacerbates Europe’s economic and geopolitical vulnerabilities due to its structural reliance on imported raw materials, notably fossil fuels and metal ores (Distefano

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et al., 2024; Wiedmann et al., 2015). Efficiency-driven decarbonization alone thus appears insufficient to address the full scope of Europe's climate and resource challenges. This calls for rethinking NZE strategies beyond domestic technological solutions, to account more explicitly for the material basis of consumption and the environmental burdens embedded in global trade.

Sufficiency-oriented strategies are increasingly recognized as an essential complement to efficiency-based approaches in climate mitigation and broader environmental policy (Creutzig et al., 2023; Grubler et al., 2018; van Sluisveld et al., 2016). While energy efficiency aims to deliver the same services using less and cleaner energy, sufficiency seeks to reduce overall demand for those services by questioning behaviors and lifestyles and rethinking how essential needs, such as housing, mobility, and food, are fulfilled (Creutzig et al., 2018, 2022; Sandberg, 2021; Sugiyama et al., 2024). Examples include reducing average dwelling size and favoring the reuse of existing buildings over new construction, limiting private car ownership and vehicle size, and shifting diets towards less meat- and resource-intensive foods (Ivanova et al., 2020; Pauliuk et al., 2021; Springmann et al., 2016; van Heerden et al., 2025). By lowering overall domestic demand, sufficiency strategies reduce upstream energy and material use along supply chains, particularly by limiting the need for new infrastructure, equipment, and industrial production, and thus decreasing associated GHG emissions and other environmental pressures (Creutzig et al., 2024; Hertwich et al., 2019). Scenario-based studies in Europe further confirm that, when combined with energy efficiency, sufficiency can make a substantial contribution to GHG mitigation (Costa et al., 2021; van de Ven et al., 2018; Wiese et al., 2024). However, a comprehensive understanding of the full potential and structural constraints of sufficiency strategies is still lacking, particularly their role in reducing GHG emissions and raw material extraction embodied in imports. Indeed, most existing assessments rely on a production-based accounting perspective, thereby underestimating the full upstream mitigation potential of sufficiency strategies beyond national borders in globally interconnected economies. Even studies adopting a consumption-based accounting framework with Environmentally Extended Input–Output (EEIO) analysis mostly focus on isolated sufficiency levers in a static manner, rather than integrating them into comprehensive, cross-sectoral prospective scenarios (Moran et al., 2020; Vita et al., 2019). To our knowledge, only one prospective study (Morfeldt et al., 2023) has fully integrated sufficiency into a national-scale, cross-sectoral transition scenario using a consumption-based GHG accounting framework. Yet, this analysis falls short of disentangling GHG emissions embodied in imports to explain its main determining factors, examining material requirements, and linking GHG reductions to underlying

material flows and dependencies. Furthermore, existing research overwhelmingly focuses on housing, mobility, and food, while largely neglecting final services, such as health, leisure, and tourism, despite their growing contribution to climate and resource impacts (Andrieu et al., 2023; Chen et al., 2026; Sun et al., 2024; Teixeira & Lefèvre, 2025).

This paper addresses these gaps by quantifying the potential and limitations of a sufficiency-oriented national strategy to reduce both GHG emissions and raw material extraction embodied in imports from a consumption-based perspective. The analysis focuses on the case of France, which offers a representative context within the European Union due to its strong national climate commitment towards Net-Zero by 2050 (Ministère de la Transition Écologique, 2015, 2020, 2021), its structural dependency on imported emissions and resources (Teixeira & Lefèvre, 2025), and the availability of a robust scenario framework (Vicard & Teixeira, 2024). In particular, the study draws on two of the four contrasted and quantified societal transition pathways to NZE by 2050 in France developed by the French ecological transition agency (ADEME, 2021). These scenarios provide cross-sectoral transition pathways aligned with national climate targets, with differing emphasis on sufficiency and efficiency strategies: a sufficiency-oriented scenario (Suff.) and a technology-focused, efficiency-driven scenario (Eff.). Both are evaluated using MatMat, a detailed Environmentally Extended Input–Output (EEIO) model designed to assess and map France's GHG emissions and raw materials impacts across supply chains and international trade, in both current and future contexts (Teixeira, 2024; Teixeira et al., 2025).

We build on this framework to assess three complementary dimensions. First, we compare overall GHG emissions and raw materials embodied in French final demand in 2015 (Ref.) and by 2050 under the sufficiency-oriented (Suff.) and efficiency-driven (Eff.) scenarios. This allows us to evaluate and contrast their effectiveness in reducing both territorial and imported environmental impacts. Second, we disaggregate these impacts across five major final consumption categories: housing, mobility, food, final goods, and final services. We identify where sufficiency strategies offer the greatest reductions, and where structural limitations remain. Third, we focus on imported GHG emissions by mapping the five final consumption categories to the imported intermediate goods and services required for their provision, and by identifying the share of imported GHG emissions originating from other EU-27 countries. This approach identifies the product groups most responsible for France's imported emissions, especially final services, whose role remains largely overlooked. In doing so, it covers key blind spots in the existing literature and highlights the external dependencies that shape the resilience of France's consumption-based environmental impacts.

2 Methods

2.1 Overview of the modeling framework

Our analysis relies on the multi-regional Environmentally Extended Input–Output (EEIO) model MatMat (Teixeira, 2024; Teixeira et al., 2025), developed to quantify both territorial and imported GHG emissions and raw material extraction embodied in domestic final demand, for the present situation and under future scenarios. The model incorporates several features designed to disentangle the upstream drivers of environmental implications of prospective scenarios.

We apply a simplified Single-country National Accounts Consistent footprints (SNAC) approach (Tukker et al., 2018), which combines a Single-Region Input–Output (SRIO) model to describe France’s domestic economy, with a Multi-Regional Input–Output (MRIO) framework to estimate GHG emissions and raw materials embodied in imported goods and services. The SRIO component for France is calibrated using the Exiobase v3.8.2 database (Stadler et al., 2018, 2021), adjusted with national and sectoral statistics, including energy balances (European Commission & Eurostat, 2019), raw materials (European Commission & Eurostat, 2018), and processed materials (ADEME et al., 2021). The reference year is 2015, consistent with the baseline used in the ADEME scenario framework. This choice has limited impact on results, as France’s consumption-based GHG emissions have remained relatively stable in level and structure since 2015, excluding COVID-19 disruptions (Baude & Larrieu, 2024). The SRIO model integrates energy and material flows in physical units to facilitate consistency with bottom-up Net-Zero Emissions (NZE) scenarios. For the MRIO component, we exclude France from the Exiobase MRIO and retain the remaining 48 world regions. No further treatment is applied beyond harmonizing trade flows between France and the rest of the world. Both SRIO and MRIO components captures four major sources of GHG emissions (fossil fuel combustion, agriculture, industrial processes, and waste treatment) and distinguishes four gas types (CO₂, CH₄, N₂O, and fluorinated gases). They also track four categories of raw materials: 10 types of biomass, 12 fossil resources, 8 metal ores, and 3 non-metallic minerals. Further detail on the data sources and calibration process is provided in previous works (Teixeira, 2024; Teixeira & Lefèvre, 2025; Teixeira & Vicard, 2025).

