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Global transport emissions in the Swedish carbon footprint

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ABSTRACT

Transport is perhaps one of the more difficult sources of emissions to address. Whilst opportunities are available for electrification of road vehicle fleets, air transport and the long distance freight of goods are more challenging. Further, due to the fragmentation of global supply chains, where materials can cross the world multiple times before ending up with a final consumer, it is important to understand the contribution of emissions caused by transport, and especially international transport, in relation to the consumption of goods and services. This paper provides evidence based insights into the contribution of CO2 emissions from transport to consumption footprints in Sweden. We give an extensive discussion of the treatment of transport in multi-regional input-output based approaches which can give insight into how different transport emissions can be accounted for. Secondly, we estimate the amount of CO2 emissions in the footprint coming from transport for Sweden. Results show that 14% (12 Mton) of the total Swedish CO2 footprint (84 Mton) was coming from transport activities occurring in the global supply chain. Most of these emissions were caused by transport in supply chains of consumed goods and services such as construction, household appliances and motor vehicles (8.5 Mton). However, the final consumption of package holidays and flights form the single biggest category with 3.5 Mton of the total 12 Mton CO2 of embodied transport emissions. With direct household emissions of vehicle transport in Sweden being 8.5 Mton, the emissions embodied in goods and services (excluding the package holidays and flights) are nearly equivalent to all the private vehicle transport of Swedish citizens.

1. Introduction

Due to the intensive globalization of supply chains, where materials can cross over the world multiple times before ending up with a final consumer (Wood et al., 2018), it is important to understand the contribution of emissions caused by international transport into the dynamics of the total footprint of final consumption. This paper assesses by how much transport emissions contributed to the carbon footprint of Swedish final consumption in 2011. This study is conducted within the framework of the PRINCE project (www.prince-project.se) for the Swedish Environmental Protection Agency and Swedish Agency for Marine and Water Management.

The aim is to provide evidence based insights into the emissions from both domestic and international transport related to consumption footprints in Sweden. As the aim is to give insight into the relative importance of different types of transport in the carbon footprint of Sweden, all transport modes are included (sea, land, rail, inland water and air).

The contribution of this paper is twofold. First, the use of multi-regional input-output (MRIO) tables to examine the issue is introduced, focusing on the data requirements of international transport flows in an MRIO table. MRIO tables cover two categories of transport costs/margins and related emissions – the national and international transport margins. The emissions related to national transport margins can *in general* be calculated rather straightforward with MRIO. Dealing with emissions related to international transport is however more complicated, in part due to the fact that importing countries usually report imports in prices that include transport costs, whereas exporting countries report export in prices without these transport costs. Suffice to say, all types of transport, including the international transport flows, should be explicitly included in the MRIO model. That is, they should be endogenous in the MRIO. This can be more of a challenge than first seen as international shipping of products is not recorded as a separate transaction in official input-output tables, and energy and emission accounts often treat fuels from international bunkers separately. Thus specific processes must be employed to treat transport in a

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consistent way. Because of the difficulty of reconciling various data sources, in this paper, we present both the theoretical framework of international transport and an empirical check of available data in order to investigate if a meaningful footprint of international transport can be estimated. Governmental institutes can play a facilitating role in this process by providing the framework in which international transport is reported for both imported as exported products. These trade data form the basis of official input-output tables, and explicit treatment of the data will enable a better understanding of the role trade and the transportation sector has.

If international transport flows are not endogenous in the model, the role of international transport is underestimated. This can lead to underestimated footprints for countries that consume many transport intensive products or overestimated footprints in the case of countries that consume few transport intensive products. Peters et al. (2011) compared CO2 footprints using MRIOs with either endogenous or exogenous international transport based on 2004 GTAP data. Some key shipping countries – with intensive transport activities – indeed had a lower footprint when using an MRIO with endogenous compared to exogenous international transport, e.g. Denmark, The Netherlands and Singapore. Similar results were found for Sweden in Peters et al. (2011), where the CO2 footprint was estimated at 90 Mton with endogenous transport, the method using exogenous transport yielded a footprint of 95 Mton. For most other countries they actually found higher CO2 footprints.

The second contribution of this paper is the estimation of the CO2 footprint associated with transport specifically for Swedish final consumption. We demonstrate where the CO2 was emitted and which products consumed in Sweden were mostly responsible for these emissions. This is done by estimating the footprint for international transport using the Environmentally Extended Multi-Regional Input-Output (EE-MRIO) table EXIOBASE v3.3 (Stadler et al., 2018; Wood et al., 2015; Tukker et al., 2013). The insights provided by the results can be used by the Swedish government in the assessment between different CO2 reduction measures.

Section 2 gives a detailed description of the MRIO data requirements for including the international transport properly in the footprint estimation. It also assesses the data quality and data requirements in the underlying trade databases that are used in the creation of MRIOs. Section 3 describes the full methodology for estimating the footprint. The estimated results on the CO2 footprint are presented in Section 4. Section 5 provides a discussion of the results and places them into context to existing literature. Finally, Section 6 concludes.

2. Data

For the estimation of emissions coming from transport in consumption footprints, it is important that the MRIO table captures both domestic and international transport explicitly. In MRIO tables the transport sector is recorded as its own sector as per any industry in the economy, showing the input into the sector (in terms of fuel, labour, capital) and in the case of most MRIO models, emissions in terms of air pollutants. The question then arises about how the allocation of the emissions of the sector are done to either direct purchases of transport services, by for example businesses using taxis or flights for in-person meetings, or to the allocation of transport services to either the domestic transport of goods, or the international transport of goods.

The different types of transport forms in an Input-Output (IO) table are shown in Fig. 1. In Section 2.1 we first introduce the treatment of domestic transport in IO tables. In official IO tables domestic transport data is often explicitly included already. However, international transport flows need to be treated with care. Because trade databases record flows in different pricing levels (related to the costs of freight and insurance), and because goods and services are reported separately in bilateral trade database, it is important to ensure both complete coverage of trade data, as well as consistent valuation. In theory, trade databases valued in free on board (f.o.b.) prices record all international transport flows as services separate from the transported good. Section 2.2 describes this in further detail and checks whether the theory also holds in practice. If true, we are able to rely on a f.o.b. valued trade database to obtain international transport data. Two data checks are done to test data against theory. Results show that international shipping in trade databases is indeed complete at EU-28 level as well as at the level of nearly all individual Member States. Then, Section 2.3 describes how international trade data should be included in the MRIO and how the MRIO should treat international transport as endogenous. Finally, the last section in this chapter, Section 2.4, describes how international transport is included in the EXIOBASE database.

