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Greenhouse gas emission accounting behind consumed products in Austria –

Principles, challenges and results of an LCA- and supply chain-based approach for consumption-based emission accounting

Cumulative dissertation to obtain the doctoral degree

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Thank you!

EIDESSTAATLICHE ERKLÄRUNG

Ich erkläre eidesstattlich, dass ich die Arbeit selbständig angefertigt habe. Es wurden keine anderen als die angegebenen Hilfsmittel benutzt. Die aus fremden Quellen direkt oder indirekt übernommenen Formulierungen und Gedanken sind als solche kenntlich gemacht. Diese schriftliche Arbeit wurde noch an keiner Stelle vorgelegt.

ABSTRACT

The knowledge of the sources behind climate impacts is one prerequisite for achieving ambitious climate targets. The greenhouse gas emissions (GHG) therefore have to be traced, regardless if they are induced by domestic activities or consumption of imported goods by international trade. Actually, there exist economic input-output models, which in principle allow such an accounting, but they are limited by the high sector aggregation level and the calculation of GHG-emissions based on monetary data. In this context, the need for a consumption-based emission accounting approach on product-level based on physical material flows has increased recently in the scientific community. In the course of this work a methodology, which allows the accounting of GHGs induced by national consumption of products, was developed and applied for Austria. This approach uses a low aggregation level for investigating the industrial supply chains of products. The origin-specific material flows of domestically produced, imported and exported goods are illustrated along the supply chain from the raw material up to the final product. These material flows are further combined with life cycle-based emission factors to calculate the GHG-emissions on the level of single products. Furthermore, the technology standard of energy supply in the respective country of origin was considered as well. Consequently, this approach shall help to identify the most emission intensive products and the most relevant process steps, regardless if they are domestic activities or occur abroad. The national differentiation of emission intensities further enables the illustration of effects as carbon leakage. Although the method allows calculation of GHG-emission on product level, uncertainties and challenges remain for future research. One essential aspect is the inclusion of processes behind imports (truncated picture of imports), which is one main strength of input-output models.

KURZFASSUNG

Die nationalen Treibhausgas (THG)-emissionen werden derzeit nach einem territorialen Ansatz bilanziert, wonach sämtliche Aktivitäten in einem Land berücksichtigt werden, Auswirkungen im Ausland (Importe und Exporte) allerdings nicht miteinbezogen. Dadurch können die Klimaeffekte hinter dem Konsum eines Landes nur bedingt abgebildet werden. In Zeiten zunehmender Globalisierung ist der Bedarf nach einer konsumbasierten THG-Bilanzierung immer lauter geworden und es sind diesbezüglich bereits Methoden entwickelt worden (z.B. Input-Output Modelle). Um jedoch ernsthaften Klimaschutz auf globaler Ebene betreiben zu können, bedarf es einer grenzübergreifenden Betrachtung und einer Identifikation der konkreten Verursacher von THG-Emissionen, um zielgerichtete Maßnahmen entwickeln zu können. Die bisherigen Methoden zeigten zwar die Klimabelastungen hinter dem Konsum eines Landes, werden aber in einem hohem Aggregationsgrad auf sektoraler Ebene auf Basis monetärer Daten durchgeführt, wodurch keine produktspezifischen Informationen verfügbar sind. Im Zuge dieser Arbeit wurde eine Methode entwickelt und für Österreich angewendet, welche die THG-Emissionen hinter dem Konsum von Produkten betrachtet. Dafür wird ein materialfluss- und lebenszyklusbasierter Ansatz entwickelt, bei dem die inländische Herstellung von Produkten mit Importen und Exporten verbunden werden. Die physischen Materialflüsse werden mit produktspezifischen und lebenszyklusbasierten (LCA) Emissionsfaktoren sowie technologischen Faktoren der Branchen und Länder verknüpft, um daraus die THG-Emissionen inklusive deren Herkunft für jedes Produkt berechnen zu können. Die Ergebnisse sollen die Ableitung der klimaintensivsten Materialien und Produkte sowie deren regionale Herkunft ermöglichen, um daraus zielgerichtete THG-Reduktionsmaßnahmen zu entwickeln. Trotzdem benötigt die Methode weitere Optimierungen, speziell um vorhandene Unsicherheiten (z.B. Vorketten hinter Importen) verringern zu können.

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1 RESEARCH FRAMEWORK OF THE THESIS

This thesis is composed as a cumulative work. Thus, the research framework consists of two published articles mainly, which are further embedded and discussed into the scientific context. In more detail, an “Introduction” (chapter 2) gives a broad overview of the actual topic and its relevance and importance for the scientific community as well as political decision makers. This chapter ends with open issues, which have not been solved up to now and will be addressed in the course of this thesis. The specific “Research objectives” are therefore explained in chapter 3.

The main emphasis of this thesis, however is the results section, which is illustrated by the two articles (chapter 4 and chapter 5). Both articles address the mentioned research objectives, whereas the first article is merely focused on an encompassing analysis of the research demand and the description of the key challenges and how to address them. Based on the results of the first article, the main emphasis of the second article is the presentation of a new method that allows handling the key challenges and research questions, mentioned in chapter 3. To guarantee a smooth connection between both articles and to fulfil the criteria of a cumulative work, a short overview of the main contents will introduce the respective article and the main results of the article will be summarized afterwards to embed it into the whole framework of this work.

As a last step, chapter 6 discusses the results of both articles in the relevant scientific context, including possible uncertainties and future research needs. Finally, recommendations will be derived out of previous results.

2 INTRODUCTION

The adoption of the Sustainable Development Goals (SDGs) by all member states of the United Nations (UN), in 2015, was a breakthrough and milestone, as all great challenges were addressed in one central agenda. The SDGs consist of 17 thematic areas, visible in Figure 1, with 169 targets and 213 measurable indicators. They cover various ecological, economic and social challenges and foster global partnerships and peace as well (Eurostat 2020).

Figure 1: Overview of the 17 Sustainable Development Goals (SDG) (Eurostat 2020, (United Nations Development Programme https://www.undp.org/sustainable-development-goals)

Climate change as one of the most severe ecological problems, mankind is currently facing, is identified as SDG 13 – Climate Action, as seen in Figure 1. The United Nations (2020) emphasize the dramatical future if an encompassing transformation towards a climate neutral world does not start immediately, as emphasized in Rogelj et al. (2016) as well. Figure 2 shows the widespread impacts attributed to climate change. Of course, the magnitude of impacts varies depending on the geographical situation as well as the current framework conditions. As an example, in Europe the impact on food production is of minor importance, but it may have a large impact in Central and South America and Africa.

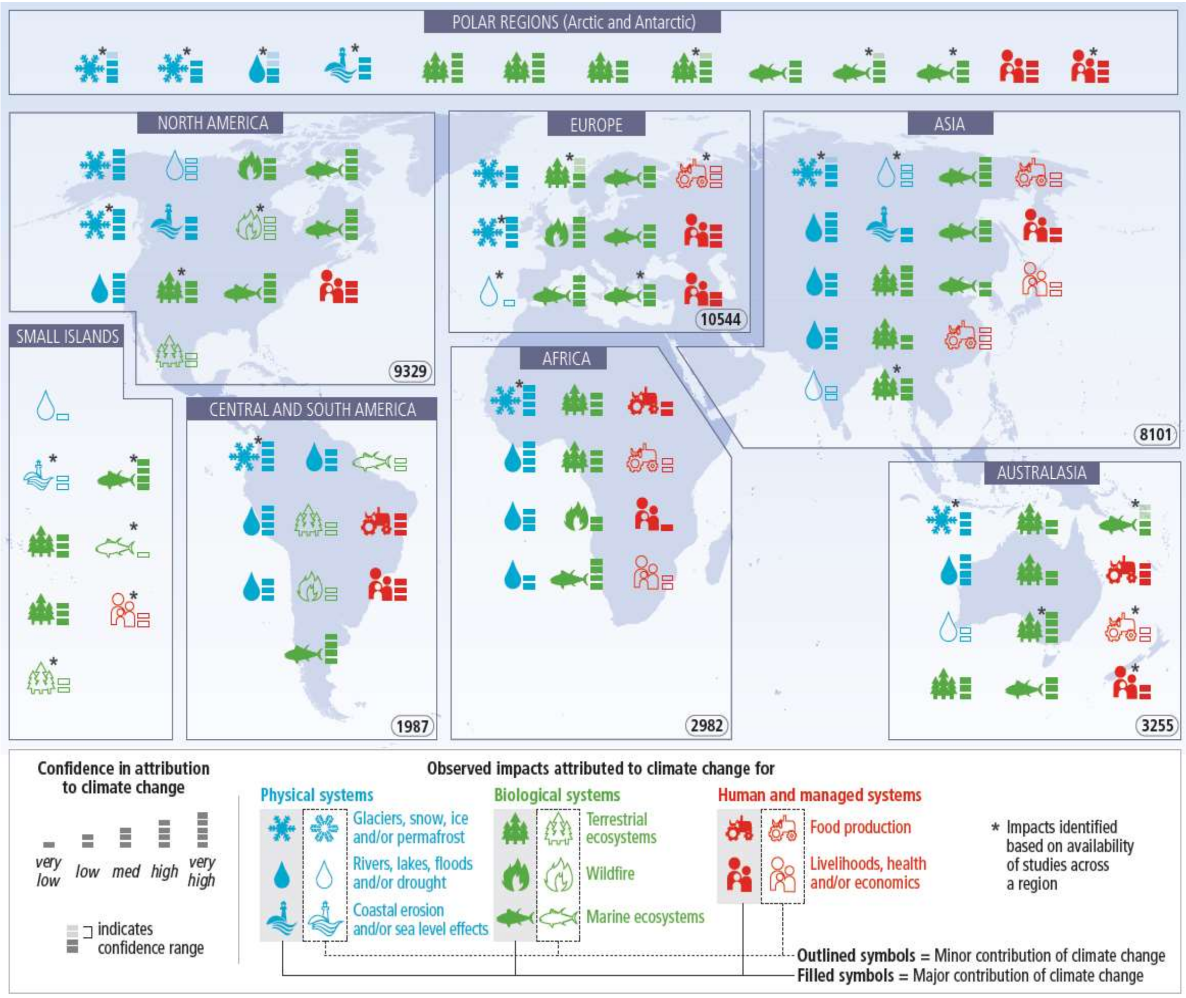

Figure 2: Widespread impacts attributed to climate change (IPCC 2014)

Rogelj et al. (2016) confirm that the global temperature increase can only be kept below 2°C or 1.5°C, if such a transformation process along our whole economy will be realized. The need to take climate protection seriously is strengthened by the Paris Agreement, which was an unprecedented breakthrough from the COP 21 (the 21st Conference of Parties) in Paris in December 2015. All states agreed to limit the temperature increase to 1.5°C (above pre-industrial levels) (Maurer et al. 2016).

Meanwhile, the IPCC (2014) confirmed in its latest progress report that anthropogenic activities may be responsible for more than the half of the observed temperature increase. Thus, climate impacts are mainly a consequence of our current lifestyle and consumption patterns. Figure 3 shows that greenhouse gas emissions (GHGs) result mainly from burning fossil energy, currently the dominant energy resource, as well as industrial processes. Furthermore, it is clear that the emissions have increased dramatically from 1970 onwards.