The SRIO model incorporates a capital flow matrix, based on the EU-KLEMS database (Stehrer, 2021), that describes sectoral investment demand, i.e. the Gross Fixed Capital Formation (GFCF), disaggregated by product. This enables the “endogenization” of capital in

consumption-based assessments consistent with a scope-3 Life Cycle Assessment (LCA) perspective. In other words, GHG emissions and raw materials embodied in infrastructure and equipment are accounted alongside the production activities they support, rather than treated separately (Södersten et al., 2018). For instance, emissions from housing include both energy use for heating and the emissions linked to residential construction, while emissions from mobility cover both fuel combustion and those associated with transport infrastructure and vehicle manufacturing. This integration also facilitates the alignment of bottom-up scenario assumptions with the SRIO framework and enables a clearer distinction of environmental impacts across final consumption categories, thereby illustrating how lifestyle changes and systemic transformations shape them. In this study, capital endogenization is limited to domestic investment. Due to methodological uncertainties in allocating the environmental impacts of capital formation over time, particularly in fast-growing economies like China (Ye et al., 2021), we do not include emissions embodied in foreign capital demand.

The model also includes a parametrization interface designed to implement economy-wide exogenous scenarios across economic, energy, and material dimensions. This allows forward-looking analyses of climate, energy, and circular economy policies (De Koning et al., 2016; Wiebe et al., 2018). On the domestic side, three main dimensions are parameterized: (i) final demand levels and structure (household and government consumption and capital formation), (ii) technical coefficients to reflect improvements in energy and material efficiency in production sectors, and (iii) trade structure by product and service. These domestic parameters are derived by translating and reconciling sectoral outputs from bottom-up energy and materials models and from the macroeconomic model ThreeME (Callonnec et al., 2013). On the international side, we parameterize the GHG emissions and raw materials content of imports according to global action assumptions. Both domestic scenarios rely on the same background trajectory for average global decarbonization, based on the IEA’s Stated Policies Scenario (STEPS), consistent with a projected 3 °C global warming pathway (IEA, 2022).

2.2 Description of policy scenarios

This study investigates two decarbonization pathways developed by the French Agency for Ecological Transition (ADEME, 2021) to achieve Net-Zero territorial emissions (NZE) in France by 2050. Both scenarios combine sufficiency and efficiency strategies but differ in the emphasis placed on each. A sectoral breakdown of their assumptions compared to 2015 is provided in Table 1.

Table 1 Description of efficiency-driven and sufficiency-oriented scenarios

	Efficiency-driven (Eff.) scenario	Sufficiency-oriented (Suff.) scenario
General approach	Technological solutions to mitigate territorial emissions and maintain current lifestyles	Deep changes in consumption patterns and production systems to mitigate territorial emissions
Baseline assumptions	Population growth of 0.2% per year Potential growth of 1.3% per year on average (including 1.1% productivity growth)	
Energy demand	–40% in final energy demand 81% share of renewable energy	–55% in final energy demand 88% share of renewable energy
Agriculture and food	–50% food waste and losses per capita –30% meat consumption 30% share of organic farming	–50% food waste and losses per capita –70% meat consumption 70% share of organic farming
Housing	Widespread demolition and reconstruction 89% of dwellings renovated, with 20% meeting French low-energy building standards Emphasis on technical innovation for equipment efficiency	Prioritizes renovations over new construction –30% in floor space/cap. in new single-family homes Optimizes the use of vacant and second homes, lowering total housing demand 93% of dwellings renovated, with 79% meeting French low-energy building standards Promotes reasonable use of housing appliances to reduce their energy consumption threefold
Personal mobility	+13% in distance travelled Low modal shift. Focusing on electrification of vehicles and decarbonization of other modes	–32% in distance travelled Greater adoption of active mobility. Shift to light cars and shared usage
Industry	Focus on electrification and energy efficiency Moderate recycling efforts: 50% incorporation rate for plastics, 44% for steel and 55% for aluminum –30% in household spending on textiles –10% on household cleaning products Reduction in plastic packaging	Focus on durability and material sufficiency High recycling efforts: 80% incorporation rate for plastics, 51% for steel and 75% for aluminum –40% in household spending on textiles –20% on household cleaning products Reduction of all packaging
Services	Growing tertiarization: services account for 89% of added value (77% in 2015) 72% of tertiary buildings retrofitted	Strong tertiarization: services account for 85% of added value (77% in 2015) 80% of tertiary buildings retrofitted Strong increase in the shared use of tertiary buildings, limiting the need for new construction

The Efficiency-driven (Eff.) scenario prioritizes technological innovation and energy and material efficiency as the primary levers for decarbonization across all sectors. It reflects a green consumerism worldview, where lifestyles remain broadly like today's, aside from moderate shifts in consumption patterns driven by the decarbonization of domestic energy supply and demand. The scenario aims to reduce final energy demand by 40% relative to 2015 levels, without major changes in social practices or production systems. It is grounded in a green growth paradigm, which assumes that environmental pressures can be decoupled from economic growth through technological innovation. It also assumes continued globalization of trade in goods and services and largely downplays the role of structural vulnerabilities or systemic risks beyond energy dependency.

The Sufficiency-oriented (Suff.) scenario prioritizes deep changes in lifestyles, behaviors, consumption patterns, and production systems. It promotes healthier and less meat-intensive diets, reduced travel demand and smaller vehicles, a decline in new construction, and an overall reduction in the consumption of goods. While it integrates technological solutions such as large-scale building retrofits and

energy-efficient transport, the scenario places them within a broader strategy of reducing overall demand and encouraging sustainable practices across all sectors. It targets a 55% reduction in final energy demand compared to 2015 levels, thereby reducing the reliance on technological mitigation options. The scenario is grounded in a sustainable development paradigm, which sees the low-carbon transition as inseparable from far-reaching societal transformations. It emphasizes resilience by aiming to lower exposure to external risks and vulnerabilities, while safeguarding finite natural resources. It also assumes a partial relocalization of supply chains, with domestic markets prioritized and international trade contracting.

3 Results

3.1 Economy-wide consumption-based GHG emissions and raw materials

Figure 1 presents the GHG emissions (a), and raw materials use (b) embodied in France's domestic final demand in

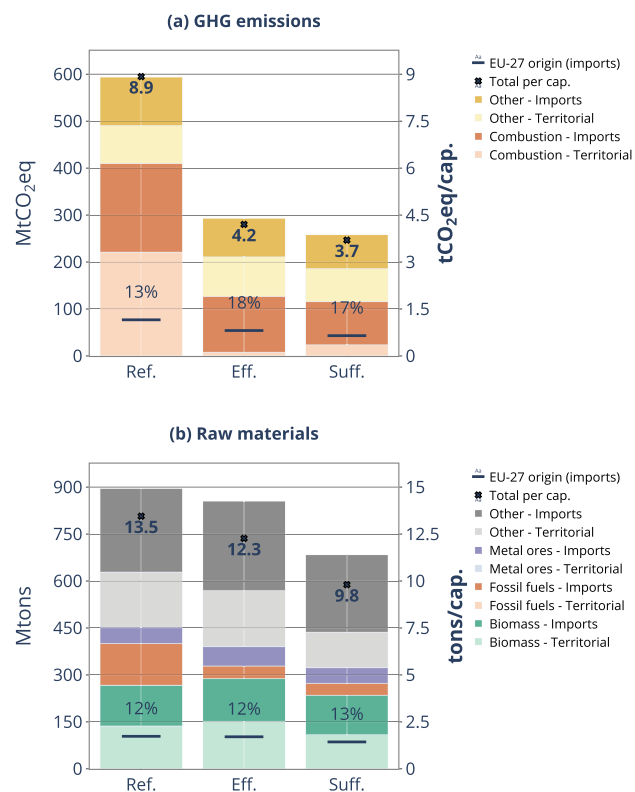


Fig. 1 GHG emissions (panel a) and raw materials (panel b) embodied in French final demand in 2015 (Ref.) and in 2050 under Efficiency-driven (Eff.) and Sufficiency-oriented (Suff.) scenarios, broken down by emission or resource types and origin. Underlying data for Fig. 1 are available in Supplementary Information S11

2015 (Ref.) and 2050 under the Efficiency-driven (Eff.) and the Sufficiency-oriented (Suff.) scenarios. Both indicators are expressed in absolute terms and broken down by type and origin. In each panel, light colors represent territorial emissions and domestic raw material extraction, while dark colors correspond to impacts embodied in imports. GHG emissions are further disaggregated into emissions from fossil fuel combustion and non-combustion sources (e.g. agriculture, industrial processes, and waste), and raw materials are broken down into biomass, fossil fuels, metal ores, and non-metallic minerals. The stacked bars show the total impacts in absolute terms (MtCO₂eq and Mtons, left axis), while black crosses indicate per capita values (tCO₂eq/capita and tons/capita, right axis). The horizontal lines mark the absolute contribution of impacts embodied in imports from EU-27 countries, with their share of total impacts (territorial and imported) reported above each line.

