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An open-access web application to visualise countries' and regions' carbon footprints using Sankey diagrams

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Consumption-based carbon assessments are essential for evaluating climate change responsibility. However, the results vary greatly depending on the boundary chosen, making them hard to understand for non-expert readers and hindering their uptake by policy makers. Sankey diagrams are a type of flow diagram where the thickness of a flow is proportional to its value. They allow to shed light on the various ways to calculate carbon footprints and on the implications of choosing one method over another. Although several multi-regional input-output databases allow for the calculation of footprints, none of them has been systematically represented as Sankey diagrams. To fill this gap, we build an open access web application to represent carbon footprints for 49 world regions between 1995 and 2019 based on EXIOBASE 3 data. We include production-based, consumption-based and consumption-based with capital endogenized accounts. We then provide examples of the insights gained with such diagrams.

International climate negotiations rely on the concept of common but differentiated responsibility¹. Currently, these negotiations are mostly based on territorial greenhouse gases (GHG) emissions. As emissions in one country can enable the consumption of goods and services in another², a fair distribution of responsibility for emissions is essential to halt climate change. The development of global multi-regional input-output databases, tracking global economic exchanges, has made it possible to include offshored emissions in what is known as the consumption-based account (CBA), as opposed to the production-based account (PBA) which is limited to local emissions³. CBA accounting is not sufficient to assess responsibilities^{4,5} but provides a useful complementary metric which could be used in climate negotiations.

In the CBA, emissions associated with the production of capital goods remain in the country where the infrastructure was built⁶. For example, if a car is manufactured in China but purchased in Europe, the emissions during the car's production process will be imputed to Europe but the car factory's production footprint will be imputed to China. An emerging body of literature addresses this problem by endogenizing capital in input-output databases⁷. With this CBA approach with capital endogenized (CBAk), for each car sold by a Chinese factory to a European consumer, part of the

factory's footprint is imputed to the European consumer. This method brings footprint calculations closer to life cycle assessments and thereby makes them more comprehensive. However, the task is complex and calculating footprints with endogenous capital is not yet as straightforward as calculating traditional CBA footprint. Including capital in footprint calculations may change the results dramatically. For example, the GHG footprint of final consumption in some regions can increase by as much as 57% when capital goods are added to the value chain⁷. The way capital is accounted for also affects temporal responsibility⁸: a factory built today is expected to produce goods for the next 50 years.

Footprint results are usually given in tons of CO₂ equivalent per person. However, the boundaries of the studies are sometimes not clearly stated or even missing. Furthermore, the specific method choices as well as their implications for the results are often hard to assess for non-expert readers⁹. For example, a study may only include final household consumption, or add government expenditures in addition, or add capital creation either directly or by endogenizing it⁹. In the end, depending on the boundaries chosen, the results can vary by up to a factor of 4⁹. This can lead to confusion about the different rankings between countries and the mitigation measures to be taken.

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A visual representation of the differences in input-output results depending on the boundaries chosen would thus be useful for policy makers commissioning studies or new users of input-output tables. Sankey diagrams – a type of flow diagram where the thickness of the flows is proportional to the flow’s value– are an appropriate visualization tool for this as they allow to follow every step of the calculation. Sankey diagrams have been used to represent the world’s GHG emissions in 2009⁸, but not for several regions and years at the same time.

Here, we develop a methodology to visually represent several possible boundaries for calculating GHG footprints as Sankey diagrams. These diagrams are constructed based on EXIOBASE 3 data for 49 regions of the world over period 1995–2019 and are accessible on a web application.

Visualization of carbon footprints in ten steps

We use EXIOBASE¹⁰ (Version 3.8.2 available on Zenodo¹¹) – a global multi-regional input-output database– to calculate GHG footprints using the PBA approach, the CBA approach and the CBA approach with capital endogenized (CBAk). Each approach can be disaggregated in several visualization ‘steps’. For example, the PBA account can be disaggregated between production sectors and production regions. In a trade-off between completeness and readability, we choose to represent 10 steps, shown as vertical dotted lines on Fig. 1 (the Sankey diagram of France in 2019) and summarized in Table 1. These 10 steps are described thereafter. Diagrams for all other regions and years are available at <https://sankey.theshiftproject.org>.

The first step allows the reader to see which GHGs are being studied, namely carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and F-gases (SF₆, HFC and PFC). It is the sum of the GHGs involved in all three approaches, ie. PBA emissions plus imports. It is therefore not specific to a single approach but encompasses all GHGs passing through a domestic economy.

Steps 2, 3 and 4 correspond to PBA accounts disaggregated between: regions (step 2), region studied or imports (step 3) and production sector (step 4). In step 2, the 432Mt of French PBA emissions correspond to the node “France (432)”. The 48 other EXIOBASE regions are aggregated in Africa, Asia, Europe, Middle East, North America, Oceania and South America. The concordance table is given in the supplementary information excel file. Step 3 is similar to step 2 but facilitates readability by aggregating all imports together. Step 4 disaggregates PBA emissions by sector. A first sector corresponds to direct emissions by households, governments and NPISHS (mainly in personal transport and heating). Then, the 200

EXIOBASE sectors are aggregated into six major industrial categories: agriculture-food, energy industry, heavy industry, manufacturing industry, services and transport services. The concordance table is given in the supplementary information excel file. The colors in the overall diagram correspond to the seven different sectors of step 4. For example, any blue flow on the diagram corresponds to GHGs emitted by the agriculture and food industries.

