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Trade and decoupling of fossil fuel use embedded in EU consumption

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ABSTRACT

The EU is frequently recognised as a frontrunner in tackling climate change; however, this assessment primarily relies on production-based evaluations, overlooking the significant role of imports. We conduct a detailed consumption-based analysis of how EU consumption drives global fossil fuel use, combining input–output with structural decomposition analysis and the subsystem approach. We find that the embedded EU fossil fuel footprint has experienced a notable decline between 2000 and 2014, but at rates incompatible with 1.5 °C. We identify trade patterns to be an important upward driver of the EU footprint through intermediate production, also thwarting the impact of the energy transition with effects from changes outside the EU lagging within EU developments. Addressing these outsourcing patterns to more fossil fuel intense production could reduce the EU footprint by almost 20%. We find that more than 50% of fossil fuels embedded in imports are linked to indirect imports. Thus, we argue for the EU Carbon Border Adjustment Mechanism to include indirect imports, particularly of electricity. Yet, given the problematic role of growth, even energy transition efforts along the global supply chain will likely need to be complemented by demand side measures, potentially entailing post-growth pathways.

1. Introduction

Fossil fuels are the dominant driver of anthropogenic CO_2 emissions (Friedlingstein et al., 2022) and in order to keep global warming below 1.5 °C, fossil fuel use has to decline immediately and rapidly (SEI et al., 2020, 2021) and a substantial amount cannot be extracted (Welsby et al., 2021; IPCC, 2022). Hence, addressing climate change means to phase out fossil fuels. However, assessing this issue solely in terms of emissions overlooks lock-in effects and uncertainty in leakage (Shearer et al., 2020). It can thus paint an overoptimistic picture, with natural gas playing an increasingly important role in the global energy system (Jackson et al., 2019). Even though a switch from coal to gas reduces emissions temporarily, it still constitutes an emitting fossil fuel required to be phased out in the absence of negative emission technologies (Peters et al., 2020).

The EU provides an insightful case study since on the one hand it is one of the major fossil CO_2 emitters, but on the other hand has made most progress as a region to reduce the fossil fuel dependence of its energy system (Jackson et al., 2019) and continues to have relatively ambitious goals (European Commission, 2021c). However, many climate mitigation analyses (Peters et al., 2017; Eskander and Fankhauser, 2020) and policies take a production-based approach, focusing on national/regional production structures, and hence do not fully incorporate the responsibility of EU consumption in driving global fossil fuel use. This is a particularly crucial shortcoming for richer regions like the EU, which typically net import environmental impacts (Wiedmann and Lenzen, 2018), as shown for emissions often increasingly from lower income countries (Wang et al., 2024). Hence, carbon leakage (we refer to weak carbon, or here fossil fuel, leakage, i.e. increases in emissions abroad driven by demand, regardless of climate policies Peters and Hertwich, 2008) plays an important role with implications for the effectiveness of current climate policies. This is not only due to geographical re-allocation of production structures and hence policy coverage, but also has been shown directly increase overall emissions (Hoekstra et al., 2016).

To tackle the concern of trade and embedded emissions, the European Commission has proposed a Carbon Border Adjustment Mechanism (CBAM), planned to commence in 2026 following a transitional phase. It will focus on direct emissions and in the first phase on the cement, iron and steel, aluminium, fertilisers and electricity sectors. Importers will have to buy certificates at the price of the EU emissions trading system (ETS), minus carbon prices that were due at the source of production (European Commission, 2021a,b). A CBAM addresses leakage by targeting distortions in competitiveness due to differing carbon prices and tilts the policy focus towards consumption-based emissions (Böhringer et al., 2022).

Thus, in this work, we analyse the dynamics and decoupling of fossil fuel dependence embedded in EU consumption, taking into account leakage by allocating responsibility of environmental impacts along the supply chain to the final consumers (Peters and Hertwich, 2008a; Davis

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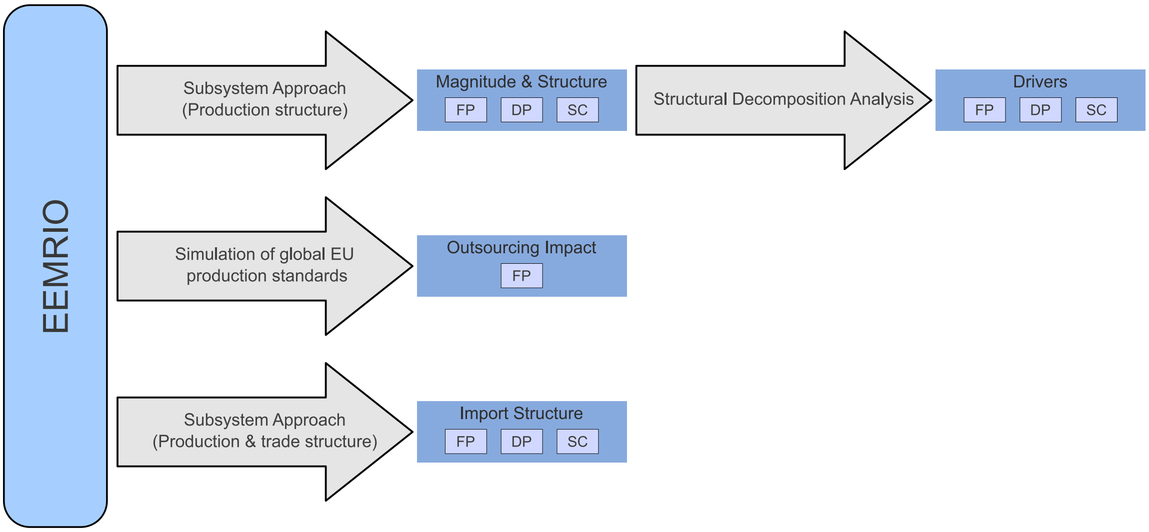

Fig. 1. Flowchart linking the methodologies used and the results obtained. FP (fossil fuel footprint), DP (fossil fuels used in direct final production) and SC (fossil fuel use embedded as intermediate inputs) indicate which components the methodology is applied to and/or provides results for.

and Caldeira, 2010). In order to trace the drivers behind decoupling or the lack thereof in detail, we combine an environmentally extended multiregional Input–output (EEMRIO) framework with the subsystem approach and structural decomposition analysis (SDA). In addition, we evaluate the potential of the proposed CBAM to address the fossil fuel footprint by quantifying its coverage using the subsystem approach and by simulating an artificial no-trade scenario.

We provide the first IO-SDA study of EU consumption focusing explicitly on fossil fuels complementing existing emission and energy studies (see Karstensen et al. (2018), Wood et al. (2020b) and Fernández-Amador et al. (2023) for the EU). As aforementioned, emission-based studies can provide a distorted picture whereas total energy use omit the role of the energy mix and hence does not adequately reflect its environmental impact. In addition, we add crucial level of detail to existing studies by singling out the energy transition and its regional developments and combining the subsystem approach with SDA. This allows us to trace drivers and policy implications more rigorously. Finally, addressing the CBAM, we introduce a novel application of subsystem approach allowing us to provide the first economy wide consumption-based quantification of directly and indirectly imported fossil fuel use into the EU.

The paper is organised as follows: Section 2 introduces the application of the EEMRIO-SDA and the subsystem framework. The quantitative results are presented in Section 3 and policy implications and methodological issues are discussed in Section 4. Finally, Section 5 summarises the main findings.

2. Material and methods

Fig. 1 illustrates the application and outcomes of the individual methodologies used in this paper. We use the Subsystem Approach (production structure) to answer questions about the magnitude of the total embedded fossil fuel footprint (FP) , how it is structured and what their dynamics are. Subsequently, we apply a Structural Decomposition Analysis to FP and its components to quantify their respective drivers. The simulation of EU production standards provides an estimate of the magnitude of the overall impact of outsourcing and hence potential gains in tackling this issue. Finally, the novel application of the Subsystem Approach (production & trade structure) is applied to quantify direct and indirect embedded imports.

2.1. Footprints

We first apply the standard Leontief EEMRIO approach in order to calculate consumption-based fossil fuel use. Total output $\boldsymbol{x}$ is given by $\boldsymbol{Ax} + \boldsymbol{y} = \boldsymbol{x}$, where $\boldsymbol{A}$ is the matrix of technical coefficients, capturing direct input requirements per unit output and $\boldsymbol{y}$ is final demand. Isolating $\boldsymbol{x}$ produces $(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} = \boldsymbol{Ly} = \boldsymbol{x}$, with $\boldsymbol{L}$ being the so called Leontief inverse, where element L_{ij}^{rs} reflects total inputs (direct and indirect) required by sector j in region s from sector i in region r per unit output.

In order to trace environmental impacts, the environmental extension vector ($\boldsymbol{e}$) assigns the impact (here TJ of fossil fuel use) per unit output to each sector in each region. Subsequently, $\boldsymbol{L}$ is pre-multiplied with the diagonalised vector $\hat{\boldsymbol{e}}$.