2.1. Domestic transport in IO models

Domestic transport is treated in three different parts of input-output tables as there are three types of domestic transport in national accounts, see Fig. 1. The most basic form of transport is private transport, which is mostly the use of private motor vehicles by households. This is recorded as an expenditure in the final demand column of IO tables on both vehicles and fuels, with energy and air emissions associated with the combustion of fuels estimated based on a range of statistics.[1]

The second type of domestic transport recorded in IO tables is as a non-margin service. This includes the demand for flights and taxi services for transporting people (recorded as an input cost on the transport sector, when looking at the cost of production in purchaser prices), as well as the demand for vehicles and fuels directly (recorded as an input cost on transport services, with direct emissions in the sector undertaking the transport activity).

The third type of domestic transport is recorded in an IO table as a margin, where transport costs are recorded as a margin to the cost of consuming a good, as part of the difference between the basic price of a product (for example the quantity of money received at the producer's gate), compared to the purchaser cost of a product (what is paid by the consumer). The estimation of margins (alongside taxes and subsidies) allows for the modelling of consumption in basic prices. In basic prices, the margin component is then recorded as a cost borne by the consumer of transport services, and as such, is recorded as input cost in an IO table. In basic prices, the distinction between margin and non-margin transport services is no longer maintained, and is simply recorded as the cost of either transport of goods or people in the cost accounts of each industry. Not all countries distinguish the costs of transport as a margin, with Sweden being one example where the basic price value includes the cost as an input to production (see point two above).

2.2. International transport in raw trade databases

When a product is exported, it is valued in f.o.b. (free on board)

[1] Note, energy balances do not often report the difference between private use of vehicles, and use of vehicles by industry or the transport sector, such as taxis. The distinction is important for a national accounting perspective, and effort must be made to make the distinction between private and industrial use of energy. As a result, Eurostat has embarked on production of energy accounts that explicitly show the use of energy by different industries and households (Eurostat, 2014). Different countries provide different resolution into the transport sector, and some effort has been undertaken to harmonise the detail between road, other land, air and water when doing cross-country analysis (Wood et al., 2014).

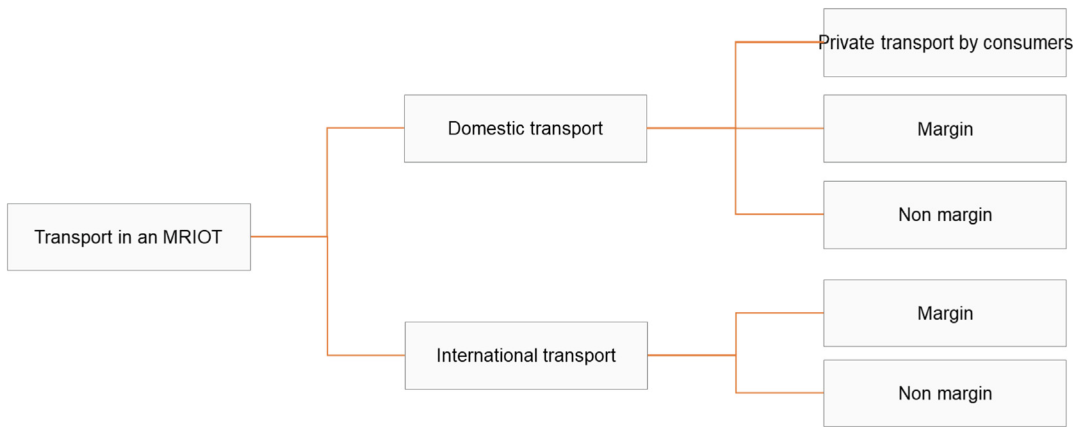

Fig. 1. Types of transport in MRIOT.

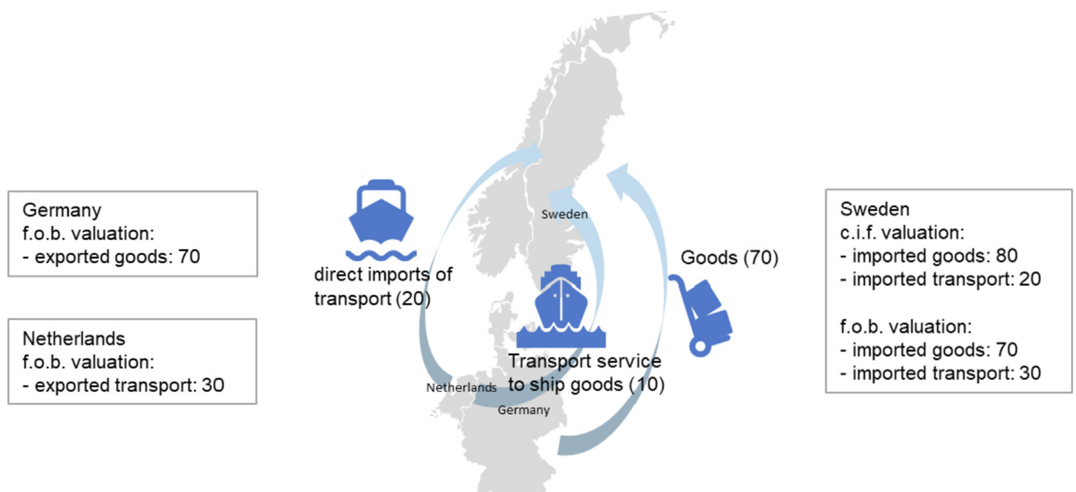

Fig. 2. Example of difference between c.i.f. and f.o.b. valuation: The Netherlands provides transport services and these services are exported both for direct transport of e.g. people in Sweden, and for the transport of goods from Germany to Sweden. The two examples of different types of valuation for Sweden are shown. Records are usually kept by importing country in c.i.f., whilst accurate modelling requires f.o.b. valuation. Thus, one can argue that in c.i.f. valuation the transport flows are underestimated.

prices at the border of the exporting country, see also Fig. 2 for an illustrative example. When that product is imported it is valued in c.i.f. (cost insurance and freight) prices at the border of the importing country. The difference between the f.o.b. and c.i.f. price of a product consists of three components which are international transport margins, international trade margins and insurance costs that occurred in the time between export and import. When an imported product is recorded in f.o.b. instead of c.i.f. prices, the associated international trade and transport services plus insurance costs should be recorded as a separate import flow of shipping services (UN, 2010). Note that this paper will limit itself to the international transport margins and hereby only look at the c.i.f./f.o.b. difference of transport services. The same procedure can however be applied on international trade margins and insurance costs, by taking the data from trade and insurance related sectors in the second data check further on in this section.[2]