Step 5 corresponds to the CBA account disaggregated across final demand categories (who buys final goods, services and infrastructure): households, governments, non-profit institutions serving households (NPISHS) and gross capital formation (GCF). Direct emissions in the region studied is disaggregated between households, governments and NPISHS. The transition from step 4 to step 5 thus corresponds to the classical use of input-output tables to transition from PBA accounting to CBA accounting.

GCF is made up of expenditures for the acquisition of fixed assets in the economy, plus net changes in the level of inventories¹². It is a measure of investments in the infrastructure used to produce goods and services. In an approach aiming to assess the responsibility of final consumption, GCF should not be treated as a separate category but rather incorporated in the footprint of other sectors. However, not all GCF should be attributed to other sectors. For example, if a region’s investments grow rapidly over a short period of time, attributing all of these investments to that period would lead to an overestimation of the footprint of final consumption⁷. On the other hand, a region experiencing an economic crisis may be underinvesting but still benefit from the infrastructure built in previous years. To overcome these issues, we follow Södersten’s methodology⁷ to endogenize (ie. add capital to the input-output framework so that its emissions are imputed to final consumption) only the consumption of fixed capital (CFC). The CFC represents the replacement value of capital used up in the process of production and is deemed to be a better proxy for the capital currently used by industries than GCF⁷. This choice implies that only the capital which reaches its end of life during the study year is considered. Net capital formation (NCF) is the difference between GCF and CFC. If NCF is positive (GCF superior to CFC), it corresponds to investments which will be used in subsequent years. If it is negative, it means that not all end-of-life capital goods are replaced by new ones.

To ensure continuity of the flows in the Sankey diagrams, it is necessary to distinguish between cases where NCF is positive and negative. When NCF is positive, GCF is divided between CFC (step 5–6) and a node called ‘Positive capital formation’ (step 5–8). The node ‘Positive capital formation’

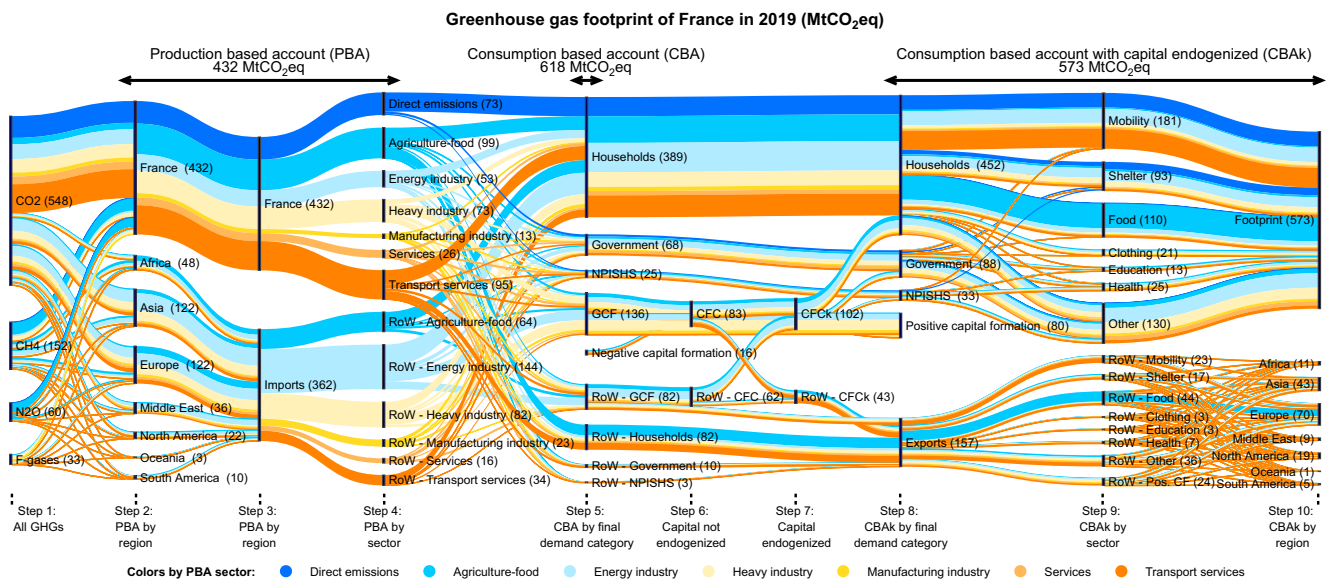


Fig. 1 | Sankey diagram of French greenhouse gas emissions in 2019. The thickness of the flows is proportional to the amount of greenhouse gases emitted. The colors correspond to the sectors of step 4. RoW stands for Rest of the World.

Table 1 | Description of the 10 steps selected

Step	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Step 10
Category	GHGs passing through economy	Production-based account	Consumption-based account	Consumption-based account	Consumption-based account	Capital not endogenized	Capital endogenized	Consumption-based account with capital endogenized	Consumption-based account with capital endogenized	Consumption-based account with capital endogenized
Disaggregation	By gas	By region (8 regions)	By region (2 regions)	By production sector	By final demand category	By region (2 regions)	By region (2 regions)	By final demand category	By consumption sector	By region (8 regions)

corresponds to the expansion of capital stock and is not included in the footprint with capital endogenized (the flows stop at step 8). When NCF is negative, CFC is the sum of the flows from GCF (step 5–6) and the flows from a node called ‘Negative capital formation’ (step 5–6). The node ‘Negative capital formation’ corresponds to the use of stocks from previous years that have not been replaced. It is possible for NCF to be positive for some sectors and negative for others. In some diagrams (such as Fig. 1), the node ‘Positive capital formation’ and ‘Negative capital formation’ both appear. In that case, NCF is equal to the positive node minus the negative node.

