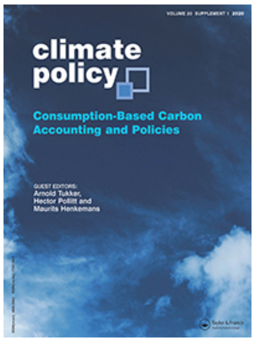

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The structure, drivers and policy implications of the European carbon footprint

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ABSTRACT

Policy to reduce the European Union's (EU) carbon footprint needs to be grounded in an understanding of the structure and drivers of both the domestic and internationally traded components. Here we analyse consumption-based emission accounts (for the main greenhouse gases (GHGs)) for the EU, focusing on understanding sectoral contributions and what changes have been observed over the last two decades, including the role of trade. The EU28 has reduced its overall GHG footprint by 8% over the two decades, mainly due to the use of more efficient technology, both at home and abroad. Emissions embodied in imports, which make up one-third of the EU28 GHG footprint, grew strongly until 2008 but have stabilized in volume since. Foreign production has been more emissions intensive than if goods were produced in the EU. However, the overall contribution of this effect is small, offset by much larger (global) technological improvements and growths in consumption. Hence the focus should now be on accounting and responsibility for enacting change, not the global impact of trade. Finally, the inclusion of non-CO_2 GHGs in the analysis shows their importance in the traded element, particularly for the mining and agricultural sectors.

Key policy insights

- The total EU carbon footprint has reduced since 2007, but at a slower rate than production-based emissions, and rarely faster than GDP growth.
- Consumption growth has had a much greater impact on the EU carbon footprint than the offshoring of production.
- Trade in both directions (imports and exports) is important for the manufacturing sector. The data does not support claims of wholesale 'de-industrialisation' but rather reflects increased trade intensity related to specialization.
- Several (but not all) of the major sources of net embodied imports are largely unavoidable consequences of European consumption because the primary production activities (e.g. mining and significant shares of agricultural) could not realistically occur within the EU.

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MRIO; carbon footprint; embodied carbon; trade; EU

1. Introduction

Consumption-based carbon accounting (CBCA) of greenhouse gas (GHG) emissions has been suggested as a complement to traditional territorial emissions inventories in order to capture the global impact on the climate of the affluent lifestyles of highly developed countries (Kokoni & Skea, 2014; Peters & Hertwich, 2008; Steininger, Lininger, Meyer, Muñoz, & Schinko, 2015). One focus of CBCA is the social justice argument about

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aiming for long-term equality in per-capita carbon emission allowances (Chakravarty et al., 2009), which makes more sense if calculated from a consumption viewpoint. A second focus of CBCA is to address the concern that domestic emissions *reductions* in many highly developed countries may have only occurred due to a shift of consumption patterns towards products that are largely imported (e.g. IT) or due to a shift of production towards foreign sites with better resource access (e.g. steel, aluminum) and/or weaker emission mitigation strategies. That is, CBCA seeks to capture the issue of relocation in addition to reduction of emissions (Droege, 2011). The displacement of emissions has been an increasing concern since the early 1990s, as the share of industrial activities in GDP of many of the OECD countries declined, and the Asian economies emerged (Peters, Minx, Weber, & Edenhofer, 2011).

With the continued growth of global trade, the de-industrialization trend in Europe, deeper domestic decarbonization, and the rise of more complex supply chains, the *fraction* of a developed country's greenhouse gas (GHG) footprint that occurs abroad will likely continue to rise for the foreseeable future (Wood, Grubb, et al., 2020). Tracking and measuring emissions embodied in trade with Europe will be crucial if the region is to make more meaningful contributions to reducing global GHG emissions. However, the policy situation becomes more complex when CBCA is applied; there are many actors along (international) supply-chains that could potentially enact change to reduce emissions (Hertwich & Wood, 2018), and administrative, jurisdictional and competitiveness issues become paramount.

A number of models and papers provide aggregate production and consumption accounts for EU countries and regions (Hertwich & Peters, 2009; Ivanova et al., 2015, 2017; Pan et al., 2017; Peters, Davis, & Andrew, 2012; Steen-Olsen, Weinzettel, Cranston, Ercin, & Hertwich, 2012; Wood et al., 2018). Data portals also exist, such as the Global Carbon Project (Le Quéré et al., 2018), the https://environmentalfootprints.org website (Stadler, Lonka, Moran, Pallas, & Wood, 2015), and the avoided emissions calculation of Eurostat (dataset: env_ac_io10). These results point to the EU being a net-importer of carbon, that is, they have a larger CBCA than emissions produced in the EU. The results reported by Eurostat are the only exception, this being a modelling artefact of assuming domestic technology used in imports.[1] However, limited detailed and specific analysis was undertaken for the EU until the parallel work of Karstensen, Peters, and Andrew (2018). These authors find a peaking of emissions for CBCA in 2006, against a steady backdrop of declining territorial emissions, principally due to the decline in emissions of manufacturing goods in imports and from domestic electricity and gas.

Here we focus on the *structure* and *drivers* of the CBCA of EU emissions over the last 20 years (1995–2016) and include all major GHGs. The main objective of the article is to provide an empirical basis for the subsequent design of policy that is explored within this special supplement (Grubb, Crawford–Brown, Neuhoff, & Shanes, 2020; Moran et al., 2020; Pollitt, Neuhoff & Lin, 2020). We focus on the trends in emissions, including the different perspective that CBCA gives to traditional measures, the role of trade and consumption in driving changes in the CBCA of the EU, and what sectors and product groups are responsible for the highest volume of emissions embodied in trade and consumption. The work goes beyond Karstensen et al. (2018) in several ways. We focus on the structure of emissions across production and consumption perspectives simultaneously to understand which sectors, sources and gases policy would need to influence. We include a full calculation of all major GHGs (not just CO_2); employ a full multi-regional input-output model of all results, rather than the trade adjustment method of Peters, Davis, et al. (2012) for the temporal trends; provide a deeper analysis of drivers through structural decomposition analysis; and finally go into much deeper sector and product detail.

The remainder of the article includes a brief description of methods with more detail in the appendix, before the presentation of a range of results showing the CBCA of the EU28 from various perspectives. A short discussion specifically on the sectoral structure of the CBCA and the implications for policy sovereignty follows, in order to set up the reader for further policy analysis of accompanying papers in this special supplement.

2. Methods

2.1. Production-based and consumption-based carbon accounts

Almost all international level studies on consumption-based GHG accounts use multi-regional input-output (MRIO) analysis. Wiedmann and Lenzen (2018) provide an overview of recent applications, whilst Peters, Davis, et al. (2012) present perhaps the most comprehensive investigation into MRIO approaches. The appendix provides a short mathematical introduction to MRIO analysis, and for further information the reader is referred to textbooks such as Miller and Blair (2009), reference articles such as Minx et al. (2009) or specific method descriptions such as Wood (2017).

Here, we use the terms: 'production-based' carbon accounting (PBCA), which refers to the GHG emissions produced by (industrial, government and private) residents of the European Union (EU28) (and differs in terms of handling international transport and purchases by residents abroad to 'territorial accounts' – see Usubiaga & Acosta-Fernández, 2015); and 'consumption-based' carbon accounting (CBCA), which refers to the GHG emissions allocated to the region where goods and services are finally consumed, and includes both private household, collective and government consumption, as well as capital formation. Emissions embodied in imports reflect those emissions that are released outside the EU28 in the supply-chain of the goods and services that go to final demand in the EU28. Similarly, emissions embodied in exports are the emissions released in the EU28 embodied in goods and services that go to final demand in countries outside the EU28. Note, to avoid double counting, emissions are allocated only to producers (PBCA) or final demand (CBCA), and not to intermediate producers (e.g. in the production of car parts before assembly into a car). The appendix provides a mathematical description of this allocation.