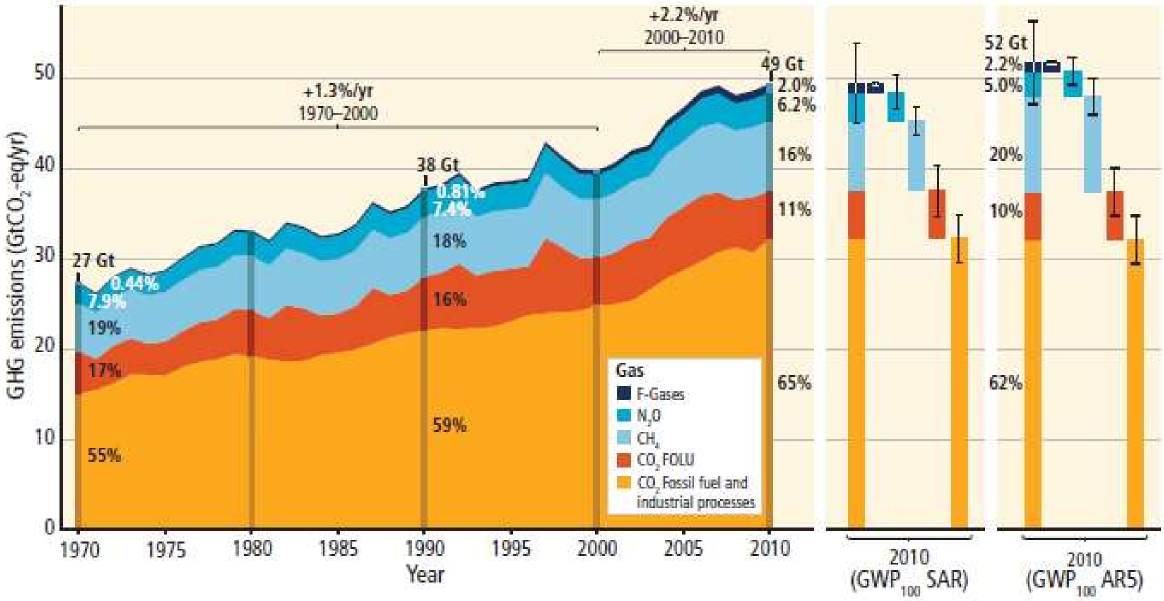

Figure 3: Total annual anthropogenic GHG emissions from 1970-2010 (IPCC 2014)

When looking at the sectors responsible for the globally increasing greenhouse gas emissions, electricity and heat production are responsible for 25% of the total GHG emissions, followed by agriculture, forestry and other land use (AFOLU) and industry (see Figure 4). In this context greenhouse gas emissions are distributed into direct and indirect emissions. According to Hertwich et al. (2008) direct emissions are an output of a specific activity (e.g. burning fossil energy) and indirect emissions are associated with the whole supply chain activities (e.g. provision of electricity or fossil energy carrier).

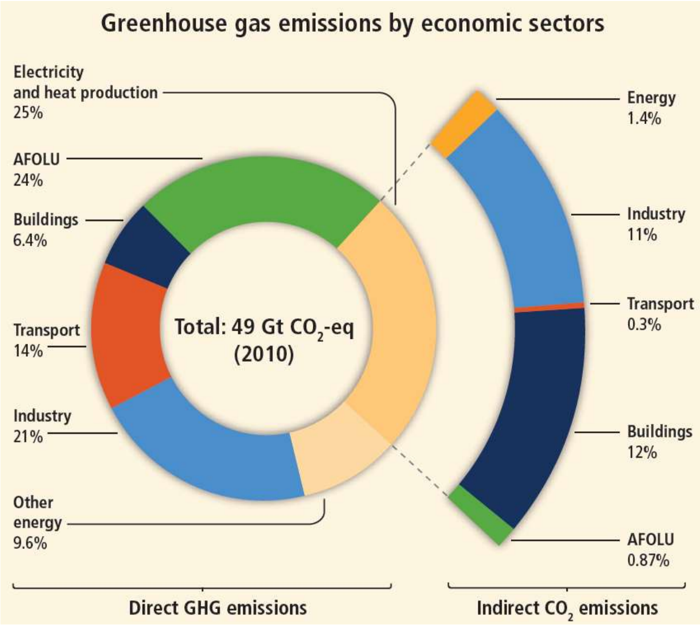

Figure 4: Greenhouse gas emissions distributed to economic sectors and distinguished between direct and indirect emissions for the year 2010 (IPCC 2014)

For achieving an encompassing transformation towards a low-carbon society every country has to implement comprehensive strategies to reduce its greenhouse gas emissions. Thus, detailed information and knowledge behind the drivers and the origin of greenhouse gas emissions are necessary to design appropriate strategies to reduce them finally at global level. Based on this information, every country could implement suitable measures and policies to reduce greenhouse gas emissions.

Meanwhile most countries conduct greenhouse gas emission inventories on national level. This type of a national GHG balance is an activity-based approach, which focuses on domestic production and on national boundaries (direct emissions). Impacts in foreign countries induced by international trade (e.g. import) are not considered wherefore the total climate effects behind the real consumption of goods are not visible. It is difficult, therefore, to develop a comprehensive national strategy for global climate protection as essential climate effects of traded goods and products as well as the associated supply chains are not considered (indirect emissions). As climate change is a global challenge, it is not enough to focus only on national boundaries as this favors the outsourcing of energy intensive production to countries with low technical standards and weak climate regulation followed by increasing imports of these products, so called carbon leakage (e.g. Sato 2012a).

In times of globalization a country's consumption mainly depends on imports and exports besides national production. Thus, consumption-based emissions are caused by a country's population, no matter where in the world these emissions are actually released. From this perspective, new modes of action to reduce global emissions can be developed. To summarize, the system boundaries between production and consumption-based perspectives differ especially concerning the impacts induced by international trade. Emissions from domestic production and exports are called production perspective, domestic activities and imports are included for a consumption perspective (see Figure 5).

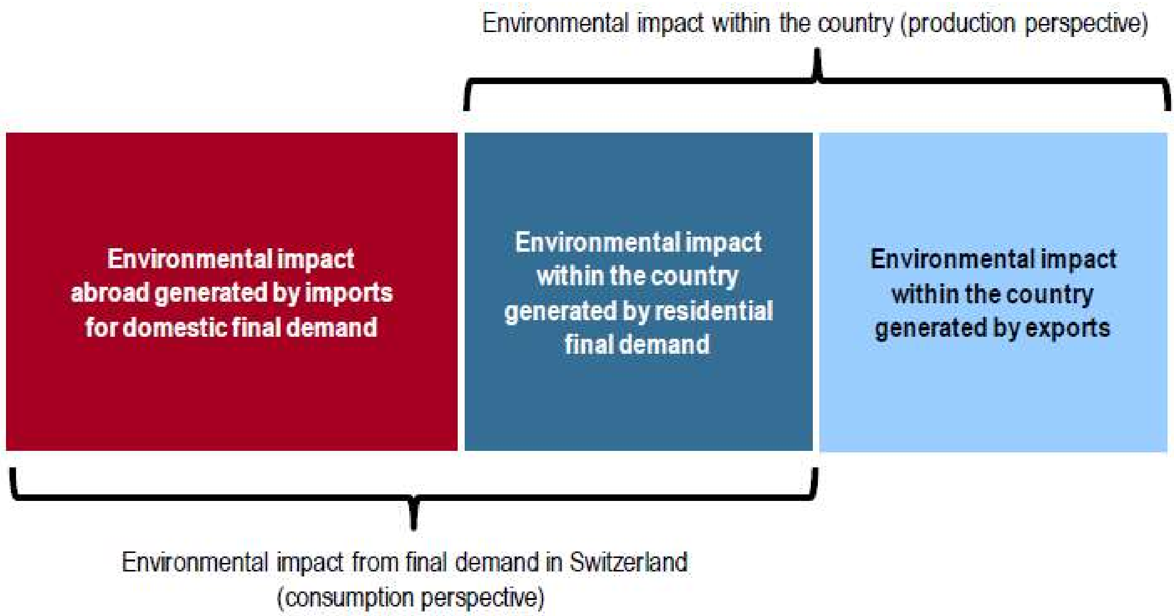

Figure 5: System boundaries of consumption- and production-based perspectives (Jungbluth et al. 2011)

Consequently, direct emissions released by the use of products and services (e.g. driving a car, heating a building) are actually of main concern for national climate mitigation strategies, as these emissions from a production-based perspective are addressed by the obligatory Paris Agreement, as mentioned before. However, climate change is a global challenge and it is not enough to focus on national activities to reduce emissions. Thus, cross-border effects along the supply chains of products have to be taken into account as well (indirect emissions), especially in times of globalization where international trade has become of increasing importance.

Therefore consumption-based emission accounting has evolved in recent years addressing imports and exports besides national activities (e.g. Bruckner et al. 2009, Munoz and Steininger 2010). For tackling climate change on global scale, it is further necessary to encompass the whole supply chains behind the products and services on detailed product-level to respect the diversity of products as well. Thus, to achieve GHG reductions at a global level, one must look at all direct and indirect emissions and ways how to reduce them along the whole life cycle of products consumed in a country.

3 RESEARCH OBJECTIVES

The aim of this work is to develop and apply a methodology for accounting greenhouse gas emissions behind the domestic consumption of products in Austria. This method shall therefore encompass all products consumed in Austria, comprising domestically produced as well as imported goods and products.

It is further foreseen to analyze the whole supply chains from raw materials up to the final products to enable a life cycle perspective. This kind of perspective shall allow the inclusion of all relevant impacts on the one hand, and the possibility to get information about the most emission-intensive process steps along the life cycle of products on the other hand.

Furthermore, this work aims at calculating the emissions at the origin of products correctly by adaption of the emission factors due to the situation of energy provision in the respective country. This kind of national information shall illustrate the share of imports on the country´s climate balance as well as the most relevant trading partners and their respective emission intensity in producing goods. The latter can also be used in terms of quantifying climate protection measures such as climate friendly procurement.

As a result, a feasible and transparent procedure for calculating origin-specific greenhouse gas emissions based on physical material flows from raw materials up to the final product will be derived. This shall allow the identification of the most climate and material intensive products as well as the most relevant processes within one supply chain, considering the contribution of imports and exports compared with national production for every manufacturing process throughout the whole supply chain, whereby effects like “carbon leakage” can be quantified. Therefore, recommendations for reducing the material and emission intensity of such supply chains could be derived.

In more detail, several research objectives will be addressed:

- Is there any demand for consumption-based emission accounting on detailed product level?
- Are existing approaches capable to account for direct and indirect emissions?
- What are the main challenges and possible solutions for implementing an accounting of greenhouse gas emissions induced by national consumption of products?
- Is it possible to develop and apply an integrative approach that enables the accounting of greenhouse gas emissions induced by national consumption of products?

4 ARTICLE 1 - GREENHOUSE GAS EMISSIONS DUE TO NATIONAL PRODUCT CONSUMPTION: FROM DEMAND AND RESEARCH GAPS TO ADDRESSING KEY CHALLENGES

4.1 Introduction and Content

To uncover the main reasons for the increasing greenhouse gas emissions, in order to design the most appropriate measures to reduce them, an encompassing and detailed emission accounting is one prerequisite. As mentioned before, “direct” and “indirect” emissions are often distinguished as they are especially heterogeneous in their release of emissions, e.g. consumer or producer responsibility, and also in their capability to account them.

