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Tracing carbon footprints to intermediate industries in the United Kingdom

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ABSTRACT

Several decades of informed warnings about climate change have been insufficient to reverse trends of rising greenhouse gas (GHG) emissions and ecological degradation. The global supply chains are increasingly complex, which has impaired discussions about the responsibility, power and agency of various actors for socio-ecological transition. Historically, environmental impact assessments have focused on the origin and consumption ends of supply chains, overlooking the role of powerful intermediate actors. In this study, we present a detailed analysis of the industrial contributors to the carbon footprint of United Kingdom's gross production using the multiregional input-output database EXIOBASE and product layer decomposition. We find that 54% of the GHG emissions associated with UK gross production in 2019 originate within four major source industries, including fossil fuel-based extraction, manufacturing and electricity, animal-based food, and air transport. Furthermore, the distribution of emissions and value added provides implications about mitigation capacity and spatial justice.

1. Introduction

Several decades of informed warnings about climate change have been insufficient to produce a lasting change in the trends of rising GHG emissions (IPCC, 2022; Stoddard et al., 2021) and energy use (Ritchie et al., 2022). These warnings have highlighted the disastrous global effects on natural systems and societies, acknowledging the need to bring human activities within planetary boundaries. The distributions of carbon, energy and resource use are highly unequal, linking to profound differences in responsibility and contribution to the problem as well as affluence and power (Stoddard et al., 2021; Wiedmann et al., 2020).

Recent studies have emphasised the significant role of power for absolute reductions in material throughput: power to initiate change (e.g. through collective action) and power to resist change (e.g. through entrenched interests and institutions) (Fuchs et al., 2016; Stoddard et al., 2021). Vested interest from the individual through the corporate to the geopolitical level have hugely profited, lobbied to prevent climate policies, and worked to discredit scientific evidence and shift social norms (Frumhoff et al., 2015; Fuchs et al., 2016; Heede, 2014; Stoddard et al., 2021). While environmental impact assessments usually do not engage with the concept of power directly, power dynamics permeate the adopted approaches and recommended strategies for impact reductions. The complexity of global supply chains – which is high and rising (Hertwich and Wood, 2018) – has also impaired discussions about responsibility, power and agency (Fuchs et al., 2016).

Agency over one's impacts refers to the ability to influence their own impacts. In the context of supply chain actors, mitigation agency refers to the ability to reduce emissions associated with their own activities, purchases and products, as well as the wider societal institutions, infrastructures and norms they may be influencing. Environmental impacts can and have been attributed to various agents along the global supply chains (Hertwich and Wood, 2018; Steininger et al., 2016). For example, multiple actors have agency over tailpipe emissions and car dependence (Mattioli et al., 2020), including the automotive industry, state actors in key policy areas, advertisers, and car owners among others. With a variety of accounting methods, questions about agency and responsibility over emissions remain widely debated, with studies highlighting the carbon impacts of high-income nations (Chancel, 2022; Hickel, 2020; Ivanova et al., 2016; O'Neill et al., 2018), powerful corporate emitters (Frumhoff et al., 2015; Heede, 2014) and mega-consumers (Chancel, 2022; Otto et al., 2019; Wiedmann et al., 2020).

Power, on the other hand, refers to the ability of one actor to influence the impacts of others. Power exertion may have positive environmental consequences where pressure is placed on dominant institutions to reduce their environmental impacts. However, actors may also exert power towards continuing activities with negative environmental consequences, where restricting such activities contradicts their core goals and priorities (Frumhoff et al., 2015; Pirgmaier, 2020). Debating agency

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and power over impacts have direct implications for the plausible mitigation strategies as well as targeting injustice.

Emissions are typically categorised as production-based or consumption-based. Territorial or production-based approaches focus on the origin of emissions and resource use; thus, these approaches tend to highlight the responsibility and agency of the actors emitting through their direct activities such as extraction or burning of fuel. Consumption-based approaches trace production emissions through global trade to the final consumers. Other accounting methods have also been developed over the last two decades (Csutora and Vetőnémózner, 2014; Gallego and Lenzen, 2005; Hertwich and Wood, 2018; Marques et al., 2012; Piñero et al., 2019; Temursho and Miller, 2020), although they are not as commonly applied. Particularly, the work of Gallego and Lenzen (2005) inspired a whole range of shared consumer and producer responsibility approaches, by introducing the concept of responsibility shares that are mutually exclusive and collectively exhaustive. All of these approaches are complementary and may support carbon mitigation. Yet, they have important policy and strategy blind spots, where emission reduction potentials may remain unidentified. Bouncing between production and consumption accounts absolves from responsibility agents that are neither at the origin nor at the consumption end of emissions; particularly, intermediate supply chain actors are often under-represented.

By shedding light on the intermediate supply chain actors, our study makes an important contribution towards unravelling emission mitigation strategies that are effective, yet understudied through traditional production and consumption approaches. The perspective in which responsibility rests with the sellers and suppliers of inputs, seen as enablers of production and emissions, is rarely addressed in the literature (Frumhoff et al., 2015; Lenzen and Murray, 2010). It is more common that studies highlight individual consumer responsibility, which is problematic in the presence of systemic social and physical carbon lock-in (Seto et al., 2016), the overpowering pursuit of economic growth (Wiedmann et al., 2020) and the need for collective action.

While we make no claim to assess the full agency and power of supply chain actors, in this analysis we link emission flows directly to source and destination industries at various product layers. We focus on how industries contribute to climate change by emitting directly or consuming high-emission inputs. Quantifying the damage of intermediate producers and consumers is a key precondition for climate action, both by the industries themselves and by other actors holding polluting industries accountable.

2. Method

2.1. The multiregional input-output database EXIOBASE

In this study we provide a complementary approach to traditional production and consumption perspectives by presenting a detailed analysis of intermediate industrial emissions across product layers. We perform the analysis for the carbon footprint of the United Kingdom's gross production (GP) with the updated EXIOBASE multiregional input-output (MRIO) version 3.8.1 for 2019, which describes the global economy in the detail of 200 products, 44 countries and 5 rest-of-the-world (RoW) regions. The UK's GP carbon footprint (Hertwich and Wood, 2018) captures all commodities produced within the UK for intermediate and final consumption, regardless of whether they are consumed inside or outside the UK. As both the MRIO model and code are openly available via Zenodo (Stadler et al., 2020) and Github, our analysis can be easily replicated for other countries, years, environmental and social stressors (e.g. energy use, water, land, employment).

GHG emissions were calculated using the Global Warming Potential 100 (GWP100) metric aggregating emissions of CO_2, CH_4, N_2O (from combustion and non-combustion) and SF_6 in tCO_2-equivalents per year (Solomon et al., 2007). Further detail about the database is offered elsewhere (Stadler et al., 2018; Wood et al., 2014).

We provide industrial product detail for the UK as a case study. We aggregate other countries and regions into EU and RoW regions in order to reduce computational runtime of the product layer decomposition. While we conduct the analysis on the 200 product level, we communicate results by 32 broader industry categories (i.e. industry sectors) and six IPCC categories (i.e. industry groups) (cf. Hertwich and Wood, 2018). We detail the concordances in the Supplementary spreadsheet, where "nec" refers to not-else-classified. The present work focuses on the inter-industry relations and associated GHG emissions, thus excluding household direct emissions, which are generally well-covered in consumption-based accounting (cf. Ivanova et al., 2016). For UK specific numbers on direct home heating and transport emissions, please see official UK statistics (DEFRA, 2023).