Results are also presented for the rate of decoupling and for the drivers of changes in emissions over time. For the calculation of the decoupling factor, the PBCA and CBCA of emissions are normalized by GDP in 2011 international dollars of the respective year, before the rate of change is calculated. For the calculation of the drivers of changes in emissions, the annual MRIO tables were deflated to previous year prices, in which we performed a structural decomposition analysis. See appendix for the description of these calculations and a range of literature for an introduction to this analytical technique (Arto & Dietzenbacher, 2014; Hoekstra, Michel, & Suh, 2016; Hoekstra & van den Bergh, 2002).

2.2. Data source

There are a number of MRIO databases available including EXIOBASE (Tukker, de Koning, Wood, Hawkins, et al., 2013; Wood et al., 2015), WIOD (Dietzenbacher, Los, Stehrer, Timmer, & de Vries, 2013), Eora (Lenzen, Kanemoto, Moran, & Geschke, 2012), the ICIO (OECD, 2015) and the GTAP database (with interpolation provided as part of work in the Global Carbon Project (Peters, Davis, et al., 2012)). We use EXIOBASE because of the ability for us to update accounts, its regional, sectoral and product detail and its suitability for calculation of impacts for the EU: EXIOBASE consists of a MRIO constructed for 44 countries (28 EU and 16 non-EU, including all major EU trading partners) and five Rest of the World regions (RoW), disaggregated into 200 products and 163 industries. A full analysis of differences between MRIO databases has been the subject of other work and is thus not covered here (Inomata & Owen, 2014; Tukker & Dietzenbacher, 2013; Wood, Moran, Rodrigues, & Stadler, 2019).

The EXIOBASE3 dataset is publicly available for 1995–2011 (Stadler et al., 2018), but was constructed using a reproducible process to update to more recent years as data has become available (nowcasting procedure as described in (Stadler et al., 2016)). As such, with the availability of macro-economic data, trade data and estimates for product output, the database has been updated to 2016, the latest year that macro-economic data was available at the time of writing. Fuel combustion data was available for estimation of GHG emissions up to 2015, with additional national level data for CO_2 available for 2016 (BP, 2017). Other GHGs were estimated based on the nowcasting procedure in Stadler et al. (2016) and rescaled at the sectoral level using PRIMAP (Gütschow et al., 2016) to 2015, with 2016 being estimated based on trends in economic output and efficiency. Emissions for CO_2, CH_4, N_2O, SF_6, HFCs and PFCs were included. All sources of emissions are included (following the Intergovernmental Panel on Climate Change (IPCC) categorization), including from agricultural production, but excluding those from the specific category of 'land use, land use change and forestry', which are difficult to attribute to production sectors within a certain year.

3. Results

3.1. EU GHG footprints and production accounts

EU GHG emissions have been decreasing since around the financial crisis of 2007–8, for both PBCA and CBCA (Figure 1). The peak value of the production account was around 2003. For the consumption account, the peaking was delayed, until 2007 (due to the carbon intensity of international trade – see Wood, Grubb, et al. (2020)), with a consistent decline since the onset of the financial crisis, apart from a very short recovery in growth (previously picked up in 2009 by Peters, Marland, et al. (2012)). The production account was 4.9 Gt in 2010, dropping to 4.4 Gt in 2015; the consumption account was 29% higher than the production account in 2010 (6.3 Gt) and 27% higher in 2015 (5.6 Gt). Emissions have decreased 13% for the production account since 1995, whilst the CBCA has decreased 8%. However, since the peaking of emissions in the mid-2000s, using 2007 as a basis, the production account has decreased 14%, whilst the consumption account has reduced 19%.

Non-CO_2 gases are a significant contributor to the gap between production and consumption accounts (see Table 1; full results for CO_2-only and on a per-capita basis are available in the supporting information). The results show that net-trade accounts for 40% of our total *non*-CO_2 footprint, whereas for $CO_{2,}$ net-trade is 15% of the footprint. The results point to the importance of trade in food/agriculture (CH_4 and $N_2$0), and mining (CH_4), which we return to later.

3.2. Emission intensity and rate of decoupling

Whilst the most recent data (since 2014) implies a potential return to emissions growth, it is perhaps too early to make any conclusions on the start of a new trend. We can investigate the level of reductions relative to economic growth through the rate of decoupling – how much reduction (or increase) in emissions is occurring for every unit change in GDP. Given potential stable economic growth in the order of 2% p.a. the

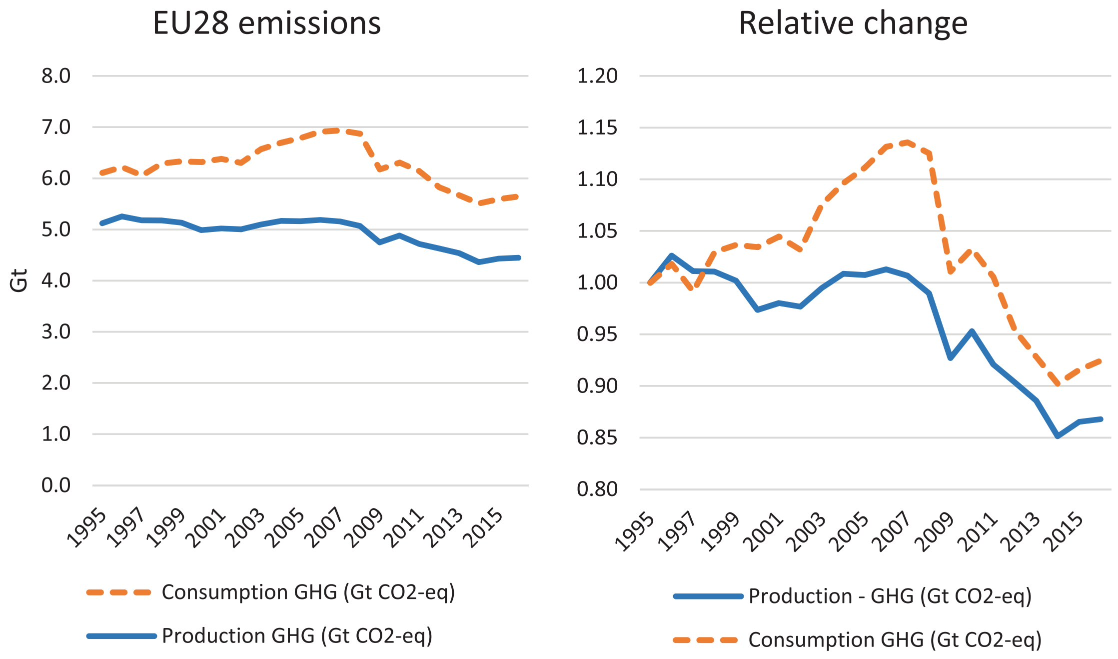

Figure 1. (a) Production and consumption accounts of GHG Emissions for the EU28. (b) Relative change in production and consumption accounts compared to 1995.

Table 1. CO_2, Non-CO_2 and GHG production and consumption accounts. Net GHG trade results are emissions embodied in imports net of emissions embodied in exports.

	1995	2000	2005	2010	2015	2016
CO_2 only:						
Production CO_2 (Gt)	4.1	4.1	4.3	4.0	3.6	3.6
Consumption CO_2 (Gt)	4.6	4.8	5.1	4.8	4.2	4.3
Net CO_2 trade relative to consumption	*11%*	*15%*	*17%*	*16%*	*15%*	*15%*
Non-CO_2 GHGs						
Production non-CO_2 (Gt)	1.1	0.9	0.9	0.9	0.8	0.8
Consumption non-CO_2 (Gt)	1.5	1.5	1.7	1.5	1.3	1.4
Net non-CO_2 trade relative to consumption	*31%*	*39%*	*46%*	*43%*	*39%*	*40%*
All Greenhouse gases:						
Production GHG (Gt CO_2-eq)	5.1	5.0	5.2	4.9	4.4	4.4
Consumption GHG (Gt CO_2-eq)	6.1	6.3	6.8	6.3	5.6	5.6
Net GHG trade relative to consumption	*16%*	*21%*	*24%*	*23%*	*21%*	*21%*

question arises whether we can decouple fast enough (noting in order to stay in line with a 1.5°C carbon budget, much larger reductions will be needed in the future). In Figure 2, the measure of emissions intensity of the economy is plotted alongside the decoupling factor – the rate of change in emissions intensities from one year to the next. Whilst there has been a general decrease in the emissions intensity of the economy, the decrease is shown by the decoupling factors to be in the order of 2%, so generally in the order of typically assumed long-run per-capita economic growth, and not exceeding it. Maximum rates are up to 4–6%, with a few isolated 'negative' decoupling years, which means that the emissions intensity of the economy actually became worse in these years. Of note, these negative values often are post-recession years (ca 2001 ca 2008) and precede a strong 'return to growth' period. We return to a deeper analysis of drivers underlying these results later.