This article presents an overview of the scientific state of the art concerning the accounting of greenhouse gas emissions in its first section. Thus, this article analyzes existing approaches dealing with an emission accounting for their capability to cover “direct” and “indirect” emissions. The different approaches are therefore investigated for the main characteristics, advantages and limitations.

In a next step, the scientific research demand for consumption-based emission accounting on a detailed product-level is derived by looking at the limitations of the existing approaches on the hand and analyzing the scientific literature on the other hand. This analysis shall emphasize the importance for a detailed investigation of single products. At the same time, the key challenges are elaborated as well, which have impeded such a kind of emission accounting up to now.

In the second part, this article proposes possible methodical solution to overcome the mentioned key challenges of a product-based emission accounting from a consumption-based perspective. Finally, this article tries to go one step further by implementing the proposed solutions for one industrial process chain in Austria.

4.2 Published article

Greenhouse gas emissions due to national product consumption: from demand and research gaps to addressing key challenges

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ORIGINAL PAPER

Greenhouse gas emissions due to national product consumption: from demand and research gaps to addressing key challenges

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Abstract

In recent years, accounting for greenhouse gas emissions due to national consumption has been of increasing interest, as transformative strategies towards a “low-carbon” economy are inevitable to restrict climate change below 2 °C temperature increase. Thus, every country has to implement effective measures to reduce its greenhouse gas emissions at global level by including impacts abroad due to international trade and avoiding the outsourcing of emissions (“carbon leakage”). The sources and origins of emissions should be known to elaborate appropriate emission reduction strategies, requiring a detailed investigation of products in consumption. This article aims at investigating whether an accounting of emissions due to national consumption of products is considered as important and feasible with current methods, what future research gaps are, and how they can be solved by presenting new methodical approaches in the form of life cycle-based physical supply chains. The results have shown that existing methods are based mainly on monetary data at sectoral level, so that a detailed analysis of the national consumption of products is still missing and global effects as “carbon leakage” cannot be identified. Nevertheless, the

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demand for calculating consumption-based greenhouse gas emissions at product level was confirmed in various studies, but is currently seen as too complex and time-consuming. Finally, proposed methodical solutions to address existing research gaps were elaborated and applied exemplarily for the mineral sector in Austria and shall further serve as a kind of guidance how an accounting of emissions due to national consumption of products can be put in practice.

Keywords Carbon leakage · Consumption-based emission accounting · Life cycle analysis · Material flows · Process chain analysis · Product-based approach

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Introduction

Background

Climate change is one of the main challenges of our time, and the major causes for this are the increasing greenhouse gas (GHG) emissions from anthropogenic activities. This dominant human influence was affirmed in the latest progress report of IPCC (2013). In order to tackle climate change and avoid a global temperature increase above the recommended two-degree target (UNFCCC), decisions for climate mitigation measures to be concluded at global level are needed (Peters et al. 2013; Sato 2012). A breakthrough was met with the most actual agreement in Paris in December 2015, where all countries concluded that climate change has to be restricted below 2 °C temperature increase (Liu et al. 2015) and to pursue efforts to limit the temperature increase to 1.5 °C (above pre-industrial levels) (Maurer et al. 2016). To fulfil the Paris Agreement and further climate targets (e.g. EU 2030 climate and energy framework), greenhouse gas emissions will have to decline dramatically in all areas of our society, which requires a comprehensive transformation process (Dawkins and Croft 2017; Sato 2012). One must look at the sources and the origin of greenhouse gas emissions first before thinking about strategies to reduce them. Different types of perspectives and methods are available to account for national emissions. The most frequently applied approach is to consider activities occurring within national boundaries (production-based approach, applied in national emission inventories). Thus, exports are accounted for, but impacts induced by imports are not included, as shown in Fig. 1.

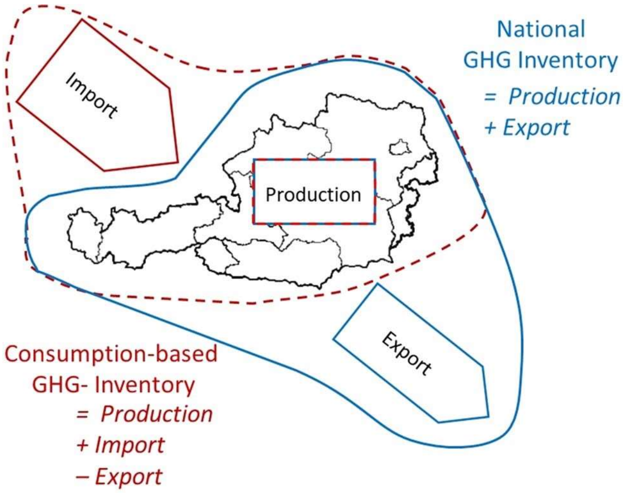

Fig. 1 System boundaries for the national GHG inventory and the consumption-based GHG inventory

For a serious climate protection at global level, it is important to extend system boundaries beyond national territories, otherwise outsourcing of energy-intensive production to countries with low technical standard and weak climate regulation will be disregarded ("carbon leakage"). Such outsourcing normally results in better GHG balances for the importing country as they get rid of territorial responsibility. In contrast, the emissions may increase on global scale, e.g. because of higher emission intensity in countries abroad (Dawkins and Croft 2017; Lenzen et al. 2006; Wiedmann 2009). Thus, an inclusion of the impacts induced by the international trade additional to domestic emissions could allow the calculation of greenhouse gas emissions due to the consumption of products (including services) for a whole country (consumption-based approach). This is of high relevance for diverse target groups to raise the consumer's awareness about the environmental impact of their consumption. Industries and organizations will get the information about their environmental performance compared to others, which would help to depict areas for improvement. Furthermore, policy-maker could make use of such information for deriving the most crucial areas for getting consumption more environmentally sound (e.g. climate-friendly procurement). However, different kinds of emissions have therefore to be taken into account, as "direct" and "indirect" emissions are associated with the consumption of products (Hertwich et al. 2008). The former result from the use of products and emissions is released directly on site. "Direct" emissions are in general more aware to the public, as they arise immediately from their activity (e.g. from driving a car or heating a house), and are usually a substantial part of emission-reducing strategies by politics. "Indirect" emissions, in contrast, are emitted by the production system domestically and abroad (through international trade) along the whole supply chain from raw material extraction up to final products. These emissions often are not available for single products, so that the producer or consumer may not be aware of the resulting negative impact on the environment. To obtain that kind of knowledge, an encompassing investigation at product level is inevitable, which has not been addressed in such detail so far (Hertwich et al. 2008; Sato 2012; Wiedmann 2009). As a result, the question of the demand for such product-specific information and the best suitable methodology capable to account mainly for all "indirect" greenhouse gas emissions due to national consumption of products in an adequate way has been of increasing interest recently, but still remains a challenging task.

Aim of this article

The aim of this article is to present the demand and key challenges inclusive practical ways for solutions to conduct an accounting for all greenhouse gas emissions due to national consumption of products (including products required for services). In this context, consumption includes the products for diverse purposes (e.g. private, public or industrial), which are remaining within a country, as a balance of national production plus imports minus exports, in one year and by ignoring eventual stockpiling. To achieve both, a complete and detailed picture of the “indirect” emissions, the consideration is focused on product level. Such an analysis of all emissions associated with national consumption shall help to identify the sources and the origin of greenhouse gas emissions and to design specific measures and strategies to reduce them. Furthermore, the relation between national production and imports for specific products could help to identify global effects like “carbon leakage”, defined as the outsourcing of national production in countries abroad, having clearly less stringent emission reduction pledges than in the original country. The results are increased emissions at global scale (Peters and Hertwich 2008). This article is structured in different tasks: first, investigating existing approaches for their potential to comprise “direct” and “indirect” emissions and to depict “carbon leakage” effects; second, analysing the demand for addressing these challenges, in particular, and identifying existing research gaps and key challenges, if available. Third, practical methodical approaches how to address existing research gaps are elaborated and applied exemplary for the case of Austria by developing a life cycle-based supply chain approach. This study was done during 2017 with the scope of Austria and presents the final results for the year 2013 (most recent year, which contained all relevant data).

Materials and methods

In the course of this article, different methodological approaches are used. From a methodical point of view, the article consists of three main parts. The first part was done by a detailed analysis of current approaches for greenhouse gas emission accounting to get an impression of the capability to account for all “direct” and “indirect” emissions due to national consumption of products and the ability to identify “carbon leakage” effects. The second part of this article addresses existing research gaps and the future research demand by elaborating the key challenges in tracing greenhouse gas emissions due to national consumption of products to a full extent and in adequate detail. An analysis to uncover the most important aspects necessary to apply such an encompassing accounting is therefore foreseen. Finally, practical ways how to solve these key challenges are suggested by introducing a methodical procedure for the case of Austria, concluding with an exemplified application of material flows and greenhouse gas emissions due to the supply chain of minerals in Austria.

Analysis of current emission accounting approaches

First, the analysed approaches, of course, differ in some key aspects, e.g. concerning their spatial scales, thus showing different orientations and issues, respectively. Anyway, each of the described approaches can be used to account for economy-wide greenhouse gas emissions, which will be addressed in the following section.

Production-based emission accounting

The most promising and well-established approach for national emission accounting was established by the UNFCCC, where all parties are required to submit annual emission inventories to guarantee progress towards the overall goal to restrict climate change below 2 °C temperature increase above pre-industrial levels (Liu et al. 2015; Maurer et al. 2016). This form of emission accounting focuses on all greenhouse gases (e.g. CO_2, CH_4, N_2O), and the calculation is based on combining activity data with appropriate emission factors. As activities, the consumption of fuels and the different energy carriers are included as well as the production of goods from which process emissions are released. The emission factors describe the emitted C O_2 per unit of energy or process activity. The resulting greenhouse gas emissions are further divided into five main sectors, each comprising individual categories and sub-categories for further differentiation (IPCC 2006). According to IPCC (2006) the five sectors investigated in such inventories are the following:

- Energy
- Industrial Processes and Product Use (IPPU)
- Agriculture, Forestry and Other Land Use (AFOLU), • Waste, and
- Other.

This kind of emission accounting considers greenhouse gas emissions coming from activities within national boundaries only, so-called production-based approach. Consequently, “direct” emissions in consumption and “indirect” emissions from national production are included, and those emissions induced abroad through imported products are not considered, as the system boundary is limited to national territory (cf. Fig. 1). Furthermore, export-oriented countries may have higher domestic emissions than countries with high imports. Hence, climate protection strategies focused on the improvement of the national GHG balances may lead to a negative impact on global level (IPCC 2006; Sato 2012). As a result, national climate inventories are an important instrument to evaluate compliance with actual climate targets and consider greenhouse gas emissions in the course of activities and are concentrated on fuel and energy consumed within one country through national industrial and private activities. Emissions due to the supply (manufacturing) of products, required for national consumption ("indirect" emissions) are not covered, if the production occurs outside national boundaries. The emissions are further not given on product level and thus cannot serve for the identification of "carbon leakage" effects. Consequently, as neither the system boundary allow to trace emissions occurring abroad, nor product-specific information are illustrated, this kind of emission accounting will not be considered any longer in the course of this article.