As expected, each scenario achieves a significant reduction in France's GHG emissions by 2050 compared with 2015 (Ref.), with Suff. proving more effective than Eff. Total emissions fall from 594 MtCO₂eq in Ref. (8.9 tCO₂eq/cap.) to 292 MtCO₂eq in Eff. (4.2 tCO₂eq/cap.) and to 258

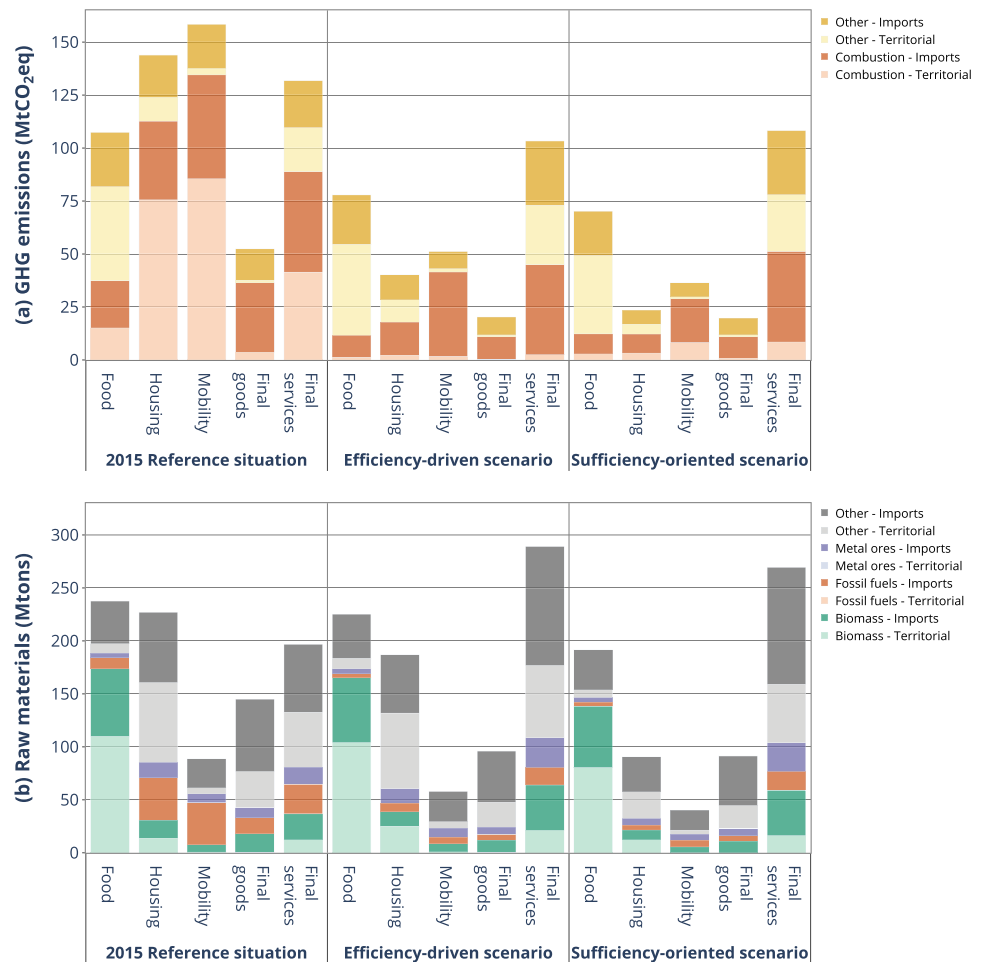
MtCO₂eq in Suff. (3.9 tCO₂eq/cap.). Most of this reduction results from the decline in fossil fuel combustion emissions, both territorial and imported. Territorial combustion-related emissions are nearly eliminated in both scenarios, with Eff. achieving slightly deeper cuts. By contrast, Suff. performs better in addressing other sources of GHG emissions. It reduces territorial non-combustion emissions, while these rise slightly in Eff. Suff. also achieves larger reductions in imported emissions overall (−44% vs. −31% in Eff.), especially those linked to fossil fuel combustion (−51% vs. −37% in Eff.). By lowering overall domestic demand and reorienting markets towards domestic and less material-intensive production, Suff. delivers substantially greater cuts in imported emissions than Eff., even under the same assumptions of global decarbonization and international trade. GHG emissions embodied in imports from EU-27 countries represent only a minor share of France's total emissions: 13% in Ref., rising to 18.5% in Eff. and 16.8% in Suff. with the sharp decline in territorial emissions. This limited contribution indicates that European climate ambitions toward NZE by 2050 will be insufficient to address remaining France's imported emissions, highlighting the need for complementary policy measures.

Only the Suff. scenario achieves a substantial reduction in France's raw material requirements by 2050 compared to 2015 (Ref.). Total raw materials decrease from 895 Mtons in Ref. (13.5 tons/cap.) to 683 Mtons in Suff. (9.8 tons/cap.), while remaining almost unchanged in Eff. at 855 Mtons (12.3 tons/cap.). Eff. reflects a shift in material dependency: while fossil fuel requirements decline by 70%, the demand for other resources increases, by 8% for biomass, 5% for non-metallic minerals, and 18% for metal ores. In contrast, Suff. reduces fossil fuels requirement similarly to Eff. while also lowering other resources requirements by 12% for biomass, 19% for non-metallic minerals and 5% for metal ores. As with GHG emissions, these reductions are driven by lower overall consumption and a reorientation toward locally produced goods and services. Yet, raw material requirements, like GHG emissions, remain largely dependent on imports from outside the EU-27, raising concerns about resilience and vulnerability. Indeed, two-thirds of raw material requirements are embodied in imported, while only 12% comes from the EU-27.

3.2 GHG emissions and raw materials embodied in final consumption categories

Figure 2 presents a sectoral breakdown of consumption-based GHG emissions and raw materials across five final consumption categories: Food, Housing, Mobility, Final goods, and Final services. This breakdown mirrors that of Fig. 1. We compare here the mitigation outcomes for both GHG emissions and raw materials across these categories,

Fig. 2 GHG emissions (panel a) and raw materials (panel b) embodied in final consumption categories in 2015 (Ref.) and in 2050 under future scenarios, by emission or resource types and origin. Underlying data for Fig. 2 are available in Supplementary Information SI2



highlighting the relative effectiveness of Eff. and Suff. in reducing environmental impacts by 2050 compared with 2015 (Ref.), beyond the sole achievement of territorial NZE.