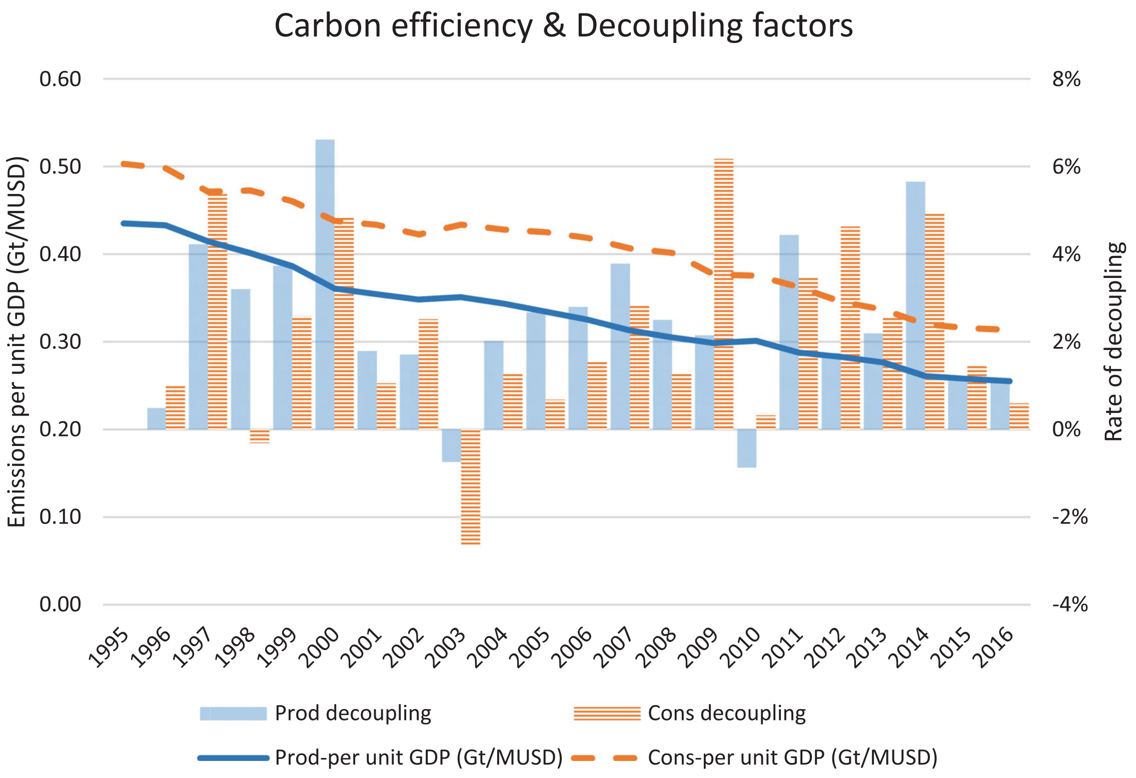

Figure 2. Production and consumption efficiency and decoupling (emission per unit GDP) rates and absolute trends for the EU28.

3.3. Growth in emissions embodied in imports

The EU GHG footprint can be broken down into the part that is induced in other regions of the world, and that which occurs domestically. Emissions in imports grew by 27% from 1.5 Gt in 1995 to 1.9 Gt in 2015, and emissions in exports grew by 44% from 536 Mt to 772 Mt. Domestic emissions for domestic consumption hence reduced from 5084 Mt to 4424 Mt (−13%). Thus for the EU, by 2015 a significant portion of the emission accounts have become associated with trade: emissions that occur overseas (33% of the EU consumption account is due to emissions embodied in imports), and due to consumption overseas (17% of the EU production account is emissions embodied in exports).

While historically, trade with Russia was the most important source for embodied GHG in imports (see supporting information for full data), nowadays imports from Asia play a more significant role (Figure 3 top). In 2015, GHG emissions embodied in imports to the EU28 were higher than the emissions embodied in exports in total (Figure 3 bottom), and also for trade with all world regions. In some of the previous years there was a slight trade deficit in regard to embodied GHG emissions with North America (1997–2006 and 2012, 2013) and Australia (2012).

Of note, emissions in imports mostly grew to 2008, and have reduced since (we return to this below). In contrast, emissions in exports have been less dynamic and generally increasing (Figure 3 bottom).

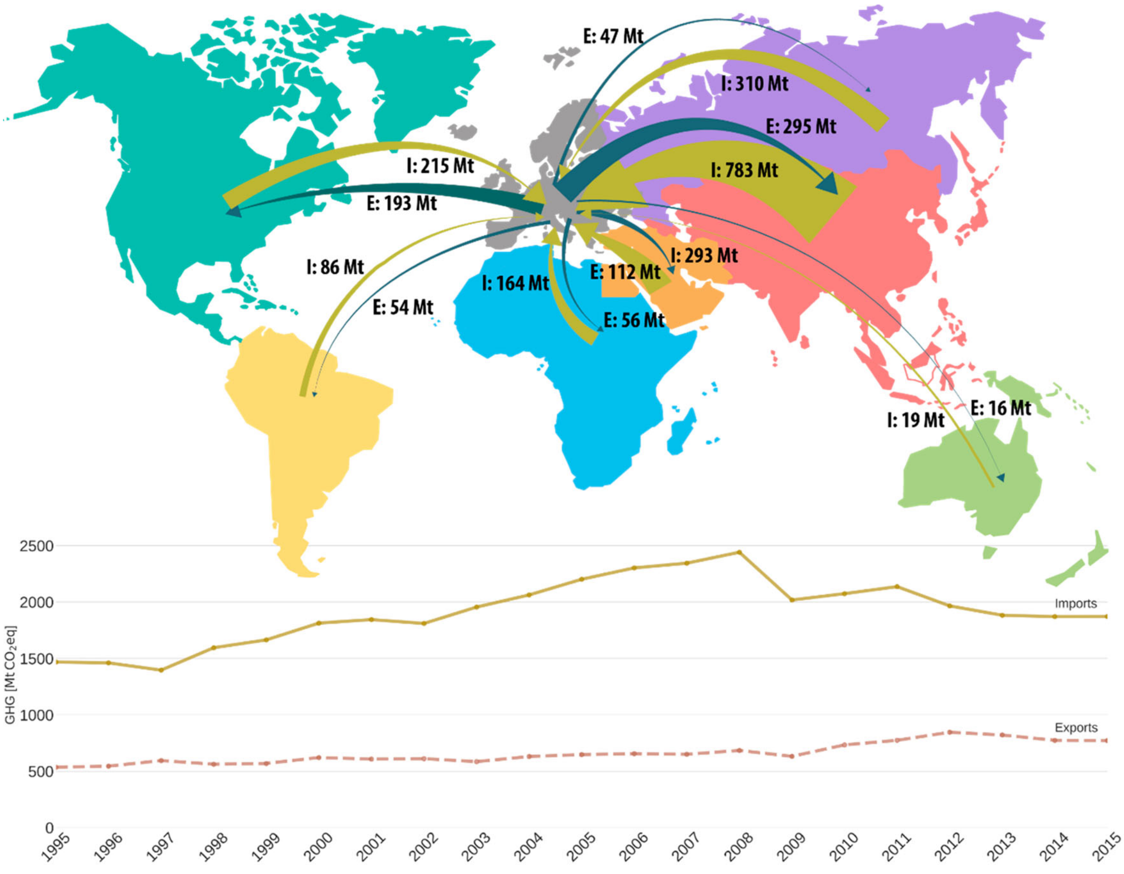

Figure 3. GHG emissions embodied in the EU trade. *Top*: Trade flows of embodied GHG emission transfers of the EU with other world regions for 2015. ‘I’: GHG emissions embodied in EU imports originating in another region, ‘E’: emissions embodied in EU exports to other world regions. Values depict GHG emissions in Mt CO$_2$ eq. *Bottom*: Totally traded GHG emissions from 1995 to 2015.

