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Greenhouse gas footprints of economic sectors at the subnational European scale

Thomas Hennequin [a,b], Jelle P. Hilbers [a,*], Harry C. Wilting [c], Olga Ivanova [c], Jeroen J.P. Kuenen [b], Mara Hauck [b,d], Rosalie van Zelm [a], Mark A.J. Huijbregts [a,b]

[a] Department of Environmental Science, Institute for Biological and Environmental Sciences, Radboud University, Heyendaalseweg 135, Nijmegen, 6525HP, the Netherlands
[b] TNO, Princetonlaan 6, Utrecht, 3584CB, the Netherlands
[c] PBL Netherlands Environmental Assessment Agency, Bezuidenhoutseweg 30, The Hague, 2594AV, the Netherlands
[d] Technology, Innovation and Society (TIS) Group, Industrial Engineering and Innovation Sciences (IE&IS) Department, Eindhoven University of Technology, The Netherlands

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ABSTRACT

Intermediate producers bear responsibility for emissions embedded in their supply chains. Here, we quantified greenhouse gas (GHG) emissions associated with 63 sectors in 264 regions of the European Union in 2017. We used a multi-regional input-output (MRIO) database with subnational European information on production and trade structures, accounting for trade inside and outside Europe. We added a subnational environmental extension for GHG emissions from an air emission database at the NUTS 2 level. We focused on quantifying the subnational variation of sector GHG footprints. We also identified spatial and sectoral hotspots and quantified the share of indirect emissions. We found that environmentally extended MRIO (EEMRIO) datasets with national coverage instead of subnational coverage in the EU miss out on 33 % of the variation in sector GHG footprints. The largest subnational variation in sector GHG footprints was found in Italy and Germany, particularly for metal manufacturing. The EEMRIO dataset can support targeted measures, on regions and on sectors, to drive climate change mitigation efforts in the EU.

1. Introduction

Industries and governments show a growing interest in understanding emissions embodied in supply chains, both locally and nationally. The scope of emission responsibility is not limited to direct emissions occurring onsite or in a territory, e.g. from combusting fossil fuels, but should include indirect emissions as well. This is, for example, reflected in a broadening of corporate environmental responsibility, across supply chains and borders (Cerin, 2002; OECD, 2001; WBCSD, 2004) and in the EU directives on corporate sustainability reporting and due diligence (Directives, 2022/3464 and 2024/1760). The rationale for looking beyond direct emissions is the idea of shared responsibility. Multiple actors can take action to mitigate a hotspot in the embodied emissions of a product or service. For instance, a construction company might reduce its electricity usage, or the electricity provider might decrease its emission intensity, both resulting in lower embodied construction emissions.

Environmentally extended multi-region input-output (EEMRIO) analysis is a key part of the effort to develop methodologies to understand embodied emissions (Wiedmann et al., 2011). EEMRIO is a framework used to connect economic exchanges and environmental data between sectors and regions. EEMRIO analysis is used to investigate the distribution of environmental impacts across space, time, and along supply chains, while accounting for the complexity of a globalized economy (Hertwich and Wood, 2018; Wiedmann et al., 2011). It has been used to study the global distribution of greenhouse gas (GHG) emissions (Davis and Caldeira, 2010; Hertwich and Peters, 2009; Hertwich and Wood, 2018; Kanemoto et al., 2016), land use (Weinzettel et al., 2013; Yu et al., 2013), material use (Bruckner et al., 2012; Li et al., 2022; Wiedmann et al., 2015), biodiversity loss (Lenzen et al., 2012; Verones et al., 2017; Wilting et al., 2017), and other impacts (Ivanova et al., 2016; Steen-Olsen et al., 2012; Wood et al., 2018).

In EEMRIO studies, two main perspectives emerge to allocate emissions: the consumption-based and the sector-based perspective.

* Corresponding author. Department of Environmental Science, Radboud University, 6525HP, Nijmegen, the Netherlands.
E-mail address: jelle.hilbers@ru.nl (J.P. Hilbers).

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Consumption-based accounts allocate emissions to the final consumer of a product or service and include both direct (i.e., on-site) emissions and indirect emissions embodied in supply chains. Recent studies have focused on achieving consumption-based accounts at geographical resolutions higher than the most common national level. Subnational accounts support local environmental policies that are key in environmental impact mitigation (Bertoldi et al., 2018; Fuhr et al., 2018; Lombardi et al., 2016; Pablo-Romero et al., 2015) and are recommended by the European Commission (European Commission, 2010. Subnational consumption-based accounts have been modeled at the scales of (1) cities (Athanassiadis et al., 2018; Chen et al., 2016, 2017; Gilles et al., 2021; Moran et al., 2018; Wiedmann et al., 2016), (2) specific countries (Deng et al., 2016; Jones and Kammen, 2014; Larsen and Hertwich, 2011; Lenzen et al., 2004; Miehe et al., 2016; Minx et al., 2013; Wang et al., 2023; Wen et al., 2021; Zhang and Anadon, 2014; Zhou and Imura, 2011), and (3) for the European Union (EU) (Ivanova et al., 2017; Wilting et al., 2021).