In addition, we modify the final demand vector $\boldsymbol{y}$ to a matrix $\hat{\boldsymbol{Y}}$, where each region to region demand vector is diagonalised. The final matrix $\boldsymbol{Q}$ produces total environmental impact by sector and region of final consumption if summed over rows (i.e. embedded environmental footprint), and region and sector of origin if summed over columns. It is given by

$$\boldsymbol{Q} = \hat{\boldsymbol{e}}\boldsymbol{L}\hat{\boldsymbol{Y}}. \tag{1}$$

The final demand matrix aggregates final consumption from the EU27 countries , yet note that due to data issues the Netherlands is excluded from our analysis. We include consumption of households, non-profit organisations serving households and the government as they can all be linked directly to lifestyles. .

For more details, the Supplementary Material provides more data on the analysis and Miller and Blair (2009) present a thorough explanation of IO analysis.

2.2. Subsystem approach

To distinguish different components in the chain of production within the environmental footprint, we apply the subsystem approach. The general approach is described in detail in Alcántara and Padilla (2009) and features a range of applications tracing environmental impacts such as Ma et al. (2019). In its typical application it reveals the production and emission structure of sectors, rendering it particularly useful for more focused policy recommendations (Alcántara et al., 2017).

Essentially, the framework distinguishes between intermediate inputs required on the one hand and final production on the other. It does so by using from the standard IO approach that $\boldsymbol{x} = \boldsymbol{L}\boldsymbol{y}$ and inserting this expression for $\boldsymbol{x}$ into the basic equation $\boldsymbol{A}\boldsymbol{x} + \boldsymbol{y} = \boldsymbol{x}$, resulting in $\boldsymbol{A}\boldsymbol{L}\boldsymbol{y} + \boldsymbol{y} = \boldsymbol{x}$ (Alcántara and Padilla, 2009).

On the one hand, we use this approach to distinguish the FP between fossil fuels used in direct final production (DP) and embedded as intermediate inputs through the rest of the supply chain (SC):

$$\boldsymbol{Q} = \overbrace{\underbrace{\hat{\boldsymbol{e}}\boldsymbol{A}\boldsymbol{L}\hat{\boldsymbol{Y}}}_{\text{SC}} + \underbrace{\hat{\boldsymbol{e}}\hat{\boldsymbol{Y}}}_{\text{DP}}}^{\text{FP}} = \boldsymbol{Q}_{SC} + \boldsymbol{Q}_{DP}. \tag{2}$$

This is the production structure subsystem approach in Fig. 1. To obtain respective consumption-based intensities of final demand, we simply omit $\hat{\boldsymbol{Y}}$ in Eqs. (1),(2), i.e. we divide FP/SC/DP by chain linked final demand.

On the other hand, to address the potential coverage of the EU CBAM, we rewrite (2) in regional block matrices

$$\widehat{\begin{bmatrix} \boldsymbol{e}^C \\ \boldsymbol{e}^N \end{bmatrix}} \begin{bmatrix} \boldsymbol{A}^{CC} & \boldsymbol{A}^{CN} \\ \boldsymbol{A}^{NC} & \boldsymbol{A}^{NN} \end{bmatrix} \begin{bmatrix} \boldsymbol{L}^{CC} & \boldsymbol{L}^{CN} \\ \boldsymbol{L}^{NC} & \boldsymbol{L}^{NN} \end{bmatrix} \begin{bmatrix} \hat{\boldsymbol{Y}}^C \\ \hat{\boldsymbol{Y}}^N \end{bmatrix} + \widehat{\begin{bmatrix} \boldsymbol{e}^C \\ \boldsymbol{e}^N \end{bmatrix}} \begin{bmatrix} \hat{\boldsymbol{Y}}^C \\ \hat{\boldsymbol{Y}}^N \end{bmatrix} = \begin{bmatrix} \boldsymbol{Q}^C \\ \boldsymbol{Q}^N \end{bmatrix}, \tag{3}$$

where the superscript C indicates all countries that are covered by or linked to the EU ETS directly (EU27, Norway and Switzerland) and N denotes all other countries who are targeted by the CBAM. Consequently, the matrix Q^C (Q^N) captures the environmental impact produced in C (N) to meet EU demand. This application is what Fig. 1 refers to as the production and trade structure subsystem approach.

To focus on the coverage of the EU carbon price system (ETS and CBAM), we solve the SC part of (3), which yields

$$\begin{aligned} \boldsymbol{Q}^C_{SC} &= \hat{\boldsymbol{e}}^C(\boldsymbol{A}^{CC}\boldsymbol{L}^{CC} + \boldsymbol{A}^{CN}\boldsymbol{L}^{NC})\hat{\boldsymbol{Y}}^C + \hat{\boldsymbol{e}}^C(\boldsymbol{A}^{CC}\boldsymbol{L}^{CN} + \boldsymbol{A}^{CN}\boldsymbol{L}^{NN})\hat{\boldsymbol{Y}}^N \\ \boldsymbol{Q}^N_{SC} &= \hat{\boldsymbol{e}}^N(\underbrace{\boldsymbol{A}^{NC}\boldsymbol{L}^{CC}}_{\text{direct}} + \underbrace{\boldsymbol{A}^{NN}\boldsymbol{L}^{NC}}_{\text{indirect}})\hat{\boldsymbol{Y}}^C + \hat{\boldsymbol{e}}^N(\underbrace{\boldsymbol{A}^{NC}\boldsymbol{L}^{CN}}_{\text{direct}} + \underbrace{\boldsymbol{A}^{NN}\boldsymbol{L}^{NN}}_{\text{indirect}})\hat{\boldsymbol{Y}}^N \end{aligned} \tag{4}$$

Here, $\boldsymbol{Q}^C_{SC}$ derives from production occurring in the EU ETS area, which can be completely covered by the EU carbon price. On the other hand, we distinguish $\boldsymbol{Q}^N_{SC}$ between direct and indirect embedded imports with the latter being systematically out of scope of the EU carbon price system according to current proposals.

2.3. Simulation

To establish an estimate of the scope of CBAM potential in terms of magnitude of FP reduction, we simulate global EU production standards along the whole production chain (SC and DP). We create an average EU $\boldsymbol{A}_{EU}$ – including all imports of intermediate inputs, but assumed to be produced in the EU – and $\boldsymbol{e}_{EU}$ – reflecting average fossil fuel intensity for EU production by sectors – from WIOD data for the year 2014 and simulate that all EU demand is met with this production structure: $\boldsymbol{Q}_{EU} = \hat{\boldsymbol{e}}_{EU}\boldsymbol{L}_{EU}\hat{\boldsymbol{Y}}_{EU}$, where $\boldsymbol{L}_{EU} = (\boldsymbol{I} - \boldsymbol{A}_{EU})^{-1}$ and $\boldsymbol{Y}_{EU}$ reflects all EU demand (imports and domestic) now assumed to be only directed an EU producers.

2.4. Structural decomposition analysis

As a final step in our analysis, we assess the dynamic drivers of the environmental footprint and its components. We mainly follow Dietzenbacher et al. (2020) and decompose the FP into the following multiplicative components which drive its development:

- Fossil fuel intensity: total energy intensity, energy mix
- Leontief: total sectoral input requirements, regional origin of inputs
- Final demand: population, total demand per capita, distribution of consumption among sectors (×2), regional origin of production.

We approximate the decomposition form using the average of the two polar forms as illustrated in Dietzenbacher and Los (1998). Finally, we combine data in previous year prices and current prices and chain the results (Arto and Dietzenbacher, 2014). This means that to analyse the changes between year t and $t-1$, we use data of year $t-1$ in current prices and of year t in previous year prices, so that only real changes are considered. Subsequently, we chain the results over the period of analysis.

For the full decomposition and more details see the Supplementary Material.

2.5. Data

Our main data source is the MRIO database from the WIOD 2016 release (Timmer et al., 2015), which covers 27 EU countries, 16 other major countries and a rest of the world (ROW) region with 56 × 56 industry resolution from 2000 to 2014. Please note, that the aforementioned exclusion of the Netherlands in this study does not only apply to final demand, but the whole input–output structure. To avoid double accounting we use the official WIOD emission relevant energy use extensions (Corsatea et al., 2019), removing electricity, heat use and losses (Usubiaga-Liaño et al., 2021). Population data is obtained from Eurostat.

To address the issue that the WIOD ends in 2014 and its last years coincide with the Great Recession and the ensuing European debt crisis (subsequently referred to as EU Crises), we complement our analysis with more recent data: Friedlingstein et al. (2022) (updated from Peters et al. (2011)) and the Exiobase 3 EEMRIO dataset (Stadler et al., 2021), described in Stadler et al. (2018).

It is important to note, that for these more recent analysis, we study GHG emissions, mainly due to issues of data uncertainty and policy relevance. To maintain comparability and coherence with the WIOD analysis, when analysing Exiobase, we only include GHG emissions from combustion, remove the Netherlands, consider consumption in final demand and use the industry-by-industry format. For a discussion on the role of growth, we additionally collect GDP and consumption data from Eurostat. The analysis is coded in Python, using the pymrio tool (Stadler, 2021) to parse Exiobase data.