3.4. Drivers of EU GHG footprints

Overall, changes in GHG emissions can be broken down into a number of both domestic and foreign changes: changes in how goods are produced (production technology); the types of goods and services traded or consumed; and the level of trade and consumption. From 1995 to 2015 we can point to the changes being driven mainly by two of these factors. First, the reduction in GHG intensity of production – both within the EU and in other countries in the upstream supply chain of consumed products – was a major driver for decreased emissions, especially in the early and mid-2000s (see table with annual changes in the supporting results). Running counter to gains in GHG efficiency, increased total consumption per capita drove growth in GHG footprints up until the financial crisis. Other factors that played a role in the increase in GHG footprints, although not as significant, were the changes in the structure of intermediate inputs – that is, the changes in products demanded by industries, regardless of where they are sourced from; the changes in the origin of these intermediate products; the composition and sourcing of final products; consumption per capita; population growth; and changes in direct emissions.

Figure 4 shows the cumulative drivers for changes in GHG footprints in the bars, and the total annual footprint change compared to 1995 GHG footprints. In the figure, negative bars indicate drivers for reductions in GHG, while positive bars indicate drivers for increased emissions. The total change is the sum of positive and negative drivers.

The emissions associated with changes in the sourcing of products – both intermediate and final products – increase until the financial crisis, reflecting the increased specialization of European production and outsourcing of intermediate production stages to other countries, especially to Asia. However, the contribution of these trade related changes are quite minor, especially for intermediate production, so that the outsourcing of, for example, steel production from Europe to China has, in the scheme of things, a relatively minor impact on emissions. Instead the growth in total consumption (including direct imports of finished products), has a much larger role in the increase of the GHG footprint.

3.5. Sector analysis

In order to target consumption-based policies, insights into sectors and product groups are required. Two different perspectives are possible: emissions organized according to which sectors are emitting the GHG

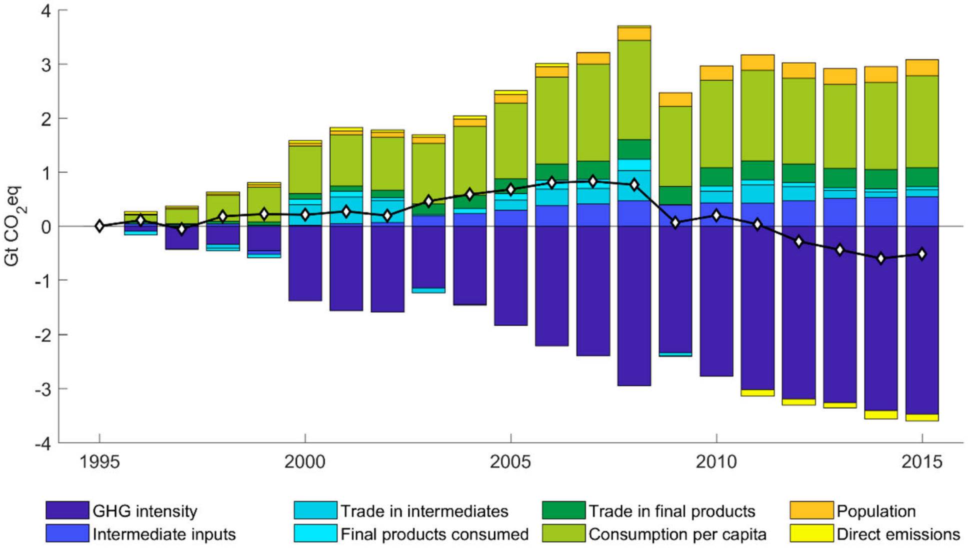

Figure 4. Drivers for cumulative changes in carbon footprints between 1995 and 2015. Solid line represents total cumulative (consumption-based) GHG emissions change in each year referent to 1995.

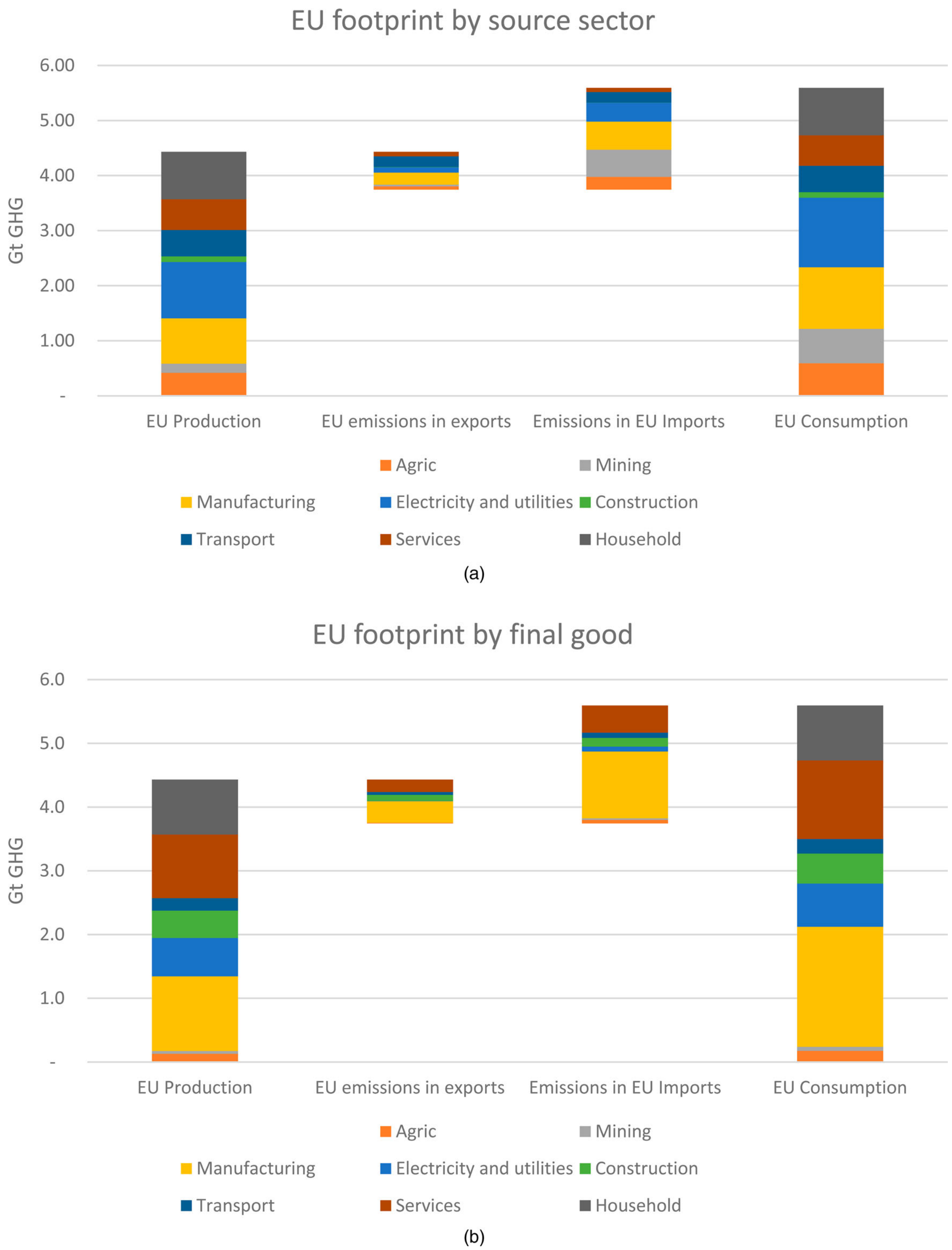

Figure 5. (a) GHG Emissions (exports, imports and net footprint) by source sector (2015). (b) GHG Emissions (exports, imports and net footprint) by sector of final good (2015).