Consumption-based emission accounting

In recent years, accounting for greenhouse gas emissions due to national consumption, comprising domestic impacts, and those induced abroad have become of increasing interest. A detailed review of the current scientific literature has shown that the number of approaches for consumption-based emission accounting has grown significantly (e.g. Lenzen et al. 2006; Wiedmann 2009). As a result, different approaches have evolved which are used for consumption-based emission accounting:

Environmentally extended input–output (EE-IO) models

Environmentally extended input–output (EE-IO) models have been the most common approaches to account for climate impacts from a consumption-based perspective by including impacts from foreign trade (Bruckner et al. 2009; Lutter et al. 2016; Wiedmann 2009). IO models are a topdown approach based on economic input–output analysis and can comprise single-country (SRIO) or multi-regional input–output (MRIO) models (Davis and Caldeira 2010; Tukker et al. 2006; Wiedmann 2009). The database of MRIO models includes a set of national input–output (IO) tables that are interlinked by bilateral trade data. IO tables depict the flow of goods and services within countries in monetary units. The set of IO tables is further extended with sectoral data on energy use, greenhouse gas emissions or other environmental impacts. The IO models allow production chains triggered by consumption in one country across country borders to be traced and the induced environmental impacts in all other countries to be calculated. Thus, it is possible to determine how many inputs (from various sectors and countries) are necessary to produce the required output for the respective sectors (see, for example, Bruckner et al. 2009; Lininger 2015; Lutter et al. 2016; Wiedmann 2009). In recent years, different types of IO-based models have been developed and used to account for greenhouse gas emissions from a consumption-based perspective for various countries all over the world, as illustrated, for example, in Lininger (2015); Munoz and Steininger (2010); Wiedmann (2009). However, the different models do not show comparable results all the time, so that a harmonization process is needed to deliver useful information to policy-maker (Wieland et al. 2017). This kind of emission accounting extends the system boundary beyond national activities to include impacts induced abroad by trade and is able to consider both "direct" and "indirect" greenhouse gas emissions due to national consumption. Nevertheless, there are some limitations that have to be taken into account, as the high level of sector aggregation. This kind of aggregating products of low and high emission intensity together in one sector leads to a significant increase in uncertainty (Lininger 2015; Lutter et al. 2016; Wiedmann 2009). These approaches are therefore suitable to deliver information for country level or regional analysis, but are not able to provide accurate data for single products. Consequently, "indirect" emissions due to the supply of products may not be depicted in a transparent way, as averaged emission factors on sectoral level are used. Furthermore, another main disadvantage and source of uncertainty are the prevailing use of monetary structures of sectors to calculate environmental impacts, as monetary data are not as suitable for the calculation of greenhouse gas emissions as physical data are (Lininger 2015; Lutter et al. 2016; Wiedmann 2009). "Carbon leakage" effects also cannot be identified as neither physical data nor product-specific information are used.

LCA-based or coefficient approach

The coefficient approach to estimate consumption-based greenhouse gas (GHG) emissions makes use of the following formula:

consumption based emissions = total domestic emissions

+ life cycle emissions of imported products

− life cycle emissions of exported products

Domestic emissions are usually taken from available emission inventories or emission accounts. The calculation of imported and exported emissions bases on multiplying traded products in physical units with appropriate GHG emission coefficients from LCA (life cycle analysis) databases. The total GHG emissions associated with manufacture and transport of the imported or exported products to a country's border are therefore measured (Dittrich et al. 2012; Frischknecht et al. 2014; Jungbluth et al. 2011). These LCA-based data can adequately account for the differences in emission intensities among the various materials and are characterized by the inclusion of whole process chains behind specific products. Production chains are traced along mass flows, which may be more adequate than the monetary flows depicted in MRIO models (Dittrich et al. 2012; Lutter et al. 2016). This approach was used, for example, by Jungbluth et al. (2007) to estimate the development of Swiss consumption-based GHG emissions between 1990 and 2014. Besides greenhouse gas emissions, material flow analysis (MFA) is another well-established approach that enables the description of material flows in our whole economy in physical units. The coefficient approach was used to calculate the domestic material consumption (DMC) or material footprint (e.g. Dittrich et al. 2012). Consequently, the LCA based or coefficient approach makes use of product-specific LCA data, but looks at imports and exports only. Domestic activities mainly are not considered at product level. It is a balancing approach, but does not allow to follow process chains from consumption to production and ultimately GHG emissions. Thus, it is not possible to identify the most emission-intensive products behind national consumption as imports and exports are not linked with national production. Furthermore, "carbon leakage" effects cannot be identified as well.

As a consequence of existing challenges associated with these three accounting approaches, as already mentioned, hybrid approaches have been developed in order to combine the advantages of the respective methods. One example is an approach combining a national EE-IO model with foreign trade data and LCA data. The national EE-IO model bases on an IO table that extends the monetary data with direct GHG emission coefficients for industries and households. With this information, imported goods in physical units are distributed to using industries and final demand sectors of the IOT. These data are linked to appropriate emission data from LCA databases at product group basis. Jungbluth et al. (2011) and Nathani et al. (2017) applied such an approach to calculate the Swiss consumption-based GHG emissions and other environmental impacts. Schaffartzik et al. (2014) used a similar approach for consumption-based material flow accounting, though restricting it to non-competitive imports. Although this hybrid approach tries to link the advantages of the LCA-based approach and the environmentally extended input–output (EE-IO) models, it is still not possible to trace all emissions based on physical data and product-specific emission factors, as the domestic activities are calculated from monetary data at aggregated sector level.

Hybrid approaches

Value-added-based emission accounting

Recently, the scientific community has scrutinized the allocation of emissions completely to the final consumer, as, for example, producers are not encouraged to improve their emission intensity in producing goods exported to countries. Thus, the question of sharing responsibility between producers and consumers among participating trade partners has been discussed to facilitate the implementation of effective and global climate protection agreements. As a result, a new approach has evolved addressing the challenge of sharing responsibility by allocating emissions based on the value-added chains (value-added-based emission accounting). This means that emissions are accounted for concerning the economic benefit of every participating country. For the purpose of illustration, the proportions of value generated along the whole supply chains in various countries, mainly due to increasing globalization, are therefore the basis for allocating emissions

Table 1 Overview of the ability of the various approaches to accomplish with the main analysis criteria

Comparison criteria	Coefficient approach (LCA)	Hybrid approach (EEIOA plus LCA)	MRIO analysis
Coverage of domestic emissions at product level	No	No (depending on the level of detail of the IOT)	No
Coverage of imported emissions at product level	Yes	Yes	No, sectoral detail depends on IOT (low–high)
Physical allocation principle for domestic emissions	No	No	No
Physical allocation principle for imported emissions	Yes	Yes	No, monetary-based calculation
Identification of carbon leakage	Not possible	Not possible	Not possible

to producers and consumers. IO models are one adequate method for calculating value-based greenhouse gas emissions, as seen, for example, in Liu and Fan (2017). Consequently, this new perspective complements existing approaches and may be of increasing importance for future policy-making, as it is a kind of mixture between production- and consumption-based emission accounting with the advantage of stimulating producers as well to reduce their induced greenhouse gas emissions (Liu and Fan 2017; Csutora and Mózner 2014). In this context, however, addressing the emissions due to national consumption of products and identifying the most emission-intensive goods is not at the core of this approach.

Accounting of greenhouse gas emissions due to national consumption of products

Demand and key challenges

The analysis has shown that several national emission accounting approaches differ in their capability to account for "direct" and "indirect" emissions. Input–output models mainly apply a consumption-based perspective by extending the system boundary for impacts behind trade, but emissions are calculated at aggregated sector level based on monetary data, as mentioned, for example, in Fischer Kowalski et al. (2011), Lutter et al. (2016) and Wiedmann (2009). Recently, value-based perspectives have arisen as well to share responsibility of emissions between producers and consumers (e.g. Liu and Fan 2017), but are not focused on emissions due to national consumption of products. Life cycle-based approaches make use of physical data and depict differences in emission intensities between specific products, but have rather focused on imported and exported products only, by neglecting domestically produced goods. Finally, hybrid approaches combine the strengths of the EE-IO and the LCA-based approach, but are still restricted by the limitations of the EE-IO approach, namely high sectoral aggregation and monetary allocation of emissions along domestic production chains. Table 1 illustrates a summary of the analysis comprising the ability of the various approaches to accomplish with the main analysis criteria.

As a result, current approaches for consumption-based emission accounting miss especially the merge of imports and exports with national production at a detailed product level based on physical data. Thus, it is not possible to trace emissions for individual products in order to identify the real drivers behind the greenhouse gas emissions and to elaborate

Table 2: Main areas of improvement for consumption based emissions highlighted by the scientific literature

Main area of improvement and future research	Studies emphasizing the identified need for research
Need for disaggregation of sectors	Bruckner et al. (2009)
	Dittrich et al. (2012)
	Fischer-Kowalski et al. (2011)
	Kander et al. (2015)
	Lininger (2015)
	Liu et al. (2015)
	Lutter et al. (2016)
	Peters (2008)
	Sato (2012)
	Wiedmann (2009)
Detailed analysis and closing of process chains	Fischer-Kowalski et al. (2011)
	Liu et al. (2015)
	Lutter et al. (2016)
	Sato (2012)
Use of physical data for calcula-tion of greenhouse gas emissions	Lininger (2015)
	Lutter et al. (2016)
	Sato (2012)
	Wiedmann (2009)

appropriate measures to reduce them. Furthermore, the identification of "carbon leakage" effects due to structural changes in the supply chain is only possible if the relation between imports and national production is known for specific products (e.g. imports increase and national production decreases). Consequently, there are still remaining questions associated with consumption-based emission accounting. Nevertheless, methodical improvements will take place for each of these approaches. IO-based calculations have been developed as the most common approach for

consumption-based emission accounting; thus, researchers will try to improve these models continuously. This may concern the harmonization of MRIO calculations in order to present robust results (Wieland et al. 2017) or the completion of physical data as a basis for the IO models (Lutter et al. 2016). LCA will remain as a product-based approach, additional to the sector-based IO methods, important to calculate all environmental impacts due to the production and use of goods. The heterogeneity of products and the huge effort, however, have impeded the economy-wide application for both, domestic and foreign emissions up to now. Consequently, this tool has been used primarily for single products or businesses. Overall, methodical revisions of the single approaches can lead to improved hybrid approaches as well, which may be extended in future, for example, by making use of MRIO models in combination with LCA approaches to avoid the domestic technology assumption, where for imports the same technological standard as for the national production is applied (Lutter et al. 2016).

A detailed analysis of the recent scientific literature concerning emission and material flow accounting has shown that especially those challenges, as identified above, are recommended for investigation in future research (see Table 2). One main area of concern is further on the high aggregation of sectoral data, as there is meanwhile growing recognition and wide consensus that a detailed analysis at product level will provide useful information for the identification of the most emission-intensive materials and products (e.g. Lutter et al. 2016; Sato 2012; Wiedmann 2009). Other topics that need further attention are the creation and analysis of supply chains to allow tracing greenhouse gas emissions from resources up to final consumption in order to address the problem of double counting, which will be explained in more detail later on. Many further studies also address the advantages of the use of physical data as a basis to calculate environmental impacts, as monetary data assume proportionality with physical data, which is an increased source of uncertainty (e.g. Sato 2012).

As it was shown in the last section, accounting for consumption-based greenhouse gas emissions at a detailed product level would be of significant importance; however, it has received little attention up to now. Such analyses have mainly been carried out for single products (e.g. carbon footprinting), or partially (e.g. for imports and exports), as it was seen as too time-consuming and too complex to construct production chains for the analysis for all emissions due to national consumption of products (Bruckner et al. 2009; Dittrich et al. 2012; Lininger 2015; Lutter et al. 2016).

