Austria's Consumption-Based Greenhouse Gas Emissions: Identifying sectoral sources and destinations

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Abstract

Greenhouse gas emissions can be addressed at the points of both production and consumption of goods and services. In a world of inhomogeneous climate policy, missing out policies on either production or consumption leaves an important policy area idle, rendering climate policy inefficient and potentially ineffective. While consumption-based emissions accounts have become readily available at the national level, we here show how their more detailed analysis by sectoral destination (which final demand sectors account for them), sectoral source (in which sectors across the globe those emissions are actually occurring) and the geographical location of the latter can inform a complementary consumption-based climate policy approach. For the example of the EU member country Austria, we find that more than 60% of its consumption-based emissions occur outside its borders, and 34% even outside the EU. The top sectors are a very different list under a consumption-based accounting perspective (construction, public administration (including defence, health and education), and retail and wholesale trade) than under a production-based one (electricity, iron and steel, and non-metallic minerals, such as cement)). While for some sectors (e.g. construction) production-based approaches can work well, emission reduction in other sectors (e.g. electronic equipment) is crucially dependent on consumption-based approaches, as a structural path analysis reveals.

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1. Introduction

The international community specifies greenhouse gas (GHG) mitigation as a responsibility at the national level (that can be delegated by subsidiarity to lower levels), with the Paris Agreement supplying the current framework for voluntary, bottom-up pledges (nationally determined contributions, NDCs) (UNFCCC, 2015). Historically it has been standard to focus on emissions that arise from production and consumption processes within the respective national territory. Correspondingly, conventional GHG emission inventories record emissions released by the agents (e.g. industries, private households and public agents) within the geographical borders of a nation. The respective indicator system, a territorial emission accounting framework, also known as Production-Based Accounting (PBA), is employed by the United Nations Framework Convention on Climate Change (UNFCCC, 1997).

With ongoing economic specialization and the growth of international trade having outpaced growth in global GDP for many decades, production supply chains are spanning many countries, and final consumption in one country is increasingly connected to GHG emissions in other countries, governed by a complex, global web of internationally linked activities. The question of which emissions each country can address can thus be answered alternatively. One could consider final consumption to ultimately drive GHG emissions, and thus allocate all emissions along the (international) supply chains to final consumption and to the country where this final consumption occurs in. The corresponding alternative indicator system is Consumption-Based Accounting (CBA) of emissions (Munksgaard and Pedersen 2001, Lenzen et al. 2004; Peters and Hertwich, 2008; Davis and Caldeira, 2010), often also referred to as Carbon Footprints (CF). Corresponding emission inventories are thus based on CBA and record emissions induced by residents' consumption irrespective of where in the world those induced emissions take place. Since production and consumption occur very often in different geographical locations, these two distinct emission accounting frameworks tend to show different pictures of the amount of emissions allocated to a nation which could potentially serve as a policy base.

If we had a world with a globally harmonized GHG mitigation architecture it would be of no relevance which climate policy a country implements, whether addressing production-based emissions or consumption-based emissions.[1] Either direction would be effective and efficient (Steininger et al., 2016). Under the Paris Agreement our current world, however, deviates in at least three aspects form such a setting:

(a) In conceptual terms, mitigation efforts are differentiated across countries, guided by the principle to ‘‘protect the climate system […] in accordance with their common but differentiated responsibilities and respective capabilities.” (UNFCCC, 1992, Article 3).

[1] If markets are complete and fully competitive, and if climate policy (i) covers all GHG emissions globally and (ii) imposes (at least implicitly) a globally uniform (shadow) price on each type of GHG (which, if it equals marginal damages, additionally ensures overall efficiency), then environmental and cost-effectiveness are guaranteed irrespective of which accounting system is chosen, that is, irrespective of where in the supply chain (producer or consumer) the targets are set and the instruments are applied. In such a setting, markets pass on the incentives fully to all other agents in the supply chain, both upstream and downstream.

(b) In practical terms, the total of current pledges globally is considered to fall short in the level necessary to achieve the Paris target of "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels". Current pledges – if successfully implemented – limit temperature increase to below 3 degrees by the end of the century at best (e.g. UNEP, 2016). Individual countries might nevertheless seek to implement higher contributions – up to what they consider their full contribution for reaching the 2 degree target – if they only could foreclose compensating emission increase elsewhere, i.e. if they could ensure global effectiveness of their efforts.

(c) While all 197 parties to the UNFCCC have agreed to the Paris agreement, to date it has been ratified by less than two thirds of them (120 as of December 2016), yet covering more than 80% of global emissions.

Given these aspects characterising a fragmented, bottom-up climate architecture, it becomes very relevant for individual countries to consider both policy strands, production-based as well as consumption-based policies, and, as we argue in the following, may be highly relevant to use policies of both types, complementing each other.

The initial introduction and discussion of the concept of consumption-based emissions (Kondo et al., 1998; Munksgaard and Pedersen, 2001; Ferng, 2003; Bastianoni et al., 2004; Rodrigues et al., 2006; Lenzen et al., 2007) was often framed in the context of "responsibility", It pointed out that final consumption can be held "responsible" for emissions, with the – mostly implicit – conclusion that this end point in the supply chain thus is offering a necessary point of policy intervention. Normative research, on the other hand, has shown that for "responsibility" in a causal sense of "contributing to climate change" (and following a compensatory justice perspective) there are serious limits making it practically impossible to allocate specific shares of contribution among producers and consumers (for an overview see e.g. Steininger et al., 2014). But this finding does not reduce the relevance of the point of final consumption as a very appropriate point of policy intervention. The identification of such points of policy intervention is our focus in the present paper.

Over the last decade, extensive quantifications of consumption-based accounts at the national level have been generated (initially by Peters and Hertwich, 2008; Hertwich and Peters, 2009; Peters, 2010; Munoz and Steininger, 2010; Davis and Caldeira, 2010), with a few groups offering even a consumption-based emissions online data base (e.g. EORA, Lenzen et al. (2013)).

Recently, further emission allocation possibilities along the supply chain were identified, beyond the just two points of allocating all emissions to either producers or to consumers. These alternatives are the allocation to resource extraction (extraction-based principle; Davis et al., 2011), or splitting across producing agents according to their respective shares in value-added (income-based accounting; Lenzen and Murray, 2010; Marques et al, 2012). It is worth noting that available consumption-based accounting meanwhile extends well beyond carbon accounting: it has been analyzed for air pollution (e.g. Kanemoto et al., 2014), biomass (e.g. Erb et al., 2009; Peters et al., 2012), biodiversity (e.g. Lenzen et al., 2012), water (e.g. Feng et al., 2011; Hoekstra and Mekonnen, 2012), material use (e.g. Munoz et al., 2011; Bruckner et al., 2012; Wiedman et al. 2013), and land use (e.g. Meyfroidt et al., 2010; Weinzettel et al., 2013). Tukker et al. (2016) combine the last three of these (water, land, and material use) with carbon in a unified dashboard approach for indicating Europe´s environmental and resource footprint.

Despite this rich literature on the concept and the broad availability of quantifications of consumption-based emissions, it is remarkable that the consequences for policy conclusions in most of this literature is rather rudimentary, and that there are only very few studies focusing on policy implications explicitly (Barrett and Scott (2012) and Scott and Barrett (2015) for the UK and Girod (2016) screening EU directives under that perspective are among the very few exceptions). The only policy instrument that both can be considered a consumption-based policy instrument and has been the subject of extensive empirical analysis is border carbon adjustment (or border tax adjustment) (for a model comparison of results see e.g. Böhringer et al. (2012)). But for the more general perspective of policies to address consumption-based emissions – beyond this single policy instrument of border carbon adjustment – there appears to be still a surprising but significant gap in the literature. Our hypothesis is that one of the reasons for this gap is the fact that many policies addressing consumption-based emissions cannot be specified at the macro level (such as border carbon adjustment is), but need to be more specific – addressing the peculiarities of particular sectors.

To open up ground for this line of research, in the present paper we analyze the sectoral structure of consumption-based emissions in much more detail, i.e. we identify the hotspots in both dimensions, sectors of destination (i.e. sectors of final consumption demand that account for particularly high consumption-based emissions) and of source (i.e. those sectors across the globe where emissions induced by final consumption of possibly other countries actually occur). Before being able to design effective policies addressing trade-embodied emissions, we need to better understand which particular products are the most relevant in triggering emissions, as well as where and what activities in their supply chain are the most significant in terms of releasing GHG emissions.

In order to be able to be specific we restrict our analysis to a single country. We analyze consumption-based emissions of the EU-member country Austria, place our results within the EU-28 context, and, using Austria as an exemplifying case, generalize our conclusions where appropriate.

The question we seek to answer is which are the sectors of demand in Austria that account for the largest share of consumption-based emissions (sectors of destination)? In which sectors in other countries across the globe is Austrian final consumption foremost responsible for GHG emissions (source sectors)? What can we learn from this analysis for possible intervention points and respective policies?

We use a global model which connects consumers in Austria and producers around the world, who use different technologies and a different energy mix in the production process.

The structure of the paper is as follows. We characterize the methodology of Multi-Regional Input-Output (MRIO) analysis in section 2. Section 3 first supplies an overview on Austria's GHG responsibilities from a CBA perspective, and afterwards we delineate these emissions across their actual origins abroad followed by a sectoral disaggregation at two different levels of detail. In section 4 policy insights are derived.

2. Methodology and data bases used

Consumption-Based Accounting

Linking the production and consumption activities of countries by international trade flows facilitates the analysis of the location and source of global emissions. The prevalent established method to account for a country's emissions is the so-called Production-Based Accounting (PBA), which attribute the emissions to the country *releasing* the carbon to atmosphere, regardless where these commodities are eventually consumed (see Fig. 1). An alternative way is to consider the consumption activities in a country and the associated emissions released along the whole production chain satisfying this demand, regardless where the production of the respective commodities (and the associated emissions) took place. This is referred as Consumption-Based Accounting (CBA). Following trade linkages over the entire production chain – from the industries that supply their output for production up to the industries that produce the final good or service – allows the allocation of global emissions from a consumption perspective.

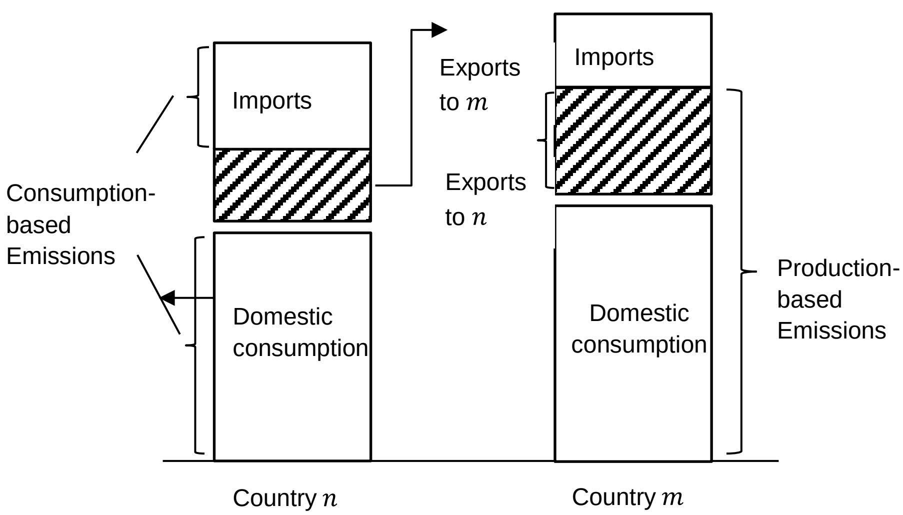


Fig. 1: Consumption vs. production-based accounting concepts. Scheme adapted from Steininger et al. (2014).