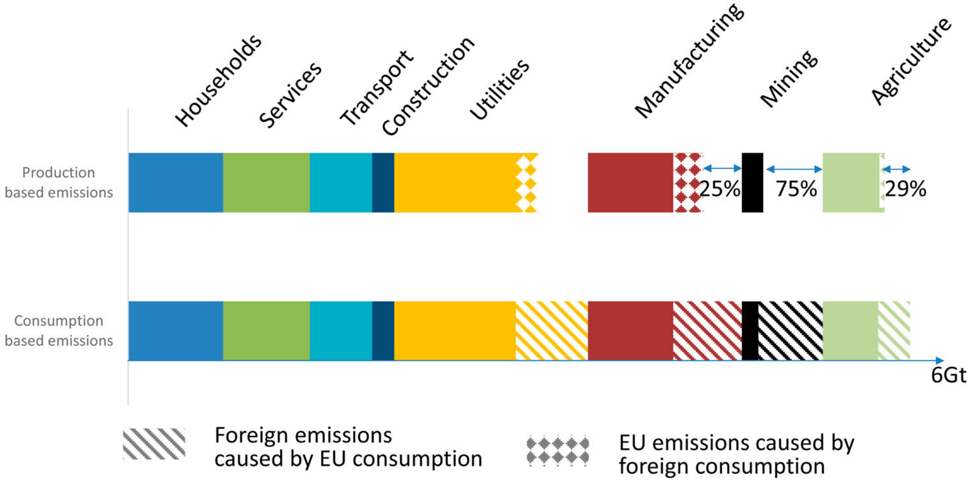

Figure 6. Production vs Consumption emissions by sector: internal and external attribution.

emissions; and emissions organized according to the product group that contains the embodied emissions in consumption.

In Figure 5(a), we firstly disaggregate the EU production account (emissions occurring in the EU28) into eight major sectoral activities. In the second column, emissions attributed to exported products and services are subtracted, and then in the third column, emissions attributed to imported products and services are added. The fourth column shows the resulting emission pattern linked to European consumption. As expected, the production account consists of a large portion of emissions in electricity production, followed by manufacturing (direct household emissions – which include personal motor vehicle driving, cooking and heating with fuels in the home – are also significant). In comparison, the largest share of exported emissions is linked to manufactured products, followed by energy/utility products and transport services. As for imported emissions, in addition to the manufacture of goods, mining and agricultural products play an important role.

In Figure 5(b), PBCA and CBCA of emissions are instead differentiated by final good. In this case, the emissions linked to exported energy/utility and transport services are attributed to the final good. These are much larger for manufacturing products but also services and construction.

These results lend themselves to a set of conclusions (Figure 6): Almost half of the embodied carbon in European consumption of manufacturing products is due to imports. However, as there are also large exports of manufacturing products, the general perception of large scale European de-industrialisation at the expense of imported goods does not hold true; instead, industrial specialization might play a bigger role in the balance of emissions in imports and exports of manufactured goods. On a net-basis, only 25% of embodied carbon from manufacturing is imported. As the majority of mining activities are located outside of EU28, 75% of emissions from mining to serve European consumption are located outside of EU28. Similarly, for agricultural products, overall EU28 exports are rather moderate compared to imports, resulting in a net import of 29% of emissions to serve European consumption.

Figure 6 therefore lends itself to a differentiated perspective on the frequently voiced concerns about European de-industrialisation. In terms of manufacturing emissions, Europe is net-importer, but ‘only’ at a scale of 25%. The larger volume of net-imported emissions is linked to mining and agriculture. However, Figure 6 is also testimony to the closely integrated nature of global supply chains. Thirty-seven percent of agricultural, 45% of manufacturing and 79% of mining emissions caused by European consumption patterns occur outside of the EU. From a European perspective, therefore, both CBCA and PBCA of emissions are important, and require careful consideration from a policy perspective.

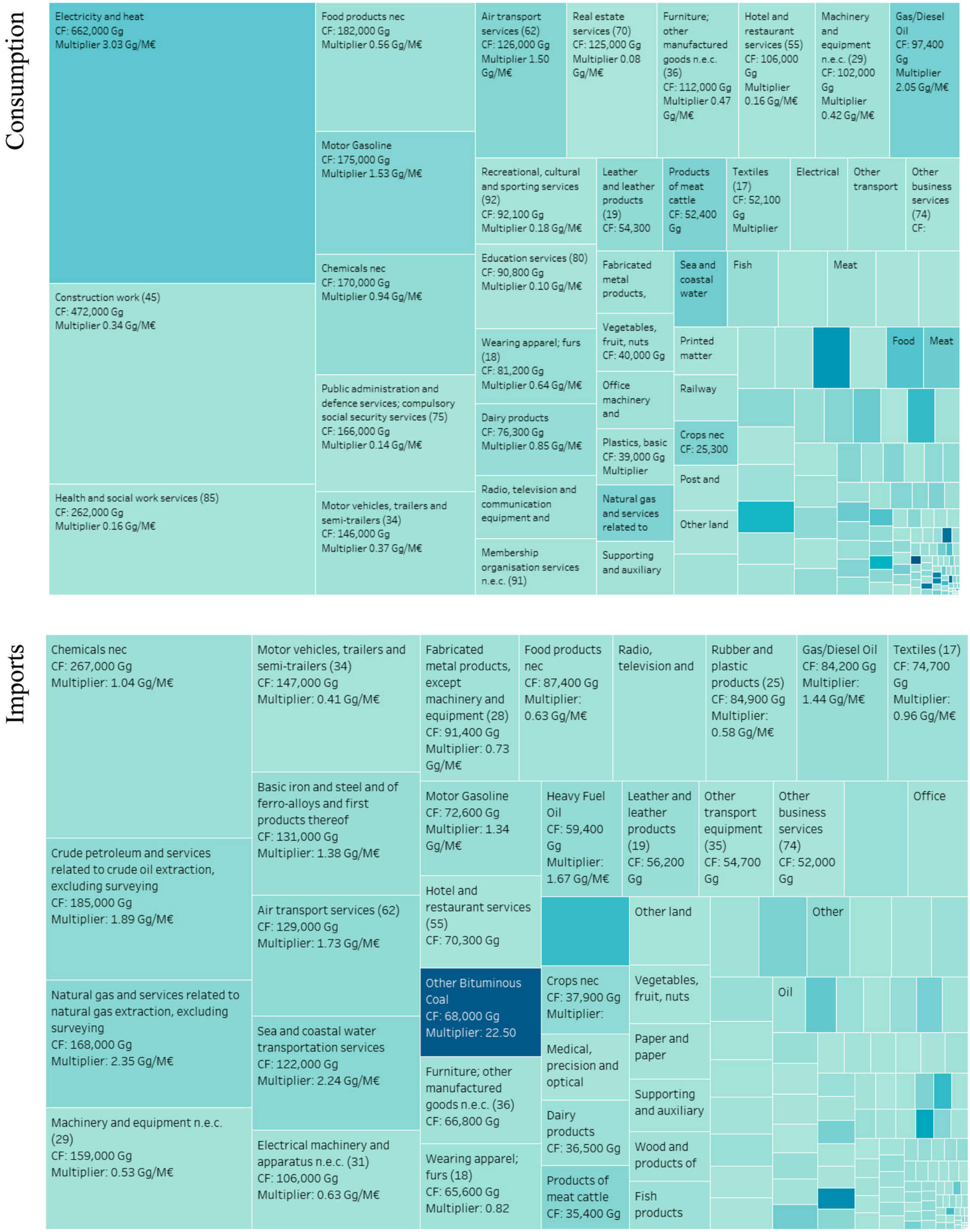

Figure 7. Product level results showing embodied greenhouse gases in consumption, imports and exports of the EU. Size of square corresponds to absolute quantity of the carbon footprint by product group, colour corresponds to the multiplier value (Carbon Footprint (CF) per unit of consumption or trade). An interactive version is available at https://public.tableau.com/shared/P6S85B7YR.