To summarize, GCF is disaggregated into CFC (steps 5–6) and positive capital formation (steps 5–8). Negative capital formation is added to CFC (steps 5–6). CFC is then endogenized (steps 6–7). The endogenized capital is added to final consumption (steps 7–8).

Step 8 presents the same disaggregation as step 5, but this time with endogenized capital. The “Households”, “Government” and “NPISHS” nodes are thus larger at step 8 than at step 5 while the GCF node does not appear on step 8. The “Positive capital formation” node is added, corresponding to the increase in capital stock. The footprint with endogenous capital is then disaggregated by service¹³ on step 10: mobility, shelter, food, clothing, education, health and other goods and services. The emissions all along the value chain ultimately enable the realization of these services. Exports are aggregated on step 8 and disaggregated on steps 9 and 10, respectively by service and region of destination. The concordance table is given in the supplementary information excel file.

The three calculation methods -production based, consumption based and consumption based with capital endogenized- are represented by black horizontal arrows on Fig. 1. The sankey diagrams allow to easily understand the differences between them. They also allow to see that for a given calculation method, several disaggregations exist. For example, the CBA footprint can be disaggregated by type of consumer (step 8) or by service (step 9).

In a recent review of consumption-based carbon assessments, Heinen and colleagues showed that for a selected location, carbon footprint estimates varied widely (between 10 and 28 tons of CO₂eq per capita in the United States, between 1.8 and 7.6 tons in China, and between 6.7 and 13 tons in the European Union). When comparing regional results from different studies, the Sankey diagrams built here may help understand where the differences come from. Any group of nodes on any step of Fig. 1 could represent a calculation boundary. Some boundaries are included in others (e.g., the CBA footprint of households’ final consumption is part of the total CBA footprint) so choosing one over the other will increase the footprint for every region. The same is true when capital endogenization is added to households, government and NPISHS Fig. 2.

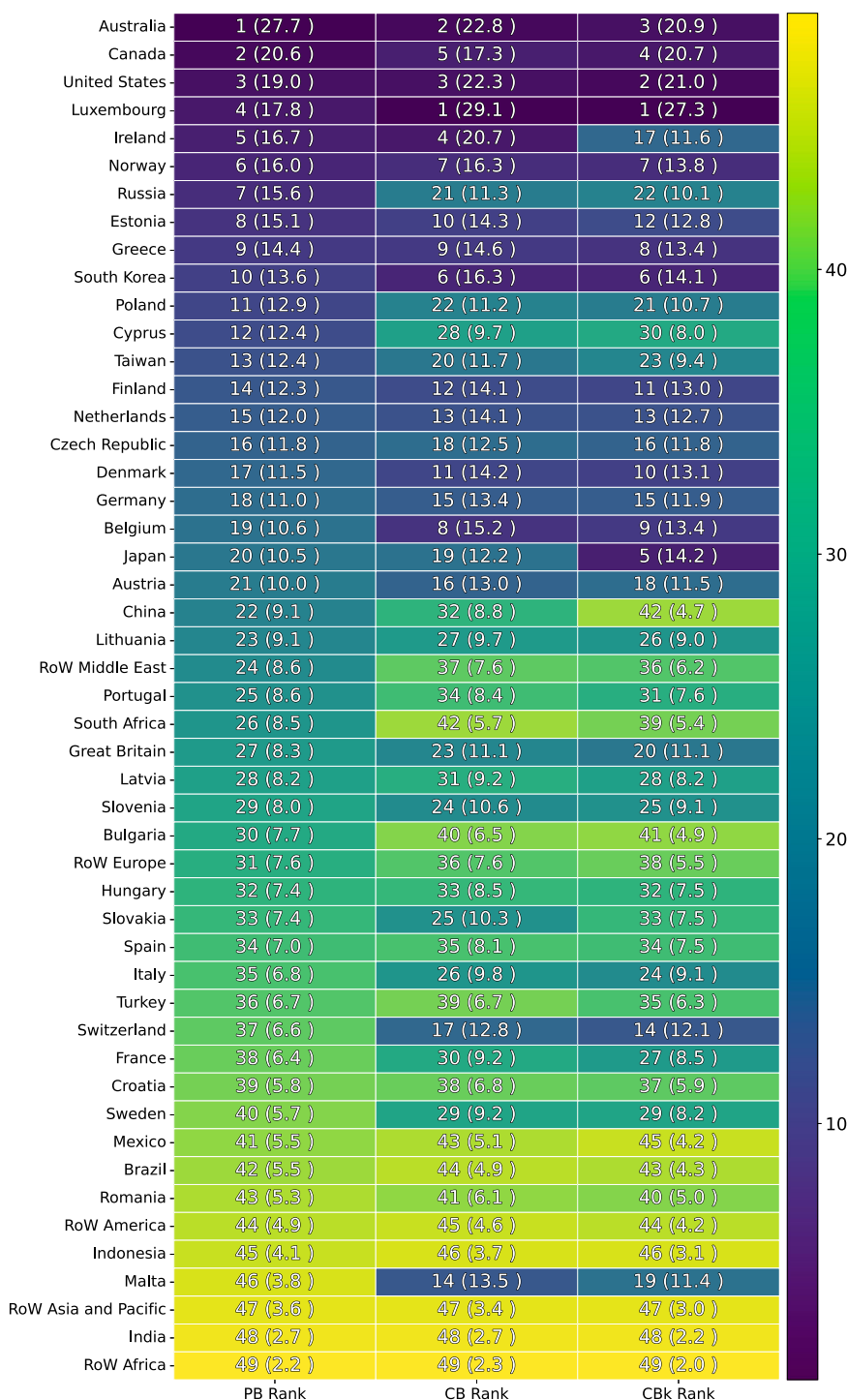
However, the relative differences between regions can change greatly depending on the calculation hypothesis, even when choosing the same boundary. For example, in 2019, the per capita footprint of the United States was 2.1 times higher than that of China under the PBA approach, 2.5 times higher under the CBA approach and 4.4 times higher in the CBA approach with capital endogenized. Choosing one boundary rather than another substantially impacts the responsibilities in emissions.