Sector-based EEMRIO accounts also include direct and indirect emissions, but allocate these to intermediate producers rather than to final consumers. This perspective leads to a better understanding of the intermediate enablers of pollution. It also provides opportunities for sector-specific and cross-sectoral action, the latter of which is recommended by the IPCC to target synergies and avoid burden shifting (IPCC et al., 2022a). Several studies have focused on sector footprints, at the national level (Acquaye et al., 2017; Foran et al., 2005; Wilting and van Oorschot, 2017) and globally (Hertwich and Wood, 2018). Wilting and van Oorschot (2017) quantified the impact of Dutch economic sectors on biodiversity and showed that large shares of the impacts are embodied in supply chains. Hertwich and Wood (2018) assessed the indirect CO_2 emissions of aggregated industries at the global scale and showed that the share of indirect emissions has been growing with time, particularly for industrial sectors. Insights into subnational environmental footprints are scarce, especially from a sector-based perspective and at the European scale. Such accounts are urgently needed to inform relevant policy action to drive climate change mitigation efforts at the regional level in the EU.

The goal of the paper was to quantify the subnational variation of sector GHG footprints in the EU. We also identified hotspots and investigated the share of indirect emissions, per region and sector. To this end, we investigated GHG emissions embodied in the supply chains of European sectors at the nomenclature of territorial units for statistics (NUTS) 2 level. We developed an EEMRIO dataset that features 264 regions and 63 sectors by combining an MRIO database, EUREGIO (Ivanova et al., 2019; Thissen et al., 2018), and an air emission database, the Copernicus Atmosphere Monitoring Service Regional inventory (CAMS-REG) (Denier Van Der Gon et al., 2017; Kuenen et al., 2022). In the EU, EUREGIO includes inter-regional trade flows at the NUTS 2 level while CAMS-REG provides emissions on a high-resolution grid (approx. 7×7 km^2), allowing to capture GHG emissions embodied in regional supply chains. This is the first study to quantify and evaluate subnational GHG footprints across the EU from a sector-based perspective with subnational data for both trade relationships as well as GHG emissions.

2. Methods

2.1. Deriving subnational environmental footprints

We developed a new subnational EEMRIO dataset to quantify the sector-based GHG emissions of economic sectors in the EU. Following the approach developed by Wilting and van Oorschot (2017), and Hertwich and Wood (2018), economic activity along the supply chains was derived using the Leontief inverse (Leontief, 1970) and multiplied by the production of intermediate producers, instead of the final demand typically used in consumption-based accounts. The emissions embodied in this activity were then mapped using direct GHG emissions per production unit for each sector. The supply chain emissions of pollutant p for sector j (in kg pollutant) were calculated using:

$$e_{p,j} = \widehat{d_p}(I-A)^{-1}\widehat{x_j^*}, \tag{1}$$

Upper case letters indicate matrices, while lower case stands for vectors. The hat indicates a diagonal matrix. d_p and x_j were diagonalized to map impacts along supply chains. Considering an EEMRIO table with r regions, s sectors, and p pollutants, we have:

- d_p is the (1 x r.s) vector of direct emission intensities for pollutant p.
- A is the (r.s x r.s) matrix of input coefficients a_{ij} which is the input from region-sector i needed to produce a unitary output of region-sector j. I is the (r.s x r.s) identity matrix. $(I-A)^{-1}$ is the Leontief inverse matrix.
- x_j^* is the (r.s x 1) adjusted vector of production. All values are null except for the value of element j which is equal to the total output of sector j divided by the diagonal element of sector j in the Leontief inverse (Wilting and van Oorschot, 2017). This differs from consumption-based EEMRIO analyses where the final demand would be used instead.

Emissions for each pollutant, $e_{p,j}$, were then characterized and summed into total (direct and indirect) sector GHG footprints e_j (in kg CO2eq):

$$e_j = \sum_p GWP_p * e_{p,j}, \tag{2}$$

Where GWP_p (kg CO2eq/kg pollutant) are the 100-year global warming potentials for pollutant p defined by IPCC (Forster et al., 2021).

2.2. Data

2.2.1. Input-output

EUREGIO is a global MRIO database that includes subnational European information on demand, production, and trade structures (Ivanova et al., 2019; Thissen et al., 2018). The EUREGIO database was used to build the matrix of input-output coefficients and the adjusted vectors of production (A and x_j in Equation (1), respectively). We used the 2017 version of the EUREGIO database which covers 63 sectors and 308 regions. The 308 regions of the EUREGIO database include 264 subnational regions for 21 countries in the EU and UK, following the NUTS 2 classification (Eurostat, 2022), 43 individual countries outside of the EU, and one rest-of-the-world region. The subnational part of EUREGIO was constructed based on European freight survey data, which allows the database to represent inter-sectoral supply chains at the regional level in the EU. See Tables S1 and S2 in the supplementary information (SI) for more information on regions and sectors classification.

2.2.2. Environmental extension

CAMS-REG-V4.2 data was used to add an environmental extension to EUREGIO. Specifically, the matrix of direct emission intensities was built, which contains direct emissions per unit of production in kg CO_2eq/EUR (yielding d_p in Equation (1)). We focused our analysis on GHG emissions, i.e. CO_2, CH_4, and N_2O which were characterized using Equation (2). CAMS-REG is a historic, European inventory of air emissions at a high spatial resolution (Denier Van Der Gon et al., 2017; Kuenen et al., 2022). Emissions are compiled from national inventories, harmonized, and spatially distributed in a gridded form (at the resolution of $0.05° \times 0.1°$) and classified into 115 sectors for the year 2017 (Kuenen et al., 2022). Data from CAMS-REG were used for all the NUTS 2 regions of EUREGIO as well as for Estonia, Iceland, Norway, Luxembourg, Croatia, Malta, Lithuania, Latvia, Lithuania, and Cyprus. For emissions of regions not covered by CAMS-REG, IEA emissions statistics were used for CO_2, CH_4, and N_2O (IEA, 2021) from 2015, which is the closest available date to the 2017 EUREGIO version used.