Multiregional Input-Output Model

In the present analysis, the CBA concept is implemented by means of a global environmentally extended Multiregional Input-Output (MRIO) model depicting global trade flows and corresponding emissions. This type of model is often featured in the literature on emission accounting as the underlying methodology which is already well established, not only in the academic community (see for example Lenzen et al., 2004; Lenzen et al, 2007; Peters and Hertwich 2008; Davis and Caldeira, 2010; Muñoz and Steininger, 2010; Steininger et al., 2015), but also among international organizations (OECD, 2016; Eurostat, 2016). MRIO applications have been fostered further by the development of new databases, such as GTAP (Narayanan et al. 2015*)*, EXIOBASE (Tukker et al. 2015), EORA (Lenzen et al. 2012; 2013), WIOD (Timmer et al. 2015) and OECD (2016). For studies carrying out comparisons of these databases, see for instance the work of Moran and Wood (2014), Arto et al.(2014), or Tukker et al. (2013).

The MRIO analysis allows tracing both direct and indirect emissions ($\boldsymbol{E}$) induced by final consumption ($\boldsymbol{Y}$) through production linkages ($\boldsymbol{A}$) between industries and countries:

$$\boldsymbol{E} = \boldsymbol{\rho}(I - \boldsymbol{A})^{-1}\boldsymbol{Y}$$

The block matrix $\boldsymbol{A} = [a_{ij}]_{\boldsymbol{NMxNM}}$ depicts the multiregional production coefficients where element a_{ij}^{km} of submatrix Z_{km} reflects the intermediate demand (per unit of gross output) of industry j in country m from industry i in country k, with $i, j = 1, \dots, N$ and $k, m = 1, \dots, M$. The element y_{ic}^{km} of the final demand matrix $\boldsymbol{Y}$ denotes industry i's output produced in country k and consumed by final users in country m, with index c denoting the different economic agents (i.e. private households, government and investment demand). The Leontief inverse $(\mathbb{I} - \boldsymbol{A})^{-1}$ thereby captures the direct and indirect inputs necessary to produce one unit of a final commodity. Finally, vector $\boldsymbol{\rho}$ depicts for all industries and countries the level of GHG emissions per unit of output. By introducing $\boldsymbol{\rho}$, total inputs required along the international production chain of final demand are translated into environmental impacts from consumption (in form of GHG emissions). The specification of the model further allows the assignment of these impacts to destination (i.e. the sectors in country m responsible for the respective emissions domestically and elsewhere) and source (i.e. the sectors across all k countries where these emissions actually take place).

Data preparation

We base our analysis on the Global Trade Analysis Project (GTAP) database in combination with EXIOBASE due to the time period and spatial coverage, as well as the level of sectoral disaggregation. We used the following GTAP versions available: GTAP v.9 (base year 2011, 2007 and 2004); GTAP v.6 (base year 2001); and GTAP v.5 (base year 1997). The most recent GTAP database includes a global representation of 140 regions, comprising 120 single countries and 20 regions representing country groups (Narayanan et al, 2015). We used the full 57 sectors in the GTAP database. Subsequently, we expand our analysis by using EXIOBASE, due to its highly disaggregated sectoral data, consisting of 163 industries for the year 2007. We decided for this two-step analysis - GTAP as primary data source and the complementary use of EXIOBASE - because (1) albeit a higher sectoral resolution in comparison to GTAP, EXIOBASE includes only 48 world regions of which 43 are individual countries; (2) GTAP has provided updates on a regular basis, with the latest version comprising the year 2011 versus 2007 in the case of EXIOBASE.

GHG emission sources

The emissions data is derived from a combination of sources covering the same year, regions and sectors as the GTAP dataset. The emissions dataset is built to include the most recent and reliable data for each country and sector combination and therefore contains a mix of sources. The sources, in order of priority, include EUROSTAT's NAMEA dataset (CO_2, CH_4, N_2O, fluorinated gases (FGAS); European Commission (2015)), the UNFCCC dataset (CH_4, N_2O, FGAS; UNFCCC (2013)), the GTAP provided dataset (CO_2, CH_4, N_2O, FGAS; Narayanan et al. (2015)) and CDIAC dataset (cement and flaring CO_2 emissions; Le Quéré et al. (2015)). The NAMEA dataset covers most European countries, while UNFCCC includes further large economies (such as Australia, Canada, US, Russia and Japan), while GTAP provides emissions for the rest of the regions. CDIAC cement and flaring emissions are applied to regions where GTAP CO_2 emissions are used, as the latter does not include cement emissions (while NAMEA does). We use the global warming potential metric with 100-year time horizon (GWP100) with parameters from IPCC's fourth assessment report (AR4; IPCCC (2007)), apart from FGAS which use parameters from the second assessment report (SAR; IPCCC (1996)) since it is hardwired from the source.

3. Results: relevant agents, destinations, sources, and their geographical distribution

We structure the presentation of results as follows: firstly, we provide an aggregated overview of Austria's GHG emissions resulting from both the consumption and production-based approach (section 3.1). Subsequently, we break down this macro perspective by attributing the CBA emissions to the three agents of final demand (households, government and firms' investment) before discussing the regional breakdown of consumption-based emissions across the globe in section 3.2. Section 3.3 identifies Austria's hotspots, i.e. the top-15 sectors responsible for the largest share of Austrian GHG emissions from a CBA perspective (destination sectors). We then identify the emitting *regions* across the world economy as well as the *sectors* in which emissions take place ('source sectors'). We also investigate Austria's consumption-based emissions in further detail by using a more disaggregated sectoral model based on the EXIOBASE database, and trace emissions from destination back to source sectors.

3.1. Austria's GHG responsibilities from a *CBA and PBA perspective: Overview and trends*

From a PBA perspective, Austria emitted 80.3 million tonnes of CO_2e (M-tCO_2e) or 9.6 tCO_2e per capita in 2011. When applying a CBA approach, the level of emissions embedded in Austria's final demand increases to 123.6 million tonnes of CO_2e for the same time period, which is equivalent to 14.7 tCO_2e per capita. Results reveal that GHG emissions are about 53 percent higher from a CBA than PBA perspective. While the difference between consumption-based and production-based emissions is remarkable, this discrepancy has been relatively stable over time (see Table 1 and Figure 3). Emissions under both CBA and PBA have declined after peaking around 2005.

CO2e emissions (in 1000 of tons)

Categories	**1997**	**2001**	**2004**	**2007**	**2011**
(1) Household (direct consumption)	**17,656**	**18,878**	**18,592**	**16,962**	**15,565**
(2) Emissions embodied in consumption	**96,787**	**96,565**	**107,389**	**101,361**	**103,816**
-Emissions embodied in HH final demand	59,525	61,623	69,096	64,933	67,452
-Emissions embodied in government's final demand	10,324	9,679	12,667	11,203	10,010
-Emissions embodied in investments demand	26,938	25,263	25,625	25,225	26,354
(3) Emissions embodied in imports of international transport	**2,425**	**4,626**	**4,969**	**4,915**	**4,254**
CBA (=1+2+3)	**116,868**	**120,069**	**130,950**	**123,238**	**123,636**
PBA	**79,753**	**80,769**	**84,924**	**82,627**	**80,308**
CBA per capita (in tons)	**14.7**	**14.8**	**16.0**	**14.8**	**14.7**
PBA per capita (in tons)	**10.0**	**10.0**	**10.4**	**10.0**	**9.6**
Ratios	**1.47**	**1.49**	**1.54**	**1.49**	**1.54**

Table 1: Austria's GHG emission inventories from a CBA and PBA perspective (in million tonnes of CO_2e).
Note: The accounting principle for PBA in the present analysis is the resident's principle, while the UNFCCC balances follow the territorial principle. The application of the UNFCCC methodology implies slightly different figures for Austria than the one presented in Table 1.

Moreover, Austria is among the countries with the highest disparities between consumption-based and production-based emissions in the EU-28 (see Figure 2). While in Belgium, Sweden and Cyprus consumption-based emissions are between 67 and 70 percent higher than their respective production-based emissions, consumption-based emissions in France, Greece and Austria are about 55 percent larger in comparison to production-based ones. Conversely, a number of EU-28 countries (Bulgaria, Denmark, Czech Republic, Poland, and Ireland) appear to be net exporters of emissions. These variations are largely explained by two factors: first, small and import dependent countries generally have higher consumption-based emissions, and second, countries with a clean domestic energy supply often have higher consumption-based emissions. The supplementary material on CBA and PBA includes more detailed information for the EU-28 countries and other world regions.

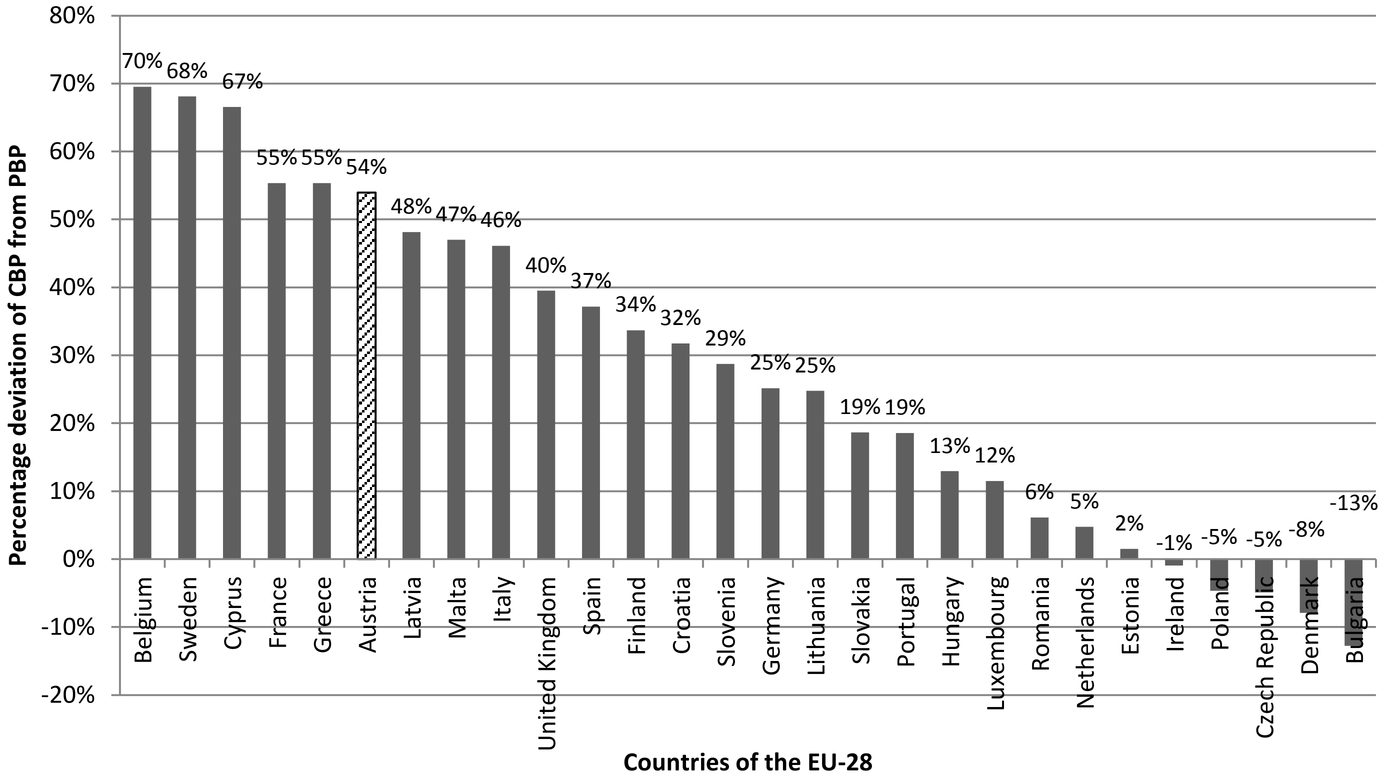


Figure 2: Percentage deviation of GHG emissions following the consumption-based principle (CBP) from those following the production-based principle (PBP) for European countries.