Essentially, the difference between c.i.f. and f.o.b. valuation is whether international shipping services are included in the product's price or are shown as separate imports. This implies that total imports of transport services in the c.i.f. database refer only to *direct imports* of transport services for any purpose, whereas transport services in f.o.b. refers to both 1) *direct imports* and 2) international shipping of imported products. To check whether these assumptions are not only true in theory but also in the international trade databases, the following two data checks are applied:

1. Total imports at country level valued in c.i.f. should equal total imports valued in f.o.b.
   Both c.i.f. and f.o.b. valued databases should include the same amount of international transport services (the only difference is whether it is included in the price or as a separate transaction), so the aggregate imports of all products and services at country level should not significantly differ (in the example as shown in Fig. 2 this would lead to a total of 100 in c.i.f. and a total of 100 in f.o.b. which are indeed equal).
2. Share of transport services should be larger in f.o.b. valued imports data than in c.i.f. valued imports data.
   Imported transport services in c.i.f. valued data refer only to direct imports of transport services. On the other hand imported transport services in f.o.b. refer to both direct and indirect transport services (through shipping of products). Therefore the ratio between imported transport and total imports of all goods

[2] The c.i.f./f.o.b. difference of a specific product that one company buys, consists of a transport, a trade and an insurance margin. However, in this data check we do not look at the c.i.f./f.o.b. difference of one product, but at the aggregate product that is the margin (rather than the product on which the margin is applied). We compare the total imports of transport services in c.i.f. and f.o.b. and with this we can estimate the size of the transport margin. If one would be interested in estimating the insurance or trade margin in addition to the transport margin, then the total imports of the insurance or trade services should be compared in c.i.f. and f.o.b.

and services is higher in the case of f.o.b. valuation (in the example as shown in Fig. 2 this would lead to 20% (20/100) in c.i.f. and 30% (30/100) in f.o.b. of which the latter is indeed higher than the former).

The data checks are done by comparing imports in c.i.f. valuation from Eurostat supply and use tables with the imports in f.o.b. valuation from the UN main aggregates data. The advantage of these databases (compared to Comtrade), is that they report estimates for both the import of goods and import of services. Results for the first data check are shown in Table 1. The two databases in c.i.f. and f.o.b. indeed have comparable total import values at the aggregate EU level, namely 5103 and 5300. At the individual country level f.o.b. values are either similar or higher than c.i.f. values. The relative small differences could be explained by the fact that these are two different data sources or by the chosen exchange rates. The results indicate that the international transport margins are indeed consistently included in both databases.[3]

The second check measures the share of imported international transport services compared to total imports of all products and services. Results are given in Table 2. The share of imported transport services in f.o.b. valuation should be larger than in c.i.f. valuation, as the imported transport in c.i.f. does not include product shipping. Indeed these values are respectively 8.6 and 2.7 percent for the EU-28. The data check holds for most individual Member States as well. Also this holds both for the comparison with UN data as well as EXIOBASE database (which contains valuation layers for the f.o.b.-c.i.f. difference which are constructed to match the UN data). The difference between the shares in f.o.b. and c.i.f. indicates the size of the international transport of goods. Thus the EU-28 average international transport margin rate equals 5.9 percent (8.6 minus 2.7), as shown in the last column of Table 2. This value is in line with estimates of overall transport margins of five to seven percent for WIOD (Timmer et al., 2012) and five to ten percent by the WTO (Streicher and Stehrer, 2014).

In Denmark, imports of transport services amount to 58% of total imports of goods (f.o.b. valuation). More than half of the imports in Denmark is hence transport services. Probably, a large part of these imported transport services is meant for re-exports, as large shipping companies are based in Denmark. With a correction on re-exports,[4] the share of imported transport services are lower but still amount to 33%. This is still a very high transport margin rate and could possibly be explained by the remaining re-exports in the EXIOBASE data.

However, Sweden and Ireland have opposite results and do not pass the second data check. The share of imported transport is in fact larger for direct imports of transport (seven percent in c.i.f.) than for both direct imports and indirect imports through shipping of products (six percent in f.o.b.). One explanation could be that Sweden and Ireland uses imported transport services for the transport of their exports, rather for their imports. Another explanation could be that the data is simply not consistent i.e. Eurostat and UN data on imports cannot be used for a comparison in this second data check.

Based on the two data checks, it would be a reasonable conclusion that international transport is consistently present in f.o.b. and c.i.f. databases at aggregate EU-28 level. Only Sweden and Ireland do not pass the second data check. This implies that aggregated international transport at country level might not be fully consistent. Nonetheless as long as aggregated EU-28 data and most individual countries are consistent, this can be seen as an indication that the UN international trade database in f.o.b. include the majority of international transport flows. This in turn implies that input-output tables that are based on f.o.b. trade data include international transport properly and these input-output tables are appropriate for estimating transport emission footprints.

Table 1
Comparison of total imports in c.i.f. and f.o.b. valuation in bln euro, 2011

	imports in c.i.f.	imports in f.o.b.
	Eurostat	UN[a]
Austria	151	158
Belgium	297	307
Bulgaria	24	25
Croatia		18
Cyprus	10	11
Czech Republic	109	110
Denmark	113	116
Estonia	13	13
Finland	76	79
France	593	624
Germany	1018	1078
Greece	64	67
Hungary	80	82
Ireland	132	145
Italy	451	467
Latvia	12	13
Lithuania	24	24
Luxembourg	62	65
Malta	11	11
Netherlands	431	442
Poland	163	169
Portugal	66	68
Romania	56	56
Slovakia	59	61
Slovenia	25	25
Spain	301	312
Sweden	159	170
United Kingdom	604	602
Total excl. Croatia	5103	5300

[a] Assuming the IMF EUR/USD exchange rate of 1.392 taken from WIOD (Dietzenbacher et al., 2013).

2.3. International transport in an MRIO

To ensure that emissions from international transport are included in the footprint estimation, it is important that international transport transactions are properly included in the MRIO. This implies three things. First, import transactions in the MRIO should be expressed in f.o.b. prices instead of c.i.f. prices. F.o.b. pricing records import of international transport separate from import of the transported product. C.i.f. pricing on the other hand does not record international transport transactions, only the total value of imported products including international transport costs. Having transport costs distinguished from the f.o.b. value of goods is highly relevant for emissions calculations, where the emissions intensity of transport services is very different to the emissions intensity of most other goods.