Regional rankings can also change depending on the calculation boundary. For example, out of the 49 regions studied in 2019, Japan is the 20th region with the highest per capita PBA footprint, the 19th highest per capita CBA footprint but the 5th highest per capita CBA footprint with endogenous capital. On the other hand, China is the 22nd region with the highest per capita PBA footprint, the 32nd when using CBA and the 42nd when using CBak.

Detecting regional differences

Exploring the sankey diagrams on the application allows to understand easily why footprints differ between regions. Comparing the size of the ‘France’ (step 3), ‘Imports’ (step 3), ‘Exports’ (step 8) and ‘Footprint’ (step 10) nodes is the simplest way to understand the overall structure of a region’s imports and exports. The reader can then dive into the details, such as the

Fig. 2 | Heatmap of regional rankings according to the three calculation boundaries. The PB, CB and CBk ranks between the 49 regions are given in columns 1, 2 and 3 respectively. The numbers between parenthesis after the rank number correspond to the carbon footprint in tCO₂eq per capita.



regions from where the imports come from (step 2), the regions where the exports go to (step 10) or the production (step 4) or consumption sectors (step 9).

The colors of the flows correspond to the production-based sector (step 4). All the direct emissions by households, governments and NPISHS correspond to dark blue. The production-based emissions in the agriculture-food, energy industry, heavy industry, manufacturing industry, services and transport services sectors correspond respectively to the blue, light blue, light yellow, yellow, light orange and orange colors. Three diagrams for which a color is predominant are given as examples in Figs. 3–6. The light blue color of the diagram of Australia in 2019 (Fig. 3) shows that an important part of its PBA emissions come from the energy industry.

Following these light-blue flows show that over a third of that sector's emissions are exported (in part corresponding to the exports of Australian coal). Second, the blue color of the diagram of Brazil in 2019 (Fig. 4) shows that the agriculture-food sector is responsible for over 50% of Brazilian emissions. Tracing back this blue color shows that most of these emissions are CH₄ emissions (second node of step 1). Third, the diagram of Cyprus in 2019 is mostly orange, showing that over 50% of its PBA emissions are related to the transport sector (Fig. 4). It is important to note that the flows appear smaller on Fig. 3 than on Fig. 4 even though the total is higher in Australia than in Brazil in 2019. This is due to the fact that the flow sizes are normalized as a function of time and not in between regions so that one can see their size change with time for every region on the web application.

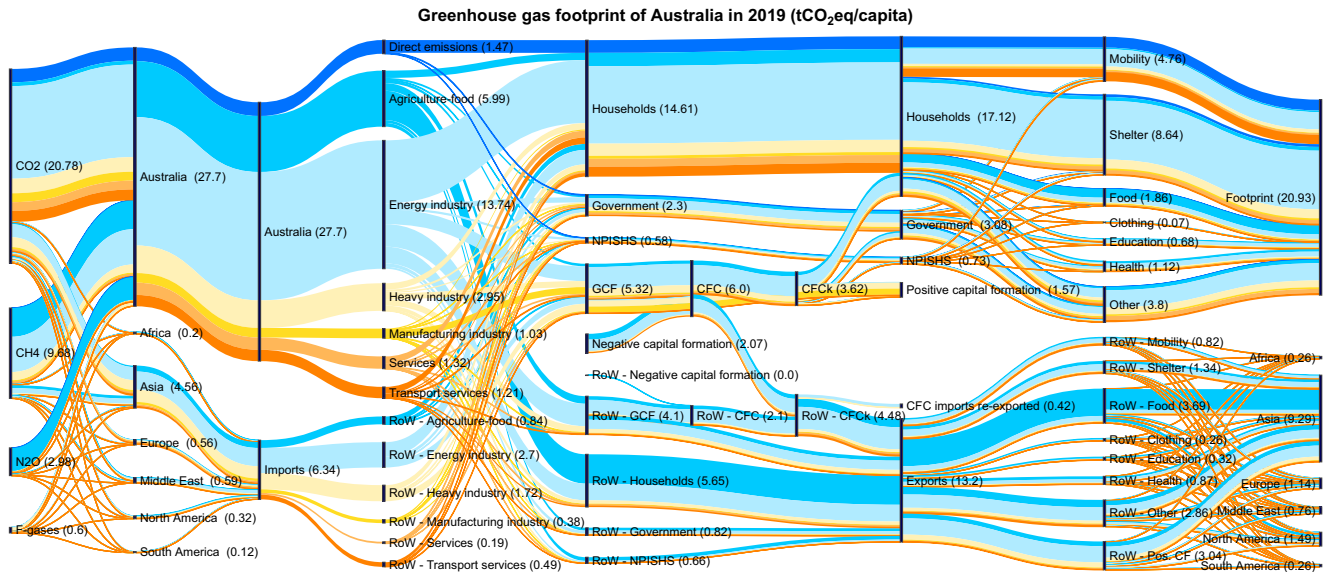


Fig. 3 | Sankey diagram of per capita greenhouse gas emissions in Australia in 2019. The light blue color of the diagram shows that an important part of Australia’s PBA emissions come from the energy industry.