Proposed methodical solutions

In the course of the final section, practical ways how to solve the key challenges for implementing an accounting of GHG emissions due to national consumption of products are illustrated. These proposed solutions are further proved for the case of Austria and shall serve as a kind of guideline how to address existing research gaps. As analysed in the section before, the disaggregation of sectoral data, the use of physical instead of monetary data and the consideration of whole supply chains were identified as those areas of main concern for future research. Thus, methodical solutions for these three areas are now suggested, respectively.

Disaggregation of sectors: using appropriate product levels reflecting the heterogeneity in emission intensities

The transparent calculation of "indirect" emissions, released by the supply of products in final consumption, requires a product-specific consideration in order to distinguish between the diverse products within the sectors. For example, from an emission point of view, it makes a difference if the aluminium sector is estimated with emission factors for primary or secondary aluminium, or the plastic sector is calculated with the emission intensity of polyethylene or polystyrene. Thus, the products behind consumption have to reflect the main differences in emission intensities. For the case of Austria, it was tried to cover all products imported, exported and produced domestically in an adequate level of detail. The main criterion for the selection of the most appropriate product level, determining the final scope of consideration, was the availability of product-specific emission factors. The Ecoinvent database (version 3.2 was used)[1] was therefore used primarily, supplemented by GEMIS[2] if necessary. Data on imports and exports were taken from foreign trade statistics. It contains all products in monetary and physical units and is structured along the different countries of origin and destination. The foreign trade statistics is available in different product classifications systems (e.g. SITC—Standard International Trade Classification or CN—Combined Nomenclature), from which the CN classification was chosen in this case, as it consists of about 100 different 2-digit (sectors) representing different material and product groups at the highest aggregate. Each of these sectors was further considered separately at the respective higher digit (= lower level of aggregation) to depict the

[1] http://www.ecoin vent.org/.

[2] http://iinas .org/gemis -de.html.

main differences within one sector. As a result, the 4-digit has, in principle, emerged as the most appropriate level of detail, as the heterogeneity of products mainly was addressed by distinct emission factors at this stage. For the purpose of illustration, it is crucial to distinguish, for example, between different kinds of animals (e.g. cow or swine). An analysis of LCA data has revealed that such a differentiation is possible, as emission factors for cow, swine or chicken are available, corresponding to a 4-digit classification (see Table 3). Finally, the appropriate level of detail between 2-digit and 8-digit was determined by comparison with the available LCA data and their aggregation level. Overall, at about 1000 different products appeared as a required level of detail in order to distinguish the main differences in emission intensities and calculate the "indirect" greenhouse gas emissions by using LCA-based product-specific emission factors.

Use of physical data as a basis for calculating the GHG emissions

For the use of physical instead of monetary data, the figures in the different databases had to be merged to develop a material flow balance behind national consumption. Physical data on imports and exports are well documented in the foreign trade statistics of Statistics Austria,[1] as it reports data for the most aggregated (2-digit) as well as for the most detailed (8-digit) products.

Physical material flows of national production are reported in the national economic statistics of Statistics Austria,[2] but offer, in contrast, a lot of missing data due to confidentiality reasons. This is of high relevance for a small country like Austria due to a limited number of companies. Nevertheless, one possibility to supplement these data is the use of monetary prices of similar goods, if available, to convert from monetary into physical units. If neither physical nor monetary data are available in the national statistics, additional data are required. In such cases, information from industrial branches (e.g. reports) was taken. Finally, data on foreign trade and those of national production have to be connected by harmonizing the different classification schemes using a correspondence list of Statistics Austria (2017) between CPA classification for the national production and CN classification for the foreign trade. It is

[1] https ://www.stati stik.at/web_en/stati stics /Econo my/forei gn_trade / index .html.

[2] https ://www.stati stik.at/web_en/stati stics /Econo my/indus try_and_ const ructi on/index .html.

Table 3: Exemplary selection of the appropriate product levels based on LCA availability

CN 2-digit	CN 4-digit	CN 6-digit	LCA-availability
LIVE ANIMALS	Live bovine animals	Pure-bred cattle for breeding	cattle for slaughtering, live weight
	Live poultry	Live cattle (excl. pure-bred for breeding)	chicken for slaughtering, live weight
	Live swine	Pure-bred buffalo for breeding	swine for slaughtering, live weight
	Live sheep and goats	Live buffalo	sheep for slaughtering, live weight
FISH AND CRUSTACEANS	Live fish	Live trout Salmo trutta	FischereiEU-Fisch-Import-Meer-2010
	Fish, fresh or chilled	Live eels Anguilla spp.	
	Frozen fish	Live carp	
	Fish fillets and other fish meat	Live Atlantic and Pacific bluefin tuna	
CEREALS	Wheat and meslin	Durum wheat seed for sowing	wheat grain
	Rye	Durum wheat (excl. seed for sowing)	rye grain
	Barley	Seed of wheat and meslin, for sowing (excl. durum)	barley grain
	Oats	Wheat and meslin (excl. seed for sowing, and durum wheat)	oat grain
PLASTICS AND ARTICLES THEREOF	Polymers of ethylene, in primary forms	Polyethylene with a specific gravity of < 0,94, in primary forms	polyethylene, low density, granulate
	Polymers of propylene, in primary forms	Polyethylene with a specific gravity of >= 0,94, in primary forms	polypropylene, granulate
	Polymers of styrene, in primary forms	Ethylene-vinyl acetate copolymers, in primary forms	polystyrene, expandable
	Polymers of vinyl chloride, in primary forms	Polymers of ethylene, in primary forms (excl. polyethylene and ethylene-vinyl acetate copolymers)	polyvinylchloride, bulk polymerised
WOOD AND ARTICLES OF WOOD	Wood in the rough	Coniferous wood in the rough	roundwood, primary forest
	Fuel wood	Red meranti in the rough	roundwood, secondary forest
	Wood charcoal	Tropical wood	roundwood, meranti
	Hoopwood	Oak "Quercus spp." in the rough	roundwood, paraná pine
IRON AND STEEL	Pig iron and spiegeleisen, in primary forms	Ferro-manganese, containing by weight > 2% of carbon	pig iron
	Ferro-alloys	Ferro-manganese, containing by weight <= 2% carbon	steel, low-alloyed, hot rolled
	Iron and non-alloy steel	Ferro-silicon, containing by weight > 55% of silicon	steel, unalloyed
	Flat-rolled products of iron or non-alloy steel	Ferro-silicon, containing by weight <= 55% silicon	reinforcing steel

illustrated exemplarily in Table 4. Any different aggregation in the two lists was reduced to the determined level coming from LCA data (see Table 3).

Tracing GHG emissions along supply chains

Supply chains (= process chain) behind national consumption were created from the merged import, export and production data. They are necessary on one hand to avoid double counting in process chains (ore–pig iron–steel ingot–steel plate). This is of major importance when using LCA data, as they comprise emissions from cradle up to the product level. For example, the figures of the steel plate include the emissions of the steps before, and a possible subsequently produced car would include the steel plate as well. Consequently, at least consumer products have to be identified to enable the calculation of LCA-based emissions by avoiding double counting. Thus, it is necessary to attribute every product separately to defined steps in the process chain. This is mainly because of the heterogeneity of goods, as different process steps (e.g. raw material extraction, commodity production) are required to

Table 4: Correspondence between product classification of national production and foreign trade. (Reproduced with permission from Statistics Austria 2017)

CPA	CN
A 01.11.20 Maize	1001.11.00 Durum wheat seed for sowing
	1001.19.00 Durum wheat
	1001.91.10 Spelt seed for sowing
	1001.91.20 Seed of common wheat or meslin, for sowing
	1001.91.90 Wheat seed for sowing
	1001.99.00 Wheat and meslin
	1005.10.13 Three-cross hybrid maize seed for sowing
	1005.10.15 Simple hybrid maize seed for sowing
	1005.10.18 Hybrid maize seed for sowing
	1005.10.90 Maize seed for sowing
	1005.90.00 Maize
A 01.13.11 Asparagus	0709.20.00 Fresh or chilled asparagus
A 01.13.12 Cabbages	0704.20.00 Brussels sprouts, fresh or chilled
	0704.90.10 White and red cabbages, fresh or chilled
	0704.90.90 Kohlrabi, kale and similar edible brassicas, fresh or chilled
A 01.13.13 Cauliflowers and broccoli	0704.10.00 Fresh or chilled cauliflowers and headed broccoli
A 01.13.14 Lettuce	0705.11.00 Fresh or chilled cabbage lettuce
	0705.19.00 Fresh or chilled lettuce
A 01.13.15 Chicory	0705.21.00 Fresh or chilled witloof chicory
	0705.29.00 Fresh or chilled chicory
A 01.13.16 Spinach	0709.70.00 Fresh or chilled spinach
A 01.13.17 Artichokes	0709.91.00 Fresh or chilled globe artichokes
A 01.13.19 Other leafy or stem vegetables	0709.99.10 Fresh or chilled salad vegetables
	0709.99.20 Fresh or chilled chard "white beet" and cardoons
	0709.99.50 Fresh or chilled fennel
A 01.13.21 Watermelons	0807.11.00 Fresh watermelons
A 01.13.29 Other melons	0807.19.00 Fresh melons
A 01.13.31 Chillies and peppers, green	0709.60.10 Fresh or chilled sweet peppers
	0709.60.91 Fresh or chilled fruits of genus Capsicum
	0709.60.95 Fresh or chilled fruits of genus Capsicum

supply the final products in consumption. On the other hand, tracing emissions along the whole supply chain would further allow seeing displacement of emissions between those countries using and those producing specific goods, essential facts for identification of carbon leakage.

Figure 2 shows an exemplary process chain behind national consumption of products, whereas the provision of products ("indirect" emissions) is shown from raw materials up to final products, including the origin and destination of products. Furthermore, the use of products ("direct" emissions) is considered as well. Of course, this is a very simplified illustration, as every product group is characterized by different process steps and types of materials required to supply the final product. Three examples shall depict how such process chains may look like. First, the chemical industry consists of a broad variety of subsectors (e.g. plastics, pharmaceuticals, textile), thus, producing diverse intermediate and final products as well. Second, the wood chain, in contrast, shows less complexity than chemicals. Roundwood mainly serve as raw material, from which sawn wood is produced, followed by the production of intermediate products (e.g. wood-based composites) and final products (e.g. furniture, construction timber). The use of wood for energy is another way of direct end use without any interim products. Third, the mineral chain with different kinds of materials is described below in more detail.