Second, international transport transactions should be endogenous rather than exogenous in the MRIO. That is, international transport should be treated as imports of the international transport sector (in the intermediate consumption or final demand blocks), rather than put in an additional row or column with the c.i.f./f.o.b. difference. This way, demand for international transport is explicitly linked to the supply of the international transport sector though the input-output coefficients.

It should be noted that the approach for treating international transport margins endogenously is similar to the treatment of national transport margins in national input-output or supply and use

[3] Or are consistently excluded. However, the second data check rejects this possibility.

[4] For this, look at the column EXIOBASE in Table 2 where trade data equals the UN trade data minus re-exports.

Table 2
Share of imported transport services compared to total imports of goods in c.i.f. and f.o.b. valuation, 2011

	imports in c.i.f.	imports in f.o.b.		estimated international transport margin rate[a]
	Eurostat	UN	EXIOBASE[b]	
Austria	5%	14%	16%	9%
Belgium	5%	11%	10%	6%
Bulgaria	4%	5%	4%	0.9%
Croatia		4%	5%	4%
Cyprus	6%	28%	13%	22%
Czech Republic	1%	5%	7%	4%
Denmark	6%	58%	33%	53%
Estonia	3%	12%	8%	10%
Finland	3%	12%	12%	8%
France	4%	9%	10%	5%
Germany	2%	8%	9%	6%
Greece	1%	16%	12%	15%
Hungary	2%	5%	8%	4%
Ireland	4%	4%	6%	−0.6%
Italy	2%	6%	7%	4%
Latvia	3%	7%	7%	5%
Lithuania	1%	12%	15%	11%
Luxembourg	2%	12%	8%	10%
Malta	1%	9%	2%	8%
Netherlands	2%	10%	8%	8%
Poland	1%	4%	7%	3%
Portugal	1%	8%	9%	6%
Romania	1%	3%	5%	3%
Slovakia	1%	4%	7%	3%
Slovenia	2%	5%	6%	3%
Spain	1%	9%	12%	8%
Sweden	7%	6%	7%	−0.6%
United Kingdom	4%	7%	7%	3%
Total	2.7%	8.6%	9.2%	5.9%

[a] International transport margin rate equals the share of imported transport in f.o.b. (UN) minus the share of imported transport in c.i.f. (Eurostat).
[b] EXIOBASE data does not include reexports whereas Eurostat and UN do.

tables (Streicher and Stehrer, 2014). National input-output table values are either expressed in basic prices excluding national trade and transport margins or in purchaser prices including national trade and transport margins (and taxes). To convert from purchaser prices to basic prices, all values are reduced by the trade and transport margins (and taxes), while the trade and transport sectors are increased with that same amount.

The numerical example of f.o.b. valuation in Fig. 2 is extended to the MRIO table in Fig. 3 and Fig. 4. The two figures illustrate the difference between an MRIO with endogenous and exogenous international transport margins. Assume a product that is imported by Sweden from Germany. The total value of the imported product is 80 units of which 10 units corresponds to the international transport costs of the product. Another (unrelated) transport service - worth 20 units – is also demanded by Sweden. The Netherlands provides both international transport services. An MRIO with endogenous international transport should record two trade flows (see Fig. 3): 1) imported product from Germany to Sweden with a value of 70 units and 2) imported transport services from the Netherlands to Sweden with a value of 30 units. Note that the MRIO shows imported transport service from Netherlands to Sweden with a value of 30, because Sweden has additional (unrelated) demand for 20 units of transport plus a shipping service of 10. An MRIO with exogenous international transport, would place the value of 10 for instance under an additional row called c.i.f./f.o.b. margin (see Fig. 4).

Streicher and Stehrer (2014) have estimated the full international transport matrix in an MRIO using WIOD data and describe in detail how the international transport margins can be placed as endogenous trade flows in the table. Unfortunately, this data is not published and the official WIOD MRIO is based on a different approach with the international transport margins exogenous in an additional row with the c.i.f./f.o.b. difference (Timmer et al., 2015). The approach respects the original import and export values from the official national input-output tables. In national input-output tables, imports are valued in c.i.f. pricing and exports in f.o.b. pricing. To balance imports with exports using bilateral trade flows, imports are converted into f.o.b. valuation. The c.i.f./f.o.b. differences are then placed in an additional exogenous row or column, due to lack of information on the bilateral trade flows of international transport margins. Peters et al. (2011) even recommend to use such an exogenous approach over the endogenous approach, due to data quality issues. To make international transport margins endogenous, one should add an extra step that adds import flows on international transport in the intermediate use and final demand blocks. For this step, little information is known about who provides the international transport margins.

Third, and finally, the energy and/or emissions dataset in physical units (environmental extensions) must include the use of fuels by the international transport sector. Whilst this paper focuses on the economic flows in the MRIO that should account for all transport, it is important to mention that the same should be true for the physical emissions data. In fact, it is equally as important to ensure that the physical emissions data includes all transport flows correctly. Energy statistics are generally of high quality for liquid fuels, bunkered fuels are reported separately, and are often difficult to allocate to the country providing transport services. Both shipping and airline fuel is reported for international and world bunkers in most energy balance datasets as global aggregates, and in order for complete coverage of these fuels, they must be properly allocated to using sector/country (Usubiaga and Acosta-Fernandez, 2015).

2.4. International transport in EXIOBASE MRIO

EXIOBASE v3.3 2011 EE-MRIO is used in this study (Stadler et al.,

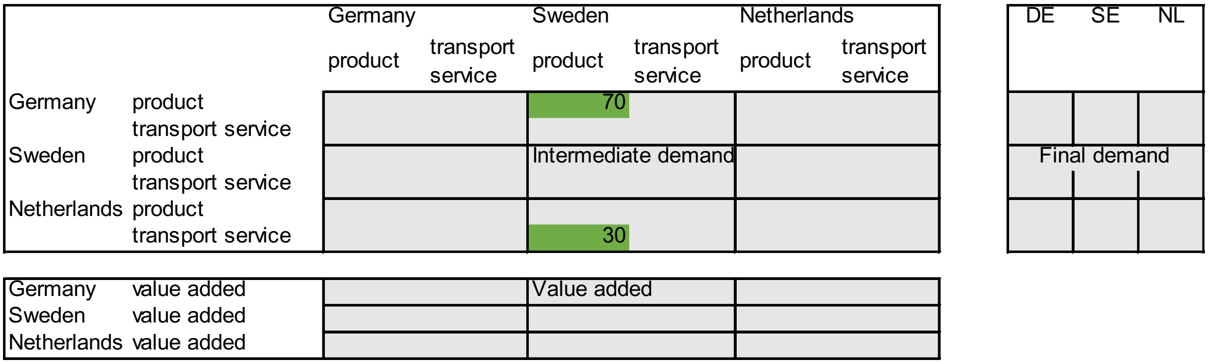

Fig. 3. Numerical example of multi-regional input-output model with endogenous international transport margin.