A sensitivity analysis using the WIOD and EORA databases leads to similar results, showing consumption-based emissions for Austria to be between 52 and 65 percent (WIOD), respectively between 51 and 74 percent (EORA), larger than production-based emissions, depending on the year under study (see Figure 3). Moreover, the robustness of the CBA analysis was checked for the case of considering CO_2 emissions only, by employing various databases for the multiregional model (GTAP, WIOD and EORA) and several CO_2 emissions datasets, as well as different methods of computing consumption-based emissions. Carrying out CBA estimates based on all these alternatives for 1970 to 2014 (or the available range of the respective time series therein), results show that Austria is still a net importer of emissions, with the largest difference between consumption-based and production-based emissions being in the range of 46% (GTAP) to 51% (WIOD) (see Supplementary Information). In this regard, the comparably higher absolute level of emissions derived from the use of EORA can be largely explained by higher production-based GHG emissions (different data source), with the relative increase from production to consumption not dissimilar in the different datasets (see Moran and Wood (2014) for a rigorous comparison of these databases). The following analysis is based on GTAP, due to the fact that data are compiled on the basis of a uniform sector classification (57 industries in total) and comprise a large set of countries (140 regions).

The share of emissions attributed to the different agents evolved along similar trends between 1997 and 2011 (see Table 1). Over this time span, the excess rate of consumption-based emissions over production-based ones was slightly moving up and down within a range of 47 percent (1997) and 54 percent (2001), with the most recent value being at 54 percent again (2011).

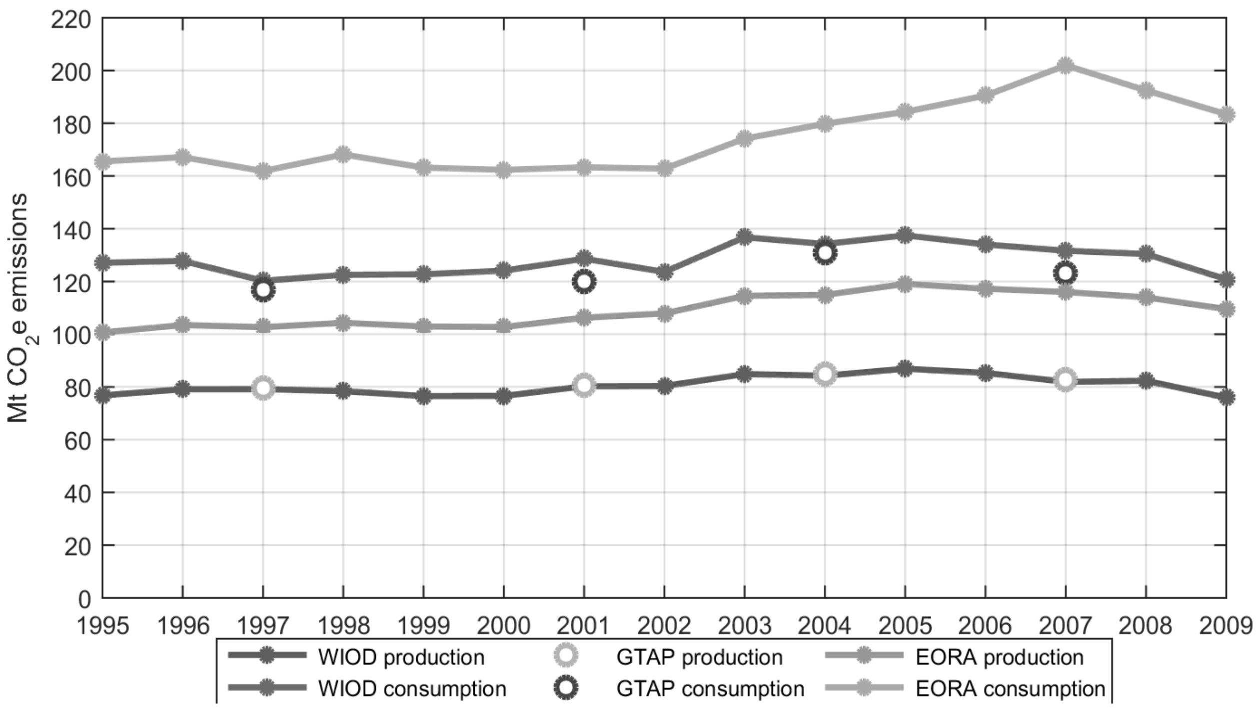


Figure 3: Austria's CO_2e emissions from a CBA and PBA perspective using GTAP (MRIO), WIOD and EORA for the years 1995-2009.

Breaking down the results for 2011 by the different agents of final demand, the analysis shows that households were the main inducer of GHG emissions from a CBA perspective. This category accounts for 68 percent of total emissions; of which 13 percent were released directly and 55 percent indirectly through consumption of goods and services that induce emissions upstream. Direct household emissions can be further broken down into transport, housing (including utilities) and other activities, as illustrated in Figure 4. Households are followed by firms' investments (21%), government (8%), and international transport (4%).

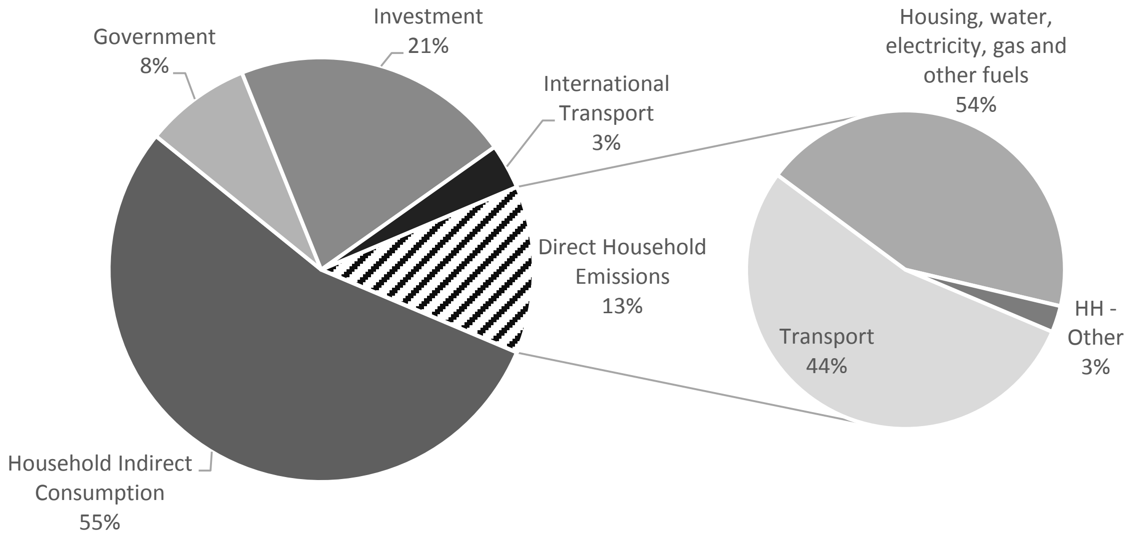


Figure 4: Shares of the Austria's CBA emissions across different agents (2011).
Note: Emissions embodied in imports of international transport were not allocated to final demand.

Consumption-based emissions over this period, 1997-2011, evolved roughly in parallel with production-based emissions (see Table 1, and the index lines in Figure 5), indicating that the share of net carbon imports remained stable. Figure 5 further shows that emission intensity of GDP has declined – with respect to both production-based and consumption-based emissions, actually in a very similar way – but absolute emissions have only been stabilized, not been reduced. Austria thus is nowhere close to reach an emission reduction required for its contribution to the two-degree target (APCC, 2014). Policies still need to be developed – and the intervention points identified below can guide such development.

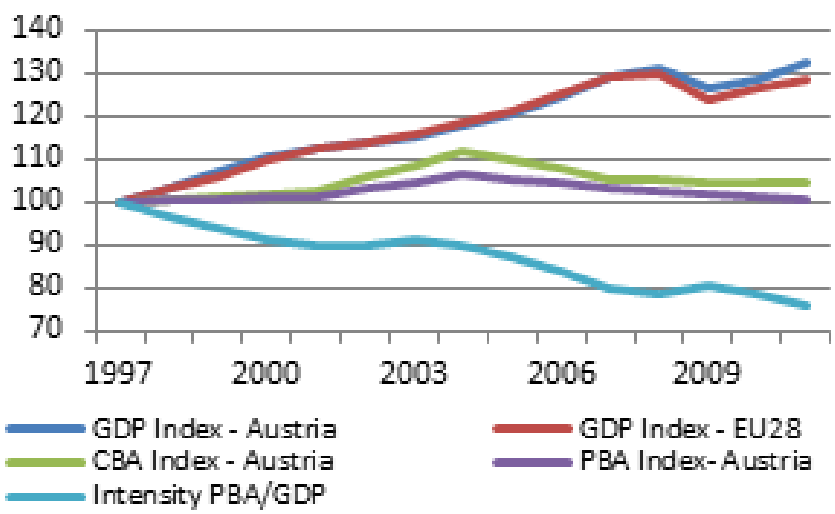


Figure 5: Changes in Gross Domestic Product (GDP), PBA emissions, and GHG emission intensity (index 1997=100).

3.2 Regional breakdown of consumption-based emissions

The MRIO analysis also provides an overview of the most affected world regions in terms of GHG emissions (source regions) as a consequence of Austria's final demand. Figure 6 depicts the source regions grouped into Austria, rest of EU-28 (i.e. EU-28 excluding Austria), and non-EU countries. Interestingly, 62 percent of the emissions to satisfy Austria's final demand occur abroad, with 34 percent in non-EU countries – mainly in China, Russia and the United States – and 28 percent within other countries of EU-28. Further, 35 percent of the total emissions embodied in final demand take place on Austrian territory. The remaining emissions due to international transport related to import activities are estimated at 3 percent.

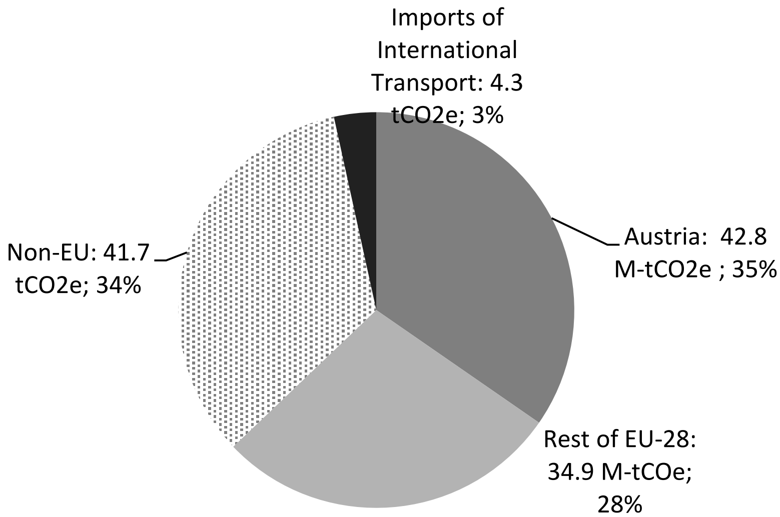


Figure 6: Regional sources of emissions induced by Austrian final demand (year 2011).
Note: Statistics on international transport do not allow identifying the country provider of the service.