CAMS-REG emissions were attributed to EUREGIO NUTS 2 regions by using a spatial join analysis. Official NUTS 2 shapes were recovered from the GISCO statistical unit dataset (Eurostat, 2023). While emissions for CO_2 and CH_4 are part of the standard release of CAMS-REG, N_2O emissions were obtained directly from the database developers. Because N_2O is not part of the standard release of CAMS-REG, it was only available at the national level rather than on the grid needed for the spatial join analysis. Since CAMS-REG uses the same spatial proxies to spatially distribute most substances, we assumed that N_2O follows the same spatial distribution pattern as CO_2 in order to attribute national emissions of N_2O to each NUTS 2 region. Specifically, we used the shares of CO_2 emissions of subnational regions relative to the national totals. Moreover, international water transportation could not be attributed to regions using the spatial join analysis as it is not recorded per country of origin. Instead, to spatially attribute international water transportation emissions, EUREGIO was used by calculating the economic output for a region relative to the output summed over all regions.

CAMS-REG and EUREGIO are based on two different sectoral classifications which were bridged. CAMS-REG follows a custom classification, based on the nomenclature for reporting (NFR) classification, while EUREGIO follows the nomenclature of economic activities (NACE). Two main sources were used to establish the bridge and find one-to-one matches where possible or allocation candidates otherwise (EMEP, 2023; Eurostat, 2015). For 106 out of 115 CAMS-REG sectors, one-to-one correspondences with EUREGIO sectors were found (see Table S3 in the SI). For the remaining 9 sectors, additional proxy data were used to perform one-to-many allocations from CAMS-REG to EUREGIO (i.e., to disaggregate CAMS-REG data into EUREGIO's sectors). This was done for road and railway transportation as well as combustion emissions for agriculture, fishery, forestry, the tertiary sector, and some manufacturing industries (transport equipment, machinery, mining & quarrying, wood, construction, and textile & leather). Details on the one-to-many allocations can be found in the SI. Finally, all passenger cars, mopeds, residential heating, and civil aviation were allocated to households.

2.3. Quantifying the importance of subnational variation

We define subnational variation as the variation in sector GHG footprints between NUTS 2 regions within a country. To quantify the importance of subnational variation, we used a linear regression model to investigate the relationship between a sector GHG footprints, its sector classification, and its country (Elshout et al., 2015). The purpose of this statistical analysis, also known as a variance decomposition analysis or analysis of variance (ANOVA), is to quantify how much variation is explained by differences between sectors, between countries, and between NUTS-2 regions within a country.

To eliminate the influence of sector size, sector GHG footprints per EUR of production value (GHG_v) were calculated as the GHG footprint of sector j (e_j, as defined in Equation (2)) divided by its total production:

$$GHG_v = e_j / x_j, \tag{3}$$

Where x_j (EUR) is the vector of total output of sector j, not to be confused with x_j^* from Equation (1). GHG_v should not be confused with the vector of direct emission intensities (d_p in Equation (1)), as GHG_v is a total (or cumulative) emission intensity also including indirect emissions (i.e., emissions embedded in the sector supply chain). GHG_v can be interpreted as a Leontief multiplier, expressed in $kgCO_2eq/EUR$.

The sector and country explanatory variables of the linear model are categorical and were coded with dummy variables. We log-transformed our data as the distribution of sector GHG footprints per EUR of production value was positively skewed.

$$\log_{10}(GHG_v) \sim sector + country + sector{*}country$$

The R^2 value of this model quantifies the amount of variation that can be explained by the country and sector of the sector-specific GHG footprints at the subnational scale. The remaining unexplained variance ($1\text{-}R^2$) was assumed to be caused by subnational variation, which is the metric of interest here. To test this assumption, we created a modified dataset where the subnational variation was eliminated. This was done by setting all footprints per EUR of production value to their national average. With this modified dataset, we found an R^2 value of 1, confirming our assumption. We limited our analysis to the 21 countries for which we have subnational accounts (see Table S1 in the SI). Finally, our model selection was confirmed by using the Akaike information criterion (AIC) to prevent overfitting, see Table S4 in the SI.

3. Results

3.1. Subnational variation in the EU

The variance decomposition analysis showed that 67 % of the variation in sector GHG footprints per EUR of production value in the EU is explained by differences between countries and sectors (see Table S4 in the SI). This leaves 33 % unexplained variation due to subnational factors.

Fig. 1 shows the subnational variation of sector GHG footprints per EUR of production value (GHG_v, as defined in Equation (3)), per sector and country, across the EU. These results demonstrate the high variability of sector GHG footprints within countries which confirms the findings of the variance decomposition analysis. The subnational variation of GHG_v was measured using coefficients of variation (CVs), calculated as the ratio of the standard deviation and mean. The highest within-country variations were found in Italy and Germany and were driven by the high subnational variation of the Italian basic metal and coke & petroleum industries, and the German basic metal sector. The lowest country-level variations were observed in Ireland, Denmark, and Slovenia. At the sector level, the highest variations were observed for the manufacturing of basic metals, and coke & petroleum. The lowest variations were found for postal and insurance services, and the manufacturing of rubber & plastic. For groups of sectors, the highest variation is observed for 'energy', followed in decreasing order by 'industry', 'agriculture, forestry, and other land uses (AFOLU)', 'transport', 'buildings', and 'services'.