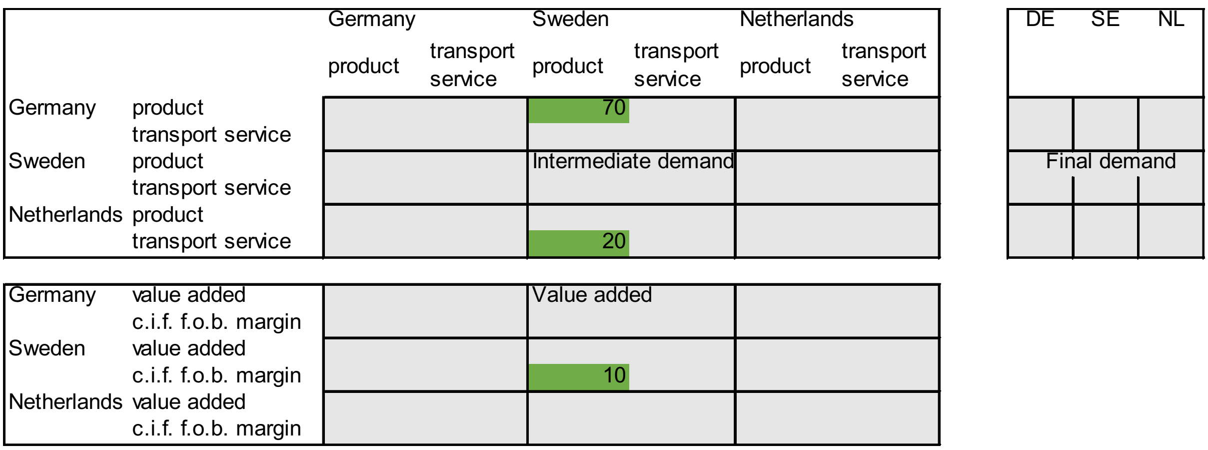

Fig. 4. Numerical example of multi-regional input-output model with exogenous international transport margin.

2018; Tukker et al., 2013; Wood et al., 2015). This EE-MRIO includes 200 products, 163 sectors, 44 individual countries and five rest of the world regions. The EXIOBASE MRIO treats the international shipping flows as endogenous. Due to the reconciliation, EXIOBASE uses the exact import and export values from the UN databases in f.o.b. valuation (after removal of re-exports), rather than converting c.i.f. imports from official national IO tables to f.o.b. values. Assuming that UN international trade databases in f.o.b. correctly include the international transport trade flows (as demonstrated in Section 2.2), EXIOBASE automatically reads international transport flows at country level correctly as imports of transport services.

The trade estimates are built up in EXIOBASE in a number of steps (see Wood et al., 2015; Stadler et al., 2018).

1. Comtrade data in the form of the BACI dataset (Gaulier and Zignago, 2010) is used as the starting point for the data on trade in goods. BACI data is reconciled to f.o.b. values already, in the reconciliation process that removes discrepancies between reporters. BACI is disaggregated for a number of energy fuels using the import and export data from the IEA energy balances (Data: IEA, 2016) due to the higher resolution of energy products in EXIOBASE than BACI/Comtrade.
2. Service trade (including transport services in f.o.b. valuation) was extracted from the UN trade in services database (Data: UN, 2016) and reconciled internally to match differences between import and export reporters. In this process, gaps were filled based on proxy values from different years. Benchmarking was done based on EXIOBASE v2 data, where individual country MSUT data records in higher detail (and quality) the value of service trade by product group.
3. Although the database already includes total transport margins as separate import flows of transport services - which is needed for an appropriate footprint estimation in this paper - we need to know additionally which products uses how much of the transport margins. This is needed to estimate purchaser prices per product using basic prices, taxes and trade and transport margins. Estimates of international transport margins per product group are made based upon a transport model for ten categories of goods in the TRANSTOOLS project (http://energy.jrc.ec.europa.eu/transtools/). These margins are only used for achieving purchaser price values.
4. Re-exports is removed from the trade data. The size of re-exports by product group is estimated based on previously derived data in the EXIOBASE v2 database (Wood et al., 2015). EXIOBASE v2 uses 2007 data of Import Use tables, which record re-exports (export column of import table) to explicitly split re-exports from total imports (see Stadler et al., 2018). In EXIOBASE v3 the same quantity (of sometimes confidential data) was not available, and change over time relative to the 2007 estimate was based on aggregate (and very incomplete) Comtrade data.
5. A complete trade database was thus set-up including both bilateral trade in goods and services excluding re-exports; with additional estimates for re-exports and international margins. This trade database was then reconciled (using a constrained optimization problem implemented in GAMS) to the UN main aggregates database to ensure adherence to this top-level data.

3. Methodology

The total CO2 emission footprint E^{SE} consists of direct emissions emitted by households in Sweden E^{SE-HH} and the indirect emissions through embodied emissions in goods and services $\boldsymbol{E}^{\mathbf{SE\_EMB}}$,

$$E^{SE} = \boldsymbol{\iota}^{\boldsymbol{T}}\boldsymbol{E}^{\mathbf{SE\_EMB}}\boldsymbol{\iota} + E^{SE\_HH}, \quad (1)$$

where ι is the column vector where all entries are 1's, $\boldsymbol{E}^{\mathbf{SE\_EMB}}$ is the square matrix with embodied emissions of size $p{\cdot}j$ by $o{\cdot}i$. Element $E_{pjoi}^{SE\_EMB}$ in matrix $\boldsymbol{E}^{\mathbf{SE\_EMB}}$ stands for the emissions embodied in Swedish consumption per production region p and producer j (in which region or sector is it emitted) and per origin region o and product i (which products for consumption caused the emissions and which region sold this product) in kg. E^{SE_HH} is a one-by-one matrix that includes all emission emitted by households in Sweden.

To estimate the embodied emissions, an environmentally extended input-output model is applied (Miller and Blair, 1985):

$$\boldsymbol{E}^{\boldsymbol{SE\_EMB}} = \mathrm{diag}(\boldsymbol{e})(\boldsymbol{I} - \boldsymbol{A})^{-1}\mathrm{diag}\left(\boldsymbol{Y}^{\boldsymbol{SE}}\right), \quad (2)$$

where $\boldsymbol{e}$ is a vector of size $p{\cdot}j$, and entry e_{pj} stands for the emission intensity per production region and producing sector pj in kg/eur. Entry A_{oipj} of square technical input coefficient matrix $\boldsymbol{A}$ ($o{\cdot}i$ by $p{\cdot}j$) is given per product and origin region oi and production region and producer pj. Vector $\boldsymbol{Y}^{\boldsymbol{SE}}$ denotes the Swedish final consumption in euro by product and origin region oi.