2.2. Production-driven MRIO analysis

Following the seminal work of Hertwich and Wood (2018), this study quantifies the embodied emissions that are associated with GP activities. Instead of allocating emissions to final demand (such as household consumption), we use an MRIO model that is driven by gross production x. In the following, hat (ˆ) indicates diagonalization of vectors. Non-italic lower-case letters stand for column vectors, italic lower-case letters for scalars and non-italic upper case letters for matrices.

Consumption-based MRIO accounting traditionally uses a demand-driven model:

$$\mathrm{C} = \widehat{\mathrm{f}}\,\mathrm{L}\,\widehat{\mathrm{y}}$$

where C signifies a consumption-based account (e.g. consumption-based carbon footprint), L stands for the Leontief inverse, y depicts final demand and f the direct intensities per unit of output (e.g. GHG emission intensities). From this perspective, final demand drives emissions. Alternatively, as detailed in the work of Wood and Lenzen (2009), one can also consider industries gross production x to be the driver of emissions. This so-called production-driven MRIO model is given by:

$$\mathrm{C} = \widehat{\mathrm{f}}\,\mathrm{L}\,\widehat{\mathrm{x}}$$

UK gross production emissions in 2019 contain the emissions associated with final and intermediate products produced in the UK and consumed in the UK or elsewhere. In the analysis, we communicate UK gross production emissions by *source industry* (i.e. the industry where emissions originate) and by *destination industry* (i.e. the industry utilising the products, whose production released the emissions). We explore both ends of supply chains – the origin and the destination – assuming that each industry has agency to mitigate them. The destination industry may link to final and intermediate demand in the UK and other countries. It is worth noting, that production-driven IO analysis shares a lot of methodological commonalities with the total flow concept, which was originally conceived in the domain of ecological network modelling (Szyrmer and Ulanowicz, 1987; Szyrmer, 1986) (REF). Readers interested in a theoretical discussion and quantitative comparison of related metrics and indicators (including the total flow concept) are referred to the paper by Wood and Lenzen (2009).

2.3. Product layer decomposition

The technique we use for quantifying the total amount of emissions produced at a specific supply chain layer is called product layer decomposition (PLD). Our analysis reveals the emissions released from a *source industry* for the production of a product destined to be used as an input to a *destination industry*, entering the supply chain at a specific *product layer* and directly or indirectly serving UK GP. The source industry depicts where emissions are physically released in the environment, while the destination industry depicts where embodied emissions are consumed. The product layer specifies the supply chain stage at which the transfer of emissions takes place.

PLD allows us to systematically single out the most environmentally relevant supply chain cluster through the power series expansion of the Leontief inverse:

$$L = (I - A)^{-1}$$

Here, A is the direct requirements or technology matrix and I the identity matrix. In theory, there are infinite layers of inputs that compose the total carbon footprint C of gross production x. C can be unravelled through the means of a power series expansion (Wieland et al., 2018):

$$C = \widehat{f}\, L\, \widehat{x} = \sum_{k=0}^{\infty} \widehat{f}\, A^k\, \widehat{x} = \widehat{f}\, A^0\, \widehat{x} + \widehat{f}\, A^1\, \widehat{x} + \widehat{f}\, A^2\, \widehat{x} + \widehat{f}\, A^3\, \widehat{x} + \widehat{f}\, A^4\, \widehat{x} + \dots$$

$$C_k = \widehat{f}\, A^k\, \widehat{x}$$

Here, $\widehat{f}\, A^k\, \widehat{x}$ quantifies the release of GHG emissions on layer *k* along the path of a product, which directly or indirectly serves the production x, where f represents the direct emission intensities per unit of output (Wieland and Giljum, 2016). Layer 0 emissions are emissions that occur directly through the activities of an industry. At layer 0, the source industry produces in the UK directly for UK gross production (i.e. final and intermediate products consumed in the UK or elsewhere). In practice, the source and the destination industry are thus the same.

$$C_0 = \widehat{f}\, A^0\, \widehat{x} = \widehat{f}\, I\, \widehat{x}$$

Element $c_k(i,j)$ reveals the emissions released in source industry *i* stemming from production of intermediate inputs that are destined to be used for the production in destination industry *j*, entering the supply chain at layer *k*. For example, Layer 1 emissions are emissions embodied in the direct inputs to the activities of a destination industry. Layer 2 emissions are emissions embodied in the indirect inputs to the activities of a destination industry. For example, consider a car manufacturer (layer 0): while the fabrication of chassis produces layer 1 emissions, the production of steel from iron ore for the fabrication of chassis brings about layer 2 emissions and so forth. As there are an infinite number of layers, PLD requires setting a truncation point by calculating a residual term in the following way:

$$L_{rest} = L - \sum_{k=0}^{r-1} A^k$$

$$C_{rest} = \widehat{f}\, L_{rest}\, \widehat{y}$$

In our analysis, we select $r = 3$ as a threshold regarding the number of layers analysed separately. Thus, C_{rest} covers all emissions from layer three and beyond. We display layer 0–2 and 3+ separately. PLD thus enables slicing up the transfer of embodied GHG emissions between distinct processing stages, while at the same time aggregating the layer results for a more concise analysis. Fig. 1 presents a simplified visualisation of product layers in the context of production-driven carbon footprints.

Compared to conventional production- and consumption-based accounts, PLD highlights potential areas of intervention at each product layer and interaction with another industry (whether located upstream or downstream). Thus, it potentially increases the mitigation agency of supply chain actors by providing information and supporting collaboration along the supply chains. It also potentially enhances possibilities of other actors to hold supply chain industries accountable.

2.4. Regression analysis

We perform a multivariate regression analysis, with industry *i* as the unit of analysis. We estimate gross production emissions in $MtCO_2eq$ (dependent variable), where beta is the regression coefficient varying by variable and category level.

$$\begin{aligned} C_i = {} & \beta_0 + \beta_1(SOURCE\ REGION_i) + \beta_2(LAYER_i) \\ & + \beta_3(SOURCE\ INDUSTRY_i) \\ & + \beta_4(DESTINATION\ INDUSTRY \times LAYER_i) \end{aligned}$$

The inclusion of source industry as an independent variable in our regression complements the descriptive analysis of the distribution of