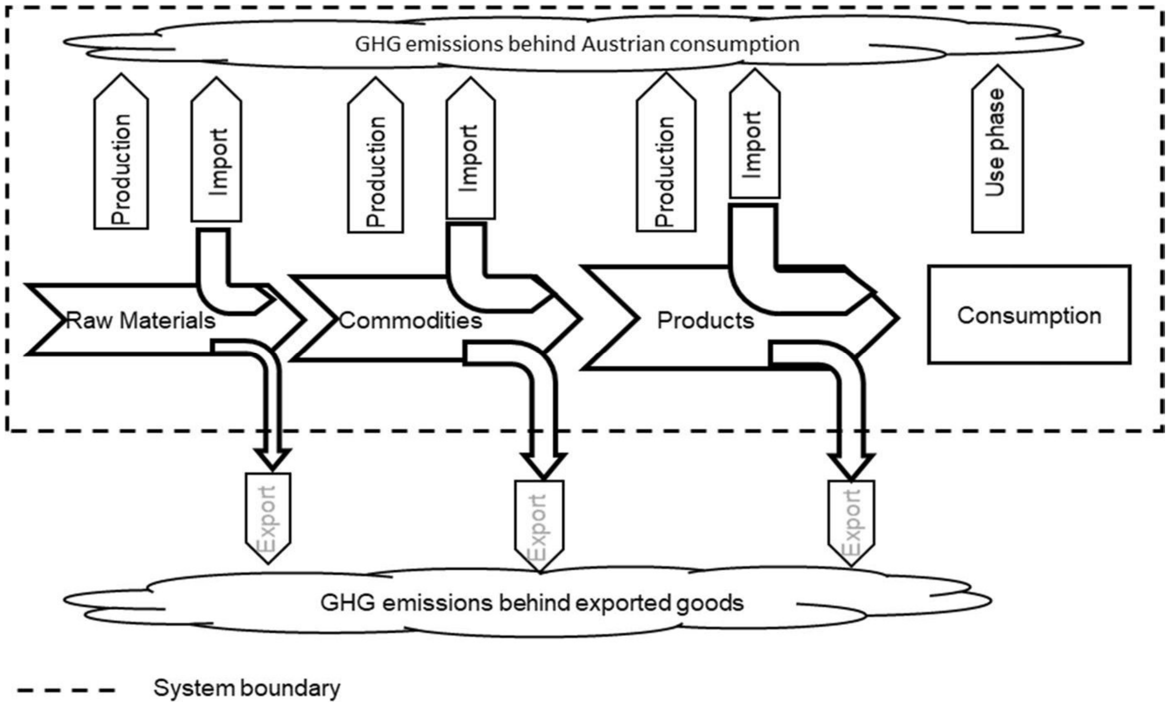

Fig. 2 Illustrative process chain behind national consumption of products

Application of the methodological approach for the mineral chain in Austria

Material flows along the supply chain of minerals

Finally, all previous methodical steps were conducted and will be shown for the exemplary supply chain of minerals in Austria. In Fig. 3, the physical material flows of this product group are illustrated by considering imports, exports and national production in every process stage, respectively, dividing into raw materials, intermediates and final products. Horizontal arrows, coming from the respective production stage, show the domestic material flows. At every single stage, some kind of imports and exports are visible, illustrated by vertical arrows coming from, respectively, going to abroad. All arrows together, as a balance of national production plus imports minus exports (P + I − E) at every stage, form the input for the next production stage. In general, it is obvious that the domestic production in Austria dominates the mineral chain, whereas imports and exports are of minor importance. This is mainly due to the high volumes and the low prices making international transportation not economically feasible. Figure 3 shows that about 100 million tonnes (Mt) of raw materials were extracted in Austria in 2013, supplemented by almost 4 Mt of imports and quite the same amount of resources was exported. In a next step, 7 Mt of intermediates such as cement or caustic lime are produced. A certain amount of raw materials was therefore used for processing (= 14 Mt). In accordance with BAT Reference document (Schorcht et al. 2013), the produced output needs about 1.2 to twice as much input as raw material (e.g. raw material factor for cement final product is 1.2, for lime between 1.4 and 2.2). Again, the intermediates are further processed to final products (e.g. concrete, glassware, brick), requiring more input than the produced output as well. Nevertheless, typical final products out of minerals need both, intermediates and raw materials. Concrete, for instance, consists of cement on one hand, but the major part comes from the raw material gravel. Consequently, as shown in Fig. 3, it is obvious that the raw materials form the major part of the final products as an admixture and, for example, filling material for buildings and underground construction (84.2 Mt compared to 7.3 Mt). As a result, it is essential to attribute all goods to appropriate steps in the process chain, as this is one main prerequisite to enable the calculation of consumption-based emissions in a correct and transparent way and to trace

material flows along whole process chains from raw materials up to the final products. This is, in itself, a further research frontier, as the establishment of a consistent link between resource inputs and outputs is still missing in current MFA (Fischer-Kowalski et al. 2011).

The results are similar to those of Schaffartzik et al. (2014, 2015), reporting the consumption of raw material equivalents rather than looking at the whole supply chain and using a hybrid approach, as mentioned before.

Our approach, however, depicts less raw materials, probably coming from the attribution of products to different process steps. Thus, some kind of raw material equivalents may recover in another process step (e.g. intermediates or final products). Furthermore, this approach does not consider some industrial minerals (e.g. fertilizer), which are accounted for in Schaffartzik et al. (2014, 2015).

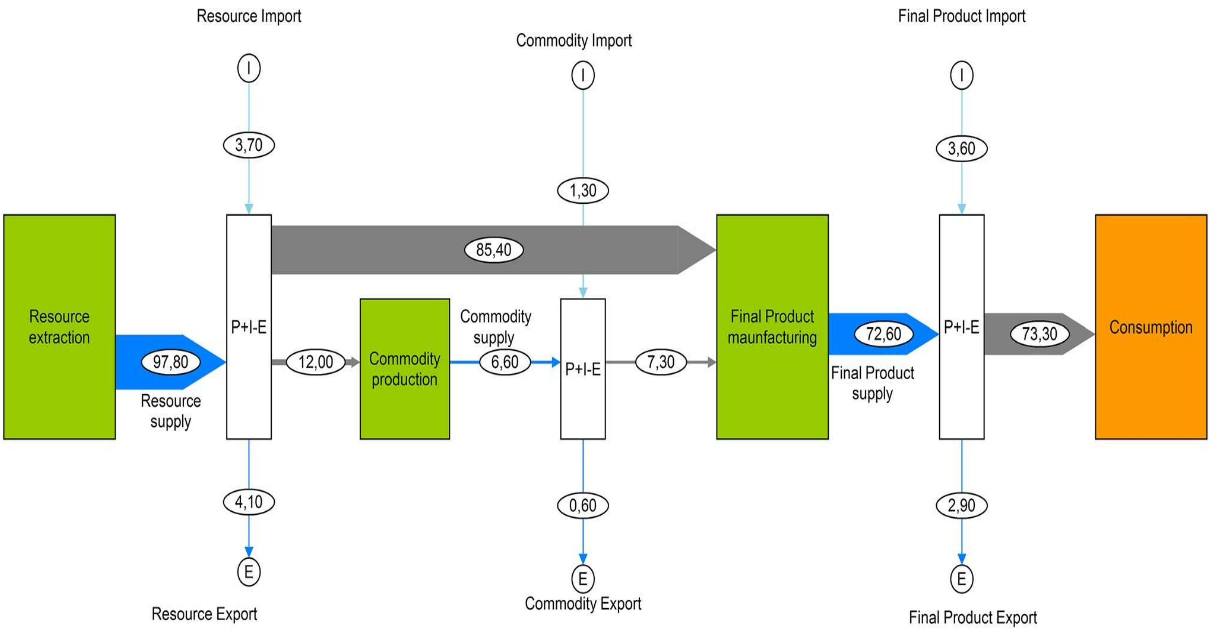

Fig. 3 Material flows along the supply chain of minerals in Austria, in 2013 (in Mt)

Greenhouse gas emissions along the supply chain of minerals

Once emission factors (kilogram CO_{2equ} per kilogram product) were attributed to every good, according to the procedure in Table 3, the calculation of greenhouse gas emissions was done by multiplying the material flows with emission factors. Figure 4 now shows the emissions along the mineral chain occurring from raw materials up to final products. In principle, the structure is similar to those of Fig. 3, but the arrows now depict the greenhouse gas emissions in million tons (Mt) of CO_{2equ}. The whole supply chain shows an emission increase in the course of the chain as LCA data comprise all emissions due to the supply chains up to the considered good. As shown in Fig. 4, it is obvious that the main part of emissions comes from the processing of raw materials to intermediates and final products. The raw material itself, in contrast, is not as emission intensive as the huge amount (cf. Figure 3) of materials has low emissions only. One can see that the major increase in emissions occurs in the commodity stage, where the production of intermediates (e.g. cement, lime) leads to significantly higher emissions (from 0.24 to 4.4 Mt CO_{2equ}) than in the final product manufacturing (from 5.7 to 6 Mt CO_{2equ}). From an emission point of view, the imports are more relevant compared to the physical amounts probably because of the higher emission intensity of imported products. Finally, the calculated emission cannot directly be compared with sectoral emissions given in national inventories, as they use detailed site oriented calculations and LCA-based data are far less specific for single sites.

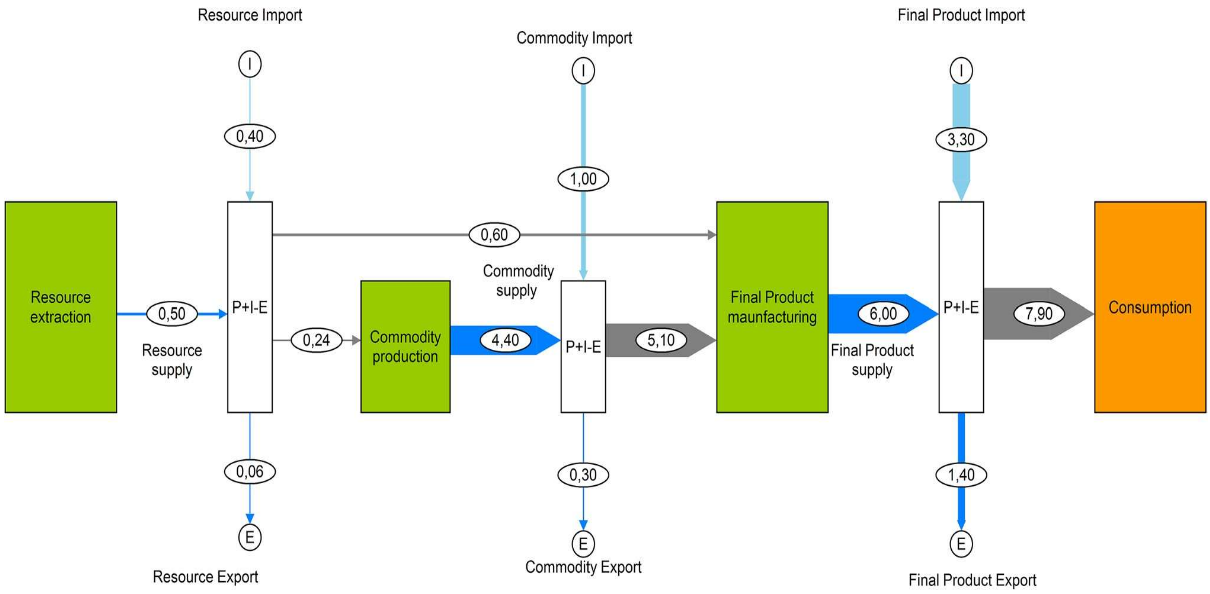

Fig. 4 Greenhouse gas emissions along the supply chain of minerals in Austria in 2013 (in Mt CO_{2equ})