Food-related impacts accounted for 18% of total GHG emissions in 2015 (Ref.), two-thirds of non-combustion sources such as livestock farming and fertilizer use, and 27% of raw material extraction, three-fourths from biomass. By 2050, both scenarios achieve significant reductions in GHG emissions (−27% in Eff. vs. −35% in Suff.), while only Suff. achieves substantial reduction in raw material extraction (−5% in Eff. vs. −19% in Suff.). The stronger performance of Suff. reflects more ambitious dietary shifts, reduced meat consumption, and wider adoption of ecological farming practices, which lower agricultural output and reduce reliance on fertilizers and pesticides. This not only cuts non-combustion emissions more effectively but also reduces biomass extraction (−27%) and, to a lesser extent, fossil fuels and non-metallic minerals. Whereas Eff. delivers only modest gains, mainly incremental dietary changes and reduced food waste, Suff. illustrates the capacity of

sufficiency measures to simultaneously mitigate GHG emissions and raw material pressures in the agri-food system.

Housing and Mobility together accounted for over half of GHG emissions (27% and 24%, respectively), with more than half originating from domestic fossil fuel combustion. They also represented together more than one third of raw material extraction (25% for Housing and 10% for Mobility), with fossil fuels making up a significant share (45% in Mobility and 18% in Housing). These two categories therefore show significant reductions in both scenarios, as fossil fuel use is almost eliminated by 2050 in line with NZE targets.

In Eff., emissions fall by 72% in Housing and 68% in Mobility, driven by improved building insulation, large-scale vehicle electrification, and a 40% reduction in final energy demand through efficiency measures. Territorial emissions drop sharply (−91% on average) while imported emissions decline only moderately (−41% on average). Raw material extraction also decreases (−18% in Housing and −35% in Mobility), but these reductions are largely explained by the phase-out of fossil fuels. Excluding fossil fuels, raw material

extraction remains close to 2015 (Ref.) levels (+5% in Mobility and -4% in Housing), both for domestic extraction and extraction embodied in imports. These figures underscore the limited effect of efficiency measures on embodied pressures.

By contrast, Suff. embeds structural lifestyle changes such as smaller living spaces, reuse of vacant homes, moderate appliance use, lighter and shared vehicles, reduced travel demand (especially less air travel), and a strong shift to active mobility. These changes lower final energy demand by 55% and reduce the need for new equipment and infrastructure based on carbon-intensive materials. As a result, Suff. achieves deeper total emission cuts (-84% in Housing and -77% in Mobility), and higher reductions in imported emissions (-41% on average) while reducing by more than half overall raw material extraction (-60% and -55%, respectively) and raw materials embodied in imports (-62% and -56%, respectively). Even excluding fossil fuels extraction, reductions remain significant (-54% and -31%, respectively). This underscores the potential of sufficiency measures in Housing and Mobility to jointly tackle GHG emissions and raw material extraction. Crucially, sufficiency is also more effective in reducing imported impacts, highlighting its greater ability to mitigate global material-intensive pressures from domestic consumption.

Final services accounted for 22% of both GHG emissions and raw material extraction in 2015 (Ref.). Two-thirds of GHG emissions came from fossil fuel combustion, while raw materials relied on 19% biomass, 14% fossil fuels, 8% metal ores, and 59% non-metallic minerals. More than half of these impacts were embodied in imports, representing 53% of GHG emissions and 67% of raw material extraction. This high dependence on imported emissions and resources may seem surprising, since services are often perceived as relatively dematerialized and low-carbon activities, aside from building energy use. Yet their upstream dependencies reveal substantial indirect impacts, particularly through imports.

By 2050, GHG emissions from services decrease only modestly (-18% in Suff. and -22% in Eff.), mostly due to the phase-out of territorial fossil fuel combustion. However, these reductions are offset by rising imported emissions (+5% in both scenarios). In parallel, raw material extraction rose sharply (+46% in Suff. and +54% in Eff.), despite more than one-third decline in fossil fuel extraction. These trends are largely driven by economic growth and increasing tertiarization. Although stronger tertiarization in Suff., widespread adoption of shared tertiary buildings mitigates new construction needs, limiting raw material extraction compared with Eff.

Similarly, Final goods (textiles, chemical products, and other consumption goods) showed strong import dependency, with imports representing 90% of GHG emissions and 76% of raw materials. By 2050, final goods display

comparable reductions in both scenarios (e.g. -62% in GHG emissions and -34% in raw materials in Suff.), with only minor additional gains in Suff. due to more ambitious sufficiency measures in textiles and household chemical products.

Taken together, Final goods and services highlight France's continued dependence on imported emissions and resources, even when domestic sufficiency measures deliver substantial reductions. This persistent reliance on imports calls for a more detailed assessment of their structure and geographical origin.

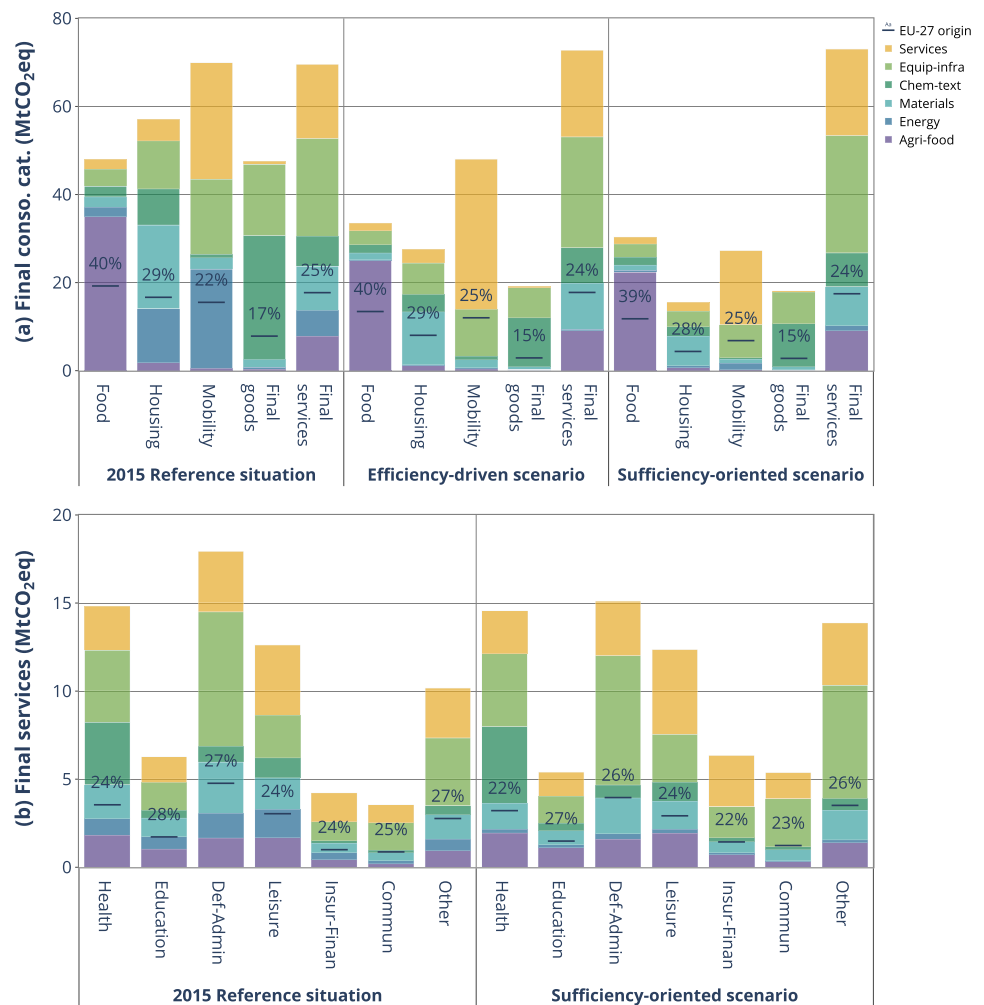
3.3 GHG emissions embodied in imports across final consumption categories

Despite substantial reductions by 2050, consumption-based environmental impacts across all final consumption categories remain structurally and substantially embodied in imports. Once territorial emissions are largely eliminated, tackling these imported impacts therefore emerges as a central challenge. Suff. outperforms Eff. by acting more broadly on material demand, thereby reducing pressures along global supply chains. To further mitigate the residual imported impacts in Suff., it is necessary to better understand their sources, particularly in Final services, which still account for around 40% of total impacts. This requires disentangling both the types of imported products and their geographical origin, particularly the share originating from the EU-27.