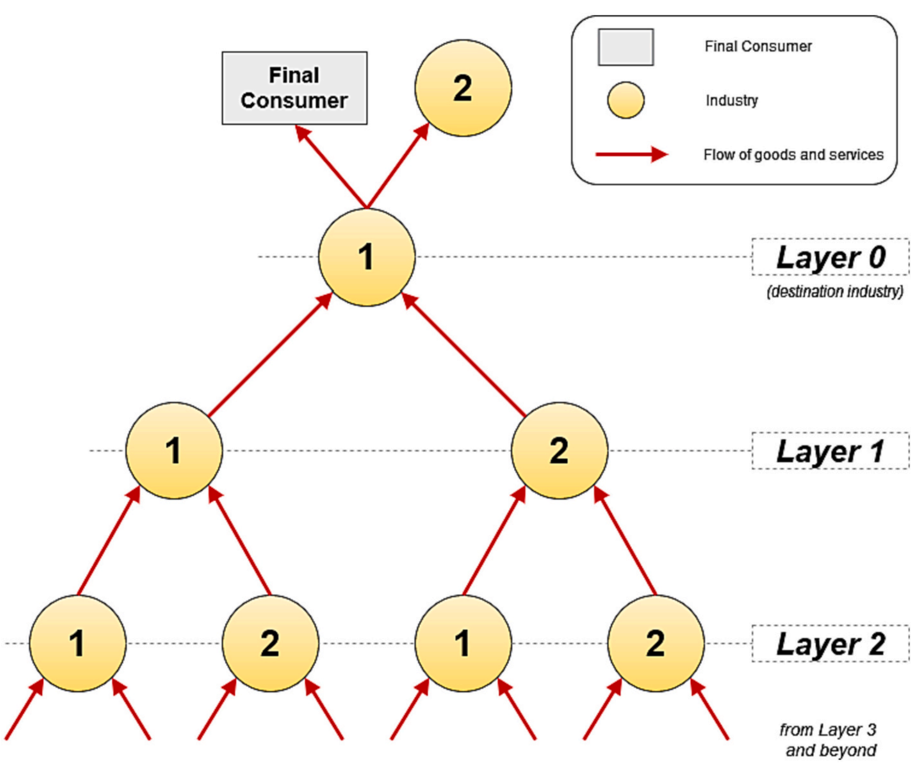

Fig. 1. Product layers in production-driven carbon footprint analysis using the hypothetical example of a two-sector economy that delivers final products to a single final consumer. The yellow circles stand for industries. The rectangle stands for final consumers and the red arrows indicate flows of goods and services between industries and final consumers. Layer 0 stands for the destination industry where upstream GHG emissions are allocated to when calculating carbon footprints of industry gross production. The destination industry produces goods and services, which are either delivered to final consumers or to intermediate consumers. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

UK GP emissions across source industries and highlights the biggest emitters, holding other factors constant. We also added an interaction term between the destination industry and product layer ($DESTINATION\ INDUSTRY \times LAYER$) in order to explore the role of intermediate and final destination industries as high consumers of emissions embodied in their inputs. We captured spatial and logistics controls in the inclusion of source region and product layer as independent variables.

2.5. Limitation and validation

In this article, we highlight the carbon emissions associated with source and destination industries. By focusing on GP, we show the level of emissions at each layer that each industry has agency along the supply chains. The summation of GP carbon footprint of different industries leads to double counting of emissions (Hertwich and Wood, 2018). Again, using the example of a car manufacturer supply chain (with two intermediate producers) and its upstream emissions, it becomes clear that adding up the production-related carbon footprints of the car manufacturer, the upstream chassis production, and the steel production must lead to double counting. The emissions from steel production are counted multiple times: in the carbon footprint of steel production, these emissions are layer 0 emissions; in the carbon footprint of the chassis production, they are layer 1 emissions; and from the perspective of the car manufacturer they are accounted for as layer 2 emissions. Similarly, MRIO-based sector footprints imply double counting when analysed as an aggregate. The outputs of one sector become the inputs of the other. When emissions from upstream inputs are allocated to outputs, i.e. sector production, we end up with double counting. The higher the degree of division of labour in an economy (i.e. the more intermediate products are traded between industries) and the more detailed the sectoral classification of the underlying MRIO, the more double counting occurs. Even within the same industry, there may be double counting when summing across the product layers due to the upstream inputs that come from this (destination) industry itself. This analysis is not a substitute of territorial footprints or carbon footprints of final demand – as when performed globally, emissions will not sum up to the global GHG emission levels. Still, it is useful to explore shared agency and responsibility along the supply chains, complementing more traditional perspectives. It may also provide more comprehensive industry-specific mitigation recommendations as it outlines each industry's role as both producer/supplier and consumer/user of goods.

PLD is sensitive to the sectoral level of database disaggregation, which affects the path length of the analysis; that is, a more aggregated sector classification will lead to shorter paths. Furthermore, using path length as a proxy for how well connected supply chain actors are may be tricky, particularly when they are largely separated geographically.

We provide an additional emission classification by Scope 1, 2 and 3 (WBCSD and WRI, 2004) in the Supplementary spreadsheet primarily to enable comparison with organisational emission accounts. However, in MRIO models the production processes of various industries are interlinked and activities occur at an industry rather than organisation level. We also generate and compare results for the global emissions in 2011 with results from Hertwich and Wood (2018) (see the Supplementary Information (SI) Fig. 1-2 for more details). However, the prior study employs a model with endogenised capital formation, different scope of GHGs and direct household emissions, which explains the differences.

3. Results

3.1. UK gross production by source and destination industry

The carbon footprint of UK's gross production (GP) in 2019 amounts to 1020 $MtCO_2eq$ (see Methods for emission double counting). Layer 0 emissions, or emissions associated with the direct activities of UK industries, amount to about 383 $MtCO_2eq$ or 38% of the total GP carbon footprint (Table 1). The sum of layer 0 emissions reflects UK territorial GHG emissions accounts (excluding direct household emissions) and is comparable to prior estimates (BEIS, 2021; Owen et al., 2020). Emission layers 1, 2 and 3+ quantify the emissions associated with the