The regional breakdown is also relevant for the architecture of future climate policy design in Austria, as those emissions occurring in non-EU countries are subject to different, potentially less strict emission regulations. With the Paris Agreement having entered into force in November 2016, almost all countries are committed to implementing effective policies and measures regarding climate change mitigation. Targets and actions have been outlined in the countries' respective Nationally Determined Contributions (or NDCs): China, for example, committed the peaking of their CO_2 emissions to be achieved by 2030 and to reducing CO_2 intensity (per unit of GDP) by 60 to 65 percent from the 2005 level; the United States pledged to lower GHG emissions by 2025 by between 26 and 28 percent from the 2005 level. Russia committed to reduce GHG emissions by 20 to 25 percent compared to their 1990 level, with all these targets referring to 2030.[2] Yet, as we indicated in the introduction, reductions across the globe take place at often quite different speeds. They also may focus on very different sectors across countries. For these reasons as well as for the UNFCCC principle of mitigation according to respective capabilities, any country in the world, also Austria, may be very much interested in

[2] The referenced NDCs are available at: w4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx.

not just reducing emissions within its own borders or those it induces in other EU countries, but very much also those it induces outside the EU (the large dotted slice of the pie chart in Fig. 6).

3.3 Key source and destination sectors of consumption-based emissions

Our analysis aims at identifying the groups of products[3] consumed in Austria that embody the largest amounts of GHG emissions globally. After presenting an overview of findings by destination and source sectors, detailed results on the hotspots are organized in two different ways: i) according to the final demand sector inducing the emissions (destination sector); and ii) on the basis of the sector where the emissions are released anywhere on the globe (source sector).

Figure 7 provides an overview of Austria's emissions from the PBA and CBA perspective highlighting the significance of the various sectors. Austria emitted 80 M-tCO_2e in 2011 according to territorial accounting procedures. The major share of these emissions (30%) came from energy-intensive manufacturing (EIM), while direct emissions induced by households rank second (19%), followed by electricity generation (13%) and agriculture (11%) (see Figure 7). Emissions exported are 47 percent of territorial emissions, while imported emissions equal 101 percent of territorial emissions or 65 percent of consumption-based emissions. Of the exports of goods and services, 49 percent of the emissions occurred in the EIM sector, while electricity and agriculture are responsible for 13 and 12 percent, respectively. Most of the imported emissions are embodied in electricity (30%), while 25 percent are embodied in EIM. Put together, this leads to 123.6 Mt-CO_2e consumption-based emissions, which can be represented either by source sectors or by destination sectors. In this regard, the investigation of the two stacked bars on the right hand in Figure 7 shows large differences in the sector attribution: whereas a large share of emissions occur in electricity generation, EIM, agriculture and mining sectors on Austrian territory or elsewhere and thus constitute the major source sectors, the sectors most responsible for these emissions (i.e. the major destination sectors) are the service sectors, construction, non-energy intensive manufacturing (NEIM) and food sectors. The following analysis presents sectoral emissions by destination and source in further depth.

[3] The words 'product groups' and 'sector' are treated interchangeably in this article.

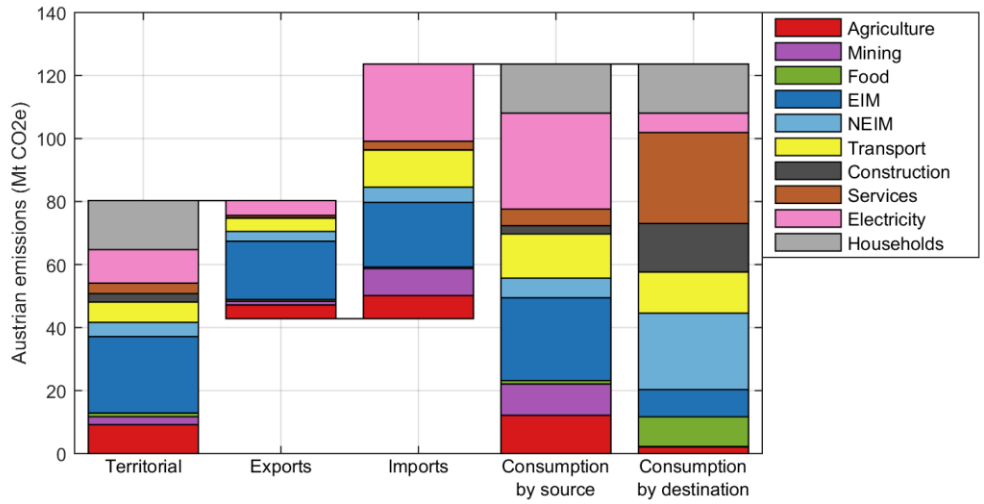


Figure 7: Sectoral emissions territorial, export, import, consumption by source sector and consumption by destination sector perspectives. Source: GTAP, NAMEA, EDGAR, own calculations.

3.3.1 Destination Sectors

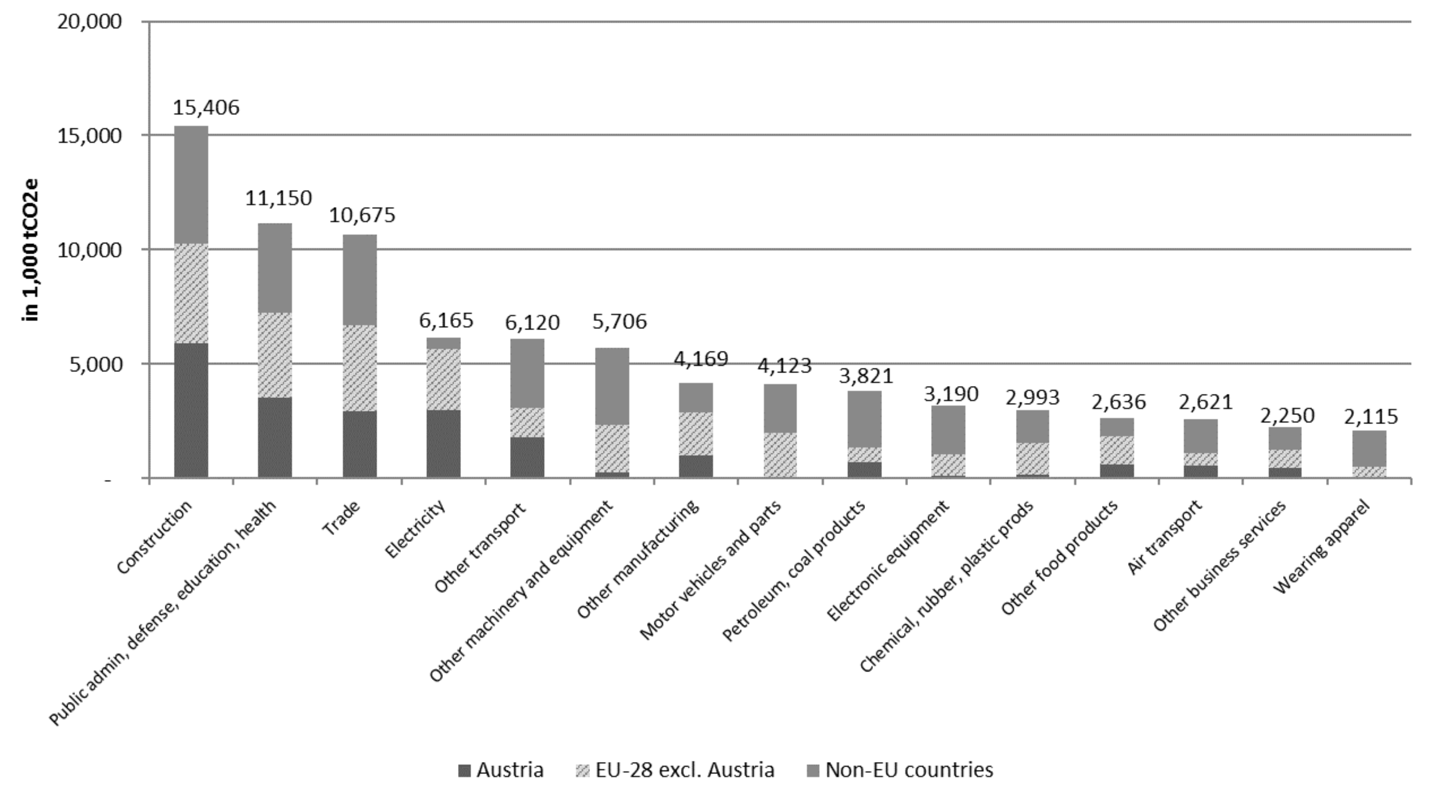
Figure 8 illustrates the top-15 sectors driving consumption-based and production-based emissions, as well as the ratios between them. In both subfigures (8(a) and 8(b)), the 15 sectors represent more than 80 percent of the respective total emission inventories. However, the set of sectors varies depending on the accounting principle applied. For instance, ‘construction’, ‘public administration’ (and its subsectors[4]), and ‘trade’ are the top three sectors driving consumption-based emissions with each of them emitting more than 10 Mt-CO_2e in 2011 (see figure 8(a)). The application of the PBA principle shows three different sectors at the top (see figure 8(b)): ‘Electricity’ is ranked first (10.6 Mt-CO_2e), followed by ‘iron and steel’ (8 Mt-CO_2e), and ‘non-metallic minerals’ (5.3 Mt- CO_2e). The two accounting principles therefore offer complementary perspectives for tackling GHG emissions that affect not solely national territory.

MRIO models have the important feature to also unveil the spatial distribution of global emissions triggered by consumption in a particular region. This is also illustrated in Figure 8(a) which depicts the emissions induced by Austria’s sectoral final demand by affected regions. For example, in the case of Austrian demand for electricity, most of the emissions occur within the EU-28, while emissions due to the demand of ‘electronic equipment’ predominantly take place outside the EU-28. The regional attribution of emissions thus provides valuable information for designing national climate change mitigation policies at sector level that seek to be globally effective.

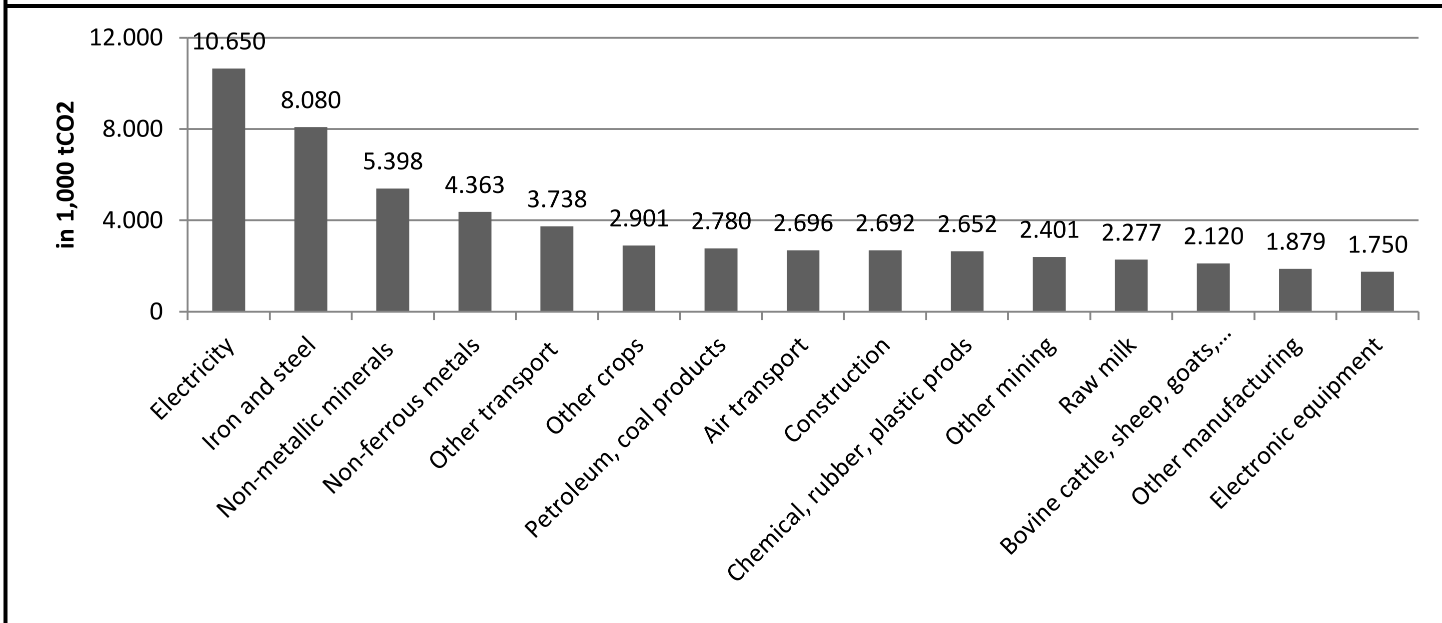
Figure 8(c) shows the sectoral deviation of consumption-based emissions from production-based in percentage for the top-15 sectors. The sectors ‘construction’, ‘other manufacturing’ and ‘electronic equipment’ show the strongest deviation between consumption-based and production-based emissions, in the range of 472 percent, 122 percent and 82 percent

[4]This sector aggregates data from ‘public administration and defense’; ‘compulsory social security, ‘education’, ‘health and social work’, ‘sewage and refuse disposal’, ‘sanitation and similar activities’, ‘activities of membership organizations’, ‘extra-territorial organizations and bodies’ (Narayanan, 2015).