To investigate these patterns, we focus on GHG emissions embodied in imported goods and services, as the link with raw materials has already been highlighted. Figure 3 provides a sectoral breakdown of consumption-based imported GHG emissions across the five final consumption categories (panel a) and, more specifically, within seven final service subcategories (panel b). As Eff. and Suff. yield similar results for service-related imports, panel b reports only the Suff. scenario. Each bar represents the total GHG emissions embodied in each final consumption category distinguishing between the types of imported intermediate inputs required for their provision. Horizontal lines indicate the absolute contribution of imported GHG emissions originating from EU-27 countries.

In 2015, imported GHG emissions amounted to 292 MtCO₂eq, distributed as follows: Food (16%), Housing (20%), Mobility (24%) Final goods (16%), and Final services (24%). Both scenarios achieve substantial reductions by 2050, more pronounced under Suff. (-44%) than under Eff. (-31%). The near elimination of energy imports, primarily fossil fuels, provides similar reductions in both scenarios (-14%) and mostly affects emissions in Housing and Mobility (see Figure S4-1a in Supplementary Information SI4). Because global decarbonization assumptions are identical across scenarios, the remaining differences are driven

Fig. 3 Imported GHG emissions embodied in final consumption categories (panel a) and in final services (panel b) in 2015 and in 2050 under future scenarios, by imported intermediate input types required for their provision, and with sectoral contributions originating from EU-27 countries. Underlying data for Fig. 3 are available in Supplementary Information S13



by demand-side transformations. Overall, Sufficiency lowers environmental impacts along global supply chains more effectively, though with contrasting effects across final consumption categories.

Food accounts for around 18% of imported emissions in both scenarios, three-quarters of which originate from agri-food imports. Suff. achieves deeper reductions than Eff. (−36% vs. −29%) by curbing overall imported demand. Housing and Mobility exhibit the most pronounced contrasts once fossil fuel imports are removed. Imported emissions embodied in Housing—mainly from materials, chemicals, and equipment—decline much more sharply under Suff. (−67% vs. −40%), reducing its share to 14% under Eff. and 9% under Suff. Mobility follows a similar pattern. Imported emissions are driven by materials and services, particularly international transport. Sufficiency cuts these impacts substantially (−57% vs. −38% for materials and −36% vs. +29% for services), largely reflecting reductions in air travel and lighter vehicle fleets. Consequently, Mobility represents 24% of imported emissions in Eff., similar to 2015, but falls to

17% in Suff. Finally, imported emissions from Final goods are almost halved in both scenarios, declining from 16% to about 10%, primarily due to global decarbonization.

A persistent blind spot in both scenarios concerns Final services, which remain the main category of GHG emissions. While absolute GHG emissions remain close to 2015 in both scenarios, their share in total imported emissions rises from 24% in 2015 to 36% in Eff. and 44% in Suff. As highlighted earlier, most of their impacts are embodied in imports and thus largely fall outside the scope of current domestic strategies. Figure 3b provides a more detailed decomposition for 2015 and for Suff. in 2050, distinguishing three broad groups: (i) Public services (health, education, defense and administration); (ii) Leisure-related services; and (iii) Market services (finance and insurance, telecommunications, and other services such as trade, equipment rental, innovation, and waste and water management). On average, more than half of imported emissions in Final services are embodied in material-intensive goods, such as equipment,

chemicals, textiles, and construction materials, yet their structure differs markedly across service categories.

Public services accounted for nearly half of imported service-related emissions in 2015. By 2050, they show a marked decline despite rising activity levels, driven by lower energy-related imports (following the decarbonization of buildings and transport) and by reduced emissions from imported materials through sufficiency measures (e.g. higher recycling rates). An exception is Health, where reliance on chemical products and medical equipment offsets these gains, shifting emissions from energy- to material-related sources. In Leisure-related services, declines in domestic fossil fuel combustion and related imports, consistent with the decarbonization of buildings, transport, and energy systems, are largely offset by rising equipment- and service-related imports. By contrast, Market services experience an overall increase in imported emissions by 2050. Their strong reliance on equipment and intermediate services supplied through long and complex global supply chains makes them less responsive to domestic decarbonization. As a result, despite efficiency gains and the phase-out of direct energy imports, significant residual emissions persist.

Overall, emissions embodied in Final services are structurally driven by imported equipment and intermediate services, as well as by the capital formation and infrastructure on which they depend, most of which are highly material- and carbon-intensive.

Figure 3a also allows us to examine the geographical origin of imported impacts across final consumption categories. Emissions embodied in imports from EU-27 countries represented about 26% of France's total imported emissions in 2015. This share varied considerably across categories: Food (40%), Housing (29%), Mobility (22%), Final goods (17%), and Final services (25%). These proportions remain broadly unchanged by 2050 in both scenarios. They reflect the composition of each category in terms of imported goods and services, and the specific value chains mobilized (Figure S4-1a in Supplementary Information SI4). For example, Food is primarily based on agri-food imports, 40% of which originate from the EU-27; Housing relies more on materials, with 44% of which come from the EU-27; while Final services depend heavily on equipment and infrastructure, with only 21% sourced from the EU-27. By contrast, dependency on non-European regions increases when considering raw material extraction, underlining Europe's limited endowment in natural resources (Figure S4-1b in Supplementary Information SI4). This suggests that if France's NZE strategy were embedded within an effective EU-wide climate policy, imported GHG emissions could be further reduced by 43 MtCO₂eq, reaching 121 MtCO₂eq by 2050.

4 Discussion

4.1 Main findings and contributions

This study makes three main contributions to the literature on sufficiency and climate policy.

First, it shows that sufficiency-oriented strategies systematically outperform efficiency-driven pathways in reducing environmental impacts. Efficiency-driven approaches prioritize technological improvements and cleaner production, achieving slightly deeper cuts in territorial combustion-related emissions, but leaving resource use largely unchanged and failing to address imported emissions. In contrast, sufficiency delivers deeper reductions in both GHG emissions and raw materials by lowering domestic demand and shifting consumption toward locally produced, less material-intensive goods and services. This demonstrates its upstream mitigation potential, extending beyond territorial boundaries into global supply chains, an aspect still overlooked in national and European NZE strategies. Beyond climate mitigation, sufficiency also strengthens resilience to economic and geopolitical supply risks, while alleviating wider ecological pressures linked to resource extraction, including biodiversity loss, water and soil degradation, and unsustainable mineral use.

Second, disaggregating impacts across final consumption categories reveals the specific domains where sufficiency is most effective. In Housing, Mobility, and Food, lifestyle and demand-side changes (e.g. smaller dwellings, reuse of existing housing stock, lighter and shared vehicles, reduced land and air travel, and dietary shifts) drive structural reductions in energy demand and material-intensive equipment and infrastructure. These mechanisms explain why sufficiency delivers deeper territorial and imported environmental impacts reductions than efficiency. This finding underscores the importance of broadening NZE strategies beyond energy supply and technological substitution, to explicitly complement technological innovations with sufficiency measures that explicitly target the material basis of everyday consumption.