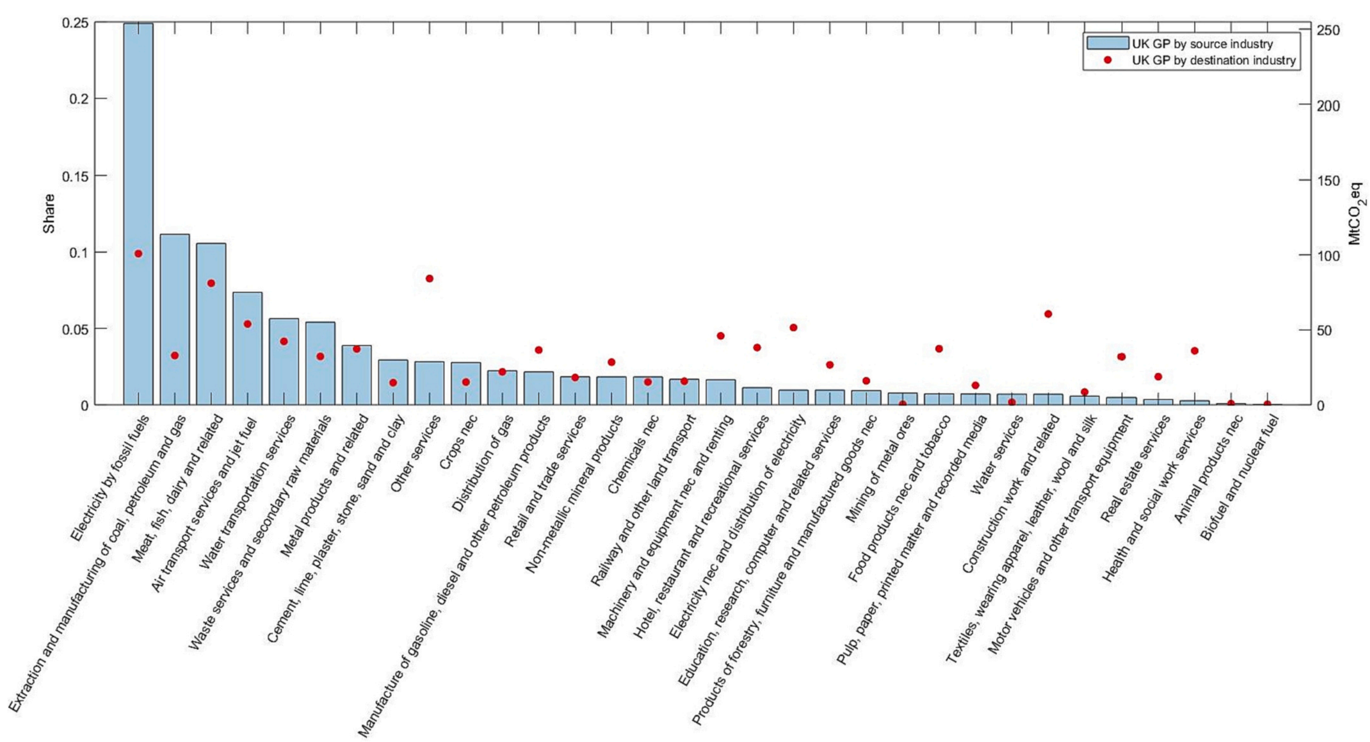

Fig. 2. GHG emissions associated with UK gross production (GP) by source industry (in blue) and destination industry (in red) across 32 industry sectors. Values are presented as shares summing up to 1 (left axis) and $MtCO_2eq$ (right axis). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Distribution of GHG emission embodied in UK gross production (GP) in 2019 by source industry group and destination industry group in parenthesis, layers and source regions. All values are in $MtCO_2eq$, except for the emission intensity per value added (VA) measured in $kgCO_2eq/EUR$ and the respective shares in %. For concordance by industry groups and detailed VA calculations, please see SI Table 1 and the Supplementary spreadsheet (cf. Hertwich and Wood, 2018). AFOLU+ refers to an expanded agriculture, forestry and other land use group, which includes the processing of food and forestry products (Hertwich and Wood, 2018).

Unless otherwise stated units are $MtCO_2eq$	By source (and destination) industry group						
	Layer 0	Layer 1	Layer 2	Layer 3+	Total GP carbon footprint	Share [%]	Emissions per VA [$kgCO_2eq/EUR$]
AFOLU+	68.9 (68.9)	40.4 (42.3)	18.1 (13.1)	20.5 (13)	**147.8** **(137.3)**	15 (13)	1.5 (0.9)
Buildings	7.3 (7.3)	1.8 (21.7)	0.7 (19.2)	0.8 (31.3)	**10.7** **(79.4)**	1 (8)	0.02 (0.1)
Energy	124.7 (124.7)	110.2 (54.9)	72.6 (24.2)	110.7 (22.2)	**418.2** **(225.9)**	41 (22)	1.71 (1.02)
Materials and industry	56.3 (56.3)	53.8 (56.3)	36.6 (42.7)	52.4 (70.3)	**199** **(225.5)**	20 (22)	0.38 (0.35)
Services	32.9 (32.9)	19.7 (52.3)	10 (45.3)	9.8 (70)	**72.4** **(200.5)**	7 (20)	0.03 (0.08)
Transport	92.5 (92.5)	33.6 (32)	19.4 (13.1)	25.7 (13.1)	**171.3** **(150.8)**	17 (15)	0.39 (0.43)
Total	**382.6** **(382.6)**	**259.5** **(259.5)**	**157.5** **(157.5)**	**219.9** **(219.9)**	**1019.5** **(1019.5)**	**100** **(100)**	**0.22** **(0.22)**
UK	382.6	189.3	78.4	54.5	**704.8**	69	0.18
EU	–	20.7	23.8	37.9	**82.4**	8	0.31
RoW	–	49.5	55.3	127.6	**232.3**	23	0.82
Total	**382.6**	**259.5**	**157.5**	**219.9**	**1019.5**	**100**	**0.22**

intermediate inputs to sectors' production. For example, layer 1 emissions are those embodied in the first order (intermediate) inputs to UK industrial activities, totalling 260 $MtCO_2eq$. About 705 $MtCO_2eq$ or 69% of the GP carbon footprint originates within the UK (Table 1), which has direct implications for UK industry and local policy. 23% of GHG emissions and only 6% of value added originate in RoW regions (SI Table 1).

Energy- and transport-related industries are associated with substantial direct emissions (layer 0) providing the most carbon-intensive inputs, while buildings and services have higher contribution as destination industries as they utilise carbon-intensive inputs from other industries (Table 1).

3.2. Major source industries

Across industry sectors, the UK GP carbon footprint is more concentrated in a few polluting industries by source than by destination (Fig. 2). For example, the Top 4 sectors contribute to 54% of the GP carbon footprint by source industry and only 32% of the emissions by destination industry. Each of the four top emitting industries have higher contribution as source rather than destination industries, meaning that they provide carbon-intensive inputs such as fossil fuels and high-methane agricultural products to other sectors, which then supply UK production and final demand (Fig. 2). These sectors include *Electricity by fossil fuels*, *Meat, fish, dairy and related, Extraction and manufacturing of coal, petroleum and gas,* and *Air transport services and jet fuel*. Three of the top source industries also stand out with some of the highest emission shares as destination industries (Fig. 2). Their emission destination shares amount to 10% (*Electricity by fossil fuels*), 8% (*Meat, fish, dairy and related*), and 5% (*Air transport services*). That is, they not only supply highly carbon intensive inputs, but also consume them. The *Extraction and manufacturing of coal, petroleum and gas* has a comparatively lower contribution as a destination industry.

Table 2, which summarises the emission shares and ranks by source industry and product layer, reveals a remarkable consistency between the importance of sectors in terms of their total contribution as source industries, and their layer specific contributions. We find correlation coefficients between 0.89 and 0.97. This shows that the major source industries will also be uncovered by a solely production-based approach, even though some differences in terms of emission shares and ranks are noted between layer 0 and total distributions (Table 2). However, in addition to that, we can trace these emissions to specific intermediate

Table 2
GHG emission shares and ranks by source industry and product layer.

Emission shares	Layer 0		Layer 1		Layer 2		Layer 3+		Total	
By source Industry	Share	Rank	Share	Rank	Share	Rank	Share	Rank	Share	Rank
Electricity by fossil fuels	8.5%	1	6.6%	1	4.1%	1	5.7%	1	24.9%	1
Extraction and manufacturing of coal, petroleum and gas	2.2%	6	3.1%	3	2.1%	2	3.7%	2	11.2%	2
Meat, fish, dairy and related	4.8%	2	3.2%	2	1.3%	3	1.3%	4	10.6%	3
Air transport services and jet fuel	4.6%	3	1.3%	5	0.7%	5	0.7%	7	7.4%	4
Water transportation services	3.1%	4	1.1%	7	0.6%	7	0.9%	6	5.6%	5
Waste services and secondary raw materials	2.3%	5	1.3%	4	0.7%	6	1.0%	5	5.4%	6
Metal products and related	0.6%	14	0.9%	8	0.9%	4	1.5%	3	3.9%	7
Cement, lime, plaster, stone, sand and clay	0.7%	12	1.1%	6	0.6%	8	0.5%	11	2.9%	8
Other services	1.0%	8	0.8%	9	0.5%	9	0.5%	13	2.8%	9
Crops nec	1.2%	7	0.5%	14	0.4%	11	0.6%	9	2.8%	10
Distribution of gas	0.9%	10	0.6%	12	0.4%	13	0.4%	16	2.2%	11
Manufacture of gasoline, diesel and other petroleum products	0.9%	9	0.5%	16	0.3%	14	0.5%	12	2.2%	12
Retail and trade services	0.8%	11	0.6%	11	0.3%	16	0.2%	19	1.8%	13
Non-metallic mineral products	0.4%	18	0.6%	13	0.4%	12	0.5%	15	1.8%	14
Chemicals nec	0.2%	28	0.6%	10	0.4%	10	0.7%	8	1.8%	15
All other	5.3%	–	2.7%	–	1.8%	–	2.8%	–	12.7%	–
Total	**37.5%**	**–**	**25.5%**	**–**	**15.4%**	**–**	**21.6%**	**–**	**100%**	**–**

and final destination industries, highlighting the agency of consuming industries.