3. Results

3.1. Fossil fuel footprints

Fig. 2 illustrates that while the global FP (d) from consumption increased relatively continuously throughout the analysed period of time, the EU FP (a) decreased since the onset of the EU Crises. Consequently, EU consumption drives a decreasing share of global FP, dropping to below 11% in 2014. Despite its improvements, EU consumption remains a significant driver of global fossil fuel use with less than 7% of the global population driving more than 10% of fossil fuel use.

SC (c) remains the dominant part throughout the period of analysis. DP (b) has been decreasing steadily, while, after initial increases, SC only started to decline after 2008 with the onset of the EU Crises. Over the whole period, DP fell by almost 25%, whereas SC only fell by around 5%, implying an increasing relative importance of SC (Fig. 3(d)).

The overlap of the acceleration in FP and particularly SC decline with the EU crises however casts doubts on the actual decoupling occurring. Consulting consumption-based intensities (Fig. A.1; references with the prefix “A” refer to the Appendix A), we still observe continuous declines over the whole period and hence relative decoupling. Yet,

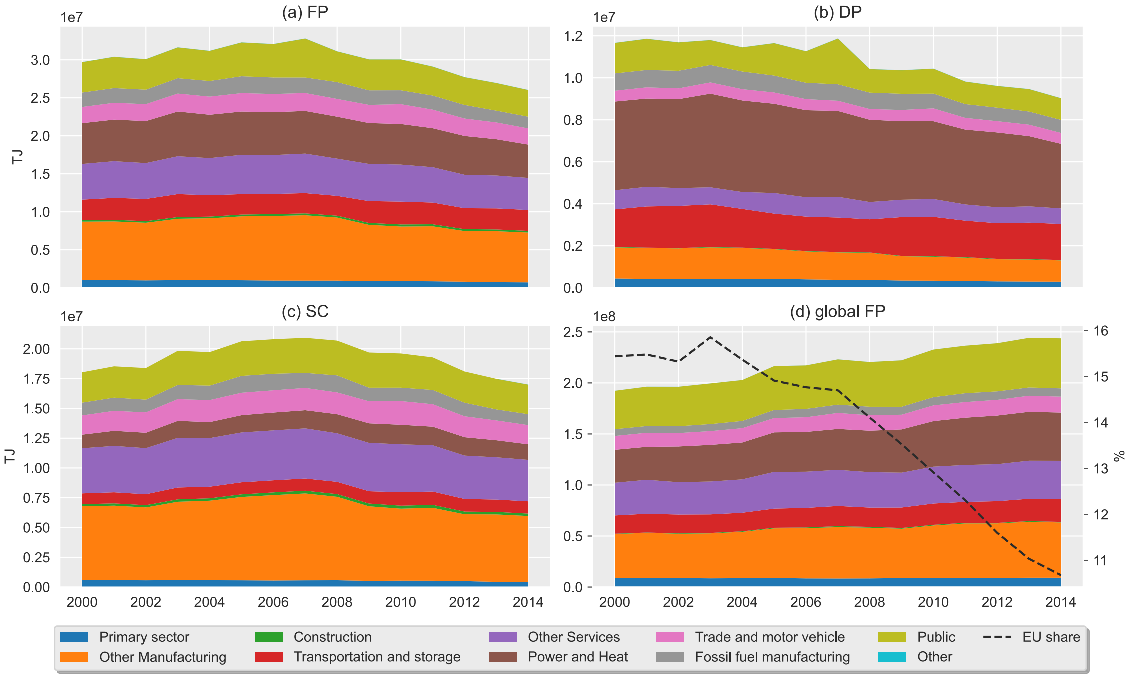

Fig. 2. The evolution of the EU (a) and global (d) fossil fuel footprint between 2000 and 2014 in TJ. The EU footprint is additionally divided into fossil fuels used in final production (b) and fossil fuel use embedded in intermediate production (c). The dashed line represents the share of EU with respect to global fossil fuel footprint.

given that the average yearly rate of decline is below 2% for FP, with SC featuring a rate of only 1.3% and clearly lagging behind, a continuous decline in the face of growing demand remains questionable.

In order to scrutinise which developments could facilitate and which impede decoupling of FP and its components, we subsequently analyse their underlying drivers.

3.2. Drivers

As depicted in Fig. 3 (a–c) the quantity of final demand is a major upwards driver of fossil fuel use until the EU crises, opposed primarily by efficiency improvements. This applies to FP and each of its components.

The second most important driver reducing FP is the composition of final demand among different sectors. Its effect is less volatile and more pronounced in SC, than in DP. This illustrates, that the shift in demand, particularly away from the primary sector, manufacturing and construction has intuitively reduced DP, but more crucially, particularly the shift away from construction and manufacturing has reduced SC fossil fuel use, as it relies on a highly fossil fuel intense supply chain (Fig. A.2).

Interestingly, the energy mix, here defined as share of fossil fuel energy over total energy required per unit production, reduced FP and its components by less than 5% until 2014. However, note that this transition is accelerating rapidly since 2007 and continues after 2014 (bp, 2022; Eurostat, 2022), suggesting a more extensive role in recent years. Also notable is that the energy mix effect mainly coincides with the period of economic crises in the EU, contributing to a reduction in absolute fossil fuel use.

Technology (here referring to the input–output structure, describing the inputs required per unit production independent of sourcing) dynamics suggest that input reduction or substitution to less fossil fuel intense inputs has not materialised yet when considering the whole supply chain.

A growing population in the EU also has lead to increases in demand and hence FP.

3.2.1. Trade

Trade plays a more complex role in the dynamics of FP, and prompts the fundamental difference between DP and SC dynamics. On the one hand, there is little outsourcing of DP (less than 10%, Fig. 4) and the shift in trade patterns seem to lead to slightly less fossil fuel intense DP processes. In contrast, trade is the most dominant upward driver of SC, with intermediate and final trade having impacts of similar magnitude. This illustrates that on the one side, input production is directly shifted to regions with more fossil fuel intense production. On the other hand it shows that even though the trade pattern of final demand does not tend to lead to higher DP fossil fuel use, it typically induces significantly more fossil fuel intensive supply chains, rendering the outsourcing of fossil fuel use even more opaque. SC is significantly more outsourced than DP, with almost half of SC fossil fuel use occurring outside the EU (Fig. 4). This is not only due to a fall in fossil fuel use for SC production within the EU, but also driven by an absolute increase outside EU borders (Fig. A.3).

Moreover, we observe that the energy transition has been significantly more impactful in the EU than for production abroad (Fig. 5). Even though almost 50% of SC occurs outside EU borders, shifts in EU energy efficiency and particularly in the energy mix far outpace improvements in the rest of the supply chain. This indicates that outsourcing production has an increasingly detrimental impact on FP, shifting production to relatively more environmental harmful production structures. It also underlines that the shift to renewables alone within the EU as only reduced FP by little over 4% ceteris paribus and that there is significant potential to reduce FP through developments outside the EU or shifts in sourcing patterns, with trade being the dominant upwards driver of FP next to demand.

One measure to address outsourcing and developments outside EU borders is the EU CBAM. Thus, we subsequently estimate the potential impact of this policy on the EU FP.

3.3. The carbon border adjustment mechanism

Simulating an EU production structure meeting all EU demand, we find that, in 2014, moving the whole supply chain to average EU

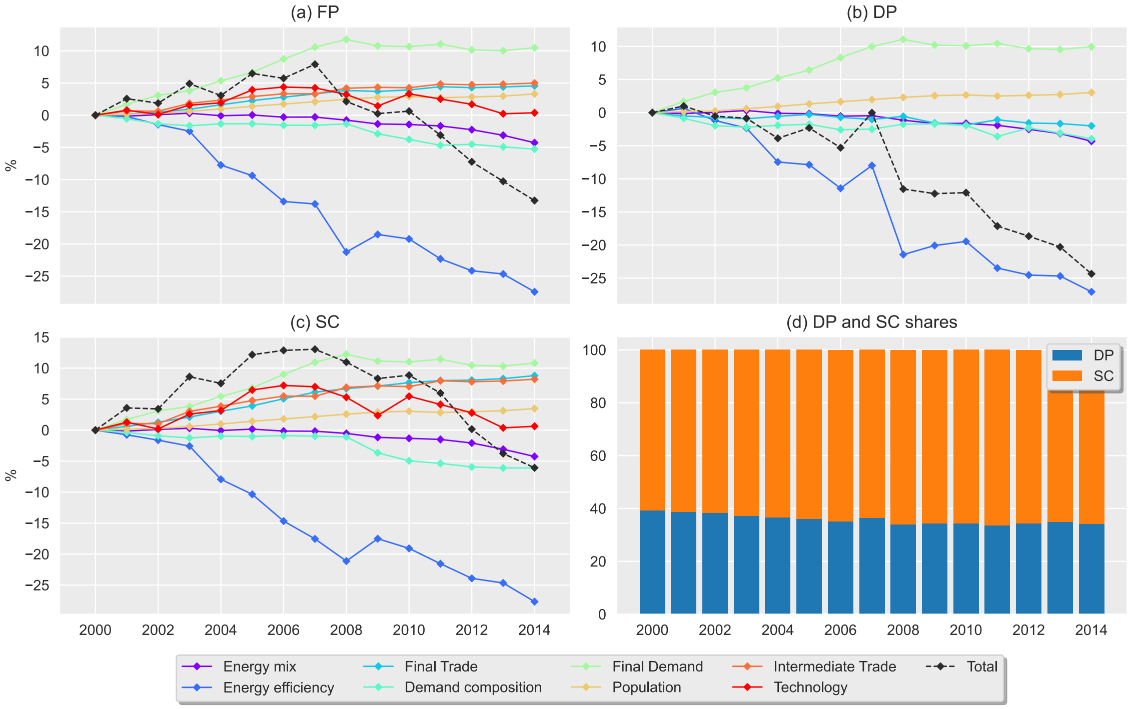

Fig. 3. The relative cumulative impact of each driver alongside total relative cumulative change respectively for the fossil fuel footprint (a) and its components: fossil fuels used in final (b) and in intermediate (c) production. The barplot (d) illustrates the dynamics of the share of final and intermediate production in the fossil fuel footprint.