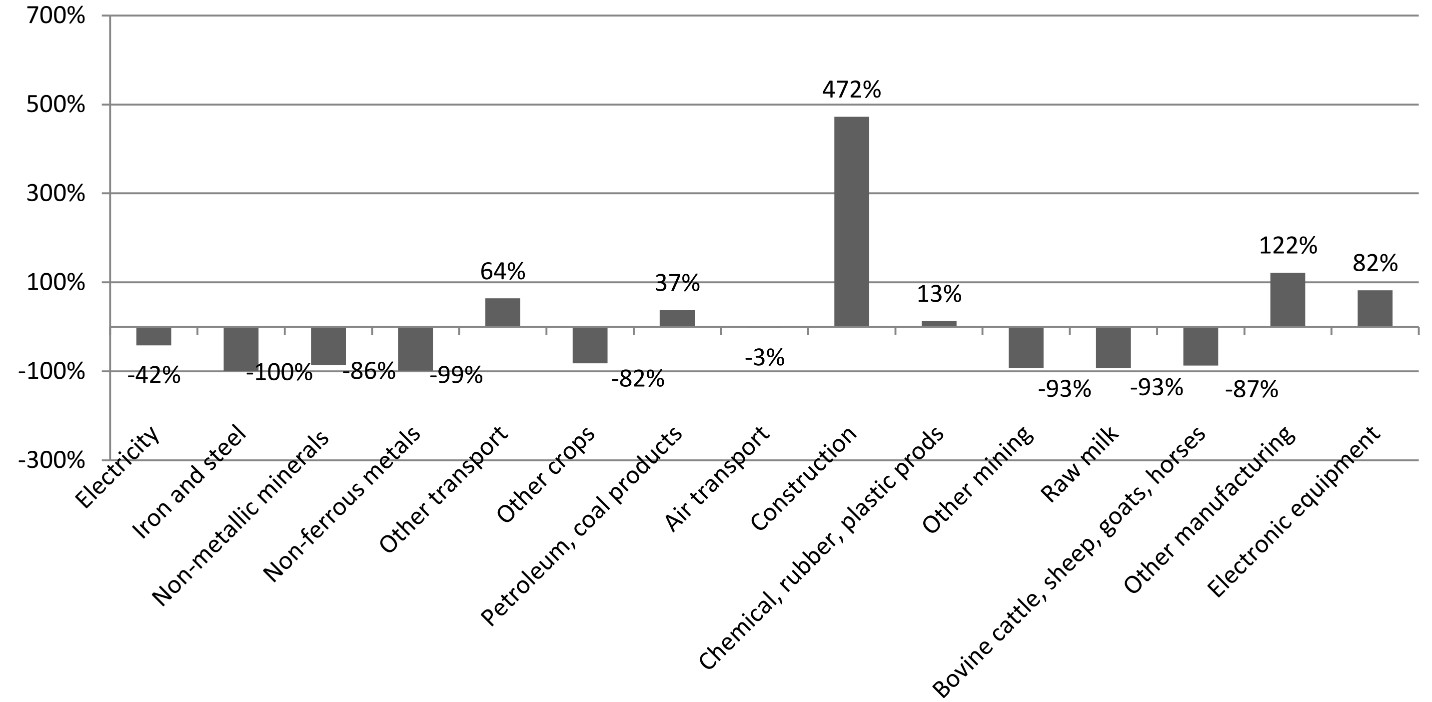
respectively. It is worth noting that several sectors show higher emissions from the PBA than the CBA perspective as these are sectors largely devoted to supply their production to other sectors.



(a) Consumption-based emissions



(b) Production-based emissions



(c) Sectoral deviation of CBA from PBA

Figure 8: Top-15 sectors driving GHG emissions from a CBA and PBA perspective (year 2011). Panel (a) reports CBA while Panel (b) shows PBA. Panel (c) reports the percentage deviation of emissions (in %) of the Top-15 sectors from a CBA perspective with respect to their PBA counterpart.

While GTAP includes a considerable amount of sectors (precisely 57), each of these sectors contain several sub-industries that in some cases show heterogeneous emission intensities. For instance, within the electricity sector one could think of different electricity generation technologies that could be treated as subsectors, e.g. ‘production of electricity by wind’ and ‘production of electricity by coal’. To further investigate differences in the emission intensities of subsectors and identify the top emitting subsectors, we apply an MRIO model using the EXIOBASE database. EXIOBASE contains a highly disaggregated sector classification, consisting of 163 sectors in total. The latest available version of this dataset, however, has 2007 as the reference year. We decompose two of the most important destination sectors, public administration and trade.[5] While results should be carefully interpreted due to the different years of analysis, it is expected that EXIOBASE sheds some light on the identification of potential subsectors of destination and source.

When using EXIOBASE to analyse public administration, this sector can be additionally disaggregated in up to 14 subsectors, from which ‘health and social work’ is the most prominent destination sector driving emissions, accounting for 49 percent of total emissions from the public sector that occur within and outside Austrian borders (see figure 9(a)). This is followed by ‘public

[5] `Construction’ is not further analysed as EXIOBASE does not present a further disaggregation of this sector.

administration and defense' (28%), 'education' (15%), 'activities of membership organizations' (7%), and 'sewage and refuse disposal, sanitation and similar activities' (1%). Regarding trade, this sector can be split into four subsectors, where 'wholesales trade and commission trade' represents the largest share with 53 percent. The other subgroups are: 'retail trade' (26%), 'sales, maintenance and repair of motor vehicles' (20%) and 'retail sale of automotive fuel' (1%) (see Figure 9(b)).

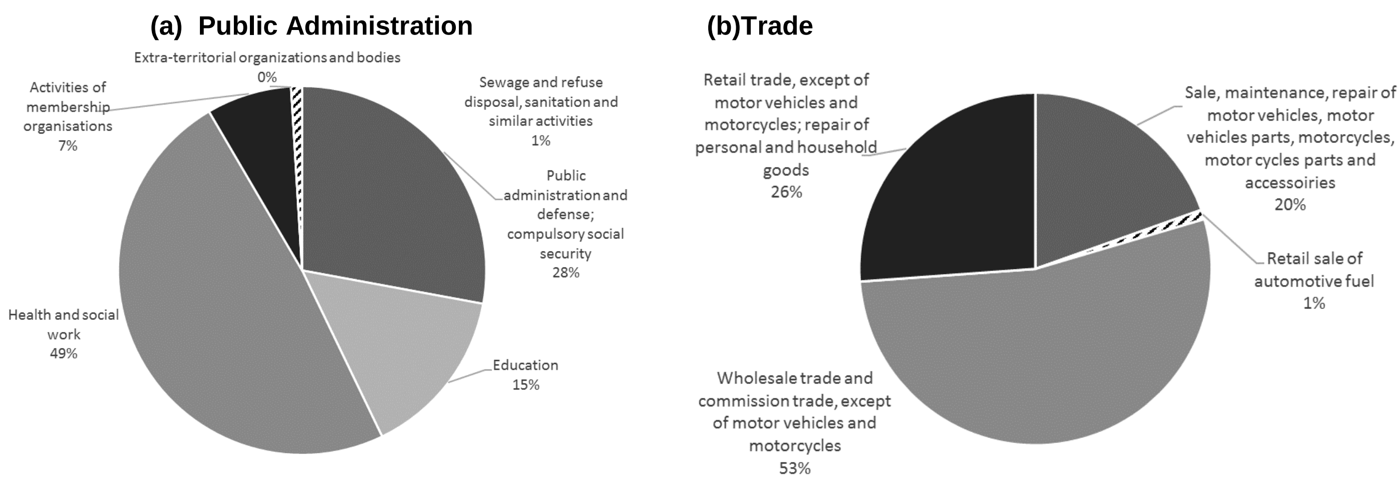


Figure 9: Break down (shares of emissions triggered) for two of the most prominent sectors driving Austria's consumption-based emissions anywhere in the world, using EXIOBASE (base year 2007): (a) public administration and (b) trade.

3.3.2. Source Sectors

Tracing back Austria's consumption-based emissions to the sectors releasing these GHG emissions across the world, 30 percent (30.4 Mt-CO2e)[6] originate in the electricity sector of various world regions. An important part of these emissions,12.6 Mt-CO_2e, occur in the electricity sector of the rest of EU-28, followed by Non-EU countries (11.9 Mt-CO_2e). Only about 5.9 Mt-CO_2e take place in Austrian territory. It is worth noting that the electricity sector from a PBA viewpoint emitted 10.6 Mt-CO_2e (see figure 8-b); whilst the emissions emitted worldwide in the electricity sector to support Austria's consumption is almost triple (30.4 Mt-CO_2e), reflecting the important indirect electricity demands induced by Austria. Moreover, looking at the Austrian top-three destination sectors driving GHG emissions (i.e. construction, public administration, and trade), electricity is the most important source sector in terms of emissions release (see Figure 10(a)). For these three sectors, electricity accounts for roughly half of the emissions