Electricity by fossil fuels has the highest share with 254 MtCO_2eq or 25% of the emissions as a source industry (Table 2), with the vast majority of emissions (81%) originating in the UK (Supplementary spreadsheet). About 34% of the sectoral emissions occur as layer 0 emissions, amounting to 86 MtCo$_2$eq, all of which associated with direct activities for electricity production by fossil fuels in the UK. Layer 1 emissions amounting to 68 MtCo$_2$eq are also substantial, embodied in the direct electricity input (by fossil fuels) to other UK industries. The strongest layer 1 contributions concern direct inputs from *Electricity by fossil fuels* to *Electricity nec and distribution of electricity* (23 MtCO_2eq), *Distribution of gas* (6 MtCO_2eq), *Other services* (4 MtCO_2eq) and *Machinery and equipment nec* (3 MtCO_2eq). The industry further supplies indirect inputs to UK destination industries accounting for 100 MtCO_2eq, 55% of which originate in the UK. The most emission intensive intermediate inputs (layer 2+ emissions) are linked to *Electricity nec and distribution of electricity* (15 MtCO_2eq), *Other services* (12 MtCO_2eq), *Construction work and related* (9 MtCO_2eq), *Machinery and equipment nec* (7 MtCO_2eq) and *Health and social work services* (7 MtCO_2eq).

The source industry of *Extraction and manufacturing of coal, petroleum and gas* follows with 114 MtCO_2eq or 11% of the UK gross production emissions. About 33% of the sectoral emissions originate in the UK and 62% in RoW countries. At the same time, the distribution of value added is reverse, with 64% originating in the UK and 34% in RoW countries (Supplementary spreadsheet). Layer 0 emissions amount to 23 MtCO_2eq or about 20% of the total sectoral contribution to UK gross production, which is a lower share compared to other top source industries. The sector provides carbon intensive direct inputs to other destination industries amounting to 31 MtCO_2eq, with 70% of emissions originating in RoW countries. In terms of indirect inputs, the *Extraction and manufacturing of coal, petroleum and gas* industry supplies *Other services* (7 MtCO_2eq), *Machinery and equipment nec* (5 MtCO_2eq), *Construction work and related* (5 MtCO_2eq), *Electricity nec and distribution of electricity* (4 MtCO_2eq), *Metal products and related* (4 MtCO_2eq), and *Motor vehicles and other transport equipment* (4 MtCO_2eq).

Another top source sector includes *Meat, fish, dairy and related* (108 MtCO_2eq), 87% of which originate in the UK. About half of the source emissions occur as layer 0 emissions at 49 MtCO_2eq. The industry supplies direct inputs with the highest associated layer 1 emissions to *Meat, fish, dairy and related* (17 MtCO_2eq), *Food products nec* (11 MtCO_2eq) and *Chemicals nec* (3 MtCO_2eq). GHG emissions embodied as indirect inputs contribute to 26 MtCO_2eq, with the biggest emission flows to *Hotel, restaurant and recreational services* (5 MtCO_2eq), *Food products nec* (4 MtCO_2eq), *Meat, fish, dairy and related* (3 MtCO_2eq), *Other services* (2 MtCO_2eq), and *Health and social work services* (2 MtCO_2eq).

The *Air transport services and jet fuel* ranks fourth in terms of GHG emissions associated with UK gross production among the source industries with 75 MtCO_2eq, 87% of which originate in the UK. The direct sectoral activities bring about 47 MtCO_2eq. This is equivalent to a layer 0 share of 62%, which is one of the highest shares across the source industries in our analysis. Embodied in direct inputs to other final industries, the layer 1 emissions amount to 14 MtCO_2eq, with the highest inputs to *Other services* (8 MtCO_2eq), *Air transport services and jet fuel* (2 MtCO_2eq) and *Hotel, restaurant and recreation services* (2 MtCO_2eq). The sector of *Air transport services and jet fuels* further supply indirect inputs to destination industries (layer 2+ emissions), with major contributions towards *Other services* (4 MtCO_2eq), *Hotel, restaurant and recreation services* (1 MtCO_2eq), *Construction work and related* (1 MtCO_2eq) and *Real estate services* (1 MtCO_2eq).

The top industries have also some of the highest emissions per value added (Fig. 3). *Electricity by fossil fuels* generates the highest emissions per value added with 9.2 kgCO_2eq/EUR as a source industry in the UK. Other sectors with high emissions per value added include *Distribution of gas, Animal products nec, Water transportation services,* and *Meat, fish dairy and related* with intensities between 6.3 and 2.8 kgCO_2eq/EUR. As expected, services sectors have among the lowest emissions per value added.