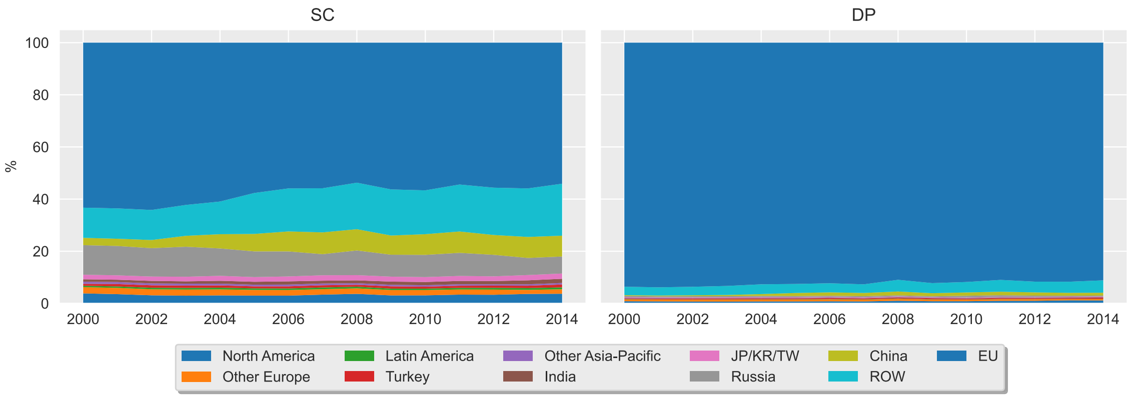

Fig. 4. The contribution to intermediate (SC) and final (DP) production of the EU fossil fuel footprint by region of origin.

production standards would reduce FP by around 19%, illustrating the potential of addressing outsourcing to more fossil fuel intense production structures.

However, given the highly fragmented global supply chain, the EU CBAM faces potential issues of coverage, as it systematically excludes indirect imports. Production within the EU still makes up the vast majority of fossil fuel use (Fig. 6). However, whereas this component is falling, fossil fuel use driven by imports is increasing due to a rise in indirect imports of fossil fuel use. This increasing importance of developments outside EU borders for the EU FP again underlines the relevance of the CBAM. However, we find that the EU carbon pricing mechanism systematically omits an increasing share of FP, almost 1/4 in 2014, and specifically the CBAM, even if applied to all sectors' direct imports, would not address more than 70% of imported fossil fuel use. The sectors covered in the first phase will account for less than 10% of imported fossil fuel use, which is a clear overestimation due to the coarse sectoral detail in the database.

In order to validate and update the CBAM analysis to the year 2019, also with more policy relevant environmental extensions, we repeat the same analysis with Exiobase data (Fig. A.7). In general, we confirm the relative magnitudes of the different components, albeit direct imports play a relatively bigger role. Indirect imports make up a smaller and relatively constant share of total imports that is however still above 50%. The share of indirect imports relative to the whole FP is stagnating since the end of the 2000s between 17 and 19% and actually seems to have fallen after 2014. Finally, Exiobase allows for a more targeted analysis of the phase-in sectors due to its higher sectoral detail, revealing that only around 2.5% of all imported emissions would be addressed in 2019. Overall Exiobase confirms and

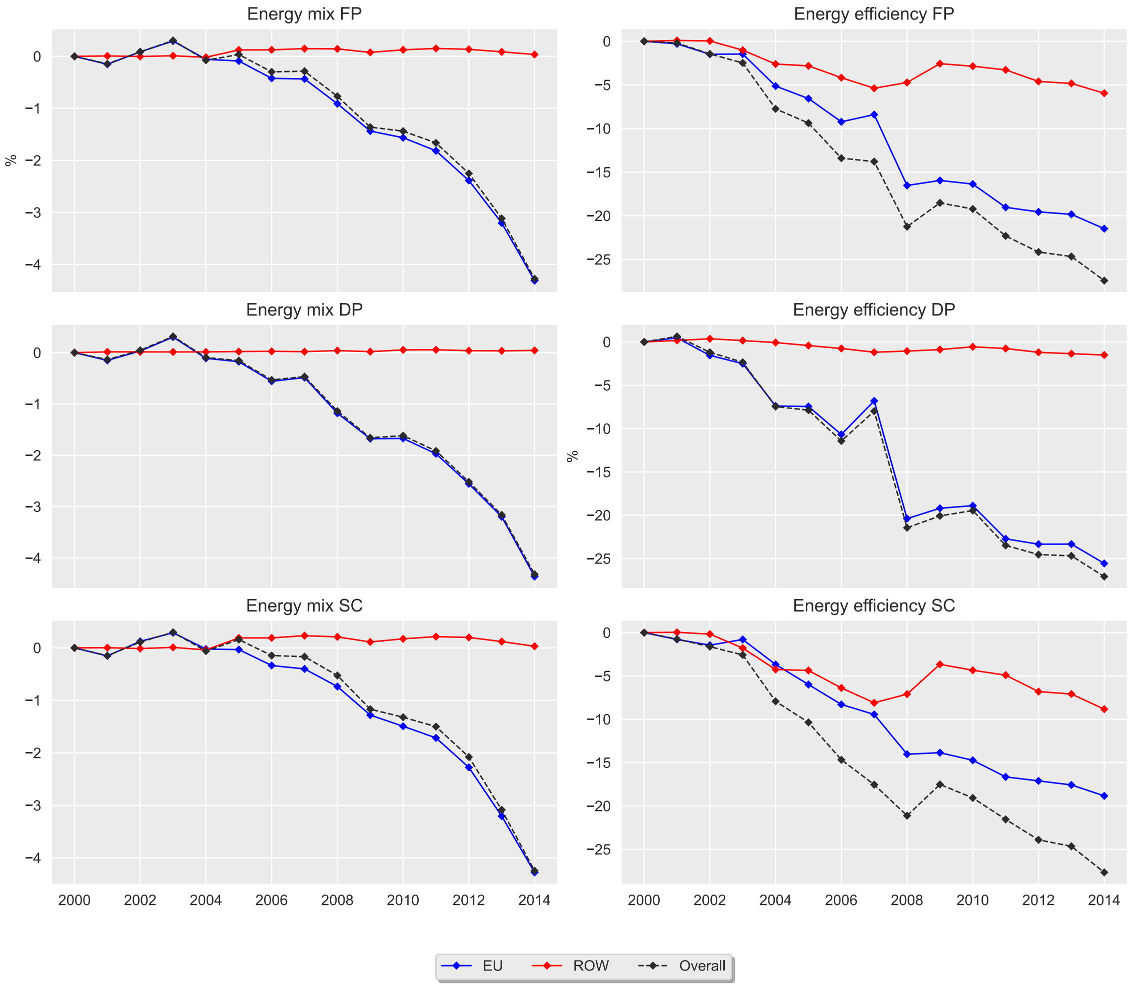

Fig. 5. The relative cumulative impact of energy efficiency and energy mix split into the impact due to the respective development within and outside the EU (ROW) respectively for the fossil fuel footprint (a) and its components: fossil fuels used in final (b) and in intermediate (c) production.