Third, the study highlights several structural blind spots that remain largely unaddressed. A substantial share of France's environmental impacts continues to be embodied in imports by 2050, confirming persistent external dependencies despite declining fossil fuel imports and partial decarbonization abroad. Among them, Final services stand out as the main category where GHG emissions and raw material use show little change across scenarios. This reflects the fact that low-carbon and sufficiency strategies have primarily targeted housing, mobility, and food, while services are often perceived as less material- and carbon-intensive. Yet their provision depends heavily on

capital formation, equipment and infrastructure, based on complex global supply chains, making them difficult to decarbonize through domestic measures alone. Moreover, a large share of imported impacts originates outside the EU, implying that even a fully effective European decarbonization strategy could only address about one quarter of France's remaining imported emissions.

Taken together, these findings highlight both the potential and the limits of sufficiency. While it addresses upstream pressures more effectively than efficiency, it cannot on its own overcome structural dependencies on imported emissions and resources. This calls for rethinking sustainability strategies beyond Housing, Mobility, and Food, toward a systemic perspective that explicitly integrates service provision and the governance of international supply chains.

4.2 Implications for sufficiency-oriented strategies

In an increasingly service-based economy and with an ageing population (European Commission, 2024), demand for services such as healthcare (Andrieu et al., 2023) is expected to grow substantially. Our results show that services account for a growing share of indirect environmental impacts, largely through their dependence on capital-intensive requirements such as buildings, IT equipment, and vehicles. Yet current sufficiency strategies focus narrowly on individual choices in housing, mobility, and food, without addressing the structural transformations needed in service provision. As a result, the environmental burden of services underscores the need for policies that explicitly target upstream supply chains and extend beyond domestic sufficiency or efficiency measures, so that progress toward Net Zero territorial emissions is not undermined by rising imported impacts.

Future sufficiency strategies should address consumption behaviors in overall services, with careful attention to potential rebound effects. Savings achieved through reductions in housing, mobility, or food consumption could otherwise be redirected toward high-impact services such as leisure and tourism (Chen et al., 2026; Sun et al., 2024), undermining the expected environmental benefits. Anticipating and mitigating these rebounds requires systemic policy design that links sufficiency with regulation on both service demand and supply sides. Beyond consumption, sufficiency should also target the production of services by promoting functional, circular, and shared-use systems (Aguilar-Hernandez et al., 2018; Homrich et al., 2018; Korhonen et al., 2018). This includes shifting from ownership-based to access-based models, extending the lifetime of capital goods, and investing in promoting shared infrastructures that reduce the need for new production. It should also directly tackle the material and land intensity of the capital and infrastructure

underpinning service provision, which remain major drivers of upstream environmental impacts (Hertwich, 2021).

4.3 Global interdependencies and policy implications

This study shows that France's ability to reduce imported environmental impacts cannot rely solely on existing European climate policies, which primarily target the decarbonization of territorial emissions without challenging current consumption levels or globalized trade patterns. Since the most carbon- and material-intensive segments of global supply chains are located outside the EU, achieving Net-Zero territorial emissions will not suffice to curb the environmental impacts embodied in European imports. Moreover, current decarbonization strategies are defined independently at the national level, with each member state pursuing its own approach. Addressing these cross-border dependencies requires strengthening policy alignment within the EU and extending the scope of climate strategies beyond territorial boundaries to explicitly account for imported environmental pressures.

Building on this need for coordination, sufficiency strategies should be complemented by EU-level measures that target upstream dependencies and external vulnerabilities. This could involve rethinking the role of strategic relocation and selective reindustrialization within the EU, not only to mitigate imported environmental impacts but also to enhance resilience to external supply shocks. In parallel, instruments such as the Carbon Border Adjustment Mechanism (CBAM), sustainability-oriented trade agreements, and stronger coordination between EU resource and climate policies are needed to align international supply chains with Europe's broader climate and industrial ambitions. Such efforts call for a genuinely European strategy integrating climate, trade, and industrial policies, rather than a set of disconnected national initiatives.

Beyond technical and economic instruments, scaling up sufficiency also requires addressing the institutional, political, and business barriers that constrain its adoption. Sufficiency challenges growth-oriented policy frameworks and entrenched profit-maximizing logics, particularly in service-based economies where profitability depends on continuous expansion of demand. Overcoming these obstacles will require new governance mechanisms, incentive structures, and cultural narratives that legitimize sufficiency as a central pillar of sustainability transitions.

4.4 Limitations and directions for future research

This study has several limitations that open avenues for future research. First, the scope of sufficiency measures and behavioral assumptions is restricted to household

consumption in housing, mobility, and food. While this reflects the sectors most commonly addressed in sufficiency scenarios, it does not extend behavioral changes to services (Briens, 2015), even though services are increasingly central to environmental pressures. Future research should therefore explore systemic sufficiency strategies that integrate all sectors, including services, in a consistent manner. Second, both scenarios rely on static trade structures and assume a uniform global decarbonization trajectory consistent with a +3 °C warming pathway. This approach limits the ability to capture differentiated regional climate efforts, shifting trade relations, or EU-level industrial policies that could reshape imported environmental impacts. Although this paper focuses on France, the results are likely relevant for the European Union as a whole, given the similarity of consumption patterns and structural import dependencies. Extending the analysis to European-scale scenarios, such as those developed in projects like CLEVER (Wiese et al., 2024), would help test the robustness of these findings under alternative trade and policy configurations.

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Author contributions A.T. was responsible for the conceptualization and overall design of the study, developed the methodology and the software, implemented the simulations and performed the formal analyses, led the interpretation of the results, designed and prepared the visualizations, and wrote the original draft of the manuscript while coordinating subsequent revisions. F.V. participated in the interpretation of the results and contributed to the writing by reviewing, revising, and rewriting selected sections of the manuscript. Both authors contributed to data curation, including model calibration and parametrization.

Data availability The MatMat v1.0.0 modeling framework, developed in Python, will be released as open source in early 2026 on GitHub and archived on Zenodo with a dedicated DOI. The model calibration is based on Exiobase v3.8.2, which is publicly available at <https://doi.org/10.5281/zenodo.5589597>. The scenario data and consumption-based results supporting the figures and key findings of this article (including GHG emissions and raw material extraction embodied in final demand and imports), are openly available on Zenodo at <https://doi.org/10.5281/zenodo.18418965>. Data supporting the figures and key results are provided in the supporting information. Additional detailed outputs can be obtained from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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References