To obtain the emission footprint of transport, the emissions are summed over the regions of origin and transport sectors t where the transport emissions are emitted:

$$E_{pi}^{SE\_EMB\_TRANS} = \sum_{\mathrm{o,j=t}} E_{pjoi}^{SE\_EMB}, \quad (3)$$

where $E_{pi}^{SE\_EMB\_TRANS}$ denotes the emission footprint for transport associated with Swedish final consumption given per production region p (where are the emissions emitted) and product i (for which products consumed in Sweden).

4. Results

This section demonstrates the CO2 footprint of transport associated with Swedish final consumption, as estimated using the methodology described in Section 3. The CO2 footprint of transport refers to emissions coming from all transport activities by industries inside and outside Swedish borders occurring somewhere in the global supply chain that was needed to satisfy final consumption of Sweden.

4.1. CO2 footprint of transport

In this study, the CO2 footprint of transport is estimated at 12 Mton in 2011, see Table 3. This equals 14% of the total national Swedish footprint of 84 Mton. This share is higher than the global average of 7%, meaning that the Swedish consumption is causing relatively more transport emissions than the global average consumption. This is probably related to the low total production and consumption based emissions of Sweden per capita compared to other countries: Sweden's power sector is largely based on hydropower and nuclear power. The actual emissions in Sweden - or the production based emissions - for transport activities (8.3 Mton) are about the same size as emissions coming from private vehicle transport by Swedish households (8.5 Mton), whereas the footprint – or consumption based emissions – are 44% larger (12 Mton). Thus, Sweden is a net importer of embodied CO2 emissions from transport activities.

At the global level air transport emits most of all transport modes and causes more than a third of the global CO2 emissions from transport. Sweden seems to be a net importer of transport emissions especially from air transport, as the difference between actual emission – or production based – of 2.2 Mton and embodied – or consumption based – of 3.9 Mton is relatively large.

4.2. The Swedish transport CO2 footprint by region of emission

The emissions from domestic transport – occurring inside Swedish borders - amount to 2.8 Mton or 3% of the total national footprint while the international emissions – occurring outside Swedish borders -amount to 9.1 Mton or 11%. The emissions from international transport are mostly emitted in Asia and Oceania (3.4 Mton) followed by EU-28 (3.2 Mton), see Fig. 5. This implies that the supply chains for the products consumed in Sweden are highly interlinked with other countries, especially in Asia and Oceania and EU-28[5] .[6]

4.3. Products responsible for Swedish transport CO2 footprint

The next question is which products consumed in Sweden were mostly responsible for the transport emissions. Fig. 6 shows several ways of presenting the Swedish footprint in more detail. The figure starts on the left with the total Swedish footprint of 84 Mton, which can be further distinguished into 12 Mton emitted by the transport sectors, 8.5 Mton of emissions directly emitted by households[7] and 63 Mton emitted by other sources. To be able to identify the products which are mostly responsible for causing transport emissions, the 12 Mton is distinguished further to product level in the figure.

Results show that the Swedish consumption of vacations[8] are causing most of the emissions embodied transport emissions, namely 3.5 Mton out of 12 Mton. The other top products with the most embodied transport emissions are 'construction', 'machinery and equipment' and 'motor vehicles'. Final consumption of 'machinery and equipment' probably relates mostly to the consumption of electric household appliances, 'construction services' to renovations, repair and maintenance of houses and 'motor vehicles' to cars and other vehicles or vehicle parts. This indicates that there is a large potential of reducing the Swedish transport footprint by reducing the consumption of vacations, electric appliances, building renovations/repair and vehicles. The transport emissions in goods and services almost equal the total emissions from private vehicle transport by households in Sweden.

4.4. The Swedish transport CO2 footprint by emitting transport sector

Fig. 6 also distinguishes the footprint by the emitting transport sector by mode. From the 12 Mton of CO2 emissions caused by transport activities embodied in Swedish final consumption, most was emitted by the sea and coastal water transport industry (4.5 Mton) and the air transport industry (3.9 Mton). Sea transport

[5] Note that the country that provides the transport service, is the country that is reported to have emitted the emissions. More specific, a product shipped from China to Sweden by a Dutch shipping company, has emissions reported in the Netherlands.

[6] Also, note that the larger the geographical region the larger the reported emissions are for that region. For instance, Asia and Oceania have the most reported emissions but this could have been the result of the fact that it includes many countries.

[7] The 8.5 Mton emitted by households refer mostly to the emissions of households using a car. These emissions are emitted by households themselves and are therefore not embodied in other goods and services.

[8] These emissions are embodied in the final consumption of 'Air transport' and 'Other transport services; Travel agencies'. We assume that the household consumption of these two products are mostly meant for package holidays and flights.

Table 3
Overview of global and Swedish CO2 emissions from industrial transport activities[a] in Mton, 2011

	Global	Sweden	
	Production/Consumption based	Production based	Consumption based
CO2 emissions	**33,197**	**49**	**84**
CO2 emissions from transport sector	**2268**	**8.3**	**12**
Sea and coastal water transport	*666*	*4.1*	*4.5*
Air transport	808	2.2	3.9
Supporting transport activities; travel agencies	*159*	*0.8*	*1.1*
Other land transport	*343*	*0.7*	*1.7*
Inland water transport	*144*	*0.4*	*0.4*
Transport via *railways*	*148*	*0.1*	*0.3*
Share of CO2 emissions from transport sector	**7%**	**17%**	**14%**
CO2 emissions from private vehicle transport by final consumers[a]	**4343**	**8.5**	**8.5**

[a] We assume that the 8.5 Mton emitted directly by households is due to private vehicle transport, as 98% of 8.5 Mton are emitted due to the use of diesel and gasoline, according to EXIOBASE.