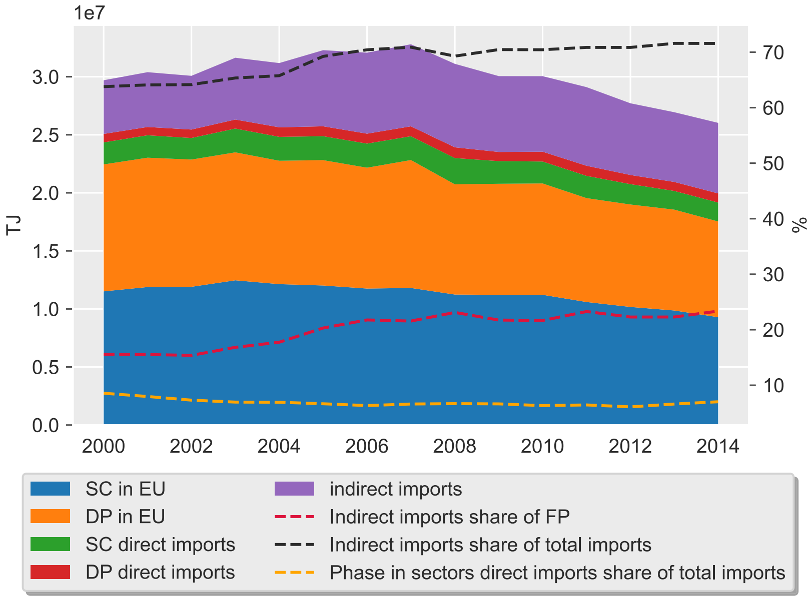

Fig. 6. The EU fossil fuel footprint disaggregated according to origin (within or outside EU) and element in the production chain (final or intermediate production). Additionally, imports are split into direct and indirect imports. The dashed lines represent the dynamics of the labelled shares.

extends our qualitative results for emissions to 2019, underlining the importance of indirect imports.

4. Discussion

In line with the energy and emission literature on the EU, we find that consumption-based impacts increase until the EU crises and fall subsequently (Karstensen et al., 2018; Wood et al., 2020b), with intensity improvements and consumption levels being dominant downwards and upwards drivers until the EU crises (Wood et al., 2020b; Fernández-Amador et al., 2023). Overall, the EU is making some progress towards reducing its fossil fuel dependence, but the pace is far from the 6% annually called for between 2020 and 2030 to limit warming to 1.5 degrees (SEI et al., 2020). Required levels of reduction are not even reached in the face of economic stagnation (see also Le Quéré et al. (2019) and Lamb et al. (2021) for emissions).

We do not only find a clear lack of the degree of decoupling but query whether meaningful continuous absolute decoupling of the EU FP has occurred, given the apparent reliance of reductions on economic underperformance with the FP intensity falling by less than 2% per year on average. We identify SC as a significant drag on decoupling developments.

Consulting more recent consumption-based *emission* data seems to confirm the reliance on stagnating economic growth for the accelerated reductions of the footprint between 2008 and 2014. An update of Peters et al. (2011) in Friedlingstein et al. (2022) shows that consumption-based fossil CO_2 emission reductions of the EU level off around the mid 2010s, coinciding with the pick up of stable economic growth and only fall again with the onset of the Covid-19 pandemic (Fig. A.5). We validate these developments using the Exiobase dataset, as it allows better comparability with our specific analysis (see Section 2.5), also confirming the stagnation of reductions in FP (Fig. A.6). We find this stagnation for SC as well as for DP but note that this recent data exhibits notable uncertainty (Stadler et al., 2021). A structural shift that facilitates continuous absolute decoupling, particularly at a pace in line with liming warming to 1.5 °C, has clearly not occurred yet.

This lack of decoupling of consumption-based measures is confirmed for EU emissions and energy use (Kan et al., 2019; Papież et al., 2022), with Kan et al. (2019) finding a mixed picture when it comes to the decoupling of different fossil fuels.

We find that trade is an important driver counteracting decoupling and only slightly outpaced by the scale of final demand. Its negative impact is channelled entirely through SC. This increasing relative importance of SC is in line with Hertwich and Wood (2018).

The emission literature confirms that a large part (almost 1/3) of the EU footprint is outsourced (Wood et al., 2020b) and predicts an increasingly important relative role of imports (Wood et al., 2020a) which we find for fossil fuels. In addition, Wu and Chen (2017)'s finding that the vast majority of energy embodied in trade is associated to intermediate trade supports our results that trade is mainly driving SC. The literature also supports trade being an upwards driver of the EU footprint for emissions (Wood et al., 2020b) and energy (Fernández-Amador et al., 2023). However, the effect of trade in our analysis is significantly larger and more in line with Hoekstra et al. (2016)'s global findings for emissions. Reasons to explain these variations range from differences in the environmental extension to distinct scopes footprints and final demand and diverse datasets. In addition, Zhang et al. (2021)'s findings underline the importance of trade. They find the emission intensity of the global value chain to be higher than of the EU and identify regional sourcing patterns as the main upwards driver of global value chains. Overall the literature generally tends to qualitatively confirm the upwards driver of trade on EU footprints.

Thus, the role of trade and developments abroad are crucial for decoupling dynamics, and focusing only on a domestic energy transition is a profoundly narrow perspective, with shifts in the energy mix in the EU only contributing to little over 4% decline in FP. Here, the CBAM constitutes a promising tool, but in its currently proposed form will not cover the majority of embedded fossil fuel imports, which constitute indirect imports.

4.1. Implications for decoupling

Evaluating individual drivers of FP and its components in detail, we aim to establish underlying reasons for why FP fell during the EU crises years but a structural shift towards continuous absolute decoupling has not materialised yet.

On the one hand, some of the drivers might only exhibit temporal changes with a return to pre-crisis conditions, endangering the continuous reduction of SC and FP. Certainly, rising levels of consumption will have an impact on the scale of economic activity and fossil fuel use. Another potentially temporal driver is the change in demand composition, due to cyclical demand behaviour. For instance (Berger and Vavra, 2014) show cyclically distinct behaviour of durable goods. This interpretation is in line with Eskander and Fankhauser (2020)'s findings of a pro-cyclical movement of emission intensities. Also (Song et al., 2022) find a significant role of consumption composition for consumption-based emissions for the U.S. and remark on the role of the economic recession on different types of products.

On the other hand, the overall impacts of developments in the energy transition interact with other drivers. Firstly, rising levels of consumption might again continue to counteract efficiency improvements. Efficiency improvements have not led to significant decoupling in SC until the economic crises, potentially also due to rebound effects which can be very significant ($\geq 50\%$) (Brockway et al., 2021). In line with Le Quéré et al. (2019), they only achieved substantial reductions in energy and fossil fuel use during phases of economic underperformance. The role of the energy mix will also be affected by the scale of demand and economic activity. The impact of the energy mix has gained traction around the time of the financial crisis, but we cannot ascertain in how far the pace and displacement of fossil fuel use due to the energy mix was fostered by the EU Crises itself (Le Quéré et al., 2019). A rising energy demand clearly hampers the improvement of the energy mix and replacement of fossil fuels ceteris paribus. This notion is also supported by data in bp (2022) and Eurostat (2022) which agree that there is a temporary (2015–2017) increase in the fossil fuel share in Europe coinciding with the end of the EU Crises. However, the share continues to decrease after 2017, illustrating that the energy mix can also move away from fossil fuels in the face economic growth. That growth is a potential hindrance, rendering decarbonisation more challenging is in line with a range of studies analysing the historic decarbonisation of regions (e.g. Le Quéré et al. (2019)) mainly from a territorial perspective.

Furthermore, trade patterns interact with the impact of the energy transition on the EU FP. Whereas relatively ambitious climate and energy measures in the EU have improved production structures within its borders, the impact of the transition in regions exporting into the EU is lagging behind (Fig. 5), thwarting the impact of the energy transition on the EU FP. Our period of analysis spans the introduction of important EU policies including the EU Emission Trading System (ETS) in 2005 and the EU Energy Service Directive in 2006, which however, in line with our findings, are found to have limited impact on energy and emission footprint measures, consistent with leakage (Fernández-Amador et al., 2023; Papież et al., 2022). Here, Wang et al. (2024) find that for many EU countries an increasing share of embedded emissions originate in lower income countries, which tend to feature higher emission intensities. To enable a structural shift towards sufficient decoupling and reductions in FP, these interactions with trade and growth have to be taken into account carefully, in particular with respect to SC.

4.2. Policy implications

Our study underlines the issue of policy coverage in global supply chains. Energy transition advancements within the EU have increasingly limited leverage on the EU FP, primarily due to developments in SC. One policy option to address this issue and promote an energy transition along the global supply chain is the CBAM. It has enormous potential to reduce the EU FP as indicated in Section 3.3, but our analysis in Section 3.3 underlines the importance of indirect imports in the EU FP, as also noted in Böhringer et al. (2022). We find that direct and indirect imports feature significantly different structures in terms of country as well as sector of origin (Fig. A.4). Thus, only addressing direct impacts will not necessarily have effective ripple effects on indirect imports. However, including electricity used to produce imported goods, as indicated as a future option by the CBAM proposal, could already be a significant improvement, covering a major part of indirectly imported fossil fuel use (Fig. A.4). Still, substantial practical, legal and political challenges around the CBAM remain (Böhringer et al., 2022).

Yet, even if covering indirect emissions, the CBAM should not remain the only tool addressing emissions abroad, as by itself it is associated with serious concerns about equity (Grubb et al., 2022). Complementary measures could help to phase out fossil fuels along international supply chains, while alleviating some concerns about equity. These can be directly in the form of clean technology transfers or support through climate finance (Wang et al., 2024), for instance using the revenue generated from the CBAM (Böhringer et al., 2022).