Discussion and conclusion

In order to tackle climate change at global level every state has to take actions to reduce the greenhouse gas emissions due to national consumption, considering both national activities and those induced by foreign trade. Otherwise, “carbon leakage” may occur if impacts within national boundaries are accounted for only, and emissions induced by imported goods are neglected. Hence, the interest in accounting for emissions induced by national consumption, in addition to the more common production-based approach, has been of increasing interest. Additionally, a value-based accounting approach has emerged recently to share responsibility between producing and consuming countries by accounting emissions based on the economic benefit of every participating country. This approach may facilitate an effective and global climate protection agreement in stimulating producers and consumers to reduce emissions. In this context of new emerging emission accounting approaches considering domestic and foreign activities, economic input–output (IO) models have established as the most common method calculating emissions at sector level based on monetary data. Such sectoral information provides important knowledge on the recent developments, but is sometimes seen as being too aggregated to develop appropriate climate mitigation options. Thus, detailed information at product level, to illustrate the most emission-intensive products and possibilities to reduce the induced greenhouse gas emissions, would help to reveal improvement potentials and to raise the people’s awareness in climate impact of consumption. The first part of this article has shown that there is broad consensus that emission accounting based on national consumption will profit from analyses at product level, as essential information on the level of individual products may be lost by using sectoral analysis only. However, existing approaches miss for taking into account such a disaggregated and detailed consideration behind all products, domestically and abroad, in national consumption. One main reason therefore is the high complexity coming from the great diversity of products and the corresponding high effort of such an approach. In the second part of this article, the authors have tried to shed light on existing research gaps in explaining the key challenges, but elaborating methodical solutions how to address them as well. The proposed approach was thereby applied exemplary for the case of Austria to serve as a kind of guideline for further product-specific analysis of other material groups and in different countries. For going beyond sector-based calculations, an appropriate level of detail for products determining the final scope of the analysis is needed, depicting the main differences within the emission intensity of single sectors. As LCA is a perfect tool to calculate the environmental impacts of individual products, the availability of product-specific LCA data is a main criterion for the best suitable product level. The exemplary analysis has shown that there are differences between product groups concerning their classification in the national statistics and the corresponding LCA data. Consequently, it is essential to consider every product group and the corresponding LCA availability, respectively, to define the most appropriate level of detail. The use of physical instead of monetary data as a basis for the calculation of emissions was another research area. So physical material flows for imported, exported as well as domestically produced goods are required. National production and foreign trade data, however, show different classification schemes, requiring a harmonization by using available correspondence lists between these two statistics. Hereafter tracing emissions along the whole supply chain is of key importance to avoid the problem of double counting which may occur, as life cycle-based emission factors usually include the whole life cycle from the resource up to the considered good or product. It is essential to identify and structure all goods along the respective production chain. Thus, as there is a great diversity of products and different process steps (e.g. raw material extraction, commodity production) are required to supply the final products for consumption, every product was attributed to defined process steps. Finally, the proposed approach was applied for the supply chain of minerals in Austria. The results deliver therefore new insights as no tracing of material flows and greenhouse gas emissions along a whole supply chain from raw materials up to final products has been made so far. This new approach enables to depict the domestic and foreign material and emission flows at every process stage as well as to identify the most emission-intensive products. In this case, the minerals processing chain operates huge amounts, but only a small share exhibit high emission intensity. Overall, the total greenhouse gas emissions are comparably low. Other characteristics are the dominating use of mineral raw materials as final products without processing (e.g. gravel as underground material in roadworks) and the minor importance of imports and exports in this case, at least from a physical point of view.

As a result, product-specific accounting can help to identify the most emission-intensive products in national consumption and facilitate the design and implementation of measures to reduce the induced emissions. This article has tried to identify the importance of product-specific information and point out the existing research gaps by depicting proposing methodical solutions, which shall support an analysis of the supply chains of further material groups in different countries at a detailed product level. The exemplary application for the processing of minerals in Austria will therefore be extended for additional material groups in Austria in a next step. However, there is a lot of future research, which has to be done to improve the certainty of the results. First, the development of supply chains by attribution of products to the single production stages is required to avoid multiple counting of products, which are processed consecutively in a production line. This means the identification of raw materials and commodities up to final product as well, which comprise all emissions of the whole production line in the LCA data, thus requiring a clearance of materials, which are contained. Second, the emission factors on one hand need to relate best to the respective processes and they should reflect the time-varying technological situation and energy mix for the respective manufacturing country on the other hand. As LCA data are not available for all countries, adaption of the data to the respective national situation is required for national production and especially for the imports (Jungbluth et al. 2011; Frischknecht et al. 2014). Third, the presented approach uses foreign trade data, which do not reflect the real origin of the products to full extent. For example, products imported from Germany may consist of some parts coming from process chains in other countries. These pre-imports in the imported products are not visible in foreign trade data, although they are origin oriented. The combination of the product-specific approach with multiregional input–output models may help to trace back to the real origin country, at least in monetary values. Finally, to reduce existing uncertainties as mentioned above, a transdisciplinary approach is needed comprising distinct disciplines: first, technical and industrial knowledge and expertise for a correct development of supply chains and description of distinct production sites in respective manufacturing countries;

second, a deep understanding of LCA data to apply the correct factor for every product in the supply chain; and third, skills in economic modelling for tracing back to the real origin behind the supply chains of imported products.

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4.3 Summary of the main results

This article was divided into two main parts. First, an encompassing review and analysis of existing emission accounting approaches, with a special regard for the inclusion of both “direct” and “indirect” emissions. The analysis was further extended for a literature review to collect information about the scientific demand for an emission accounting on a high disaggregated product-level. Second, this article tried to identify the main challenges and elaborate possible methodical solutions how to manage such a detailed kind of emission accounting. This more practical part ended with a first try to trace greenhouse gas emissions for the mineral chain in Austria on the level of single goods and products.

The results have shown that various approaches dealing with an accounting of greenhouse gas emissions exist. The analysis further depicted large differences between those approaches, varying from the respective perspective and system boundary up to the used aggregation level. The most common approach for national emission accounting, established by the UNFCCC, is focused on all greenhouse gas emissions occurring within national borders. Thus, a production-based perspective is used as the calculation is based on national activity data, which are extended with energy-specific emission factors. The emissions are finally illustrated on the level of five sectors, subdivided into further categories. In contrast, many approaches dealing with a consumption-based perspective have evolved recently, as the international trade has become of increasing importance in times of globalization.

Input-Output models have established themselves as a main instrument, which is able to extend the system boundary up to impacts induced by foreign trade. These approaches are based on Input-Output tables, which are interlinked with monetary data at sector level and further extended with aggregated emission factors for the calculation of emissions. Thus, this approach is suitable for tracing trade flows and the associated climate impacts within and between countries. But, they are limited in the high aggregation level and the use of monetary data for the calculation of emissions.

The LCA-based approach tries to make use of more disaggregated emissions factors from LCA (life cycle analysis) databases as well as physical data for calculating consumption-based emissions. However, the life cycle emissions are only applied for imported and exported products. Domestic emissions are taken from national statistics and are not calculated on this way. Furthermore, it is not possible to trace emissions or material flows along the process chain, as it is more a balancing approach. As a consequence of these two last approaches, hybrids have evolved, which shall combine the advantages and reduce the respective limitations, but are still restricted in the high aggregation or use of monetary data in Input-Output models. Recently, further approaches have developed, focusing rather on the question how to share the responsibility between producers and consumers, but not on the calculation of consumption-based emissions on product-level (Value-based perspective).

As a result of this encompassing review of current emission accounting approaches, none of them is actually suitable for conducting an entire analysis of the greenhouse gas emissions induced by the national consumption of products. It is therefore necessary to trace all "direct" and "indirect" emissions on the level of single products, for which the existing approaches are only of limited suitability. Thus, it is actually not possible to trace emissions for single products along their process chain to depict the real emission drivers. "Carbon leakage" effects can also be quantified only if the relation between imports and domestic production is available on the level of single products. But, the further literature review has confirmed the scientific demand for consumption-based greenhouse gas emissions at the product level, as the main challenges identified for the existing approaches are declared as recommendations for future research. This includes especially the high aggregation level of Input-Output models as meanwhile there is a broad consensus that product level analysis will deliver further information regarding the most emission intensive products. Using physical material flows as a basis for the emission calculation as well as tracing material flows and emissions along the whole life cycle are further areas of concern.

This article further aimed at going more into practice by elaborating possible methodical solutions how to overcome the key challenges for a product-based emission accounting behind the national consumption. These methodical approaches were further tested through an exemplary application for the mineral chain in Austria and shall serve as a guideline how such an accounting could be applicable for other material groups or in other countries.

In general, the following methodical steps were identified as the most important ones, which were implemented in the course of this test run:

- Definition of an appropriate level of detail for products

This step is one core element for managing the great diversity of products on one hand, but being able to depict the main differences in the emission intensity of products on the other hand. As LCA is an instrument, which is focused on the analysis of environmental impacts of single products, those databases were investigated to get an overview of the availability as well as differences between emission factors. Thus, the decision regarding the appropriate level of detail was primarily based on the availability and heterogeneity of LCA-data.

- Collection of product-specific physical data for imports, exports and national production

Once the level of detail was determined for the single products, physical data for imports, exports as well as the domestic production were collected out of statistical data, supplemented by scientific studies and industrial reports.

- Creation of supply chains

As life cycle data usually include the impacts of the whole life cycle beginning with the resource extraction up to the respective product, double counting must be avoided. It was therefore foreseen to trace material flows and attribute every product to defined steps in the supply chain (e.g. raw material, commodity, final product).

- Attribution of LCA-based emission factors

The last step before calculating greenhouse gas emissions was the attribution of product-specific emission factors out of LCA-databases (e.g. Ecoinvent). The calculation of the greenhouse gas emissions was further done by multiplying the material flows with the emission factor of every single product.

The results of the case study in Austria have finally shown that accounting of emissions on a detailed product-level is applicable and delivers new insights both for material flow analysis and greenhouse gas emissions. This approach enables the differentiation between the whole supply chains as well as between the origin of products, if they were produced in domestically or abroad. In future, this case study should be extended for further material groups as well as for the whole consumption of products in Austria. Nevertheless, there is still a lot to do for developing and applying a new approach which is capable to account for all “direct” and “indirect” emissions a country is responsible for from a consumption-based perspective.

5 ARTICLE 2 - GREENHOUSE GAS EMISSIONS OF THE PRODUCTION CHAIN BEHIND CONSUMPTION OF PRODUCTS IN AUSTRIA - DEVELOPMENT AND APPLICATION OF A PRODUCT- AND TECHNOLOGY-SPECIFIC APPROACH

5.1 Introduction and content

The first article highlighted the importance for a detailed consideration at product-level in order to derive the most appropriate and practical climate mitigation measures. It further depicted the main methodical prerequisites for implementing such a disaggregated emission accounting. The second article now directly builds on the results of the first article, as the key methodical steps identified in the first article, will be incorporated into a new approach on one hand, and the case study of the mineral chain will be extended for the whole consumption of products in Austria. Thus, this article goes one step further as a new methodology will be described in a more detailed way and will be applied for the whole supply chains behind national consumption of products in Austria.

The article is therefore structured into two different parts. First, the "Materials and Method" section, where the developed approach is described in detail. The description includes all relevant methodical steps required to implement such an emission accounting on product-level. The second section, "Greenhouse gas emissions behind consumption of products in Austria", presents for the first time the results of a product-based emission accounting for the whole economy-wide consumption. In this context, the consumption of products in Austria was chosen as reference system.