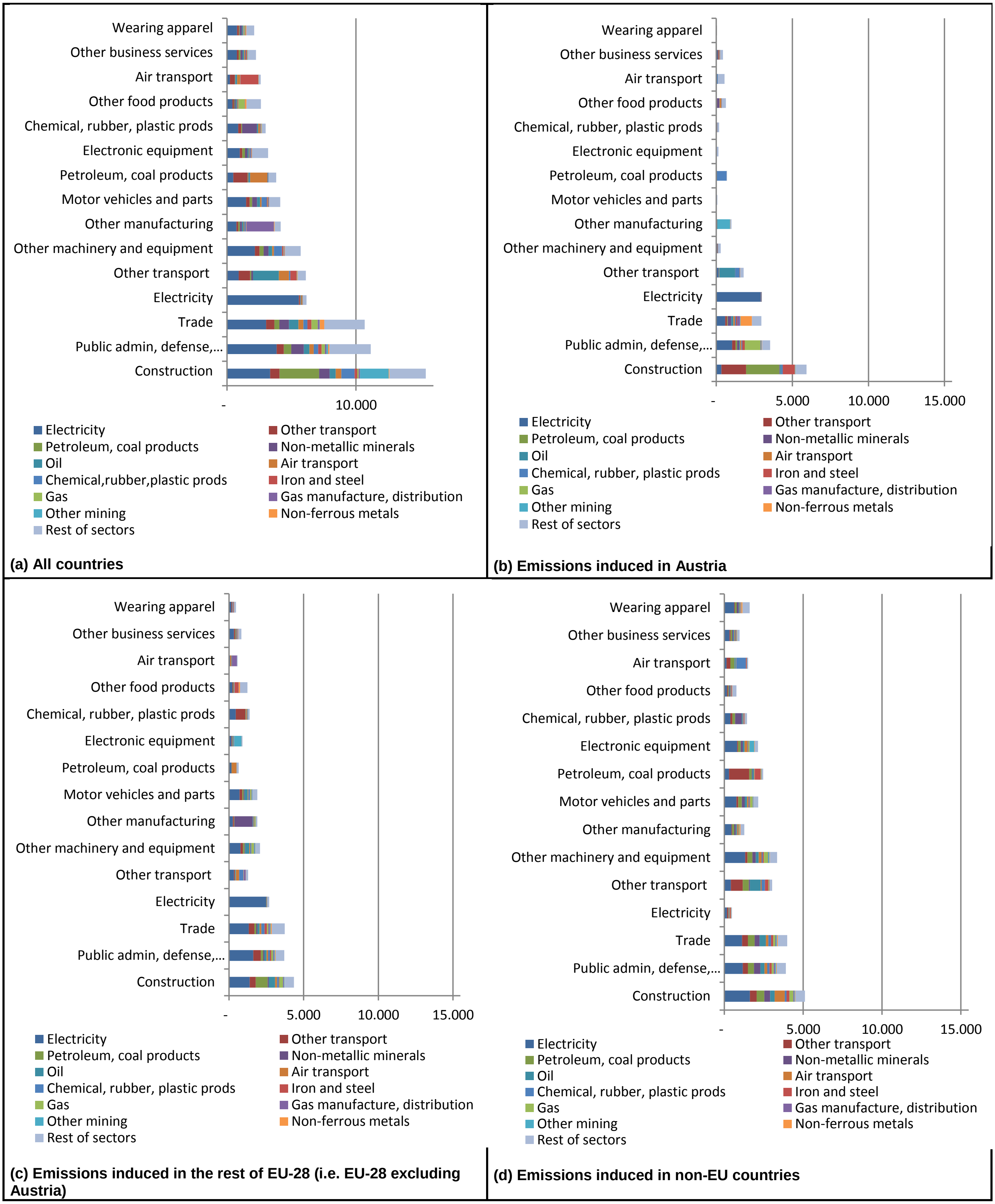
[6] This figure excludes direct emissions from household and international transport.

released in other EU countries (Figure 10(c)), and about a third of the emissions in non-EU countries (Figure 10(d)).

The analysis of the top-15 sectors shows that the structure of the source sectors depend on the destination sector under examination, as this influences to some extent the geographical region where production and hence emissions take place (e.g. Austria, rest of EU-28 or Non-EU countries). If we focus, for example, on Austria's source sectors related to the construction sector, national emissions occur primarily in 'other transport[7]' and the sector 'petroleum and coal products' (Figure 10(b)); whilst the emissions related to the construction sector and released in other EU and non-EU countries primarily take place in the electricity sector (Figures 10(c) and 10(d)). Though 'other transport' and 'petroleum and coal products' thus contribute significantly to total emissions in Austria, the shares that these sectors are accountable for turn out to be substantially different when the focus is on the rest of EU and Non-EU countries.

In contrast, for public administration, the electricity sector plays a significant role as a source sector across all the three regions discussed. Other relevant source sectors – apart from electricity – represent 'gas' in Austria; 'other transport' in the rest of EU; and 'petroleum and coal products', and 'non-metallic minerals' in non-EU countries (Figures 10(b), 10(c) and 10(d)).

[7] 'Other transport' includes activities via road and rail; pipelines; auxiliary transport activities and travel agencies.



(a) All countries

(b) Emissions induced in Austria

(c) Emissions induced in the rest of EU-28 (i.e. EU-28 excluding Austria)

(d) Emissions induced in non-EU countries

Figure 10: Breakdown of the top-15 sectors driving Austria's emissions by affected industry and region.

We take advantage of the high level of resolution in the EXIOBASE also to further understand the most affected sectors (source sectors) across the world due to Austria's consumption. These two sectors are *Electricity* and *Transport*, emitting 30.4 Mt-CO_2e and 6.8 Mt-CO_2e, respectively, worldwide in order to meet Austrian intermediate and final demand. EXIOBASE offers a disaggregation of the Electricity sector into 14 subsectors (see figure 11(a)). As one could intuitively suspect, 'production of electricity by coal' is the subsector releasing most of the emissions - about 70% of total emissions attributed to this sector. This is followed by 'production of electricity by gas' (23%) and 'production of electricity by petroleum and other oil derivatives' (6%). The remaining subsectors within *Electricity* play a minor role.

Regarding the disaggregation of the transport sector, EXIOBASE allows splitting up this sector into seven subsectors. The two subsectors most affected by Austrian consumption are 'air transport' (37%), and 'sea and coastal water transport' (26%). The remaining subsectors, including land transport, are illustrated in Figure 11(b).

(a) Electricity **(b)Transport**

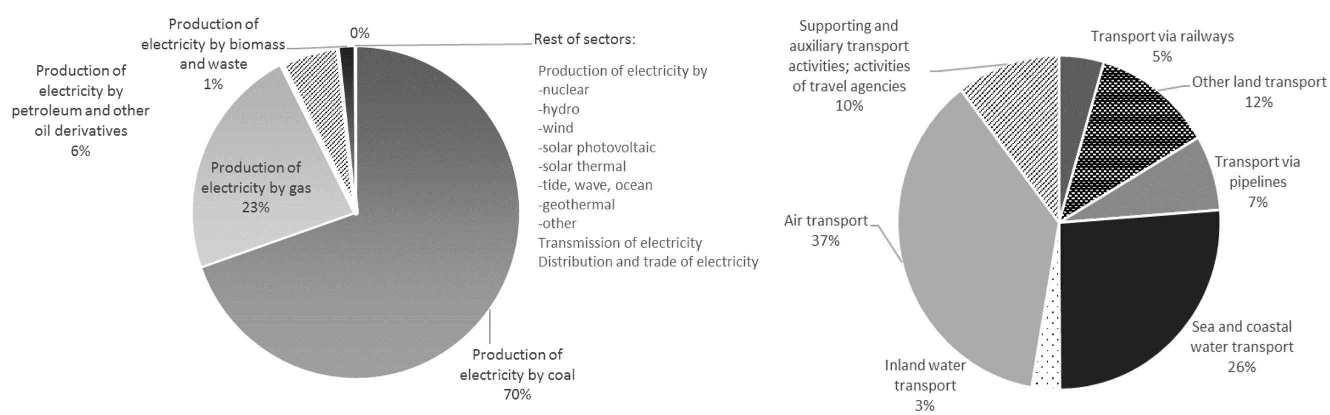


Figure 11: Break down (shares of emissions triggered) in the two sectors globally most affected by Austrian consumption using EXIOBASE (base year 2007): (a) Electricity and (b) Transport.

4. Policy insights

The empirical analysis of consumption-based GHG emissions, using the exemplifying case of Austrian emissions by source and destination sectors and by geographical regions, has revealed the following.

1. Emitting sectors that policies are advised to focus on differ by accounting principle

The sectors with the highest absolute amounts of emissions – that a country may prioritize to reduce – these can be completely different sectors that gain our attention under the consumption-based emission perspective than under the production-based one.

For the case of Austria, the top-three sectors are completely different under the consumption-based perspective (construction, public administration (including defence, health and education), and retail and wholesale trade), than the top sectors under the production-based perspective (electricity, iron and steel, and non-metallic minerals, such as cement). This clearly indicates that the consumption-based emission perspective identifies core further policy areas that need to be addressed – complementary to those derived from the standard production-based analyses – if an industrialized country such as Austria seeks to effectively reduce *global* emissions.

2. Effective policy approaches and instruments differ across sectors as they need to address different geographical source regions

The consumption-based emission analysis identifies the shares that emission source regions have in global supply chains, from predominantly domestic up to almost exclusively international, and given this result, how the type of policy has to change accordingly to be effective in emission reduction, i.e. whether a production-based policy approach can be effective, or whether a consumption-based policy approach is required.

For Austria, to address consumption-based emissions of a sector with predominantly domestic emissions, e.g. the construction sector, both types of policies can be considered. The traditional production oriented policy instruments (focusing on reducing territorial emissions) could reduce consumption-based emissions pretty well, as emissions induced by Austrian construction occur almost exclusively within Austrian borders, albeit due to the activity in a range of different sectors. But also instruments addressing final consumption would work, e.g. shifting construction investment to wooden buildings. The situation is very different for other sectors, e.g. electronic equipment, where the analysis shows that emissions are mainly occurring abroad. This implies that within a country such as Austria for addressing these emissions only consumption-oriented policy instruments, such as ecolabeling (e.g. based on the carbon footprint of the whole supply chain of the product) will be able to address global emission reduction.

Structural Path Analysis (SPA) can inform policy choice more specifically (Peters and Hertwich 2006), as it facilitates for a specific destination sector a detailed breakdown of the size as well as the sectoral and geographical locus of the emissions induced, thus identifying high-emission pathways in the upstream stages (tiers) of the supply chain. As indicated in section 3, the structure of source emission sectors across world regions depends on the destination sector under analysis. We exemplify this tool of a structural path analysis in the following for the construction and electronic equipment sectors, given their different characteristics in terms of source sectors and regions.

Figure 12 illustrates the supply-chain emissions embodied in Austria's construction sector (15,4 Mt-CO2e), where at the first tier 96 percent of emissions relate to the national construction sector, leaving the remaining 4 percent of emissions to activities of construction sectors abroad. The Austrian construction sector has 85 percent of its emissions coming from indirect sources, although direct emission from this sector (denoted by • in Figure 12) is the largest hotspot of emissions in this SPA (about 2 Mt occur directly in the construction sector). The emission number denoted by Σ is the total of emissions at the respective tier, acknowledging both direct and all upstream emissions. The Austrian construction sector is heavily dependent on inputs from other sectors, such as raw materials (metals, minerals), electricity and machinery & equipment. Around 14 percent of total emissions come from the domestic non-metallic minerals sector (which is mostly cement), which is also the second largest hotspot (the ranking of hotspots is indicated in Figure 12 by respective numbering in red circles). Roughly 60 percent of the emissions in the non-metallic minerals sector are direct emissions, where the rest is from other mining (e.g. metal ores), transport and electricity. The third emission hotspot is the construction sectors' use of other mining, which is itself dependent on electricity. Around 3 percent of the emissions from Austria's construction sector come from the German non-metallic minerals sector, which relies on the local sectors regarding inputs. Overall, the construction sector contributes to a large extent to Austria's national consumption-based emissions, where more than 4 percent of Austria's emissions comes from the construction sector tier 1.