Still, energy efficiency measures face rebound issues and eventual thermodynamic limits. Moreover, a shift in energy mix faces technical and institutional difficulties (Davis et al., 2018). Crucially, as aforementioned economic growth can be a significant hindrance to the energy transition and the displacement of fossil fuels.

Given the urgency and scale of the challenge, this underlines the importance of complementing energy transition efforts with demand side measures (Creutzig et al., 2018; Grubb et al., 2020). Concrete policy proposals include infrastructure improvements, charges and taxes and recycling or product lifespan requirements (Grubb et al., 2020). Applied in the EU, they can facilitate the energy transition and the phasing out of fossil fuels globally by reducing the pressure of energy demand along the entire supply chain. Furthermore, they can mitigate rebound effects from energy efficiency improvements. Note that we find the FP intensity to fall by less than 2% per year on average illustrating that stagnating demand is not sufficient, but demand would need to change more fundamentally while the energy transition would need to be expanded rapidly. This might imply post-growth pathways (Hickel and Kallis, 2020; Hickel et al., 2021), even for climate ambitious regions like the EU.

4.3. Methods and limitations

Typical for IO analysis, this analysis is prone to issues due to aggregation bias and linearity assumptions. Aggregating EU countries into one EU region certainly results in the loss of country specific characteristics, but has apparent political relevance. In addition, results for large economies like the EU tend to be relatively robust (Moran and Wood, 2014; Wood et al., 2020b).

Furthermore, note that the ceteris paribus interpretation of the SDA has to be scrutinised with caution. The drivers cannot be assumed to be independent. For instance energy efficiency improvements can affect economic growth or sector specific demand via the rebound effect, or the energy mix can alter energy efficiency.

Moreover, we systematically underestimate the EU FP by excluding the Netherlands, direct final use of fossil fuels and gross fixed capital formation (GFCF). This is because of data issues, the specific scope of the study and in order to avoid the introduction of an additional bias respectively. GFCF can distort consumption-based accounting, as investment demand is partly driven by production for exports. Hence, GFCF should not be allocated to the country where it is demanded, but to the country where it is producing for (Södersten et al., 2018).

The impact assessment of the EU CBAM is mainly for illustrative purposes, not exactly quantifying its potential impact. On the one hand the simulation of global EU production structures is only a thought experiment, since many production activities like mining occur in certain locations outside the EU due to the location of natural resources (Grubb et al., 2020), which is why the EU mining industry and its production structure is not representative to a mining industry that would produce all products required by EU consumption. Also note that industries outside the EU can produce less fossil fuel intensively than within the EU. Thus, the resulting change does not constitute an upper limit on the possible emission reduction due to sourcing patterns. On the other hand, the coverage of the EU carbon price system crucially depends not only on the type of imports but on the sectoral coverage of the policies, which we neglect given the coarse sectoral detail of the WIOD.

Finally, we chose the WIOD even though the timeseries ends in 2014 as it provides current year price and previous year price data, allowing to remove price effects in a structural decomposition analysis. When updating the fossil fuel based results derived from this data with emission data from other databases we expect a certain comparability of the results given the dominance of fossil fuels as driver of emissions (Friedlingstein et al., 2022). Also note, that a reason fossil fuels were used until 2014 was that emission reductions can paint a distorted positive picture. However, here we use the data to confirm the absence of significant reductions, which in all likelihood implies an absence of significant fossil fuel reductions.

5. Conclusion

Applying the IO subsystem approach in combination with SDA to analyse the embedded fossil fuel footprint of EU consumption, we find that the EU FP has declined steadily, but at an insufficient rate to limit global warming to 1.5 °C.

We identify trade as one important driver counteracting decoupling and pushing up FP, with its adverse impact entirely driven by intermediate production. In addition, trade interacts with the effects of the energy transition on FP, with the impact of the energy transition in regions exporting into the EU lagging behind EU developments. The shift in energy mix in the EU only contributed to little over 4% decline in FP. This underlines the importance of extending a territorial policy focus, promoting an energy transition along the global supply chain, in particular to address SC. We find that targeting outsourcing patterns to more fossil fuel intense production could reduce the EU FP by almost 20% The EU CBAM has the potential to provide a suitable tool to address this issue. However, to effectively reduce the fossil fuel intensity of EU consumption, the EU CBAM has to incorporate indirect imports , which constitute the majority of embedded fossil fuel imports. Here, including indirect imports of electricity would already pose a significant improvement. Yet, given the urgency and scale of the challenge, in combination with the problematic role of economic growth, our results underline the importance to complement the supply side transition with demand side measures, potentially involving post-growth pathways.

Future research can provide more targeted policy recommendations by reducing the geographical scale or focus on specific sectors or households, also when evaluating the CBAM coverage and impact. More recent data will allow to trace drivers, in particular the impact of the energy transition, after the EU Crises, providing crucial implications about interactions with economic growth and potential to achieve sufficient decoupling.

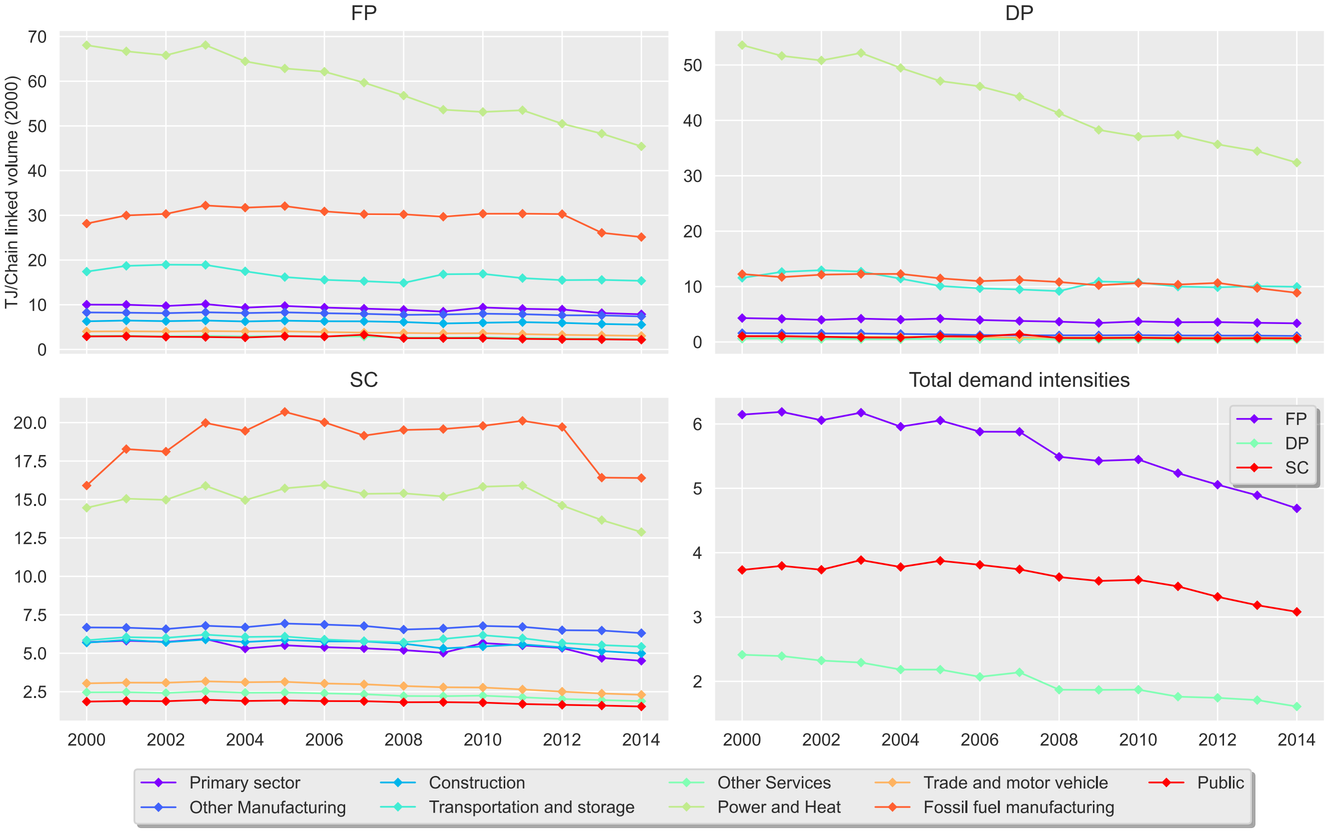

Fig. A.1. The dynamics of fossil fuel intensities from a consumption-based accounting framework per chain linked volume of final consumption. The total intensities for each industry category (a) are split into intensities linked to final (b) and intermediate (c) production, as are intensities for average overall consumption (d).

CRediT authorship contribution statement

Till Heydenreich: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The code to replicate the results can be found in the Supplementary Material.

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Appendix A. Additional graphs

A.1. Fossil fuel intensities

See Fig. A.1.

A.2. Structural decomposition analysis results by good

See Fig. A.2.