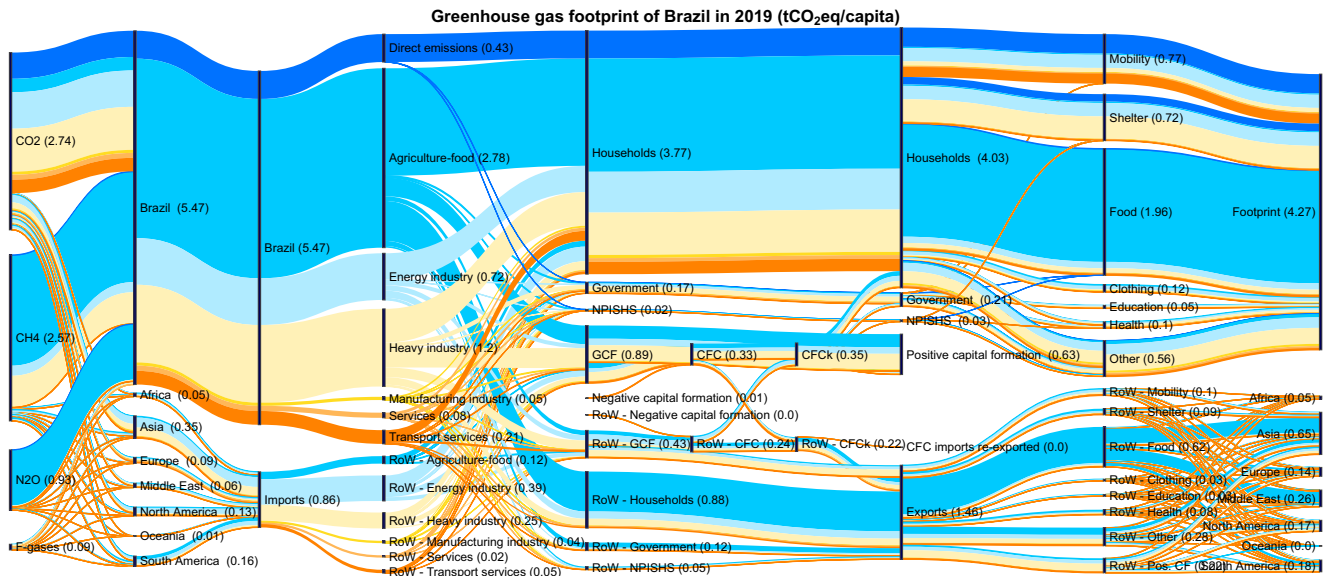


Fig. 4 | Sankey diagram of per capita greenhouse gas emissions in Brazil in 2019. The blue color of the diagram shows that the agriculture-food sector is responsible for over 50% of Brazilian emissions.

Another color code could have been chosen (ie. by making the colors correspond to any other step than step 4). Allowing the user to choose the color code is thus a possible improvement for the next versions of the application.

Capital dynamics: the examples of Russia and China

The sensitivity of results to capital endogenization is particularly important in times of crisis or strong economic growth. Following the collapse of the Soviet Union, Russia suffered from a total lack of investments¹⁴. Its gross fixed capital formation was divided by 4 between 1990 and 1995¹⁴. In 1995, Russia’s consumption of fixed capital was estimated at 188 billion US\$, over two times above that year’s gross fixed capital formation level, estimated at 83 billion US\$¹⁵. It means that the existing capital stock was depreciated at a faster rate than it was replaced. In other words, one can consider Russia in 1995 as a net “importer” of 105 billion US\$ of capital from previous years, equivalent to 27% of the 1995 GDP. The red box of Fig. 6 highlights the

associated imports of 895 Mt CO₂eq from previous years. It represents 56% of the traditional CBA footprint. The CBA footprint with capital endogenized yields a result 32% above the traditional CBA footprint.

On the other hand, China’s consumption of fixed capital in 1995 was only of 83 billion US\$ while its creation of fixed capital was of 238 billion US\$. Net capital formation was thus of 155 billion US\$ which corresponded to 21% of its GDP. The box of Fig. 7 shows that 1565 tons of GHG have been emitted in 1995 for the capital that will be depreciated in the future. It represents 39% of the traditional CBA footprint. The CBA footprint with capital endogenized yields a result 40% lower than the traditional CBA footprint.

When neither in crisis nor in important growth phase, economies have a constant share of net capital formation in their gross fixed capital formation and a constant share of gross fixed capital formation in their GDP. In 2019, the consumption of fixed capital represented respectively 77% and 82% of the United States and France’s gross fixed capital formation. As a