- Ademe, Devauze, C., Koite, A., Chretien, A., & Monier, V. (2021). *Bilan national du recyclage 2010–2019: Évolutions du recyclage en France de différents matériaux: Métaux ferreux et non ferreux, papierscartons, verre, plastiques, inertes du BTP et bois* (p. 99). ADEME. (2021). *Transition(s) 2050—Decide now. Act for the climate*.
- Aguilar-Hernandez, G. A., Sigüenza-Sanchez, C. P., Donati, F., Rodrigues, J. F. D., & Tukker, A. (2018). Assessing circularity interventions: A review of EEIOA-based studies. *Journal of Economic Structures*, 7(1), Article 1. <https://doi.org/10.1186/s40008-018-0113-3>
- Andrieu, B., Marraud, L., Vidal, O., Egnell, M., Boyer, L., & Fond, G. (2023). Health-care systems' resource footprints and their access and quality in 49 regions between 1995 and 2015: An input–output analysis. *The Lancet Planetary Health*, 7(9), e747–e758.
- Baude, M., & Larrieu, S. (2024). *Estimation de l'empreinte carbone de la France entre 1990 et 2023*. <https://www.statistiques.developpement-durable.gouv.fr/media/7856/download?inline>
- Briens, F. (2015). *La Décroissance au prisme de la modélisation prospective: Exploration macroéconomique d'une alternative paradigmatique* [PhD Thesis]. Ecole Nationale Supérieure des Mines de Paris.
- Callonnec, G., Landa, G., Malliet, P., Reynès, F., & Yeddir-Tamsamani, Y. (2013). *A full description of the Three-ME model: Multi-sector Macroeconomic Model for the Evaluation of Environmental and Energy policy*. <https://www.threeme.org/documentation>
- Chen, P., Malik, A., Song, J., Lenzen, M., Chen, Z., Li, M., & Chen, Z.-M. (2026). Disparities and flows analysis of global leisure carbon footprints. *Resources, Conservation and Recycling*, 224, Article 108535. <https://doi.org/10.1016/j.resconrec.2025.108535>
- Costa, L., Moreau, V., Thurm, B., Yu, W., Clara, F., Baudry, G., Warmuth, H., Hezel, B., Seydewitz, T., Ranković, A., Kelly, G., & Kropp, J. P. (2021). The decarbonisation of Europe powered by lifestyle changes. *Environmental Research Letters*, 16(4), Article 044057. <https://doi.org/10.1088/1748-9326/abe890>
- Creutzig, F., Niamir, L., Bai, X., Callaghan, M., Cullen, J., Díaz-José, J., Figueroa, M., Grubler, A., Lamb, W. F., Leip, A., Masanet, E., Mata, É., Mattauch, L., Minx, J. C., Mirasgedis, S., Mulugetta, Y., Nugroho, S. B., Pathak, M., Perkins, P., ... Ürges-Vorsatz, D. (2022). Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nature Climate Change*, 12(1), 36–46. <https://doi.org/10.1038/s41558-021-01219-y>
- Creutzig, F., Roy, J., Devine-Wright, P., Díaz-José, J., Geels, F. W., Grubler, A., Mäzi, N., Masane, E., Mulugetta, Y., Onyige, C. D., & others. (2023). Demand, services and social aspects of mitigation (Chapter 5). *IPCC 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 503–612.
- Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M. L., de Bruine Bruin, W., Dalkmann, H., Edelenbosch, O. Y., Geels, F. W., Grubler, A., Hepburn, C., Hertwich, E. G., Khosla, R., Mattauch, L., Minx, J.

- C., Ramakrishnan, A., Rao, N. D., Steinberger, J. K., Tavoni, M., Ürge-Vorsatz, D., & Weber, E. U. (2018). Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, 8(4), 260–263. <https://doi.org/10.1038/s41558-018-0121-1>
- Creutzig, F., Simoes, S. G., Leipold, S., Berrill, P., Azevedo, I., Edelenbosch, O., Fishman, T., Haberl, H., Hertwich, E., Krey, V., Lima, A. T., Makov, T., Mastrucci, A., Milojevic-Dupont, N., Nachtigall, F., Pauliuk, S., Silva, M., Verdolini, E., van Vuuren, D., ... Wilson, C. (2024). Demand-side strategies key for mitigating material impacts of energy transitions. *Nature Climate Change*, 14(6), 561–572. <https://doi.org/10.1038/s41558-024-02016-z>
- De Koning, A., Huppel, G., Deetman, S., & Tukker, A. (2016). Scenarios for a 2 C world: A trade-linked input–output model with high sector detail. *Climate Policy*, 16(3), 301–317.
- Distefano, T., Lodi, L., & Biggeri, M. (2024). Material footprint and import dependency in EU27: Past trends and future challenges. *Journal of Cleaner Production*, 472, Article 143384. <https://doi.org/10.1016/j.jclepro.2024.143384>
- European Commission & Eurostat. (2018). *Economy-wide material flow accounts handbook* (2018th ed.). Publications Office.
- European Commission, & Eurostat. (2019). *Energy balance guide: Methodology guide for the construction of energy balances & Operational guide for the energy balance builder tool*. Publications Office.
- European Commission. (2024). *2024 Ageing Report: Economic & Budgetary Projections for the EU Member States (2022–2070)*. European Economy Institutional Papers, Institutional Paper 279, European ...
- Grubb, M., Jordan, N. D., Hertwich, E. G., Neuhoff, K., Das, K., Bandyopadhyay, K. R., Van Asselt, H., Sato, M., Wang, R., Pizer, W. A., Hertwich, E., & Oh, H. (2022). Carbon leakage, consumption, and trade. *Annual Review of Environment and Resources*, 47, 753–795.
- Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McColm, D. L., Rao, N. D., Riahi, K., Rogelj, J., De Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., & Valin, H. (2018). A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nature Energy*. <https://doi.org/10.1038/s41560-018-0172-6>
- Hertwich, E. G. (2021). Increased carbon footprint of materials production driven by rise in investments. *Nature Geoscience*. <https://doi.org/10.1038/s41561-021-00690-8>
- Hertwich, E. G., Ali, S., Ciacci, L., Fishman, T., Heeren, N., Masanet, E., Asghari, F. N., Olivetti, E., Pauliuk, S., Tu, Q., & Wolfram, P. (2019). Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—A review. *Environmental Research Letters*. <https://doi.org/10.1088/1748-9326/ab0fe3>
- Homrich, A. S., Galvão, G., Abadia, L. G., & Carvalho, M. M. (2018). The circular economy umbrella: Trends and gaps on integrating pathways. *Journal of Cleaner Production*, 175, 525–543.
- IEA. (2022). *World Energy Outlook 2022*. IEA, Paris, France. <https://www.iea.org/reports/world-energy-outlook-2022>
- Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., & Creutzig, F. (2020). Quantifying the potential for climate change mitigation of consumption options. *Environmental Research Letters*, 15(9), Article 093001. <https://doi.org/10.1088/1748-9326/ab8589>
- Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: The concept and its limitations. *Ecological Economics*, 143, 37–46.
- Krausmann, F., Wiedenhofer, D., & Haberl, H. (2020). Growing stocks of buildings, infrastructures and machinery as key challenge for compliance with climate targets. *Global Environmental Change*, 61, Article 102034. <https://doi.org/10.1016/j.gloenvcha.2020.102034>
- Ministère de la Transition Écologique. (2015). *Loi Transition Écologique Pour la Croissance Verte n° 2015–992 du 17 août 2015*. <https://www.legifrance.gouv.fr/loda/id/JORFTEXT000031044385/>
- Ministère de la Transition Écologique. (2020). *Stratégie Nationale Bas-Carbone*. <https://www.ecologie.gouv.fr/strategie-nationale-bas-carbone-snb>
- Ministère de la Transition Écologique. (2021). *Loi Climat et Résilience n° 2021–1104 du 22 août 2021*. <https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000043956924>
- Moran, D., Wood, R., Hertwich, E., Mattson, K., Rodriguez, J. F. D., Schanes, K., & Barrett, J. (2020). Quantifying the potential for consumer-oriented policy to reduce European and foreign carbon emissions. *Climate Policy*, 20(sup1), S28–S38. <https://doi.org/10.1080/14693062.2018.1551186>
- Morfeldt, J., Larsson, J., Andersson, D., Johansson, D. J. A., Rootzén, J., Hult, C., & Karlsson, I. (2023). Emission pathways and mitigation options for achieving consumption-based climate targets in Sweden. *Communications Earth & Environment*, 4(1), Article 342. <https://doi.org/10.1038/s43247-023-01012-z>
- Müller, D. B., Liu, G., Løvik, A. N., Modaresi, R., Pauliuk, S., Steinhoff, F. S., & Brattebø, H. (2013). Carbon emissions of infrastructure development. *Environmental Science & Technology*. <https://doi.org/10.1021/es402618m>
- Pauliuk, S., Heeren, N., Berrill, P., Fishman, T., Nistad, A., Tu, Q., Wolfram, P., & Hertwich, E. G. (2021). Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nature Communications*, 12(1), Article 5097. <https://doi.org/10.1038/s41467-021-25300-4>
- Sandberg, M. (2021). Sufficiency transitions: A review of consumption changes for environmental sustainability. *Journal of Cleaner Production*, 293, Article 126097. <https://doi.org/10.1016/j.jclepro.2021.126097>
- Södersten, C.-J.H., Wood, R., & Hertwich, E. G. (2018). Endogenizing capital in MRIO models: The implications for consumption-based accounting. *Environmental Science & Technology*, 52(22), 13250–13259. <https://doi.org/10.1021/acs.est.8b02791>
- Springmann, M., Godfray, H. C. J., Rayner, M., & Scarborough, P. (2016). Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, 113(15), 4146–4151. <https://doi.org/10.1073/pnas.1523119113>
- Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., ... Tukker, A. (2021). EXIOBASE 3. <https://doi.org/10.5281/zenodo.5589597>
- Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., & Tukker, A. (2018). EXIOBASE 3: Developing a time series of detailed environmentally extended multi-regional input-output tables. *Journal of Industrial Ecology*, 22(3), 502–515. <https://doi.org/10.1111/jiec.12715>
- Stehrer, R. (2021). *Wiiw Growth and Productivity Data*. <https://eukle.ms.eu/>
- Sugiyama, M., Wilson, C., Wiedenhofer, D., Boza-Kiss, B., Cao, T., Chatterjee, J. S., Chatterjee, S., Hara, T., Hayashi, A., Ju, Y., Krey, V., Godoy León, M. F., Martínez, L., Masanet, E., Mastrucci, A., Min, J., Niamir, L., Pelz, S., Roy, J., & Zimm, C. (2024). High with low: Harnessing the power of demand-side solutions for high