A.3. Input structure

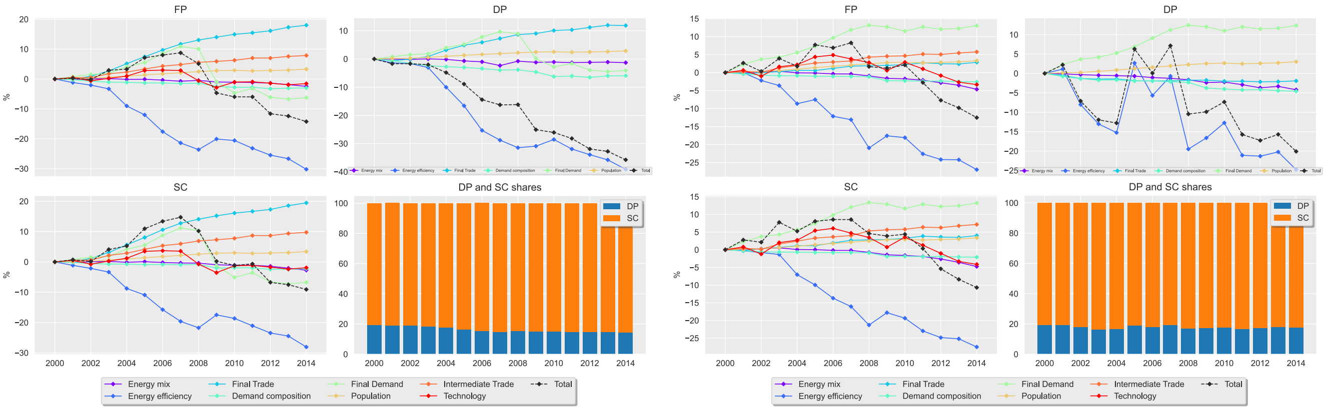
See Figs. A.3 and A.4.

A.4. Emissions

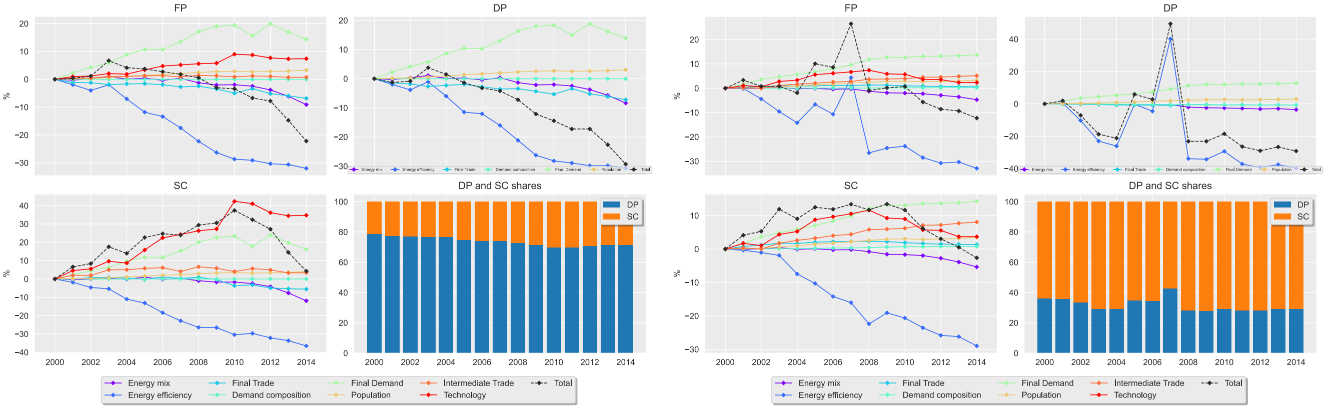
See Figs. A.5–A.7.

Appendix B. Supplementary data

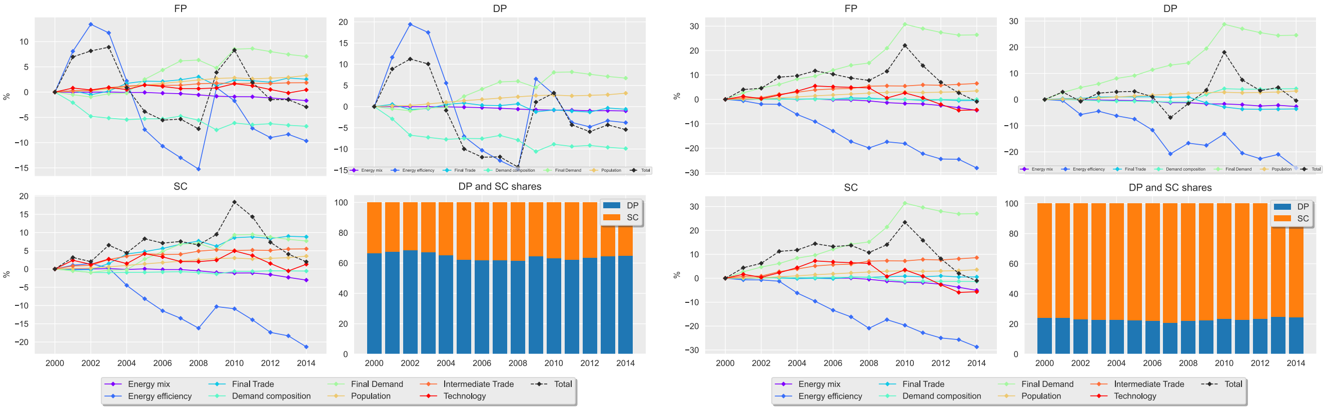
Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142702.



(a) Other Manufacturing **(b)** Other Services

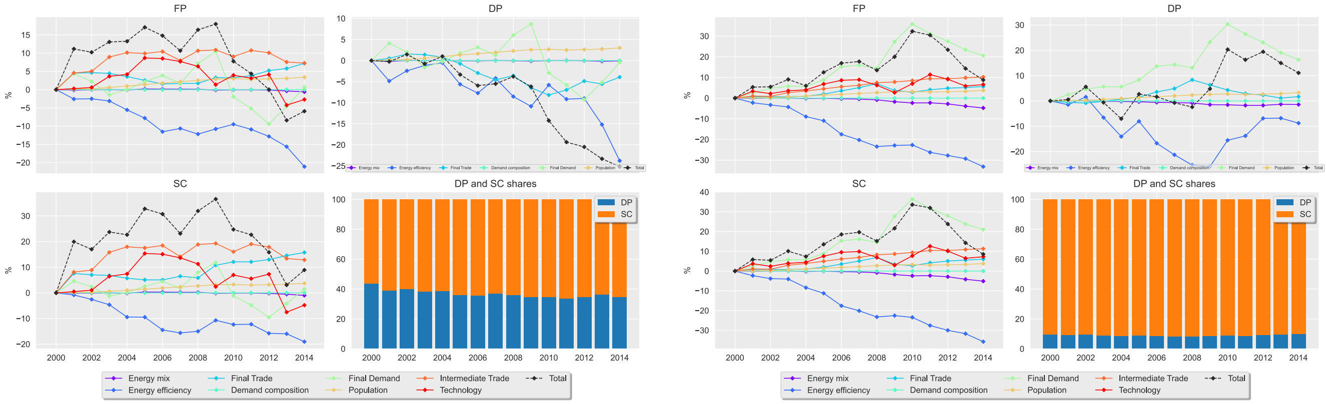


(c) Power and Heat **(d)** Public



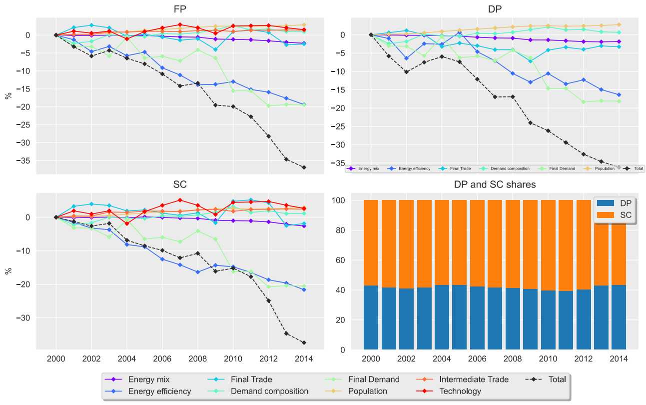
(e) Transportation and Storage **(f)** Trade and Motor Vehicles

Fig. A.2. The relative cumulative impact of each driver alongside total relative cumulative change for sector specific fossil fuel footprint and its components, fossil fuels used in final and in intermediate production. The barplot illustrates the dynamics of the share of final and intermediate production in the fossil fuel footprint of sector specific demand.



(g) Fossil Fuel Manufacturing

(h) Construction



(i) Primary Sector

Fig. A.2. (*continued*).