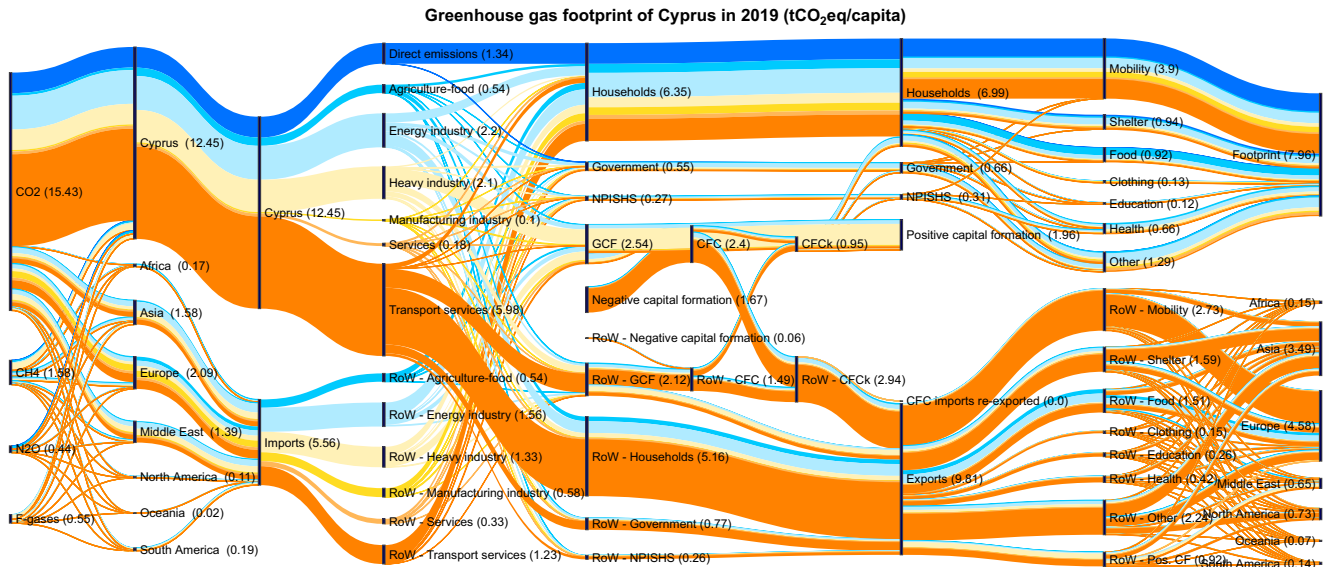


Fig. 5 | Sankey diagram of per capita greenhouse gas emissions in Cyprus in 2019. The diagram of Cyprus in 2019 is mostly orange, showing that over 50% of its PBA emissions are related to the transport sector.

share of gross fixed capital formation in GDP, it respectively represented 21% and 23%. The emissions associated with the net capital formation (positive capital formation, minus negative capital formation) represent respectively 6 and 10% of the traditional CBA footprint in the United States and France. In a steady state economy, there would be a balance between capital depreciation and construction, and GHG emissions associated net capital formation would be at zero.

Conclusion

To easily understand the implications of choosing a production-based, consumption-based or consumption-based with endogenized capital approach when calculating carbon footprints, we built a web application containing 1225 sankey diagrams of regional carbon footprints using EXIOBASE v3.8.2. The diagrams provide first order explanations of regional variations in carbon footprints. They will be useful to policymakers and to scholars interested in learning input-output analysis.

Methods

Input output

We use the product by product version of EXIOBASE v3.8.2 to calculate emission accounts. The production-based account is obtained by adding the direct emissions of region *i* (f_{direct}^i) to the factor of production emissions of region *i*.

The consumption-based account of region *i* for a given gas and final demand category (fd_{cat}) is obtained by multiplying the factor of production coefficients (s^{gas}) by the Leontief inverse (*L*) itself multiplied by a vector of final demand ($y_{fd_{cat}}^i$):

$$d_{cba,fd_{cat}}^{i,gas} = s^{gas} Ly_{fd_{cat}}^i \tag{1}$$

With $L = (I - A)^{-1}$, *I* being the identity and *A* the direct requirement matrix.

The production coefficients s^{CO2} , s^{CH4} , s^{N2O} correspond to the following EXIOBASE extensions:

- Carbon dioxide (CO2) CO2EQ IPCC categories 1–4 and 6–7 (excl land use, land use change and forestry)
- Methane (CH4) CO2EQ IPCC categories 1–4 and 6–7 (excl land use, land use change and forestry)
- Nitrous Oxide (N2O) CO2EQ IPCC categories 1–4 and 6–7 (excl land use, land use change and forestry)

The production coefficients $s^{F-gases}$ are obtained as $s^{F-gases} = s^{GHG} - s^{CO2} - s^{CH4} - s^{N2O}$, with s^{GHG} obtained from extension “GHG emissions (GWP100) | Problem oriented approach: baseline (CML, 2001) | GWP100 (IPCC, 2007)”.

The total consumption-based account footprint is thus obtained by summing over the gases and final demand categories, and adding the direct emissions by households:

$$d_{cba}^{i,ghg} = \sum_{gas} \left(\sum_{fd_{cat}} s^{gas} Ly_{fd_{cat}}^i + f_{direct}^{gas} \right) \tag{2}$$

We adopt Södersten et al.’s¹⁶ methodology for capital endogenization. The capital endogenization process consists in modifying the direct requirements matrix to consider the CFC as intermediate production and not as a final demand category. Matrix \bar{K} is the capital transaction matrix, such that the sum of its lines (*i*) equals *cfc*:

$$\sum_i \bar{k}_{i,j} = cfc \tag{3}$$

One line of \bar{K} provides the information of what the CFC of a given sector in a given region is used for. A column of \bar{K} corresponds to the CFC needed from all sectors and all regions to produce a given product in a given region. We use the \bar{K} matrices built by Södersten et al.¹⁶ for years 1995–2015. These matrices have been updated by Wood and Södersten¹⁷ for years 2016–2019 but they appear to use a different methodology, as the totals seem not to have been rescaled to WorldBank data as done in the original study by Södersten. We thus choose to now-cast the matrix of year 2015, using WorldBank and EXIOBASE data for years 2016–2019, as done by Andrieu et al.¹⁸ for year 2017.

The direct requirement matrix with capital endogenized writes:

$$A^K = (Z + \bar{K})\hat{x}^{-1} \tag{4}$$

with *Z* the transaction matrix and \hat{x}^{-1} the diagonalized and inverted total industry output *x*.