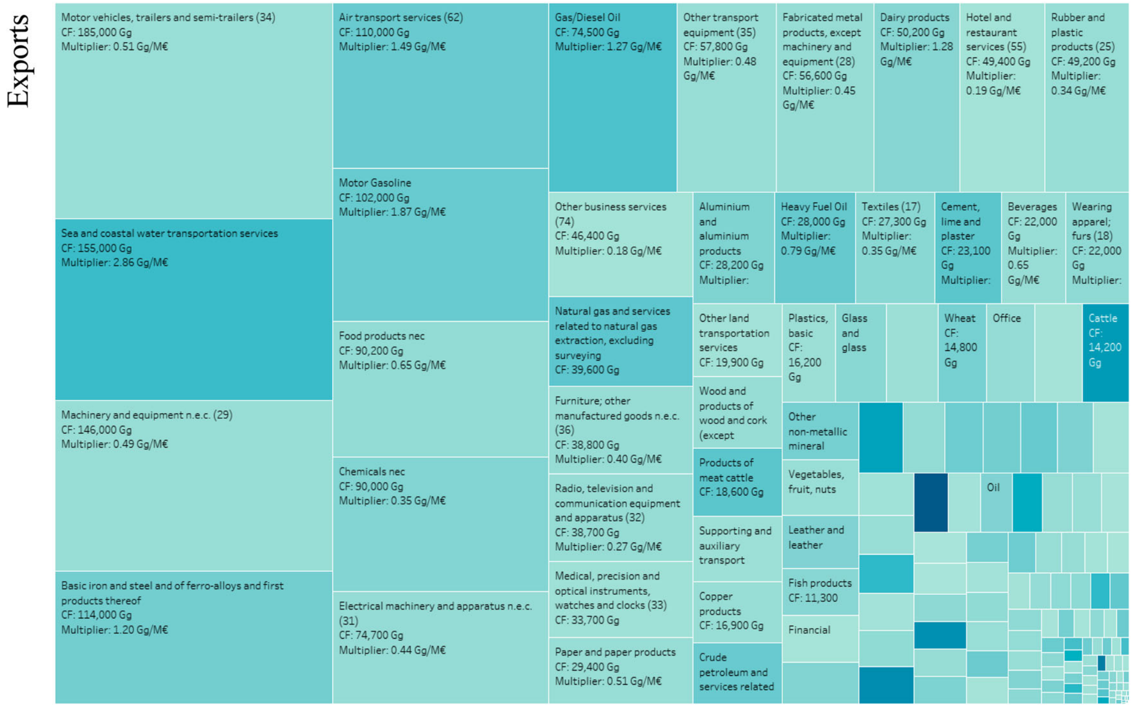

Figure 7. Continued.

3.6. Detailed product results

Underpinning the sector results are quite a diverse range of products. Results in Figure 7 show the product level results of EXIOBASE for consumption (products to final demand of the EU28), imports and exports. The size of the block shows the product level contribution to the carbon account, whilst the colour indicates the emissions intensity of the product. A link is provided to an interactive version of the figure for further investigation. A further breakdown of product level results by sector of origin of emissions is also included in the supporting information.

Unsurprisingly, the 'Electricity, gas and water' product group is the largest contributor to the EU28 GHG footprint and has a relatively high GHG multiplier of 3 Gigagrams/million Euro (Gg/M€). (Note that, whilst EXIOBASE has a disaggregation of electricity generation types and heat, the co-production of them makes interpretation of the aggregate product group more useful). Construction work is the second largest footprint category, with a GHG multiplier of 0.3 Gg/M€, followed by health and social services (0.2 Gg/M€). Other notable items related to construction are furniture and other manufactured goods (0.5 Gg/M€); and chemicals not elsewhere classified (nec) with a multiplier of 0.9 Gg/M€. Transport items such as motor gasoline, vehicles and gas/diesel oil also show up strongly.

When compared to the emissions embodied in imports, we see chemicals nec as the largest category, with the multiplier of the imported chemicals (1 Gg/M€) slightly higher than the average consumption (0.9 Gg/M€). Oil and gas extraction are the next largest, followed by a range of manufactured products (both highly manufactured such as motor vehicles, and basic iron and steel). Air and sea transport services, and somewhat later, hospitality services (holidays), break up the list of manufactured products. For exports, it is motor vehicles that embodies the most significant GHG emissions, followed by a number of transport services, and other types of machinery, equipment and other manufactured items. Of note is the reasonably high carbon intensity of the major export groups.

4. Discussion

4.1. Future relevance of CBCA

Whilst attention is being placed on CBCA to help position additional policy options on reducing global GHG emissions, there is no longer a strong evidence base that emissions under CBCA are growing, whilst PBCA of emissions are declining. As such, there is no further divergence between production and consumption accounts in comparison to that which occurred in the mid-2000s (Figure 1). Furthermore, whilst a significant portion of the CBCA of the EU28 is sourced from overseas (Figure 2), there is no evidence that the displacement of domestic industry by foreign industry has had anywhere near as big an impact on emissions as increases in consumption levels. Hence, the access to increased 'cheap' imports as well as domestically produced goods, rather than the displacement of domestic industries, is responsible for the major growth in CBCA. That is, there is little evidence that off-shoring has had a major impact on CBCA, especially for intermediate goods (Figure 4).

These conclusions, as well as the major impact of the financial crisis (Figures 1–4), point to the strong relationship between GDP growth and GHG emissions. Can the decline in emissions during the late 2000s and early 2010s be simply due to slow economic growth, that might not resume, or were there enough improvements in emissions intensity? Karstensen et al. (2018) conclude that strong links between CO_2 emissions and GDP have driven the changes in emission levels over the years. Our results show no major changes in the decoupling between GHG emissions and GDP at times of low emissions growth; in fact, the opposite is more clearly visible, where recessions cause a disruption to the average 2–3% annual rate of decoupling (Figure 2). Since the financial crisis, emissions intensity (mainly of production, Figure 4) was the main driver of the larger than average decoupling rate (Figure 2), but these improvements have not been seen in the last two years (Figure 4), resulting in reduced rates of decoupling for the EU (Figure 2). It remains to be seen if these trends continue or not.

If the main drivers of changes in the CBCA are both overall affluence (increasing factor) counteracted by improvements on the production side (decreasing factor), the question arises about the potential future relevance of CBCA. Firstly, the percentage of GHG embodied in *imports* for the EU is high, at 33% (SI data) and is only likely to grow (Wood, Grubb, et al., 2020). Hence policy must consider governance issues related to these emissions; quite simply domestic policies are not covering one third of the GHG footprint of EU consumption (though they are covering significant emissions that go into exports). Secondly, the use of CBCA may be useful to motivate policy options for the decarbonization of international supply-chains (Wiebe, 2018), taking advantage of the knowledge of trade relationships.

4.2. Relevance of sectoral results for policy

Comparison of the PBCA and CBCA of emissions for different sectors (Figures 5 and 6) shows that, for household, services and transport (the transport sector in MRIO tables conceptually covers both personal transport and transport of goods, domestically and internationally, (Hu, Wood, Tukker, Boonman, & de Boer, 2019)), international trade of embodied emissions is limited, and PBCA and CBCA largely coincide. For these sectors, energy and climate policies have been largely tailored to consumption choices (efficiency standards, financial support, advice), combined with attention to electricity generation. Pricing instruments, especially gasoline taxes, have also been implemented as a consumption charge. For these products and sectors, there has been a considerable focus on efficiency standards for the operations phase of products, for example for buildings, appliances and vehicles. However, in many cases, a substantial share of the whole life-cycle emissions of these goods occurs during the production stage. To lower entire life-cycle emissions from consumption, these embodied emissions must be considered (Scott, Roelich, Owen, & Barrett, 2018).