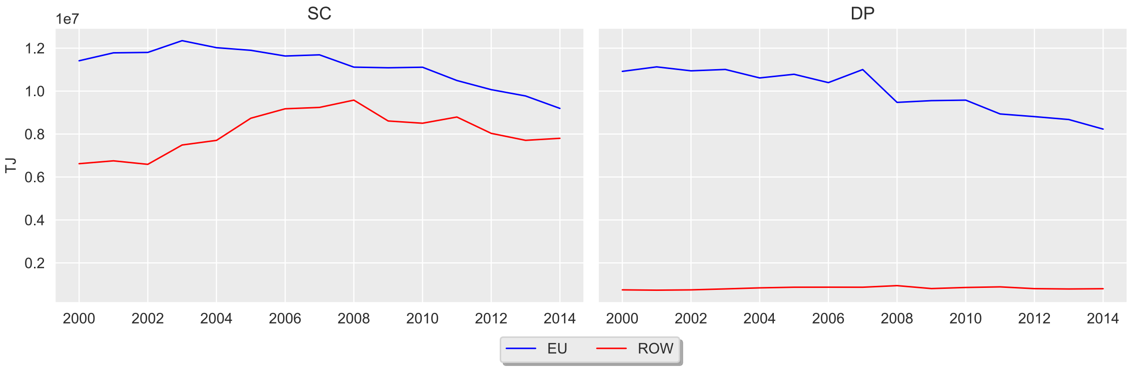


Fig. A.3. Absolute levels of fossil fuels embedded in final and intermediate production of the EU fossil fuel footprint by EU and non-EU (ROW) origin.

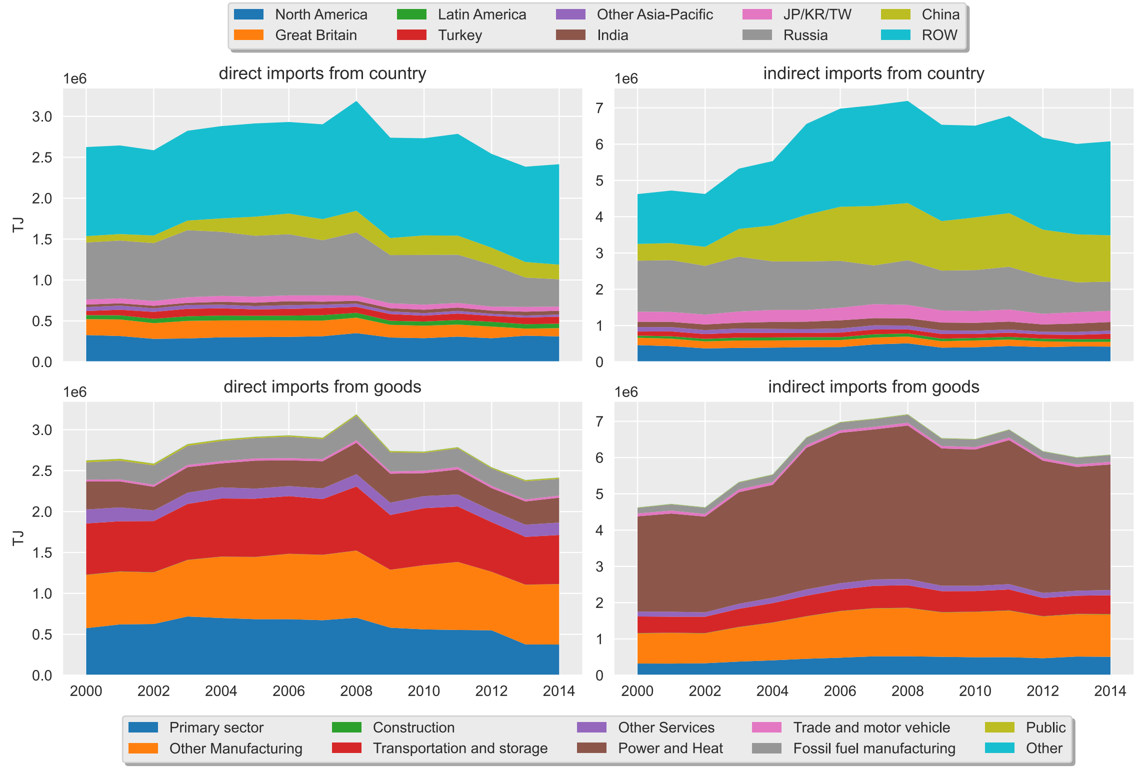


Fig. A.4. Fossil fuels embedded in direct and indirect imports into the EU, structured by region and sector of origin respectively.

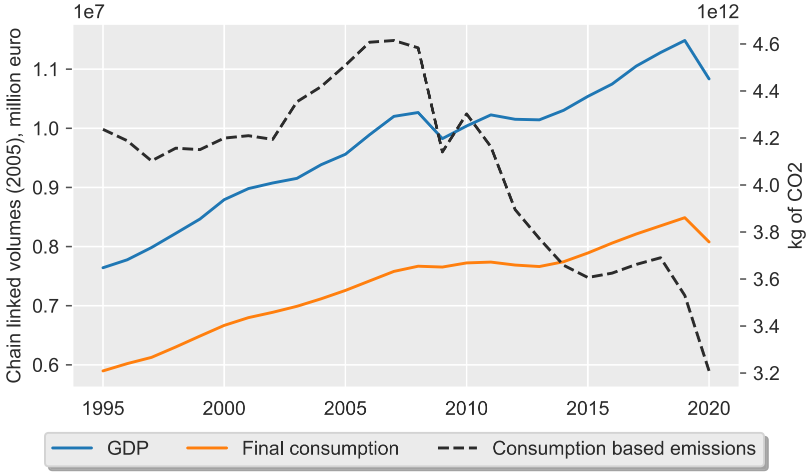


Fig. A.5. EU 27 GDP, consumption and fossil CO2 emission footprint. Data sources: Eurostat (GDP and consumption) and update of Peters et al. (2011) in Friedlingstein et al. (2022) (emission footprint).

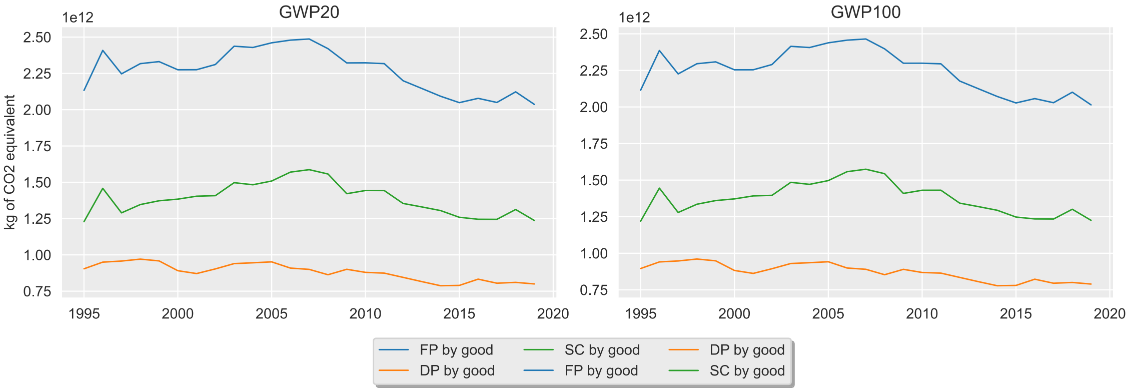
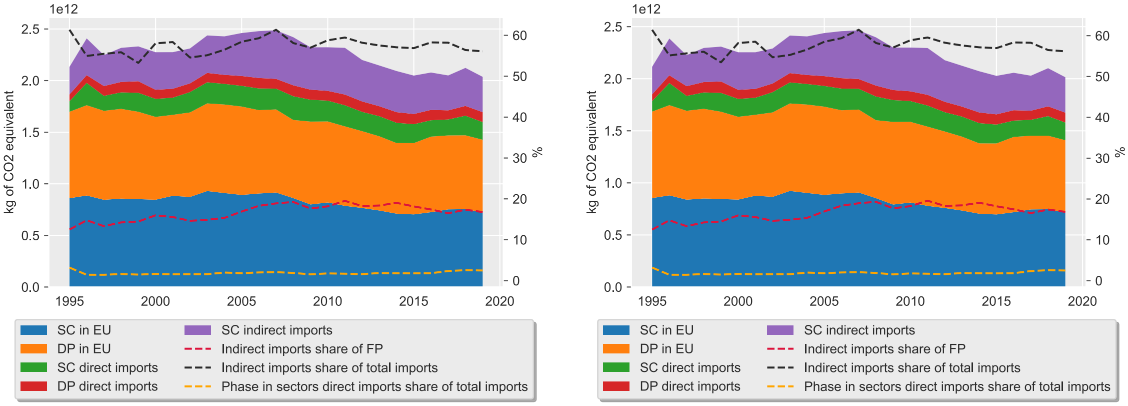


Fig. A.6. The evolution of the EU emission footprint, using GWP20 and GWP100 data, decomposed into fossil fuels embedded in intermediate and final production. Based on Exiobase data.



(a) (b)

Fig. A.7. The EU emission footprint, using (a) GWP20 and (b) GWP100, is disaggregated according to origin (within or outside EU) and part of the production chain (final or intermediate production). Additionally, imports are split into direct and indirect imports. The dashed lines represent the dynamics of the labelled shares. Based on Exiobase data.

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