3.2. Sector GHG footprints per EUR of production value

Fig. 2 shows the GHG footprints per EUR of production value (GHG_v, as defined in Equation (3)) over 264 regions and for four sectors, which were selected as examples. We choose to highlight four sectors here to illustrate the potential uses and interpretation of our results. The remaining 59 sectors are shown in the SI in Figs. S1 and S2. Basic metals, and coke & petroleum have relatively high GHG footprints per EUR of production value, averaging at 1.6 and 1.5 $kgCO_2eq/EUR$, respectively. Construction, and rubber & plastic have relatively low footprints of 0.3 and 0.2 $kgCO_2eq/EUR$, respectively. Results also show the wide variation of footprints per EUR of production value between countries. For coke & petroleum manufacturing, Italy shows an average footprint of 12 $kgCO_2eq/EUR$, more than six times the second highest for Romania at 1.9 $kgCO_2eq/EUR$. Basic metal manufacturing in Italy and Finland also results in high footprints of 4.9 and 3.0 $kgCO_2eq/EUR$, respectively. The lowest footprints were found in Slovenia and Austria for coke & petroleum, at 0.04 and 0.10 $kgCO_2eq/EUR$, respectively.

Fig. 2 also corroborates the findings of the previous section, showing the high variation of footprints per EUR of production value within countries. The largest absolute range of GHG footprints was observed for coke & petroleum manufacturing in Italy, ranging from 0.08 $kgCO_2eq/EUR$ in Trentino to 103 $kgCO_2eq/EUR$ in Sardinia. Similarly, German basic metals manufacturing ranges from 0.14 $kgCO_2eq/EUR$ in upper Bavaria to 73 $kgCO_2eq/EUR$ in Bremen. In contrast, the lowest absolute range was observed for the Irish coke & petroleum sector, ranging

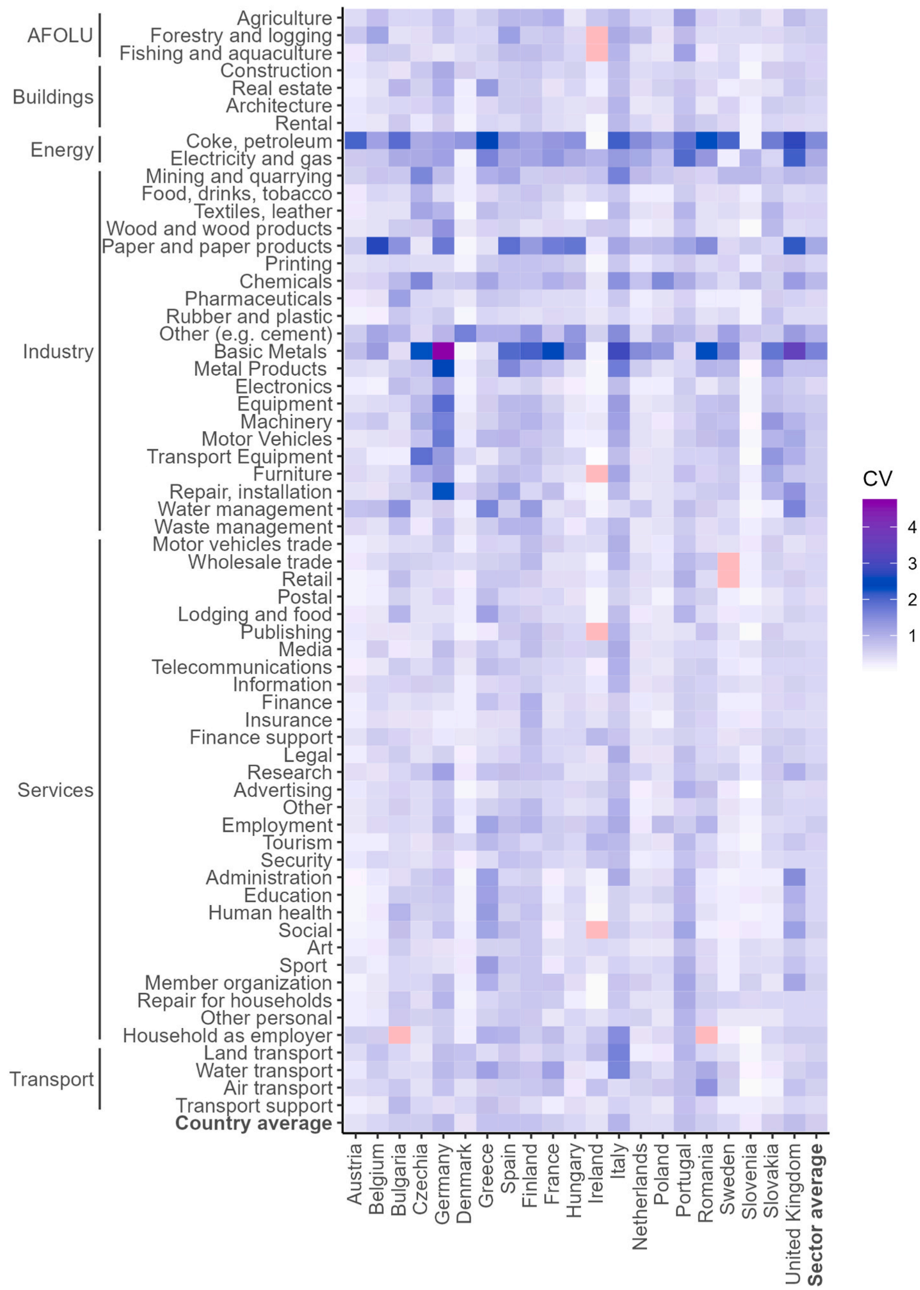

Fig. 1. Heat map of subnational variation of sector GHG footprints per EUR of production value, measured in 21 countries (x-axis) and 63 sectors (y-axis). CV stands for coefficient of variation which is the ratio of the standard deviation and mean of GHG_v (as defined in Equation (3)). Sectors were grouped into six categories based on IPCC classification, where AFOLU stands for agriculture, forestry, and other land uses. Pink cells show missing data. The sector and country averages are unweighted averages of the sector-region CVs. A correspondence between the short sector labels and their NACE codes can be found in the SI.

between 0.13 and 0.14 $kgCO_2eq/EUR$.