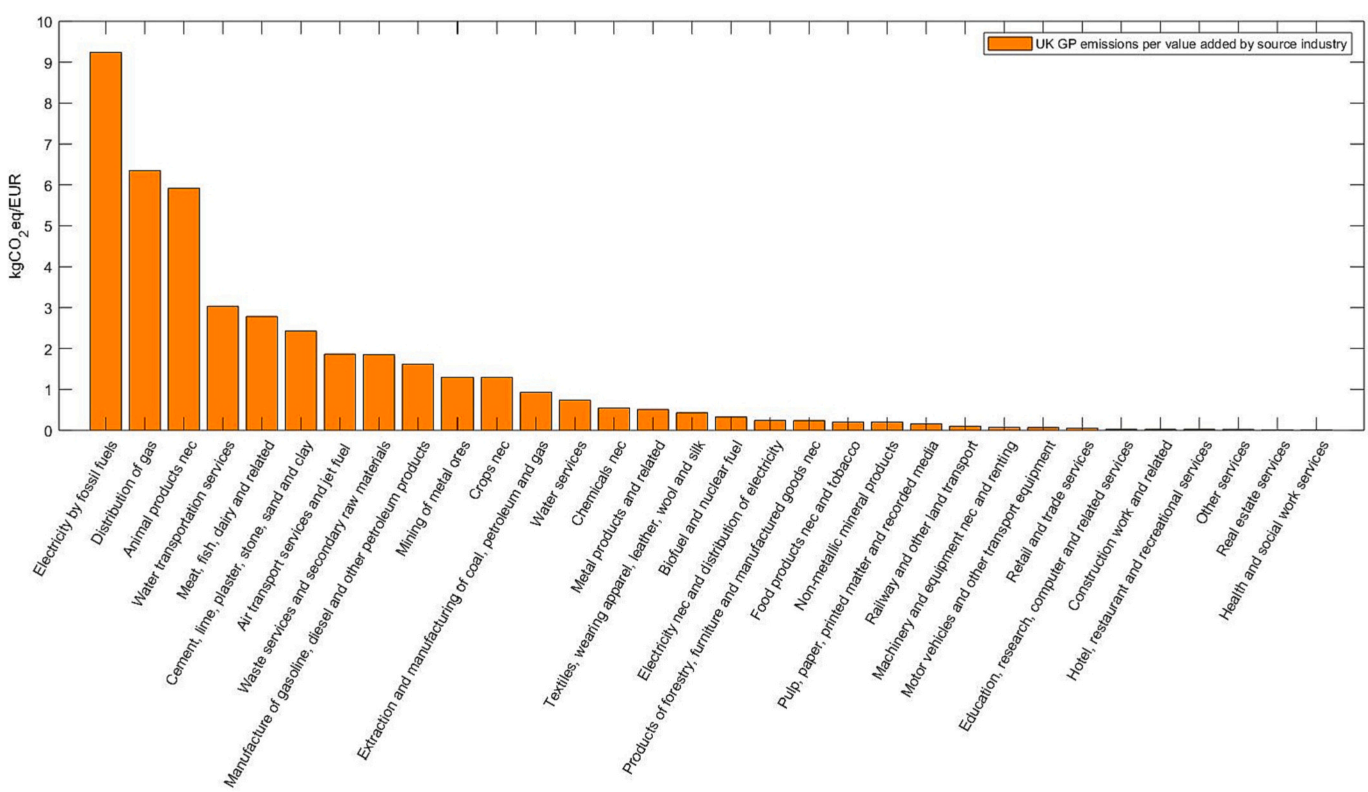

Fig. 3. GHG emissions from UK gross production (GP) per value added by source industry across 32 industries. Values are presented in kgCO_2eq/EUR. Calculations feature EURs rather than GBPs for consistency with EXIOBASE.

3.3. Major destinations at various layers

The regression analysis in Table 3 confirms the most emission-intensive source industries from our descriptive analysis, with the positive and highly significant coefficients among the top 8 industries from Fig. 2. EU-originating production has significantly lower emissions compared to UK and ROW production. The interaction effect highlights key consuming industries and the product layer, i.e. how far upstream carbon intensive inputs were supplied. Several industries are highlighted as high carbon-input consuming at multiple product layers, even though the significance level of the results vary. Examples include *Construction work and related*; *Electricity nec and distribution of electricity*; *Hotel, restaurant and recreational services*; *Machinery and equipment*; *Other services; Health and social work services;* and *Metal products and related.* These destination industries serve both intermediate and final consumption. The multivariate regression has an adjusted R-squared of 0.91.

Fig. 4 traces the destination industries and product layers highlighted in the regression analysis (Table 3) to their source industries for three sectors as examples: (1) the *Construction work and related*, (2) *Health and social work services*, and (3) *Hotel, restaurant and recreational services*. We noted substantial differences in the distribution by source industry across various product layers. For example, layer 1 emissions destined for construction originate primarily in the *Cement, lime, plaster, stone, sand and clay* sector (49%), while only 6% of layer 3+ emissions originate in the same sector. Similarly, only 1% of the layer 1 emissions destined for construction originate at the *Extraction and manufacturing of coal, petroleum and gas* sector, while 16% of all layer 3+ emissions originate in the same sector (Fig. 4). *Electricity by fossil fuels* supplies direct inputs to construction, associated with 9% layer 1 emission share; the share of emissions originating as fossil fuel electricity increases to 25% at layer 3 + .

Layer 1 emissions associated with direct inputs to the *Health and social work services* originate primarily in three sectors: *Chemicals nec* (24%), *Electricity by fossil fuels* (23%), and *Waste services and secondary raw materials* (19%). Emissions embodied in indirect inputs further upstream (layer 3+) are supplied by *Electricity by fossil fuels* (27%), *Extraction of manufacturing of coal, petroleum and gas* (16%), and *Meat, fish, dairy and related* (8%).

Finally, direct inputs to the *Hotel, restaurant and recreational services* originate in the *Air transport services and jet fuel* (18%), *Electricity by fossil fuels* (16%), *Water transportation services* (11%), *Food products nec and tobacco* (8%). Layer 3+ emissions originate at the *Electricity by fossil fuels* (23%), *Extraction and manufacturing of coal, petroleum and gas* (14%), *Meat, fish, dairy and related* (12%), and *Crops nec* (6%).

Some consistencies emerge across the three destination sectors and their supply chains. The top source industries that we identified earlier are major suppliers of their direct and indirect inputs. Decarbonising

Table 3
Factors contributing to emission differences across industrial actors, including source region, product layer, source industry and the interaction between destination industry and product layer. Dependent variable: emissions in Mt. The table does not disply all destination layer 0 coefficients and all insignificant coefficients for source and higher layer destination industries. The symbols *, **, and *** denote significance levels of 10%, 5%, and 1%, respectively.

Independent variables and base	Variable levels	Coefficients
Source region (base UK)	EU	−0.08***
	ROW	−0.02*
Layer (base Layer 0)	Layer 1	−0.78*
	Layer 2	−0.78*
	Layer 3+	−0.78*
Source industry	Air transport services and jet fuel	0.10 ***
	Cement, lime, plaster, stone, sand and clay	0.08 **
	Distribution of gas	0.06 *
	Electricity by fossil fuels	0.66 ***
	Extraction and manufacturing of coal, petroleum and gas	0.31 ***
	Meat, fish, dairy and related	0.20 ***
	Metal products and related	0.11 ***
	Other services	0.06 *
	Waste services and secondary raw materials	0.11 ***
	Water transportation services	0.09 **
Destination industry # Layer	Construction work and related # layer 1	0.21 ***
	Construction work and related # layer 2	0.15 **
	Construction work and related # layer 3+	0.24 ***
	Distribution of gas # layer 1	0.11 *
	Electricity nec and distribution of electricity # layer 1	0.29 ***
	Electricity nec and distribution of electricity # layer 2	0.13 **
	Electricity nec and distribution of electricity # layer 3+	0.11 *
	Food products nec and tobacco # layer 1	0.22 ***
	Health and social work services # layer 1	0.11 *
	Health and social work services # layer 3+	0.15 **
	Hotel, restaurant and recreational services # layer 1	0.11 *
	Hotel, restaurant and recreational services # layer 2	0.11 *
	Hotel, restaurant and recreational services # layer 3+	0.12 **
	Machinery and equipment nec and renting # layer 1	0.12 *
	Machinery and equipment nec and renting # layer 2	0.10 *
	Machinery and equipment nec and renting # layer 3+	0.21 ***
	Manufacture of gasoline, diesel and petroleum products # layer 1	0.22 ***
	Meat, fish, dairy and related # layer 1	0.25 ***
	Metal products and related # layer 1	0.12 *
	Metal products and related # layer 3+	0.13 **
	Motor vehicles and other transport equipment # layer 3+	0.16 ***
	Non-metallic mineral products # layer 3+	0.10 *
	Other services # layer 1	0.27 ***
	Other services # layer 2	0.19 ***
	Other services # layer 3+	0.33 ***
Number of observations		**9018**
R-squared / Adjusted R-squared		**0.91**