The associated Leontief inverse is thus:

$$L^K = (I - A^K)^{-1} \tag{5}$$

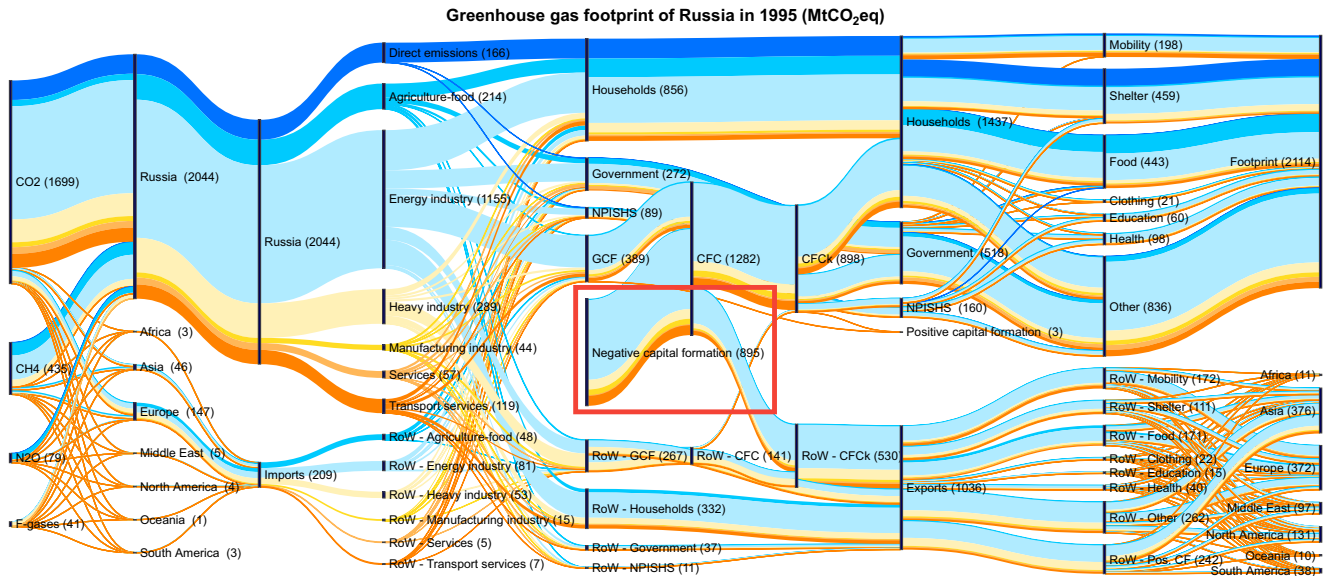


Fig. 6 | Sankey diagram of Russian GHG emissions in 1995. The “negative capital formation” is higher than for other regions and is circled in a red box.

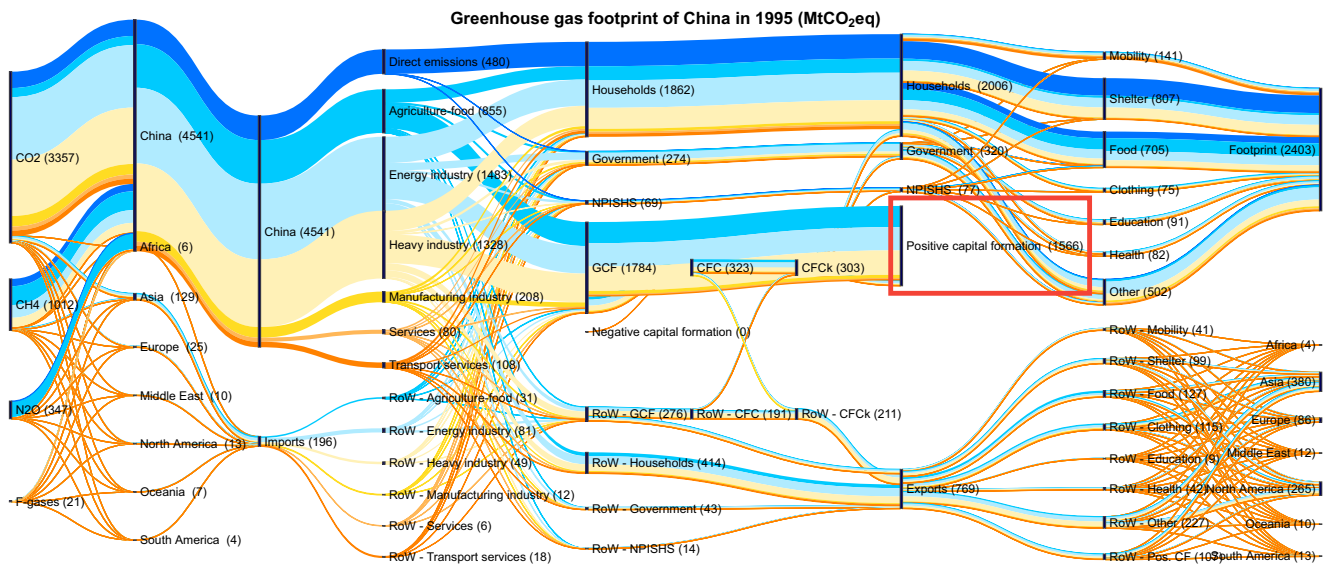


Fig. 7 | Sankey diagram of Chinese GHG emissions in 1995. The “positive capital formation” is higher than for other regions and is circled in a red box.