Fig. 3 shows the proportion of indirect emissions embedded in the supply chain of the four selected sectors. The remaining 59 sectors are shown in the SI in Fig. S3. The high variability in the share of indirect emissions within a sector is in part due to regions with low activity. In those cases, indirect emissions account for a large share of total footprint in that region while the total footprints of that sector-region are typically negligible at the national level. See Fig. S4 in the SI for more details.

The averages of indirect shares weighted by the sector-region GHG footprints (denoted by dots in Fig. 3) show a representation of the share of indirect emissions at the country level. Plastic & rubber manufacturing has the highest proportion of indirect emissions, with a weighted average of 99 % across all regions. It is followed by construction, coke & petroleum, and basic metals, with weighted averages of 86, 22, and 20 %, respectively.

3.3. Total sector GHG footprints

Fig. 4 shows the sector GHG footprints (e_j in kt CO2eq, defined in Equation (2)) over 264 regions and for the four sectors selected sectors (see SI for a complete collection of sector GHG footprints). High regional contributors to sector GHG footprints can be identified. The top 10 % of regions (26 out of 264) emit 75 %, 54 %, 41 %, and 35 % of the total GHG for the manufacturing of basic metals, coke & petroleum, rubber & plastic, and construction, respectively. Conversely, the bottom 50 % of regions (132 out of 264) emit 3 %, 4 %, 12 %, and 17 % of the total GHG for the manufacturing of basic metals, coke & petroleum, rubber & plastic, and construction, respectively. At a higher level of granularity,

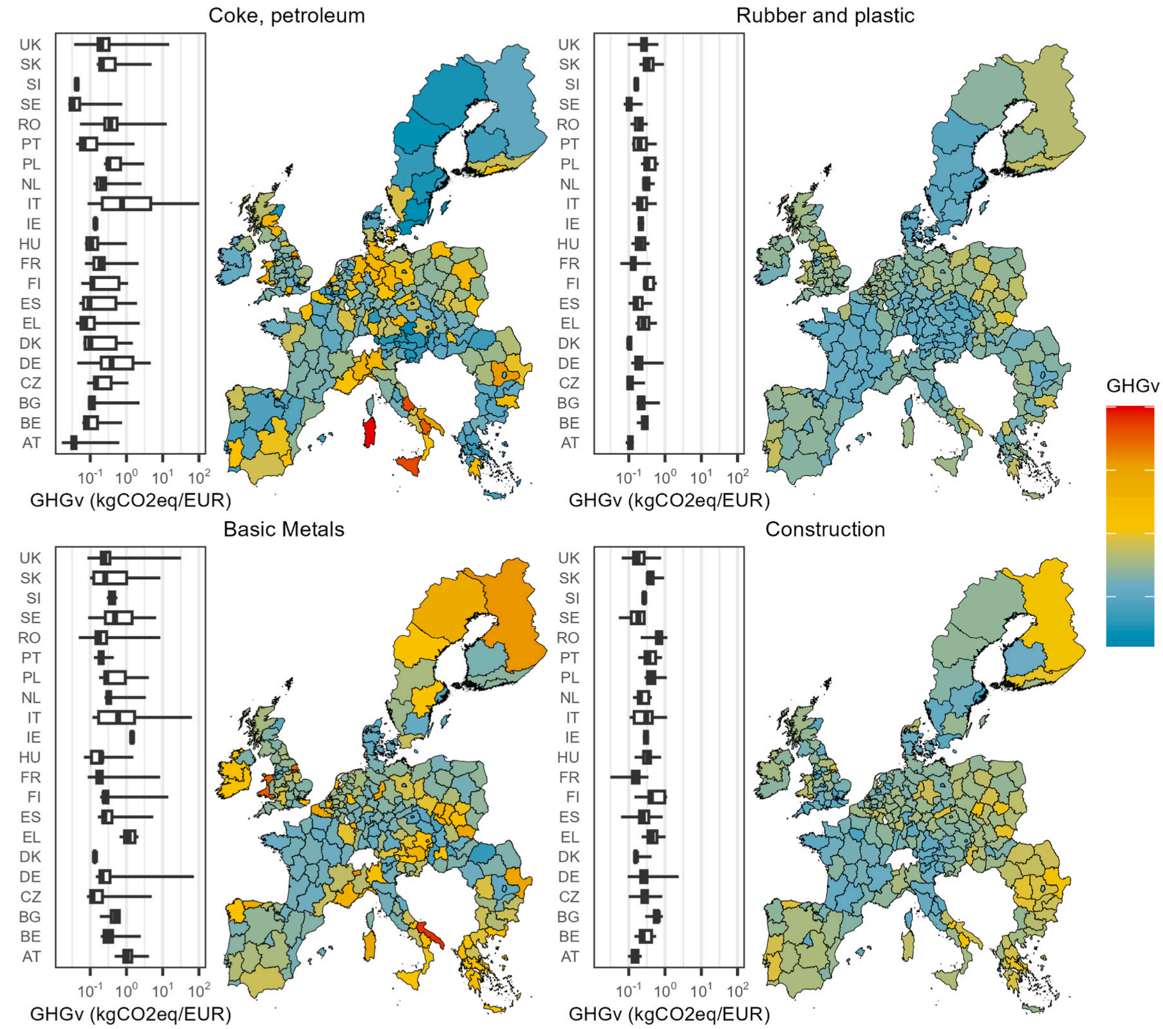

Fig. 2. – Map and box plot of the sector GHG footprints per EUR of production value (GHG_v in kg CO2eq/EUR, defined in Equation (3)) for four selected sectors and 264 regions. Overseas countries and territories are not shown on the maps. In the box plot, the box is delimited by the 1st and 3rd quartile, the middle bar is the median, and the whiskers show the extrema. A correspondence between the short sector labels and their NACE codes as well as the country abbreviations can be found in the SI.

key sector-regions can be identified. For example, in the sector of basic metal manufacturing, the regions of Düsseldorf and Bremen in Germany together with Nord-Pas-de-Calais in France account for 24 % of Europe's footprints. Similarly, Zuid-Holland in The Netherlands, Sicilia and Sardegna in Italy, and Münster in Germany contribute to 15 % of the European footprints in coke & petroleum manufacturing.