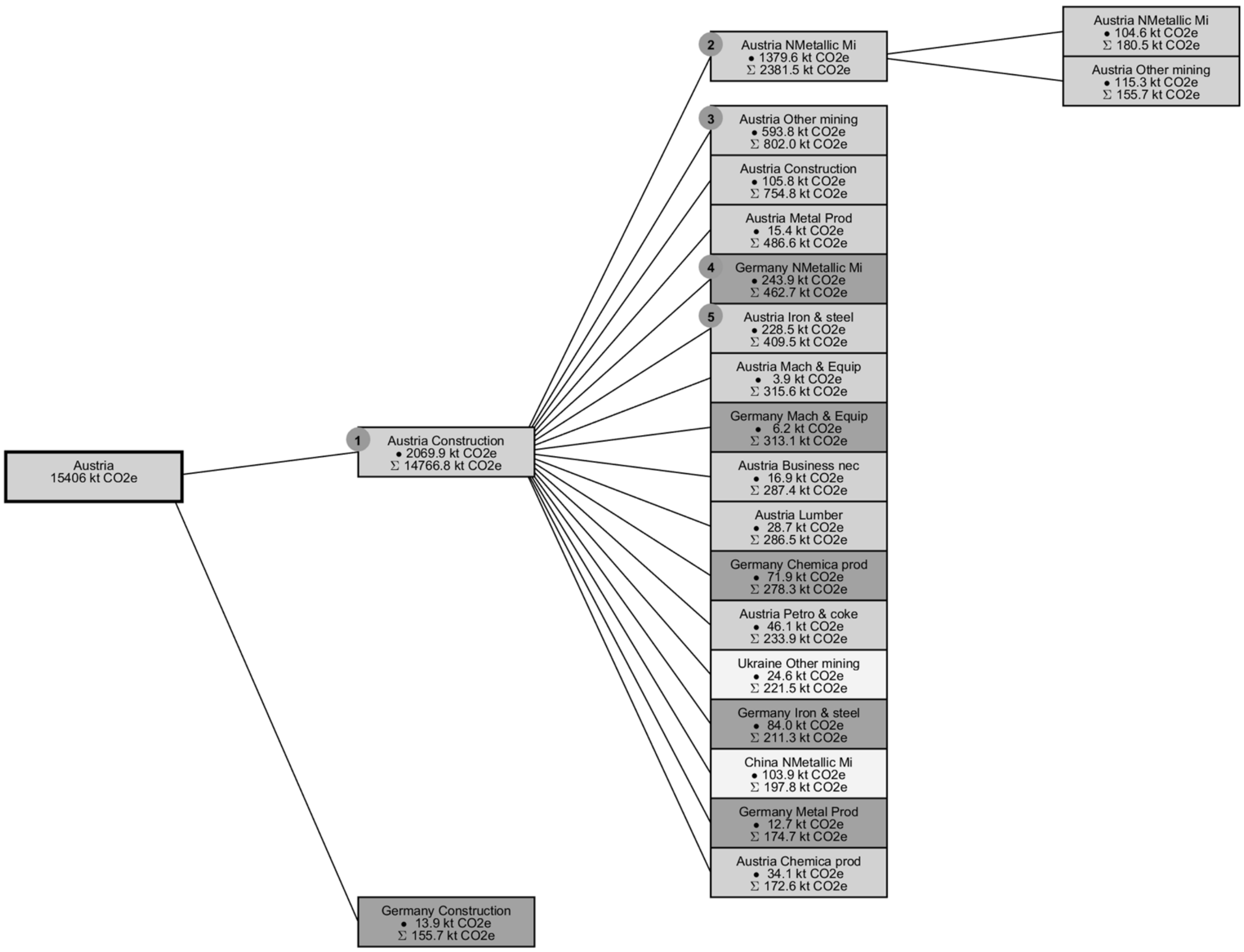


Figure 12: SPA for Austrian consumption of construction in 2011. The leftmost box depicts Austria's total consumption-based emissions in construction. Boxes are coloured to distinguish domestic, rest of EU (darker) and non-EU regions (brighter), while the numbers in the red circles highlight the top five hotspots (single points in the supply chain where the direct emissions are largest). Boxes are ordered top to bottom from high to low total supply-chain emissions. The numbers in the boxes are direct emissions (•) and supply-chain emissions (Σ; sum of direct and upstream emissions). The figure includes only sectors by country responsible for at least 1% of total sectoral consumption-based GHG emissions.

Conversely, a large part of electronic equipment is not manufactured in Austria and requires many production steps leading to large indirect emissions upstream. Most of the emissions (94%) come from electronic equipment sectors in other regions, such as China, Germany and Slovakia (Figure 13). Nested nodes such as the Chinese electronic equipment sector buying from the same sector show the effect of aggregation of different industries into sectors. Figure 13 indicates that for electronic equipment supplied to Austrian final consumption hardly any emission occurs within Austria (denoted by the medium intensely colored boxes; 117 kg CO2e out of the total 3190 kg CO2e per 1.000 € production value; i.e. 3.7%), some emissions occur in the rest of the EU (high intense colored boxes; about 295 kg CO_2e direct emissions, or 9.2%) and the largest share occurring outside the EU (at least 40%).

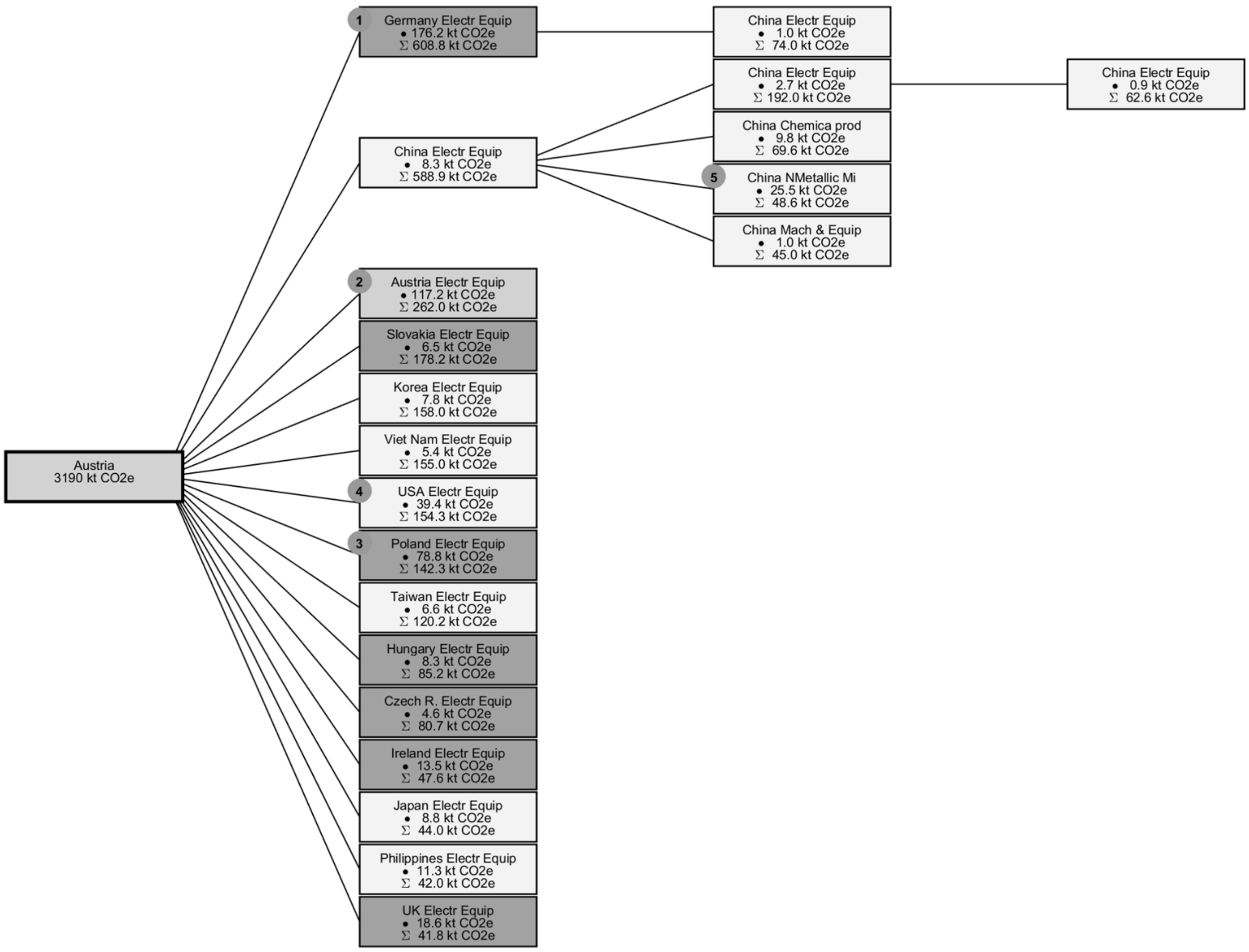


Figure 13: SPA for Austrian consumption of electronic equipment in 2011. The leftmost box is Austria's total consumption-based emissions in the electronic equipment sector. Boxes are coloured to distinguish domestic, rest of EU (darker) and non-EU regions (brighter), while the red badges highlight the top five hotspots (single points in the supply chain where the direct emissions are largest). Boxes are ordered top to bottom from high to low total supply-chain emissions. The numbers in the boxes are direct emissions (•) and supply-chain emissions (Σ; sum of direct and upstream emissions). The figure includes only sectors by country responsible for at least 1% of total sectoral consumption-based emissions.

3. For policies inducing demand shift, marginal emission intensities are to be acknowledged

Analysing CBA emission *intensities* by destination sector allows understanding the sectoral direct and indirect emissions induced by a marginal change in the final demand of a specific sector (all other things held constant). Such information is of high relevance if the climate policy context is one that works via a shift in demand to other sectors. Consumption-oriented policy instruments may mostly be able to induce relatively small changes in, for example, the quantities demanded of a destination sector. While policy measures are hardly able to completely remove the total demand of a hotspot sector and its underlying emissions from the economy, they can well bring about changes at the margin. Within this category of demand shifting policies it may be more cost-effective to carry out CBA policies on the basis of intensities (emissions per unit of final demand) than tackling the hotspots based on the absolute CBA emissions level.

Figure 14 illustrates Austria's sectoral CBA intensities for: i) the five sectors with the highest CBA intensities; ii) the five sectors with the highest intensities from the PBA perspective; and iii) the CBA intensities for the top five hotspot destination sectors identified in the previous sections (note that electricity is already included in group 'i'). Results show that four out of the top five sectors presenting the highest intensities are the same for CBA intensities and PBA intensities in the year 2011 (Figure 14). These sectors are: 'iron and steel', 'metals', 'electricity', and non-metallic minerals'*.* It is worth remarking that CBA intensities are in general higher than those of PBA. In the iron and steel sector, for instance, CBA intensity is 65 percent higher than the PBA intensity in the same sector. 1000 € spent in this sector would translate into 1.14 t-CO_2e from the CBA perspective; while the PBA intensity would report an emissions level of 0.69 t-CO_2e per € 1000 spent (Figure 14).

Regarding the CBA intensities for the hotspot sectors, Figure 14 shows that shifting equal levels of purchasing power away from hot spot sectors would be less emission effective in e.g. the construction sector, as it would mean a reduction in emissions of "only" 0.27 t-CO_2e per 1000 €, while an equivalent decrease in the final demand of the iron and steel sector would imply a reduction of at least three times more emissions (1.14 t-CO_2e). On the other hand, the demand of the public administration sector would have to be reduced about ten times in order to achieve emission reductions in a similar order as in the Iron and Steel sector. As a hotspot, however, public administration would still have higher emissions due to the fact that the total final demand of this sector outweighs that of the iron and steel sector by several times.