For mining, manufacturing and agriculture, products are intensively traded internationally, and PBCA and CBCA of emissions differ significantly. In comparison to Karstensen et al. (2018) (who only look at CO_2 for sectoral results), the inclusion of other GHGs furtrher increases the importance of the mining and agricultural sectors in both CBCA of emissions and emissions embodied in trade. The major energy and climate policy instruments (EU ETS, EU common agricultural policy) have been largely focused on the production side (and focused on CO_2), while consumption-based policies like the EU-Ecodesign and Eco-labelling Directive retain limited product coverage and largely focus on emissions during operation and not embodied in the product. This is despite significant public support for climate policies that focus on resource efficiency (Cherry, Scott, Barrett, & Pidgeon, 2018).

With hindsight, energy and climate policies for manufacturing, mining and agriculture should also be considered for their effects in the upstream and downstream supply chains, complementary to the production side. With the international tradability of their products, concerns about competitiveness or carbon leakage have resulted in a persistent watering down of stringency of production-based policies and the use of special provisions like free allowance allocation or reductions from energy taxation, muting much of the desired incentive effect. The extent of such market distortion was recently highlighted by Shapiro (2019), who finds several hundred billion dollars of global subsidies on CO_2 due to protectionist measures of downstream industries.

4.3. Jurisdiction

The large share of industrial and agricultural emissions embodied in international trade points to the importance of explicitly considering the difference between the statutory incidence and the economic incidence of policy instruments. The statutory incidence refers to the actor liable to comply with a standard or pay a carbon tax, whilst the economic incidence refers to which actors are exposed to the policy because of pass-through of carbon costs or impacts on product markets.

Without international trade, making producers liable for carbon emissions is in most instances sufficient. Upstream producers will pass carbon costs along the value chain, and thus all actors along the value chain receive incentives for emission reductions (economic incidence).[2]

With international trade this picture changes. Statutory responsibility for carbon pricing in industry (in the EU, New Zealand, Korea, California, Quebec, Ontario and Chinese provincial pilots) currently rests with emitters, e.g. producers of materials. These producers will however only pass some of the carbon cost on to product prices where products are traded and priced in global markets (Demailly & Quirion, 2008). Concerns that incremental policy costs in one region could trigger relocation of production or investment to other regions (carbon leakage) has resulted in carbon leakage protection measures like free allowance allocation, further muting the carbon cost pass-through (Neuhoff, Martinez, & Sato, 2006). As a result of the limited carbon cost pass-through, the economic incidence of the policy instrument is largely constrained to the production stage, and mitigation options along the value chain are not incentivised (Grubb et al., 2020).

As a response, border adjustments have been long proposed. Border adjustments aim to include carbon costs also in the price of imported products and materials and could be highly relevant for a number of the key sectors in our analysis (e.g. chemicals, oil and gas, transport and transport equipment, machinery). Under border adjustments, carbon related production cost increases would be reimbursed for exports to avoid distortions of international competition. A variety of detailed implementation options have been proposed. However, in order to enhance political acceptance and reduce the risk of challenges at the World Trade Organisation (WTO), all these options have provisions attached that increase their complexity and reduce their effectiveness with respect to environmental and carbon leakage protection (Cosbey, Droege, Fischer, & Munnings, 2019)

Some analysts argue for moving the (statutory) responsibility for carbon pricing from producers to consumers. At the point of sale of a product to final consumers, a charge corresponding to the carbon embodied in the production of the product would be due (Bruyn, Nusselder, Rooijers, & Wijngaarden, 2018). Implementation would require that emissions are monitored, reported and verified along the (individual) value chain (including emissions in plants and farms in third countries). However, the administrative effort involved to reliably monitor and report emissions, and to attribute these to individual products along the entire global value chain, may be rather high, as will the public verification of product specific emissions for all products (discussed in (Grubb et al., 2020)).

A combination of production and consumption-based pricing instruments has been proposed as an alternative (Neuhoff et al., 2016). Producers would pay the carbon price for emissions exceeding a benchmark and benefit to the extent that they outperform the benchmark. Consumers would pay a carbon price for emissions intensive products – including as part of products and buildings – at the benchmark level for specific materials.

Such approaches could capture a significant portion of the GHG footprint that escapes traditional measures (Figure 5). The full carbon price can be reinstated along the entire value chain, while carbon leakage risks are avoided and administrative complexity is minimized.

4.4. Robustness of the empirical basis for policy design

Whilst not the focus of this article, the robustness of CBCA has come under considerable scrutiny due to the variability in results from different modelling exercises and the subjective nature of some decisions when undertaking MRIO modelling. Regarding the latter, MRIO approaches have a number of strengths and weaknesses for CBCA that should be kept in mind when interpreting results. The strengths include a complete coverage of goods and services in the economy, including (in the case of most developed countries) imputations of the non-formal economy. Furthermore, with the investment in global MRIO models over the last 10 years (see Tukker & Dietzenbacher, 2013), data are available for most countries individually, and for all regions of the world in total. The availability of country level input-output tables allows for the explicit capture of trade and onward processing through an economy, thus capturing the regionally delineated emissions intensity of production as it contributes to intermediate processing before final consumption. However, most MRIOs operate at an aggregated product level, usually discerning somewhere between 30 and a few hundred product groups. If goods within a product group have a very distinct emissions intensity to others in the same product group, then aggregation errors can be introduced (Bouwmeester & Oosterhaven, 2013; de Koning et al., 2015; Steen-Olsen, Owen, Hertwich, & Lenzen, 2014; Wood, Hawkins, Hertwich, & Tukker, 2014). The choice of EXIOBASE for this paper is due to the enhanced resolution on emissions intensive processes (Wood et al., 2014), but sector level results have not seen much verification apart from at an aggregated resolution by Owen, Wood, Barrett, and Evans (2016), Wieland, Giljum, Bruckner, Owen, and Wood (2018), and Rodrigues, Moran, Wood, and Behrens (2018). A further weakness of CBCA in general (and particularly for MRIO) is that intertemporal concepts are difficult to treat. Specifically, we mean investment in capital for production in later years (included in the account of the year of investment (Södersten, Wood, & Hertwich, 2018a, 2018b), and emission spikes, such as from land-use change (Pendrill et al., 2019) which are not included in this work).

To enhance the overall robustness of MRIO results, a number of studies have attempted to quantify uncertainty, by parametrizing errors of either original source data (Karstensen, Peters, & Andrew, 2015; Lenzen, Wood, & Wiedmann, 2010) or the actual MRIO data (Moran & Wood, 2014; Rodrigues et al., 2018), and running montecarlo simulations to estimate error distributions. From such work, it is clear that uncertainty of the CBCA of large regions such as the EU is relatively low (in the order of a few percentage points), with most of the error either due to the temperature metric chosen (Karstensen et al., 2015), or the GHG emission account itself (Moran & Wood, 2014). Exercises on database comparisons lead to similar results (Owen, 2017; Owen, Steen-Olsen, Barrett, Wiedmann, & Lenzen, 2014).

5. Conclusions

CBCA of GHG emissions has the potential to help inform more effective climate change policy aimed at reducing global carbon emissions. However, the debate over the EU's GHG footprint in aggregate is almost pointless without an appreciation of its structure. This is because some emission sources are unavoidable, whereas others may have strong policy implications: the purpose of this paper is to present a complete overview and explain where and what matters in the debate (and why). We hence applied CBCA of emissions to the EU over the period 1995–2016, focussing on levels and drivers of change, as well as on which sectors or product groups policy could focus. We found that, firstly, the EU28 CBCA has declined over the period, reducing by 8%. This is in the direction of, but somewhat less of a reduction than the PBCA of emissions of the EU, which reduced by 13%. Whilst around one-third of the EU28 GHG footprint occurs overseas, the gap between the PBCA and CBCA (reflecting net-trade) has stabilized at just over 20% of the CBCA.