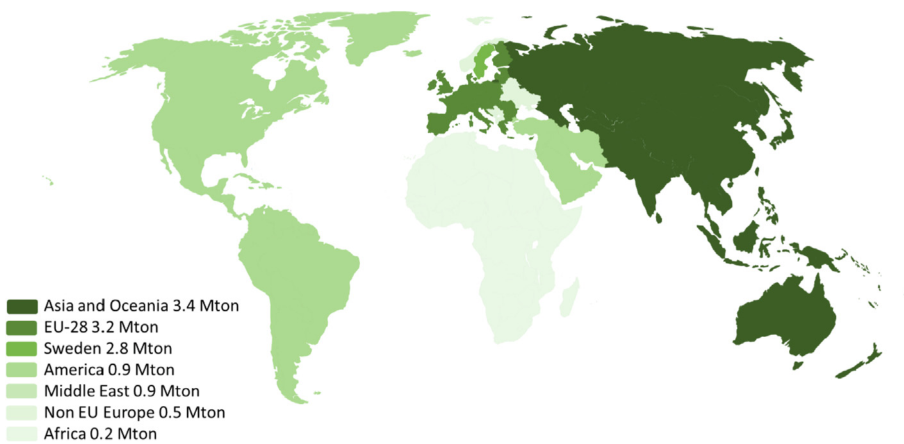

Fig. 5. CO2 footprint of transport for Swedish consumption by region of emission in Mton, 2011) (Label: Country, Mton).

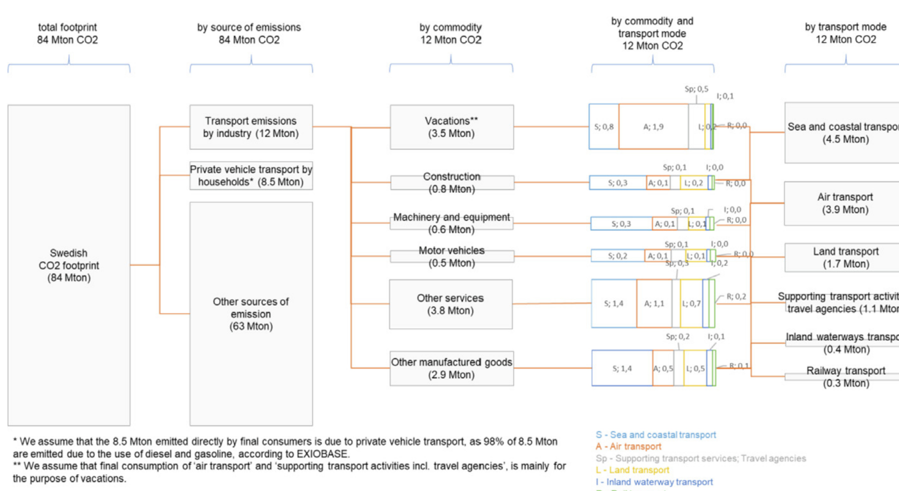

Fig. 6. Swedish CO2 footprint and embodied transport emissions in 2011, split by commodity and transport mode.

emissions are mostly embodied in the consumption of manufactured goods. This is in line with expectations as manufactured goods require freight transport, which is in terms of volume mostly done via sea. Almost half of air transport emissions are caused by the consumption of holiday packages and passenger flights (1.9 out of 3.9 Mton).[9] Another large part of air transport emissions is embodied in services (1.1 Mton out of 3.9 Mton) rather than in manufactured goods. This implies that air transport is largely needed to supply services, including the transport of personnel for

[9] Note that the final consumption of package holidays and passenger flights emitting emissions other than from air transport may seem counterintuitive, but it also includes all the transport needed to enable this air transport, such as sea transport to import technical parts of the plane or land transport needed for catering services.

in-person meetings and conferences.

In the 'Land transport' sector 1.7 Mton CO2 emissions are emitted globally, to meet the demand of Swedish final demand. Results indicate that all goods and services require a certain share of land transport except for vacations. Vacations hardly have embodied land transport emissions. The remaining other transport sectors, 'supporting transport activities; travel agencies', 'inland waterways transport' and 'railway transport' only emit 1.8 ton in total. A detailed table of the Swedish footprint is given in Appendix A.

5. Discussion

5.1. Results

This study has estimated the global transport emissions in the Swedish footprint. Results indicate that Sweden is a net importer of transport emissions. Most of the transport emissions are embodied in the Swedish consumption of vacations, construction services, household appliances and motor vehicles. Although the globalization of supply chains and freight transport may have increased substantially in the last decades (see Ortiz-Ospina and Roser (2018)), we should not underestimate the emissions caused by personal transport demand of households. Of the 12 Mton of CO2 emissions, that is emitted by the transport industry and embodied in Swedish final demand, almost a third was embodied in the final consumption of vacation related services, including passenger flights and holiday packages from travel agencies. On top of that final consumers emitted 8.5 Mton themselves directly, mostly by driving their cars. By indicating which products consumed in Sweden have a large international transport footprint, this paper could guide policy makers on where to focus efforts for demand-side mitigation efforts.

5.2. Data quality

These results are based on an input-output table that treats transport endogenously. Two data checks are introduced in order to check whether the international transport flows are indeed treated endogenously in the raw f.o.b. transport data. Here we should place the footnote that databases, like Eurostat and UN main aggregates database can be based on the same national sources like statistical offices or tax authorities. Comparison of these databases are therefore also likely to give comparable results. However, Eurostat and UN performed different data treatments on the raw data sources in order to place it in their desired format (c.i.f. for Eurostat and f.o.b. for UN main aggregates). Comparison of these results remains valuable, since it gives an indication of the trustworthiness of slightly transformed varieties of the national raw data. When Eurostat and UN would have reported results that show large differences, and would not pass our data checks, it would be a signal that these mentioned data sources should be used with care in the future. However, our results show that we are confident that Eurostat and UN correctly report transport data in c.i.f. and f.o.b. respectively.

For our input-output analysis we have used the MRIO table EXIOBASE 3.3 for year 2011. This is a highly detailed database. Also, for this database it holds that, in order to achieve a required balance, data manipulations are necessary (see for details Stadler et al., 2018). Deviations from official nation data is inevitable (see for a discussion, Tukker et al., 2018a; Tukker et al., 2018b). Also trade data as discussed above had to be adjusted to ensure the MRIO is balanced, implying that the cross-check if the c.i.f. and f.o.b. values in EXIOBASE are in line with those in UN COMTRADE and the Eurostat trade statistics, is useful. So, as Peters et al. (2016) points out, 'each of the currently available MRIO databases has its advantages and disadvantages, and it is not clear which should be used over the other'. However, it seems that the estimated footprint in this study falls within the range of results from the literature, measuring a CO2 footprint for Sweden of about 78–105 Mton (Peters et al., 2011, 2016; Dawkins et al., 2019).