- wellbeing with low energy and material demand. *Joule*, 8(1), 1–6. <https://doi.org/10.1016/j.joule.2023.12.014>
- Sun, Y.-Y., Faturay, F., Lenzen, M., Gössling, S., & Higham, J. (2024). Drivers of global tourism carbon emissions. *Nature Communications*, 15(1), Article 10384. <https://doi.org/10.1038/s41467-024-54582-7>
- Teixeira, A. (2024). *MatMat—Hybrid Input-Output framework to estimate country-level carbon and material footprints in future scenarios*. HAL. <https://hal.science/hal-04672116>
- Teixeira, A., & Lefèvre, J. (2025). Global supply chains and domestic climate policy: Addressing the substantial material-related carbon footprint of final consumption in France. *Journal of Industrial Ecology*. <https://doi.org/10.1111/jiec.70001>
- Teixeira, A., & Vicard, F. (2025). Comparing the sustainability of energy sufficiency & technological change in NZE strategies in France. *19th Society and Materials (SAM) International Conference*. <https://hal.science/hal-05076611>
- Teixeira, A., Grand, J., Vicard, F., Lefevre, J., & Fontaine, B. (2025). MatMat v1.0.0—A modular Input-Output framework: Assessing country-driven environmental and socio-economic impacts of forward-looking scenarios along global supply chains. *19th Society and Materials (SAM) International Conference*. <https://hal.science/hal-05076595>
- Tsiropoulos, Nijs, Tarvydas, & Ruiz Castello. (2020). *Towards net-zero emissions in the EU energy system by 2050* (No. KJ-NA-29981-EN-N (online), KJ-NA-29981-EN-C (print)). *KJ-NA-29981-EN-N (online), KJ-NA-29981-EN-C (print)*, Article KJ-NA-29981-EN-N (online), KJ-NA-29981-EN-C (print). <https://doi.org/10.2760/081488%2520>
- Tukker, A., Giljum, S., & Wood, R. (2018). Recent progress in assessment of resource efficiency and environmental impacts embodied in trade: An introduction to this Special Issue. *Journal of Industrial Ecology*, 22(3), 489–501. <https://doi.org/10.1111/jiec.12736>
- van de Ven, D.-J., González-Eguino, M., & Arto, I. (2018). The potential of behavioural change for climate change mitigation: A case study for the European Union. *Mitigation and Adaptation Strategies for Global Change*, 23(6), 853–886. <https://doi.org/10.1007/s11027-017-9763-y>
- van Heerden, R., Edelenbosch, O. Y., Daioglou, V., Le Gallic, T., Baptista, L. B., Di Bella, A., Colelli, F. P., Emmerling, J., Fragkos, P., Hasse, R., Hoppe, J., Kishimoto, P., Leblanc, F., Lefèvre, J., Luderer, G., Marangoni, G., Mastrucci, A., Pettifor, H., Pietzcker, R., & van Vuuren, D. (2025). Demand-side strategies enable rapid and deep cuts in buildings and transport emissions to 2050. *Nature Energy*, 10(3), 380–394. <https://doi.org/10.1038/s41560-025-01703-1>
- van Sluisveld, M. A. E., Martínez, S. H., Daioglou, V., & van Vuuren, D. P. (2016). Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, 102, 309–319. <https://doi.org/10.1016/j.techfore.2015.08.013>
- Vicard, F., & Teixeira, A. (2024). *Feuilleton Évaluation des empreintes carbone et matières des scénarios Transition(s) 2050*. ADEME. <https://bibliothèque.ademe.fr/changement-climatique-et-energie/6250-prospective-transitions-2050-feuilleton-empreintes.html>
- Vita, G., Lundström, J. R., Hertwich, E. G., Quist, J., Ivanova, D., Stadler, K., & Wood, R. (2019). The environmental impact of green consumption and sufficiency lifestyles scenarios in Europe: Connecting local sustainability visions to global consequences. *Ecological Economics*, 164, Article 106322. <https://doi.org/10.1016/j.ecolecon.2019.05.002>
- Wei, W., Li, J., Chen, B., Wang, M., Zhang, P., Guan, D., Meng, J., Qian, H., Cheng, Y., Kang, C., Feng, K., Yang, Q., Zhang, N., Liang, X., & Xue, J. (2021). Embodied greenhouse gas emissions from building China's large-scale power transmission infrastructure. *Nature Sustainability*, 4(8), 739–747. <https://doi.org/10.1038/s41893-021-00704-8>
- Wiebe, K. S., Bjelle, E. L., Többen, J., & Wood, R. (2018). Implementing exogenous scenarios in a global MRIO model for the estimation of future environmental footprints. *Journal of Economic Structures*, 7(1), Article 1. <https://doi.org/10.1186/s40008-018-0118-y>
- Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. *Proceedings of the National Academy of Sciences*, 112(20), 6271–6276.
- Wiese, F., Taillard, N., Balembois, E., Best, B., Bourgeois, S., Campos, J., Cordroch, L., Djelali, M., Gabert, A., Jacob, A., Johnson, E., Meyer, S., Munkácsy, B., Pagliano, L., Quoilin, S., Roscetti, A., Thema, J., Thiran, P., Toledano, A., & Marignac, Y. (2024). The key role of sufficiency for low demand-based carbon neutrality and energy security across Europe. *Nature Communications*, 15(1), Article 9043. <https://doi.org/10.1038/s41467-024-53393-0>
- Wood, R., Neuhoff, K., Moran, D., Simas, M., Grubb, M., & Stadler, K. (2020). The structure, drivers and policy implications of the European carbon footprint. *Climate Policy*, 20(sup1), Article sup1. <https://doi.org/10.1080/14693062.2019.1639489>
- Ye, Q., Hertwich, E. G., Krol, M. S., Font Vivanco, D., Lounsbury, A. W., Zheng, X., Hoekstra, A. Y., Wang, Y., & Wang, R. (2021). Linking the environmental pressures of China's capital development to global final consumption of the past decades and into the future. *Environmental Science & Technology*, 55(9), 6421–6429. <https://doi.org/10.1021/acs.est.0c07263>

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