Results can also be interpreted from the point of view of a region, to find the sectors that have the highest contribution to a region's footprint and identify priorities for mitigation strategies. Coming back to Bremen in Germany, the manufacturing of basic metals amounts to approx. 23 ktCO2eq. or 50 % of the regional sector GHG footprint. While basic metals amount to a similar footprint in Düsseldorf (approx. 23.5 ktCO2eq.), it accounts for 15 % of that regional sector GHG footprint. Instead, electricity & gas is the sector with the highest contribution in Düsseldorf, accounting for 32 % of the regional sector GHG footprint. Hotspots and hierarchies of prioritization for regional mitigation strategies can similarly be derived for all the regions and sectors included in the EEMRIO database (see SI).

4. Discussion

To the best of our knowledge, this is the first study to analyze subnational GHG footprints across the entire EU from a sector-based perspective and to use subnational GHG emission data as input at this level of detail. High sectoral and geographical resolutions were achieved by combining MRIO and air emissions databases, with 63 economic sectors and 264 European regions. We show that sector-based EEMRIO datasets with national coverage instead of NUTS 2 coverage in the EU miss out on 33 % of the variation in sector GHG footprints per EUR of production value. Below, we discuss the limitations and implications of our study.

4.1. Limitations

Sector-based EEMRIO accounts can be influenced by double counting when the direct emissions of one sector are the indirect emissions of another. This issue is known (Hertwich and Wood, 2018; Wilting and van Oorschot, 2017) and methods have been proposed to address it (Cabernard et al., 2019; Dente et al., 2018, 2019; Lenzen, 2008). Those methods rely on different forms of allocation between producers and consumers. However, they were not considered suitable for our goal as they cannot cover the whole economy without resulting in a consumption- or production-based account (Cabernard et al., 2019; Dente et al., 2018, 2019), or they involved a subjective choice for allocation (Lenzen, 2008). Instead, we argue that double counting is a reflection of reality, as there are several leverage points from which multiple actors can

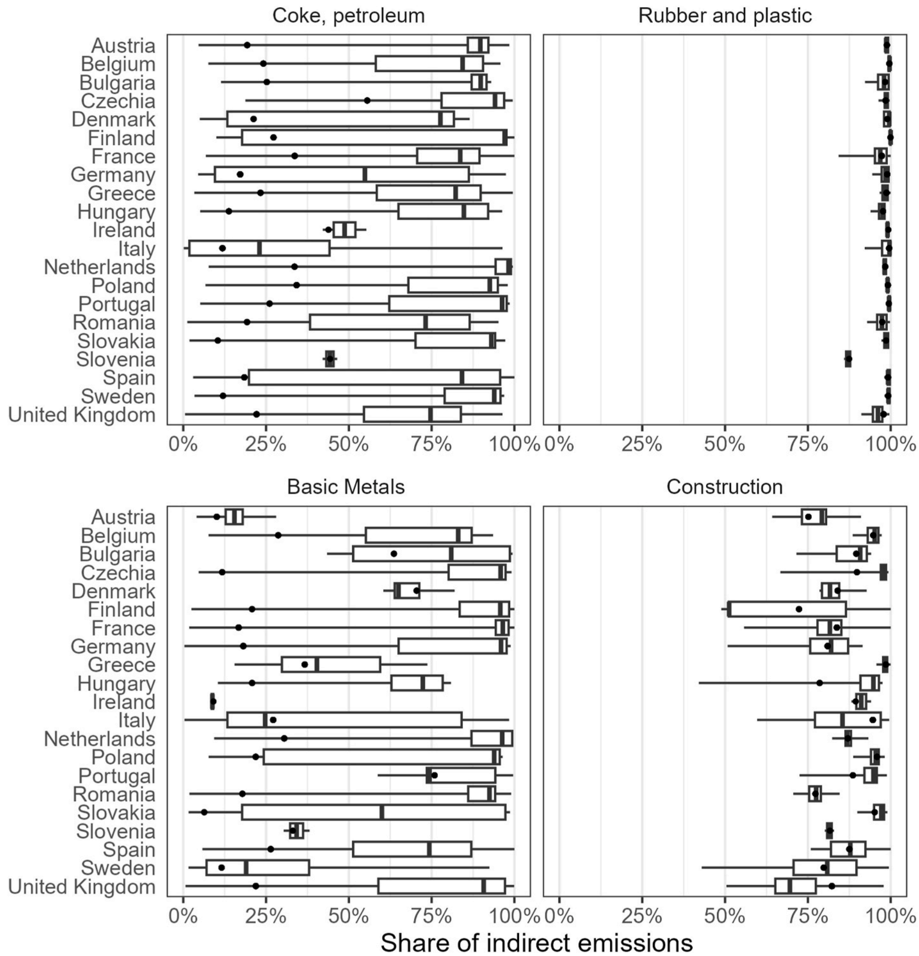

Fig. 3. – Box plot of the proportion of indirect GHG emissions for four selected sectors and 264 regions. Indirect emissions are embedded in the supply chain of the sector as opposed to direct emissions which occur on-site. The dots show averages of the share of indirect footprints per country which were weighted by the sector-region GHG footprints. In the box plot, the box is delimited by the 1st and 3rd quartile, the middle bar is the median, and the whiskers show the extrema. A correspondence between the short sector labels and their NACE codes can be found in the SI.