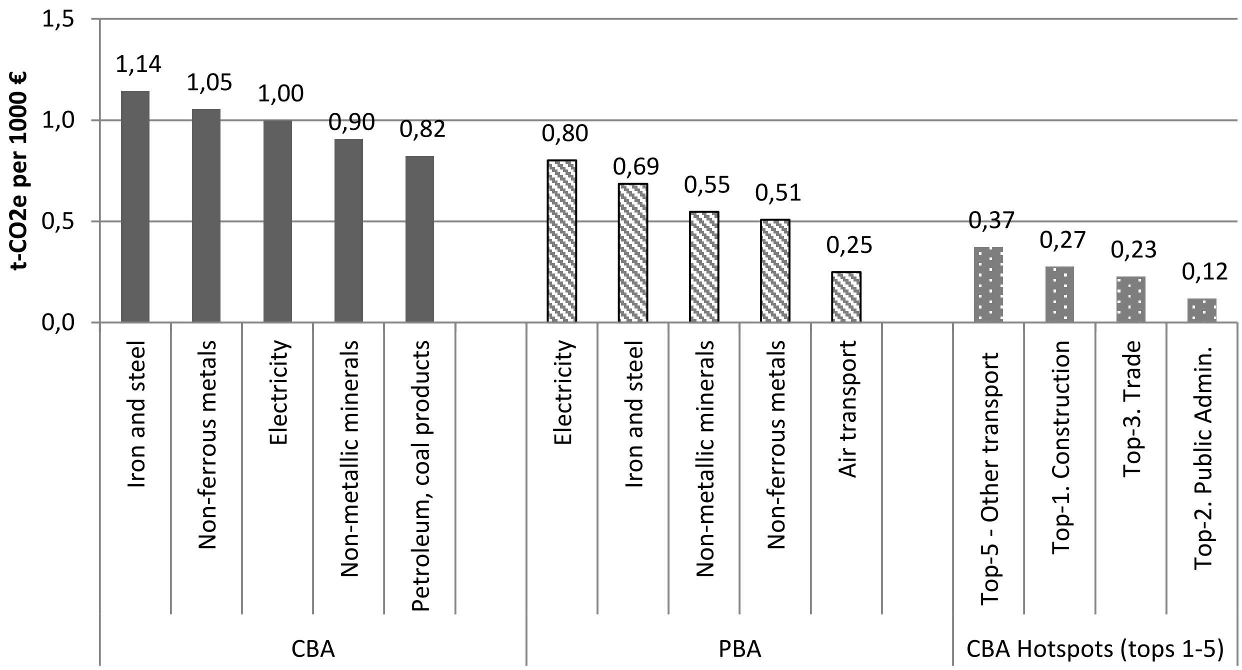


Figure 14: GHG emission intensities from CBA and PBA for the top-5 sectors in Austria (year 2011).

5. Reflection and conclusions

The present analysis is oriented toward understanding the emission profile of an industrialized country, Austria in this case, from a consumption-based accounting perspective. This is particularly relevant due to the increasing spatial separation between production and consumption activities resulting from globalization, and the divergence of climate policy efforts as indicated by the NDCs to greenhouse gas mitigation set in the Paris Agreement. Findings reveal that the emissions needed to sustain Austria's consumption are about 50% larger than those reported by the conventional production-based accounting system.

The Austrian demand sectors responsible for Austria´s consumption-based emissions are different than those identified when just focusing on Austrian production-based emissions, indicating that focusing also on global emission implications suggests a different sectoral focus. For consumption-based emissions it is Construction, Public administration and Trade that account for a share of 31% of total consumption-based emissions of Austria which were induced globally, i.e. emissions occurring within Austria and abroad that are triggered by Austrian final demand. From a production perspective these sectors account for only less than 8% of Austrian emissions.

Further, while more than one third of Austrian consumption-based emissions are triggered to occur outside EU-28 borders, the single most relevant sector that these emissions occur at these locations abroad is electricity. For the above top-3-emission sectors (Construction, Public administration and Trade) the share of electricity emissions is roughly a third in overall embodied emissions traded across the borders of these countries.

We thus find that climate policy, when followed in a setting of Nationally Determined Contributions (as set forth in the Paris Climate Agreement) in order to be globally effective does need to also focus on further demand sectors, that would not come to one´s mind first when following a production-based perspective. The analysis presented here further allows to distinguish for those ´new´ hotspot sectors whether in principle a national policy along traditional production-based policy instruments can be effective in global emission reduction or not. In particular, structural path analysis reveals that when emissions are dominating that ultimately occur within the national territory – albeit in other sectors – it can be effective (for Austria the example is construction), while effective emission reduction in sectors that are dominated by embodied emissions imported from abroad requires a complementary consumption-based approach (for Austria the example is electronic equipment).

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Supplementary Information

GHGs overview

Austria has had territorial GHG emissions in the range from 77 Mt CO_2e in 1995 to a peak in 2005 at 87 Mt CO_2e, which declined to 76 Mt CO_2e in 2009. This includes CO_2, CH_4 and N_2O, using the World Input-Output Database (WIOD; Figure A.1), with the GTAP-TSTRD method only available for CO_2 (see Figure A.2). The territorial emissions include emissions occurring within the administrative boundaries of Austria, which includes goods and services destined for export. On the other hand, consumption-based emissions exclude exports but include imports. The consumption-based emissions have been nearly 60% higher than territorial emissions over the period, which is the highest of any EU27 countries apart for Luxembourg, which has 74% higher consumption emissions than territorial emissions. This means that Austria has been a net importer of emissions embodied in products and services throughout the period, with the average from 1995 to 2009 being around 48 Mt CO_2/year, and remaining relatively constant. Using the metric GWP to compare the pollutants with parameters from IPCC's fourth assessment report (AR4), CO_2 is dominating with 78% of the emissions, followed by CH_4 at 12% and N_2O at 10%.

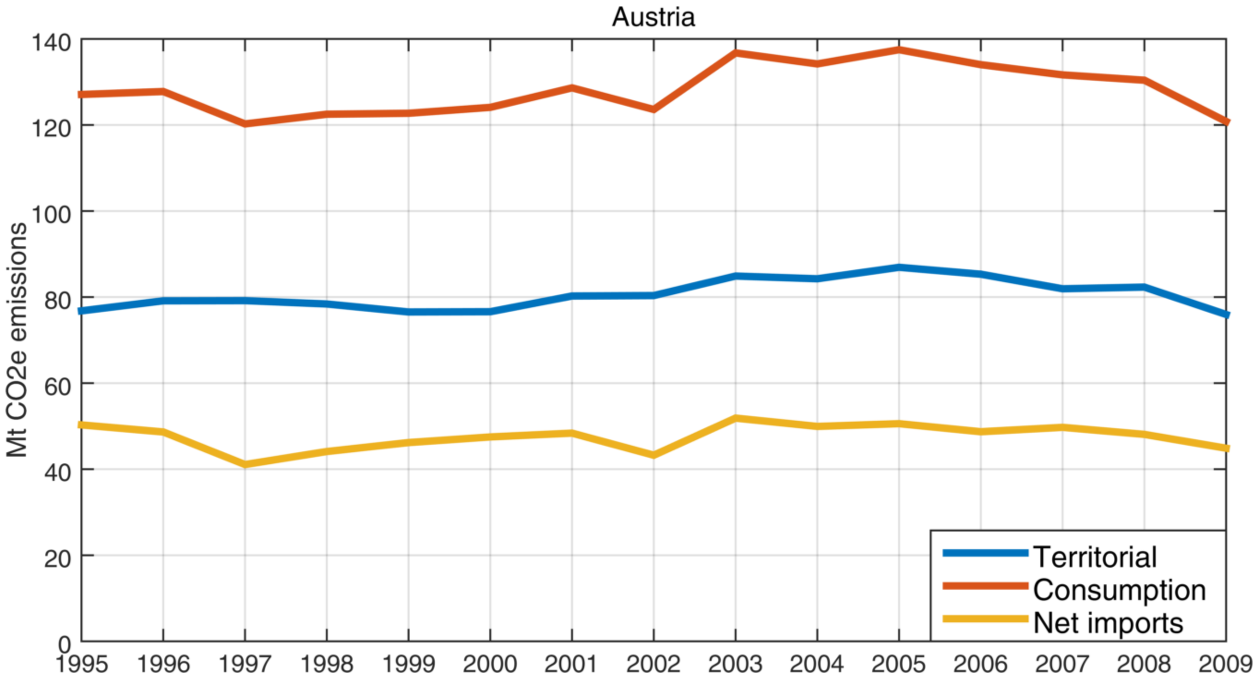

Figure A.1: Austria's greenhouse gas emissions from both production and consumption perspectives, 1995-2009 (GHGs: CO_2, CH_4, N_2O). Source: WIOD, own calculations.

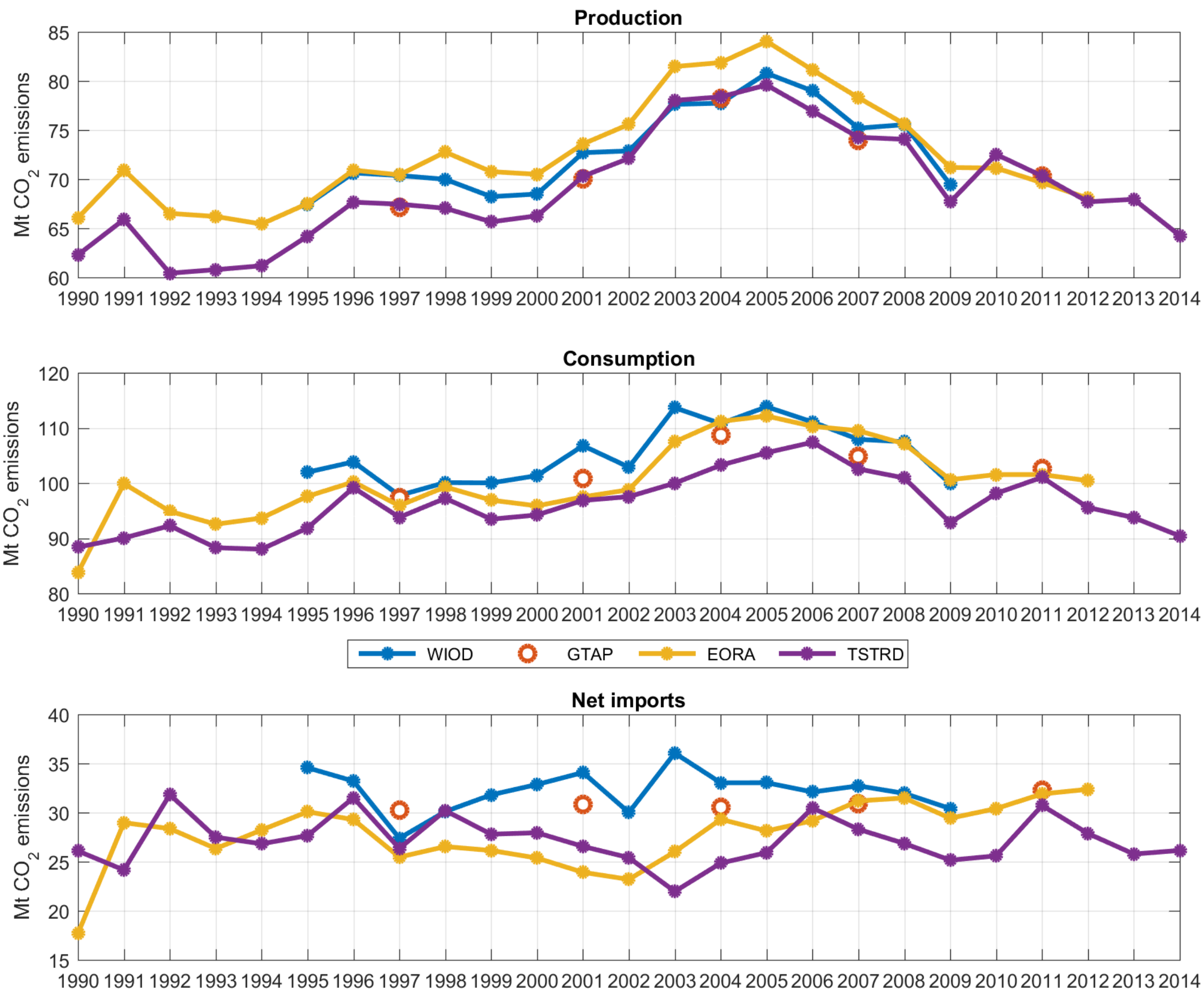

Figure A.2: Austria's CO_2 emissions from multiple datasets, as production emissions (top), consumption-based emissions (middle) and as net imports (bottom). Sources: WIOD, GTAP, EORA, TSTRD, own calculations.