The consumption-based account footprint with capital endogenized is calculated by summing over the gases and final demand categories apart from GCF (fd_k_cat):

$$d_{cbaK}^{i,ghg} = \sum_{gas} \left(\sum_{fd_k_cat} s_{fd_k_cat}^{gas} L^K y_{fd_k_cat}^i + f_{hh_i}^{gas} \right) \quad (6)$$

Flows per diagram

The strategy for constructing the Sankey diagram consists of (i) calculating the footprints with all possible methods (ii) selecting only the relevant flows for the region under consideration, without duplicates (iii) assigning to each flow a node of passage to the different stages (iv) color coding the flows and aggregating them so that the diagram is readable (v) plotting the diagram. The different steps are developed below and are available in the source code provided with the paper.

To select the relevant flows for a region (France for example), we start by taking the CBA footprint of France (partly from France, partly from other

regions), we add the emissions in France which are allocated to the CBA footprint of other regions (allowing to build the export nodes and to complete the part of the CBA footprint of France). We then add the imports and exports related to the endogenization of capital. In particular, some of the flows imported to create GFCF in France are re-exported during capital endogenization, which includes the additional node “re-exported imports”.

Once all the flows have been selected, they are grouped in a table where each flow corresponds to a row and each column to the different steps. The information contained in $d_{cba,fd_cat}^{i,ghg}$ is used to complete levels 1–5 (Fig. 1). The main difficulty appears at the junction between levels 6 and 7 (Fig. 1) because input-output formalism allows to go from PBA to CBA or from PBA to CBk but not from CBA to CBk. In particular, net fixed capital formation can be negative. We therefore start by adding these negative emissions - considering them as imports from previous years - in order to ensure the continuity of the flows throughout the diagram (there cannot be any negative flows). The transition between levels 6 and 7 is then made by an algorithm that ensures the continuity of flows and colors despite a lack of information to trace exactly the flows from CBA to CBk. From level 8 to level 10, the definition of the different crossing points simply depends on that of $s_{fd_k_cat}^{gas} L^K y_{fd_k_cat}^i$.

To disaggregate direct emissions by sector, we use an internal EXIO-BASE dataset calibrated on data from the International Energy agency.

The column corresponding to level 4 of the created table allows to define a color code so that the color of each flow corresponds to its emission sector in the PBA approach. The flows are then aggregated by color to avoid duplicating flows of the same color between the same nodes. The diagram is then built with the python plotly library. The code to build and put online the application to visualize the results is available with this article.

Limitations

The sankey diagrams built here allow to visually represent the production-based, consumption-based and consumption-based with endogenized capital accounts but several other responsibility allocation schemes exist. Examples include the downstream responsibility (in which the responsibility of emissions is enabled by purchases and not sales)¹⁹, income-based responsibility (the downstream emissions enabled by primary inputs of individual nations or sectors)²⁰, the labor and capital based footprint (the emissions that individuals enable by providing labor and capital to companies)²¹, the emission responsibility allotment (a regional metric which credits actions contributing to reduce global emissions and penalizes actions increasing them)⁴, the value-added based responsibility (which allocates emissions responsibility according to the share of value-added they generate)²², or mixes of the above^{23,24}.

Input-output calculations can allocate emissions based on either the place of consumption (territory principle) or the place of residence of consumers (residential principle)²⁵. EXIOBASE3 is built using the residence principle^{9,26}. Another limitation of these diagrams is that they do not represent the differences between the residential or territory principle.

The limitations of EXIOBASE specifically is its limited regional disaggregation, which is a trade off to its large and consistent product classification. her limitations are those inherent to input-output in general²⁷. For example, the calculations are made under the assumption of homogeneous prices within sectors, which can oversimplify real-world scenarios where products or services within a single sector can diverge substantially in pricing due to factors like quality or branding. The databases are also unable to accurately represent physical flows of low or no economic value, such as waste treatment processes.

As for the method used to endogenize capital, its main limit is that it is not dynamic. It considers that the capital depreciated a given year was built using the technologies of this same year whereas it actually stems from different age cohorts. Södersten and colleagues carried out sensitivity analysis about this steady state assumption and showed that the results for some regions could change substantially if environmental extensions from previous years were used rather than that of the current year⁷.

Data availability

All the sankey diagrams are available on an open-access web application: <https://sankey.theshiftproject.org>. EXIOBASE3 is available at [EXIOBASE 3 | Zenodo](#). The capital use matrices are available at [Capital use matrices | Zenodo](#). Population data is available at [Population, total | Data \(worldbank.org\)](#). WorldBank CFC and GFCF data are available at [Gross fixed capital formation \(current US\\$\) | Data \(worldbank.org\)](#). The supplementary information concordance table is available at https://github.com/baptiste-an/Mapping-global-ghg-emissions/blob/main/SI_concordance_tables.xlsx.

Code availability

The code used to calculate the footprints is available on github: <https://github.com/baptiste-an/Mapping-global-ghg-emissions>. The code to build the application is available on github: <https://github.com/baptiste-an/Application-mapping-GHG>.

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Author contributions

B.A. conceptualized the study, developed the code, conducted the visualization. B.A. and G.W. developed the application and deployed it on the web. B.A., H.B., L.D., F.V., G.W., O.V. and K.S. contributed to the data analysis. B.A. wrote the first draft and B.A., H.B., L.D., F.V., G.W., O.V. and K.S. contributed substantially to the following versions. O.V. supervised the work. K.S. developed the initial EXIOBASE MRIO and supervised the last version of the paper. The authors acknowledge the financial support of the project SCARCYCLET (ANR-21-CE03-012) and « Sous-sol bien commun » (ANR-22-EXSS-0003).

Competing interests

The authors declare no competing interests.

Additional information

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