influence an emission (Hertwich and Wood, 2018). We focused on relative analysis, mainly on total emission intensities (GHG_v defined in Equation (3)), so double counting is not an issue for the results and interpretation presented here. However, the results presented in this study should not be summed to represent an aggregated picture of the economy. If we sum all sector GHG footprints in the EU, they are 55 % higher than the total direct emissions from CAMS-REG (see the SI). This is higher than the 30 % double counting quantified by Cabernard et al. (2019) for the global impacts of materials and the 10–30 % range reported by Dente et al. (2018) for the GHG emissions of products in the Japanese economy. This may be caused by the higher granularity of our dataset, which results in more overlap between the supply chains of sector-regions.

By using a spatial join analysis, we assumed that the region in which an emission is recorded is responsible for this emission. This is particularly relevant when interpreting regional emissions of transportation sectors, where high-traffic areas will be responsible for higher emissions. Another approach is to allocate emissions either to the region where the transport originates or ends, but the necessary data was lacking to do so. This also means that we may have introduced a mismatch between the economic and environmental data in cases where economic activity in EUREGIO is recorded in a different NUTS 2 region than the emission in CAMS-REG. This discrepancy could be responsible for some of the outliers observed for example in Fig. 2. During the spatial allocation of emissions, we also assumed that N_2O follows the same distribution pattern as CO_2. We argue that this is a fair approximation because CAMS-REG uses the same spatial proxies for different substances, in most cases. However, it might result in spatial inaccuracies for some point source emissions in the chemical industry where N_2O is a by-product, e.g. adipic and nitric acid production (Mainhardt and Kruger, 2002). These mismatches, either introduced in the spatial join analysis or already present between EUREGIO and CAMS-REG, may have influenced the extent of the subnational variation shown in our results. In future research, the extent of this influence should be quantified and included in an uncertainty analysis of the MRIO and environmental extension data sources.

Allocating all passenger car emissions to households is an overestimation of households' emissions (Melo, 2019). Part of those emissions should be allocated to economic sectors, for example to sectors with business fleets or to taxi services, but a proxy to allocate business and private passenger car transportation could not be found. Therefore, we might underestimate sector emissions, particularly for land transport. Finally, the NUTS 2 division used throughout this work is not even over the countries covered, with a different number of regions per country (see Table S1 in the SI), which are heterogeneous in size, population, and activity. This could influence the measure of subnational variation, as countries with fewer NUTS 2 regions may tend to have lower subnational variation. However, a weak overall correlation was observed between subnational variation and the number of regions per country (R^2 of 30 %). To improve the current dataset, further research is needed to enhance the spatial and sectoral allocation of subnational GHG emissions, particularly related to transportation. In addition,