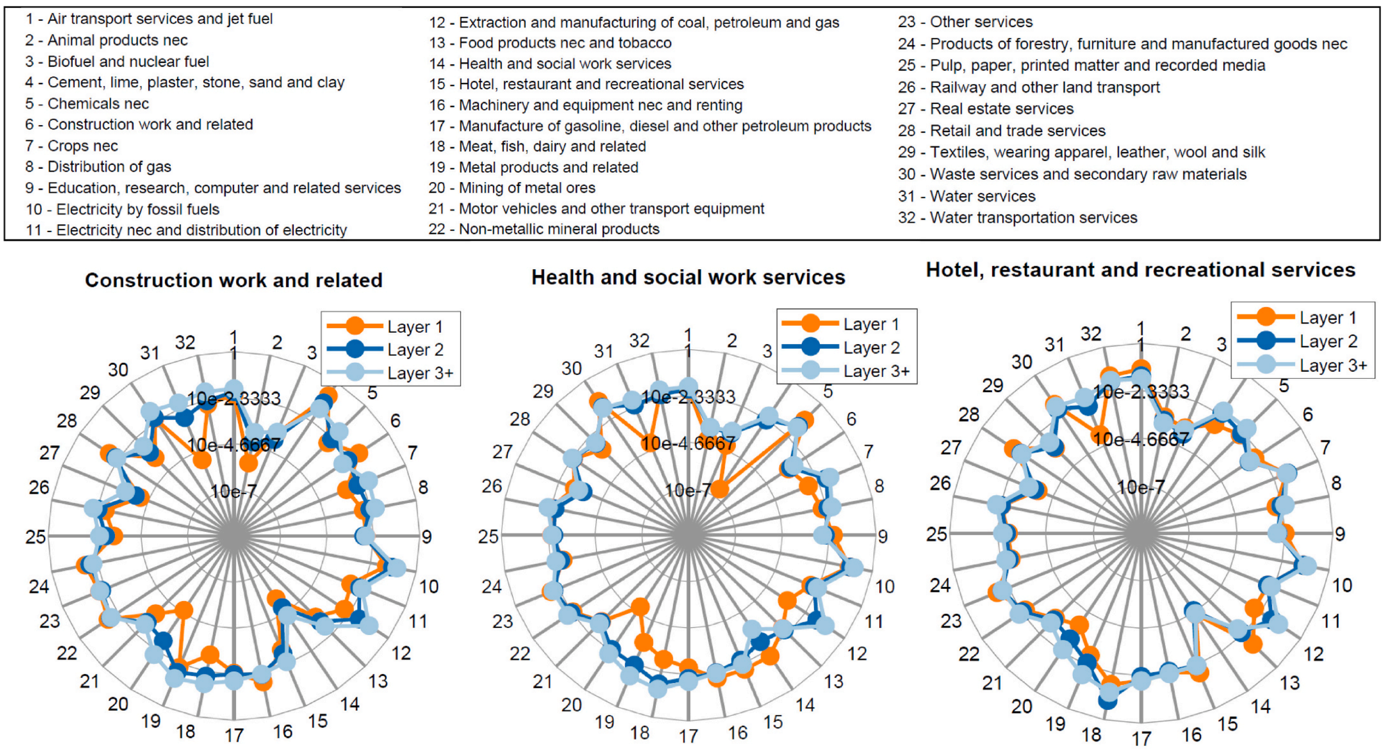

Fig. 4. Three example destination industries for UK GP GHG emissions and their source industries at various product layers. The three destination industries were highlighted in the regression analysis in Table 3. The radius reflects the share of emissions to various destination industries with logarithmic scales, where each circle of the spider plots represent the shares of 100%, 1%, 0.001%, 0.00001%, and a centre of zero. The emission flows by source and destination industry and product layers are also available across all 32 industries in the Supplementary spreadsheet.

electricity and shifting away from fossil fuel sources will decarbonise both direct and indirect inputs to these destinations, resulting in substantial reductions in sectoral footprints. The share of emissions originating at the *Electricity by fossil fuels* sector ranges between 16% and 25% across all product layers among the three destination industries (Fig. 4). Certain emission suppliers such as the extraction and manufacturing of fossil fuels and animal-based food appear primarily important upstream and, hence, dominate higher product layers as source of emissions. The primary suppliers of layer 1 emissions are more versatile and destination-specific.

3.4. Industrial concentration across product layers

Finally, we explore destination industries in terms of how concentrated the emissions embodied in their inputs are across product layers. We do so based on the Herfindahl–Hirschman Index (HHI), which is one of the most popular indices indicating market concentration (Evren et al., 2021). Whether supplied emissions are concentrated in a few source industries or not determines how consuming industries address their embodied impacts. We categorise destination industries in three clusters based on the degree of supply chain concentration that they demonstrate.

A first cluster emerges characterised by industries with a high concentration of embodied emissions from their own inputs throughout the product layers. An example of such a destination includes the *Mining of metal ores* (87% of supplied emissions across all product layers) (Table 4). There are also destination industries with concentrated inputs from fossil fuel extraction, manufacturing and electricity, as in the case of the *Electricity nec and distribution of electricity* sector dominated by emissions originating from *Electricity by fossil fuels* (72% of supplied emissions across all product layers). This is the only cluster where we find a high concentration of industrial input even at the third product layer and beyond.

A second cluster has high concentration of emissions embodied in layer 1 and layer 2 inputs, but lower concentration of inputs further upstream. Similar to the first cluster, some destination industries are dominated by own inputs. For example, about 85% of the emissions embodied in the inputs to the *Meat, fish, dairy and related* originate in the same sector; yet, only 15% of layer 3+ emissions originate there, with higher emission shares from suppliers from top source industries such as the *Electricity by fossil fuels* (23%) and *Extraction of manufacturing of coal, petroleum and gas* (16%) sectors. Destination industries that demonstrate similar trends include the *Air transport services and jet fuel, Cement, lime, plaster, stone, sand and clay, Electricity by fossil fuels* sectors, and *Waste services and secondary raw materials*. Other industries within the same cluster are associated with higher emission concentrations of inputs from top source industries, but also other industry-specific suppliers. For example, layer 1 emissions destined for the *Real estate services* are supplied from *Electricity by fossil fuels* (43%), *Other services* (24%) and *Construction work and related* (10%). Layer 1 emissions destined for the *Motor vehicle and other transport equipment* sector are supplied from the *Electricity by fossil fuels* (34%), *Metal products and related* (27%), and *Non-metallic mineral products* (7%).

Finally, a third cluster is characterised by low to medium concentration of inputs throughout the product layers (Table 4). The *Retail and trade services* is an example of a sector with a relatively low concentration of inputs even at layer 1: emissions associated with dominant supplies from the *Railway and other land transport* (22%), *Electricity by fossil fuels* (15%) and *Air transport services and jet fuel* (12%) sectors.

4. Discussion and conclusion

While we conduct and communicate the assessment of carbon footprints and value added, there is a much wider sustainability relevance for this kind of analysis. Particularly, we emphasise the power concentration in supply chains and exemplify a way to link environmental

Table 4
Industry concentration index measuring how concentrated emissions are by source industry across all destination industries and product layers. We measure industry concentration based on the HHI, where smaller HHI values indicate that the market concentration is not high. Please see Evren et al. (2021) for details about HHI formula and categories.