6. Conclusions

This paper has provided evidence based insights into the contribution of CO2 emissions coming from transport services in the Swedish consumption footprint. Here, emissions from transport services refer to emissions emitted by all transport modes – except private transport by households and government -, in all regions incl. Sweden, needed to satisfy the Swedish final consumption. The contribution of this paper is twofold. First, specific data requirements for including international transport flows are identified and assessed in detail. Second, the size of the CO2 footprint of transport services is estimated using an environmentally-extended input-output model using 2011 EXIOBASE v3.3 data.

For the research question at hand, we identify specific data requirements for treating international transport flows in a Multi-Regional Input-Output (MRIO) table. Firstly, in the underlying UN trade databases we recommend to use trade data valued in f.o.b. prices. As opposed to trade data in c.i.f. valuation, trade data in f.o.b. prices records transport flows as separate bilateral trade flows. Note that trade data in f.o.b. prices requires that international transport should be reported as a separate service for imported products as well (instead of only exported products). This change in reporting needs to be supported and facilitated on the governmental level. Secondly, bilateral trade flows of international transport should be treated endogenously in the model. That is, they should be treated as (bilateral) import flows of transport in the MRIO (endogenous) rather than in an additional column or row called 'c.i.f. f.o.b. difference' (exogenous). An MRIO, such as EXIOBASE, that fulfills these requirements is able to estimate CO2 footprints that take into account the full contribution of transport.

Results show that the CO2 emissions from transport services embodied in the Swedish final consumption amount to 12 Mton which equals 14% of the total national Swedish footprint of 84 Mton. Sweden is a net importer of CO2 emissions and especially of air transport. A large part of these transport emissions were embodied in the consumption of vacations (3.5 Mton) incl. package holidays and passenger flights. The remainder of the emissions (8.5 Mton) was embodied in other goods and services (mostly in 'machinery and equipment', 'construction services' and 'motor vehicles') used by Swedish consumers and nearly equals the volume of CO2 emissions emitted directly by households themselves via private vehicle transport. The contribution of CO2 emission from transport embodied in goods and services may be relatively large but the role of private vehicle transport and vacations should not be underestimated either, implying that policy to reduce CO2 emissions should focus both on private vehicle transport as well as on the consumption of other goods and services. These results form the basis for our take-home message for Swedish policy makers. By placing extra attention and tailoring policy measures for those activities that are shown to take a large share of total CO2 emissions for which Swedish consumption is responsible, CO2 reduction can most easily be achieved.

Declaration of interest

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Annex A. Swedish footprint split by region and sector of emission

The table below summarizes the full Swedish national footprint and shows how much is emitted in each region and each producing sector. The sum of all values in the table equals the national Swedish footprint of 84 Mton. The green block shows the emissions that were emitted during international transport activities needed to meet Swedish final demand while the blue block represents the domestic transport emissions needed to meet Swedish final demand (the two blocks sum up to 12 Mton).

Table 4
Swedish footprint split by region and sector of emission in Mton, 2011.

	Sweden	EU-28	Rest of Europe	Asia and Oceania	America	Africa	Total
Agriculture, forestry and fishing	0,4	0,5	0,1	0,3	0,1	0,1	1,5
Mining and quarrying	0,5	1,5	0,1	2,3	0,2	0,1	4,7
Manufacture of food products, beverages and tobacco	0,4	0,4	0,0	0,2	0,0	0,0	1,0
Manufacture of textiles and textile products	0,0	0,1	0,0	0,2	0,0	0,0	0,4
Manufacture of wood and wood products	0,0	0,1	0,0	0,1	0,0	0,0	0,2
Manufacture of pulp, paper and paper products	0,3	0,2	0,0	0,1	0,0	0,0	0,6
Manufacture of coke and refined petroleum products	0,3	1,8	0,2	1,3	0,2	0,1	3,8
Manufacture of chemicals and chemical products	0,1	0,4	0,1	0,7	0,2	0,0	1,4
Manufacture of rubber and plastic products	0,0	0,2	0,0	2,0	0,1	0,0	2,3
Manufacture of other non-metallic mineral products	1,5	0,8	0,2	0,8	0,1	0,1	3,4
Manufacture of basic metals	0,6	1,6	0,2	2,4	0,3	0,1	5,2
Manufacture of machinery and equipment n.e.c.	0,1	0,3	0,0	0,1	0,1	0,0	0,6
Manufacture of electrical and optical equipment	0,2	0,6	0,1	0,9	0,1	0,0	1,8
Manufacture of transport equipment	0,1	0,2	0,0	0,1	0,0	0,0	0,4
Manufacturing n.e.c.	0,1	0,2	0,0	0,4	0,0	0,0	0,8
Electricity, gas and water supply	8,2	3,7	0,3	8,0	1,0	0,4	21,7
Construction	1,0	0,1	0,0	0,2	0,0	0,0	1,3
Wholesale and retail trade	1,7	0,8	0,1	0,4	0,2	0,1	3,2
Hotels and restaurants	0,8	0,2	0,0	0,2	0,1	0,1	1,5
'Railway transportation services'	**0,1**	**0,1**	**0,0**	**0,1**	**0,1**	**0,0**	**0,3**
Land transportation services'	**0,5**	**0,2**	**0,1**	**0,7**	**0,2**	**0,0**	**1,7**
'Sea and coastal water transportation services'	**0,7**	**1,5**	**0,3**	**1,7**	**0,3**	**0,0**	**4,5**
'Inland water transportation services'	**0,2**	**0,1**	**0,1**	**0,1**	**0,0**	**0,0**	**0,4**
'Air transport services (62)'	**0,8**	**1,0**	**0,1**	**1,4**	**0,4**	**0,1**	**3,9**
Supporting and auxiliary transport services (63)'	**0,6**	**0,3**	**0,0**	**0,2**	**0,0**	**0,0**	**1,1**
'Post and telecommunication services (64)'	0,3	0,1	0,0	0,1	0,0	0,0	0,5
Financial intermediation	0,8	0,1	0,0	0,1	0,0	0,0	1,1
Real estate, renting and business activities	2,0	0,9	0,1	0,6	0,1	0,0	3,7
Public administration and defence	0,1	0,0	0,0	0,0	0,0	0,0	0,1
Education	0,3	0,0	0,0	0,0	0,0	0,0	0,3
Other community, social and personal service activities	0,7	0,6	0,0	0,1	0,1	0,0	1,6
Activities of households	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Extra-territorial organizations and bodies	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Direct emissions by final consumers	8,5	0,0	0,0	0,0	0,0	0,0	8,5
Total	31,7	18,4	2,3	25,7	4,0	1,5	83,6

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