The high percentage of emissions on foreign soil has three implications. First, several (but not all) of the major sources of net carbon embodied in imports are largely unavoidable consequences of European consumption because the primary production activities (e.g. mining and some food production) could not realistically occur within the EU. These emissions therefore require policy responses at the consumption level. Second, emissions embodied in trade for basic materials and industrial products is high. This can reduce the carbon cost pass-through along the value chain and thus render purely production-based policies less effective in incentivising mitigation measures along the value chain. To ensure effective incentives along the entire value chain, it is warranted to (i) consider carbon border adjustments, (ii) a shift to targeted consumer policies, or (iii) combining policies to incentivise carbon efficiency of production with policies to incentivise efficient material use and substitution. Third, when looking at the regional differences in production (and not explicitly looking at the role of transport), with few exceptions, the emissions of EU consumption would differ little whether the products are produced at home or abroad. Hence the debate is not primarily about the global impact of trade, but about measures to enhance carbon efficiency of domestic production and consumption and to encourage and support other regions in their efforts towards the same objectives.

Notes

1. Eurostat does not currently use a multi-regional approach for CBCA because of the reliance on other regions' statistics. They use what is known as the 'domestic technology assumption' (see Andrew, Peters, & Lennox, 2009; Tukker, De Koning, Wood, Moll, & Bouwmeester, 2013), which assumes that goods produced overseas are produced with the same technology as that of Europe. Such approaches generally underestimate the emissions embodied in imports of developed countries. Work is ongoing at Eurostat on new data to avoid this assumption.
2. Policy makers may still target policies directly to intermediary producers or final consumers first to allow for differentiation or compensation of distributional impacts of pricing instruments, second, to address (organizational or) behavioural aspects with for example product standards (Scott, Giesekam, Barrett, & Owen, 2019), building standards or to address strategic aspects (innovation, infrastructure) of decisions (Grubb, 2014).

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Appendix

Extended methods: multi-regional input-output analysis and footprinting

Input-output analysis is an economic approach, constructed from observed data from a particular region, which considers inter-industry flows between economic sectors (Leontief, 1941; Miller & Blair, 2009). Environmental impacts can be calculated in this framework by using an environmentally extended input-output table, attributing requirements and impacts to each of the industries or products. However, the original national model does not account for technological and productivity differences among countries, which is of contemporary significance, as economies shift from local to global production chains. Multi-regional input-output (MRIO) analysis can account for offshore impacts and requirements, allowing the evaluation of a region's social and environmental impact to be calculated from its consumption, rather than its production. MRIO analysis has been described in detail elsewhere (see, for example, Miller & Blair, 2009), and thus, this section will provide only a brief summary of the background for the analysis.

A MRIO model, comprising n regions, relates total output from a region r, to the inter-industry demand and final demand, and can be expressed as:

$$\begin{pmatrix} \boldsymbol{x}^1 \\ \boldsymbol{x}^2 \\ \boldsymbol{x}^3 \\ \vdots \\ \boldsymbol{x}^n \end{pmatrix} = \begin{pmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} & \mathbf{A}^{13} & \dots & \mathbf{A}^{1n} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \mathbf{A}^{23} & \dots & \mathbf{A}^{2n} \\ \mathbf{A}^{31} & \mathbf{A}^{32} & \mathbf{A}^{33} & \dots & \mathbf{A}^{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{n1} & \mathbf{A}^{n2} & \mathbf{A}^{n3} & \dots & \mathbf{A}^{nn} \end{pmatrix} \begin{pmatrix} \boldsymbol{x}^1 \\ \boldsymbol{x}^2 \\ \boldsymbol{x}^3 \\ \vdots \\ \boldsymbol{x}^n \end{pmatrix} + \begin{pmatrix} \sum \boldsymbol{y}^{1s} \\ \sum \boldsymbol{y}^{2s} \\ \sum \boldsymbol{y}^{3s} \\ \vdots \\ \sum \boldsymbol{y}^{ns} \end{pmatrix} \tag{1}$$

In the above equation, $\boldsymbol{x}$ is the vector for total output in each sector; $\mathbf{A}$ is the multi-regional coefficient matrix, which shows the relation between the output from each sector being used as input for production; $\boldsymbol{y}$ is the final demand vector, representing all final consumption, such as households and government expenditures, capital, and stock variation. Imports are implicitly recorded either as inputs into intermediate demand, or as purchases by final users.

Given emissions of production as a row vector $\boldsymbol{f}$ showing the emissions occurring in each industry in each region of the world, as well as those occurring in final demand (e.g. cooking, heating) $\boldsymbol{f_{hh}}$. GHG impacts of consumption can be calculated via the input-output model:

$$Q = \boldsymbol{s}\,(\mathbf{I} - \mathbf{A})^{-1}\boldsymbol{y} + \boldsymbol{f_{hh}} \tag{2}$$

Where Q represents the GHG (or CO_2) footprint of consumption taking place in the EU (due to consumption of the EU: $\boldsymbol{y}$), and $\mathbf{s}$ is a vector containing direct GHG (or CO_2) emission coefficients for each industry ($\boldsymbol{s} = \boldsymbol{f}\hat{\boldsymbol{x}}^{-1}$). Emissions by source region/industry are simply a diagonalization of the emissions intensity vector (where emissions occur):

$$\boldsymbol{q}_{\mathbf{ind}} = \hat{\boldsymbol{s}}\,(\mathbf{I} - \mathbf{A})^{-1}\boldsymbol{y} \tag{3}$$

Emissions by final product consumed are simply a diagonalization of the final demand vector:

$$\boldsymbol{q}_{\mathbf{prod}} = \boldsymbol{s}(\mathbf{I} - \mathbf{A})^{-1}\widehat{\boldsymbol{y}} \tag{4}$$

All results are a simple aggregation of the most detailed product/country combinations, following the aggregation keys as provided in the supporting information.

Extended methods: decoupling rates and structural decomposition analysis

Results are also presented for the rate of decoupling D^t for year t. Production and consumption accounts are firstly normalised by GDP in 2011 international dollars:

$$D^t = 1 - \frac{\frac{Q^t}{GDP^t}}{\frac{Q^{t-1}}{GDP^{t-1}}}$$

See Gupta (2015) for further discussion around decoupling metrics.

Furthermore, we decompose the changes in GHG footprints over time as the sum of the changes in the different components of Equation. 1:

$$\Delta \boldsymbol{q} = \boldsymbol{q}_{t+1} - \boldsymbol{q}_t = \Delta \mathbf{s} + \Delta (\mathbf{I} - \mathbf{A})^{-1} + \Delta \mathbf{y} + \Delta \boldsymbol{f}_{\boldsymbol{hh}}$$

We further decompose **A** into two components, following the method introduced by (Xu & Dietzenbacher, 2014): changes in inputs required for production, regardless of where they come from (**H**), and sourcing of these intermediate inputs (**T**). Likewise, we decompose changes in final demand **y** into changes in the composition of final products consumed, regardless of their origin or volume (**c**), the sourcing of these final goods ($\mathbf{y}_t$), total consumption per capita ($\mathbf{y}_{cap}$), and population (**p**). We can then re-write Equation 1 as:

$$\boldsymbol{q} = \boldsymbol{s}(\mathbf{I} - \mathbf{H} \otimes \mathbf{T})^{-1} \mathbf{c} \mathbf{y}_t \boldsymbol{y}_{\mathbf{cap}} \boldsymbol{p} + \boldsymbol{f}_{\boldsymbol{hh}}$$

For each pair of years, the tables for year $t + 1$ were deflated to previous year prices following product-specific deflators for each country and year, without new balancing of the input-output tables. We applied the structural decomposition method of the average of the polar decompositions (Dietzenbacher & Los, 1998).