Industry concentration	Layer 1	Layer 2	Layer 3+
Cluster 1: High/medium concentration throughout the product layers			
Electricity nec and distribution of electricity	0.83 (high)	0.52 (high)	0.34 (high)
Distribution of gas	0.19 (medium)	0.21 (high)	0.19 (medium)
Mining of metal ores	0.33 (high)	0.43 (high)	0.24 (high)
Water services	0.60 (high)	0.34 (high)	0.21 (high)
Water transportation services	0.83 (high)	0.49 (high)	0.18 (medium)
Cluster 2: High concentration at layer 1/2, low concentration upstream			
Air transport services and jet fuel	0.32 (high)	0.22 (high)	0.11 (low)
Biofuel and nuclear fuel	0.44 (high)	0.47 (high)	0.12 (low)
Cement, lime, plaster, stone, sand and clay	0.25 (high)	0.15 (low)	0.13 (low)
Chemicals nec	0.24 (high)	0.13 (low)	0.12 (low)
Construction work and related	0.26 (high)	0.13 (low)	0.11 (low)
Electricity by fossil fuels	0.54 (high)	0.32 (high)	0.13 (low)
Food products nec and tobacco	0.38 (high)	0.18 (medium)	0.12 (low)
Manufacture of gasoline, diesel and other petroleum products	0.73 (high)	0.30 (high)	0.12 (low)
Meat, fish, dairy and related	0.64 (high)	0.20 (medium)	0.11 (low)
Motor vehicles and other transport equipment	0.20 (high)	0.13 (low)	0.12 (low)
Non-metallic mineral products	0.22 (high)	0.12 (low)	0.12 (low)
Pulp, paper, printed matter and recorded media	0.28 (high)	0.21 (high)	0.13 (low)
Real estate services	0.26 (high)	0.12 (low)	0.11 (low)
Waste services and secondary raw materials	0.75 (high)	0.40 (high)	0.11 (low)
Cluster 3: Medium/low concentration throughout the product layers			
Animal products nec	0.19 (medium)	0.14 (low)	0.11 (low)
Crops nec	0.19 (medium)	0.19 (medium)	0.11 (low)
Education, research, computer and related services	0.17 (medium)	0.14 (low)	0.13 (low)
Extraction and manufacturing of coal, petroleum and gas	0.19 (medium)	0.13 (low)	0.11 (low)
Health and social work services	0.16 (medium)	0.11 (low)	0.12 (low)
Hotel, restaurant and recreational services	0.10 (low)	0.15 (medium)	0.10 (low)
Machinery and equipment nec and renting	0.18 (medium)	0.13 (low)	0.12 (low)
Metal products and related	0.17 (medium)	0.12 (low)	0.12 (low)
Other services	0.14 (low)	0.10 (low)	0.11 (low)
Products of forestry, furniture and manufactured goods nec	0.17 (medium)	0.10 (low)	0.11 (low)
Railway and other land transport	0.12 (low)	0.17 (medium)	0.11 (low)
Retail and trade services	0.11 (low)	0.09 (low)	0.11 (low)
Textiles, wearing apparel, leather, wool and silk	0.20 (medium)	0.12 (low)	0.12 (low)

impacts and intermediate actors. Thus, we highlight an understudied area and a key enabling factor for a socio-ecological transition, making the code available for a replication of the results for any of the EXIOBASE's environmental or social stressors, years and countries.

This article promotes transparency about key supply chain links, which can be a powerful intervention (Meadows, 2009), and cautions against isolated and incremental mitigation efforts. While the analysis that we present is conducive for supply chain collaborations towards improving environmental performance (Lenzen et al., 2007), perhaps even more importantly it allows for accountability and pressure from external actors and institutions to decarbonise supply chains. We hypothesise that shedding light on direct and indirect emission contributions is a precondition for holding industrial actors accountable for climate change. As an example, we highlighted the role of carbon intensive inputs of animal-based food consumption, air travel and fossil fuel electricity to the hotel, restaurant and recreational services and other sectors.

The majority of the GP carbon footprint originate in the UK (69%), meaning that taking action domestically may reduce a considerable emission share, assuming it does not give rise to carbon leakage. Furthermore, our analysis raises questions about spatial justice with substantial differences in the GHG emission and value added distributions by source region. For example, in the major emitting sector focused on extraction and manufacturing of fossil fuels as much as 62% of GHG emissions originate in RoW countries, while only 34% of the value added. This is consistent with a prior analysis on excessive damages, which reveals that Global North countries have appropriated essential resources and labour and continue to do so in a process of atmospheric and resource colonisation (Hickel, 2020; Hickel et al., 2022). In essence, there are less resources and budget allocated towards the Global South, worsening global inequality and ecological degradation (Hickel et al., 2022).

UK GHG emissions are more concentrated from a source compared to destination perspectives. A handful of major source industries bring about the majority of the GP carbon footprint. Particularly, the Top 4 source sectors with activities around fossil fuels (electricity production, extraction and manufacturing, and air travel) and animal agricultural products contribute to 54% of the emissions from gross production. These industries also tend to have some of the highest emissions per unit of value added. Focusing regulation and policy mechanism on such key source industries through low-carbon investments, retiring polluting assets or carbon taxes has huge potential to bring about decarbonisation in the whole supply chain. While there is now increasing industry recognition about the risks associated with climate change, there is still strong resistance to changing business models and reducing the extraction and use of fossil fuels in absolute terms (Frumhoff et al., 2015; Haberl et al., 2020). Existing lock-in mechanisms advantage fossil fuel industry over renewables and electrified end-use industries through existing economies of scale, network externalities, regulatory and incentive failures, and social norms (Klitkou et al., 2015). The transition to low-carbon supply chains requires facing powerful polluting industries (Roberts et al., 2020). Opposition from special interests was rated the most important obstacle for limiting the global temperature increase to well below 2 °C according to survey responses from over 900 IPCC and UNFCCC experts (Kornek et al., 2020).

A number of factors play a role in determining mitigation agency and power for both source and destination industries. For example, the size and concentration of industrial actors and coalitions likely play a major role, where concentration of capital and ownership also translates into political control (Michie and Lobao, 2012). For example, the NHS net zero strategy accounts for scope 3 and travel emissions (i.e. NHS Carbon Footprint Plus), covering the products of over 80,000 suppliers and using "its considerable purchasing power to influence change" (NHS England, 2022). While we could not capture the size of industrial actors and coalitions in our analysis, we provided a measure of emission concentration within the inputs of various destination industries. For example, we found a low to medium concentration of the inputs to *Health and social work services* across product layers. We note that the industrial concentration varies substantially across product layers for most destination industries, suggesting that they would have to employ a variety of supply chain strategies in mitigating their embodied carbon. The agency of supply chain actors may also drop at higher product layers, as "the further a receiving sector is located from the producer of the impact, the less influence it has over the impact"(Gallego and Lenzen, 2005). Future research may contribute towards assessing and systematising factors determining agency and power along the global supply chains.

Beyond emission allocation, it is key to explore how (and whether) intermediate supply chain actors contribute to human and ecosystem well-being. Addressing well-being and sufficiency on a company and sectoral level would require targeting the strong profit-making orientation and expansion tendencies contributing to aggregate growth dynamics (Frumhoff et al., 2015; Gossen et al., 2019; Wiedmann et al., 2020). There is a need for industry alternative goals and models that are not structurally inclined towards expansion; this is particularly important in sectors providing basic goods such as food, housing, transport, health care and education (Pirgmaier and Steinberger, 2019). More broadly, there is a need for alternative and diverse models and experimentation around provisioning that are redistributive (socially) and regenerative (environmentally) by design (Meadows, 2009; Pirgmaier and Steinberger, 2019). The ability to change and evolve the industrial, consumption and governance practices signals system resilience (Meadows, 2009). Reimagining the supply chains towards a socio-ecological transformation shows utmost resilience by demonstrating the ability to survive any change by changing itself.

Declaration of Competing Interest

We declare no conflict of interest.

Data availability

The R scripts of the present work can be found and downloaded from a Github respository (Github account is a prerequisite to access the files): https://github.com/Hanspeter85/PLD_Carbon_Footprint_UK

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