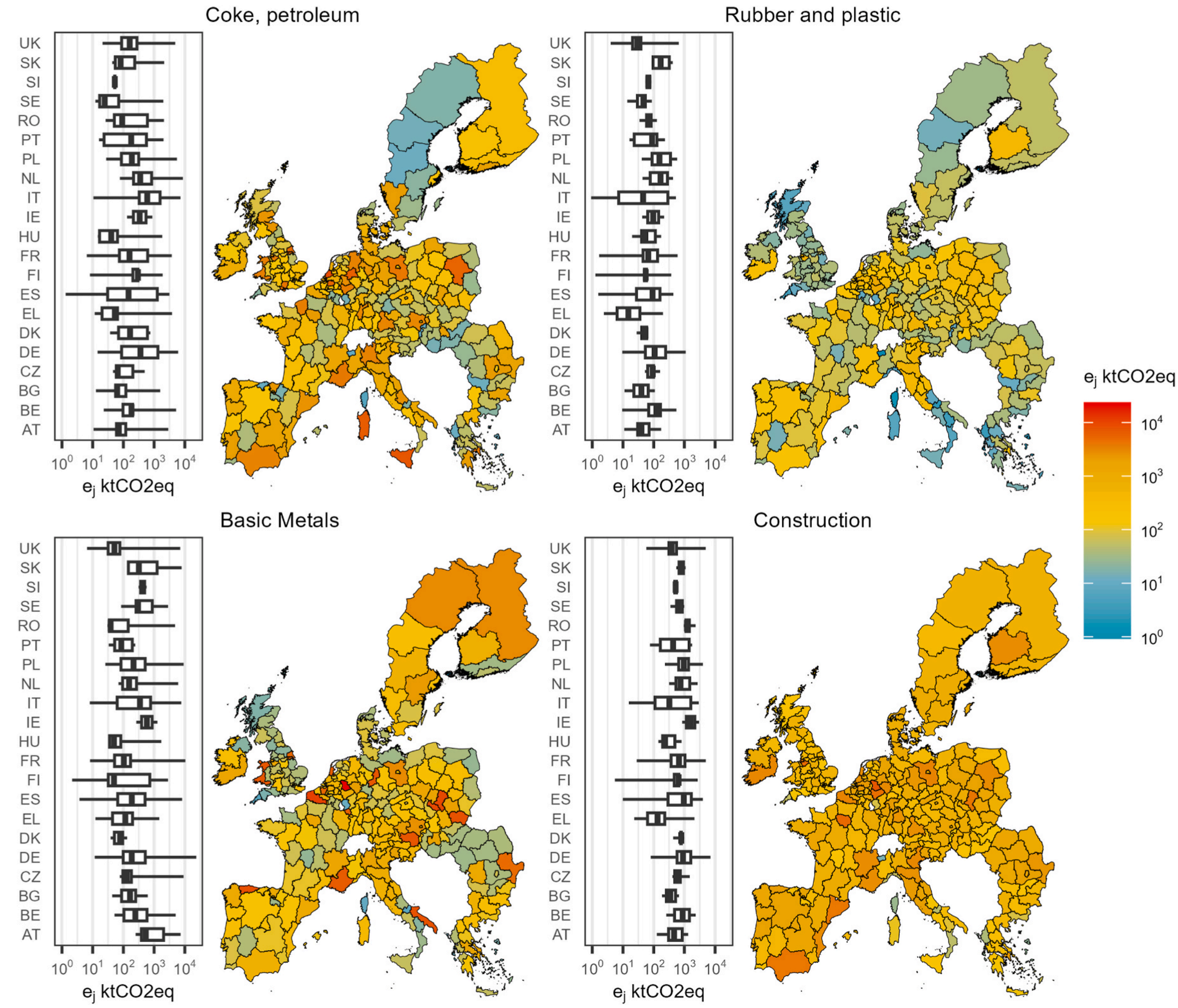

Fig. 4. – Map and box plot of the sector GHG footprints (e_j in kt CO2eq, defined in Equation (2)) for four selected sectors and 264 regions. Overseas countries and territories are not shown on the maps. In the box plot, the box is delimited by the 1st and 3rd quartile, the middle bar is the median, and the whiskers show the extrema. A correspondence between the short sector labels and their NACE codes as well as the country abbreviations can be found in the SI.

future research should include the other pollutants that are readily available in CAMS-REG and investigate the impact of air emissions on human health and biodiversity, next to the impacts through climate change.

4.2. Implications

The use of EEMRIO results to support policies has been extensively discussed, particularly from the consumption-based perspective (Afionis et al., 2017; Ottelin et al., 2019; Wiedmann et al., 2011). It is presented as an alternative to the territorial emission (i.e., direct emissions) accounts that are mainly used in environmental policies and mitigation strategies. Measures based on territorial accounts, while offering a simple solution to the issue of responsibility, can lead to the undesirable outsourcing of emissions. Consumption-based EEMRIOs can help alleviate this issue by quantifying emissions embedded in supply chains.

Here we provided a sector-based EEMRIO, the results of which can be used to support decision-making and policies. The sector-based perspective allows us to examine the supply chain emissions of intermediate producers rather than of consumers which highlights their responsibility and can lead to sector-specific insights. The high degree of subnational variation in sector GHG footprints that we identified highlights the need for targeted climate action at the subnational level. Regional environmental policy has been identified as a key to mitigate and adapt to climate change (IPCC et al., 2022b; Kuramochi et al., 2021). For instance, specific industries or regions can be targeted for carbon taxes as part of the EU Emissions Trading System (ETS). Sector GHG footprints with high proportions of non-EU indirect emissions can also be identified, and the specific product causing such emissions can be addressed in the Carbon Border Adjusted Mechanism (CBAM). With further data collection, EEMRIOs could even support a global carbon market, which is needed given the promising agreements for such a market at COP29 (UNFCCC, 2024). Finally, subnational EEMRIOs can also be used by the industry to estimate their supply chain emissions in compliance with the EU corporate sustainability reporting directive (2022/3464).

The results of our study can also be used to prioritize targets for regional mitigation strategies. Forty-nine of the European regions included in this study have a single sector contributing to more than a third of their total sector GHG footprint, which urgently warrants targeted action. In particular, the electricity & gas and agriculture sectors are most often responsible for the majority of European region's sector GHG footprints, in 140 and 66 regions, respectively. The mitigation potential of the economic sectors can also be quantified by comparing footprints per EUR of production value within a sector across countries and the EU. The share of indirect emissions can help sectors focus on measures that address either their direct emissions or their supply chain emissions (Wilting and van Oorschot, 2017). The dataset can also be used as a basis to assess cross-sectoral action, as recommended by the IPCC (IPCC et al., 2022a) while avoiding burden shifts. Cooperation between economic sectors has an important role to play in the mitigation and adaption of climate change (Gereffi and Lee, 2016; Humphrey and Schmitz, 2008; Pietrobelli and Rabellotti, 2011), e.g. at the level of industrial clusters.

Our study provides a detailed understanding of the GHG footprint of European economic sectors. It helps to identify sectors and regions that are responsible for larger shares of GHG emissions, which ultimately should be correspondingly liable for climate action. Finally, the dataset created here can be used to conduct a consumption-based EEMRIO analysis, which would provide an update to the GHG footprints calculated by Wilting et al. (2021).

CRediT authorship contribution statement

Thomas Hennequin: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Jelle P. Hilbers:** Writing – review & editing, Methodology, Conceptualization. **Harry C. Wilting:** Writing – review & editing, Methodology, Conceptualization. **Olga Ivanova:** Writing – review & editing, Methodology, Data curation. **Jeroen J.P. Kuenen:** Writing – review & editing, Methodology, Data curation. **Mara Hauck:** Writing – review & editing, Conceptualization. **Rosalie van Zelm:** Writing – review & editing, Methodology. **Mark A.J. Huijbregts:** Writing – review & editing, Methodology, Conceptualization.

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Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145761.

Data availability

All the data supporting the findings of this article are available in the supplementary information.

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