The results of this article encompass three different kind of information: first, the total consumption-based emissions of Austria are illustrated. Additionally, the greenhouse gas emissions along the whole supply chain from raw materials up to final consumption are visible, including the origin of emissions in every process stage as well. Second, the main products responsible for the emissions are shown. The contribution of the single material groups and the most emission intensive products are therefore illustrated for every process stage. Third, one further aim of this article and this method was to shed light on the differences between countries in producing goods. Thus, the main trading partners of Austria and their respective emission intensities for producing goods are shown.

5.2 Published article

Greenhouse gas emissions of the production chain behind consumption of products in Austria - Development and application of a product- and technology-specific approach

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RESEARCH AND ANALYSIS

Greenhouse gas emissions of the production chain behind consumption of products in Austria

Development and application of a product- and technology-specific approach

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Abstract

Globalization has been one main driver affecting our whole economy. Thus, greenhouse gas emissions (GHGs) associated with imports and exports should get addressed in addition to the national emission inventory according to the United Nations Framework Convention on Climate Change (UNFCCC), which is focused on territorial emissions only. To enable a correct calculation for imports and exports and to find the most emission-intensive products and their origin, a product and technology-specific approach would be favorable which has not been applied up to now. This article addresses this research gap in developing and applying such an approach to calculate the GHGs behind consumption of products in Austria. It is based on physical flows combined with lifecycle-based emission factors and emission intensities derived from sector- and country-specific energy mix, for calculating all emissions behind the production chain (resources to final products) of products consumed in Austria. The results have shown that consumption of products in Austria leads to about 60% more emissions than those of the national inventory and that the main part of these emissions comes from the provision of products. The most emission-intensive products are coming from the chemical and the metal industry. In particular, imports are the main driver of these emissions and are more emission intensive than those produced in Austria. As a result, it is necessary to look at practical measures to reduce emissions along the production chain not only in Austria, but especially abroad as well.

KEYWORDS

consumption, energy systems, greenhouse gas emissions, life cycle analysis, product consumption, production chain

1. INTRODUCTION

Climate change and other great challenges were addressed in one universal agenda in 2015, as the Sustainable Development Goals (SDGs) were adopted by all member states of the United Nations (United Nations, 2018). With this all countries pledged to take action in 17 different fields of sustainability. Concerning climate change, the Paris Agreement, concluded at the Conference of Parties (COP) in Paris 2015 (European Union, 2018), was one further step forward as all parties confirmed that climate change has to be restricted at least to 2°C. To achieve this, it is necessary to reduce greenhouse gas emissions (GHGs) dramatically in all areas of our society, requiring encompassing transitions at global level (Maurer et al., 2016; Peters et al., 2013). Thus, detailed information about the sources of GHG emissions will be required to implement appropriate measures and strategies to reduce them. The national reporting system of the UNFCCC has become a worldwide accepted instrument for GHG accounting at the national level. All countries, committed to the UNFCCC, are bound to report their emissions annually in national inventories. This reporting scheme includes all activities occurring within national boundaries only, but neglecting impacts induced by international trade. In times of globalization, however, imports and exports have become of increasing importance and should be taken into account as well (e.g., Bruckner, Polzin, & Giljum, 2010; Sato, 2012). The EU has stated in its Intended Nationally Determined Contribution (INDC) a binding target of an at least 40% domestic reduction in GHGs by 2030 compared to 1990, in order to fulfill the Paris Agreement (UNFCCC, 2018). Hence there is a strong reason for an EU country to consider at least its national emissions, but no incentive to reduce emissions globally. As climate change and the Paris Agreement are global challenges, an extended system boundary across national boundaries should be applied to avoid the outsourcing of national production sites, often associated with higher emission intensities and weaker climate regulation than within the EU (Lenzen, Murray, Sack, & Wiedmann, 2006; Wiedmann, 2009). Consumption-based approaches (CBA) have evolved to account for all emissions induced by national consumption, as emissions from international supply chains behind the global economy are considered (Lutter, Giljum, & Bruckner, 2016). Several studies, for example, Davis, Peters, and Caldeira (2011); Hertwich and Peters (2009); Peters (2008); Wiedmann (2009), have dealt with such an accounting recently, using predominantly global multi-regional input–output (MRIO) models. These approaches are based on databases comprising national input–output tables, which are connected with bilateral trade data illustrating the flow of goods in monetary units. These input–output (IO) tables are extended with sectoral data on environmental impacts and enable the calculation of GHG emissions induced both within and across country borders (e.g., Bruckner, Giljum, Khoroshun, Lutz, & Wiebe, 2009; Lenzen et al., 2006; Tukker et al., 2006; Wiedmann, Lenzen, Turner, & Barrett, 2007). But, there are some key challenges and sources of uncertainty that need to be addressed in future research as shown, for example, in Dittrich, Bringezu, and Schütz (2012); Lininger (2015); Liu, Liu, Fan, and Zou (2015); Lutter et al. (2016); Peters (2007). One main challenge is concerned with the high level of sector aggregation. This means that products of low and high emission intensity may be aggregated in one sector leading to a significant increase of uncertainty. Consequently, these approaches are appropriate for country-level or regional analysis, but are limited in providing accurate information on the level of single products. Recently, the need and interest for such detailed information at product level has grown significantly to shed light on the emission intensity of products. Besides the aggregation problem, the predominant use of monetary data as a basis for the calculation of GHGs is a further source of uncertainty, as physical data may be more appropriate for emission calculation than monetary data. In this context, some approaches combine physical with monetary data, however, further research is necessary to get a complete and sufficient dataset on global level (Lutter et al., 2016). Furthermore, the analysis of production chains is another important step which should be regarded in future research. This allows to trace GHGs from resources up to final consumption considering domestic, imported, and exported emissions at every production stage. When we look at the situation in Austria, as a UNFCCC-member state, it has to report GHGs, which occur within national boundaries only. But, in recent years different studies (e.g., Bruckner et al., 2009; Munoz & Steininger, 2010; Steininger et al., 2016) focused on the calculation of national

GHGs from a consumption-based perspective as well. The results, using economic IO models, have shown that Austria's consumption-based emissions (CBE) are about 50% higher than those of the national inventory. The real drivers behind the emissions induced by the Austrian consumption, however, have not been visible so far mainly because of the aggregation problem. To avoid the main challenges associated with CBE accounting using input–output models, further approaches emerged in recent years. The LCA-based or coefficient approach makes use of emission factors from life cycle analysis (LCA) databases especially to calculate the imported and exported emissions. The domestic part is mainly taken directly from available statistics and documents (Dittrich et al., 2012, Frischknecht et al., 2014). This approach tries to avoid the problem of high aggregation by calculating emissions of imports and exports on product level with emission factors from LCA databases, which differentiate between various materials and products. LCA data include all emissions occurring along the production chain up to the respective product, but are limited in avoiding truncation errors as global supply chains cannot fully be analyzed (Dittrich et al., 2012; Lutter et al., 2016). The domestic emissions, however, are not considered at such a detailed product level. Consequently, the domestic contribution at national consumption is not visible at product level, as there is no link between domestic and foreign products. Besides LCA-based approaches, which are predominantly used for single products or product groups (e.g., Castellani, Fusi, & Sala, 2017) because of the high effort and complexity (Bruckner et al., 2009; Lininger, 2015), hybrid approaches have established as well. This kind of emission accounting mainly combines input–output models with LCA data to avoid the respective weaknesses and make use of the advantages. The basis for such a hybrid is an input–output model, which is extended with LCA data to calculate key (mainly imported) products at a disaggregated level (Lutter et al., 2016; Sato, 2012). None of these approaches, however, is able to account for all emissions behind national consumption at a detailed product level avoiding the use of monetary data.

This article aims at going beyond previous research in calculating the GHGs induced by consumption of products in Austria. In this context, consumption is defined as all products (for private, public, and

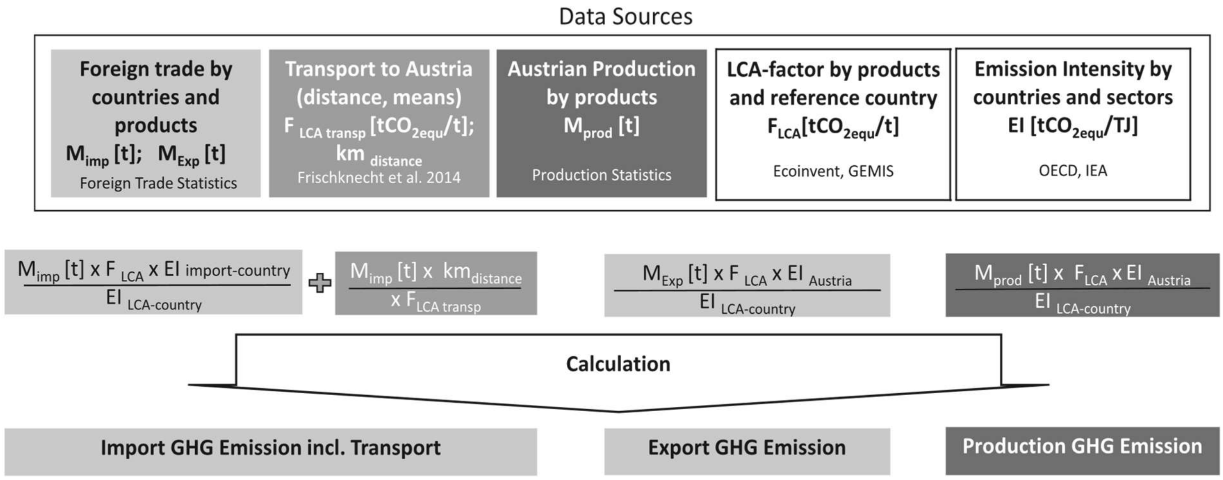

Fig. 1 Overview of the data sources and calculation principles of the product- and technology-specific approach

industrial purpose) remaining in Austria in 1 year as a balance of national production plus imports minus exports, by ignoring possible stockpiling. Services are so far considered as they are related to the use of products. A product- and technology-specific approach was therefore developed and applied to allow the calculation of GHG emissions behind imports, exports, and national production by considering the production chain from raw materials to final consumption on detailed product level and calculating the emissions based on physical data with LCA-based emission factors. Whereas the physical flows in the production chain are regarded in this approach, the supply chain, in contrast, reflects especially the monetary international interlinkages in foreign trade used in input–output models. Furthermore, this article aims at identifying the real emission drivers in national consumption and their origin by analyzing which products are the most emission-intensive ones and the portion of emissions coming from national activities and abroad.

The technological focus of this approach can further be used to depict feasible negative effects coming from a territorial perspective, if emissions increase at global scale due to higher emission intensities in the foreign production countries than in Austria.

2. MATERIALS AND METHODS

This article applies a product- and technology-specific approach, developed in the course of a recently finished research project (Windsperger et al. 2017). Thus, this article builds on that project, particularly from a methodological perspective, but disclosing the methodological details in this paper including a discussion of uncertainties and limitations as well as bringing to light new analysis of results in the context of the main drivers behind national consumption. Furthermore, the focus of this article is to make available this kind of approach to the scientific community, which was not the key role of the project. Overall, Figure 1 shall give an overview of the main elements, data sources, and the calculation principle of this method.

The bases for the calculation are physical material flows for the national production, imports, and exports in Austria (see Figure 1). Product-specific emission factors from LCA databases are used to calculate the emissions by multiplying them with the mass flows of the respective product. Additionally, country- and sector-specific emission intensities for depicting the energy system in the respective production countries are applied twice; first, for adjustment of the LCA data to the respective foreign country of origin and second, for the adjustment to national production and exports, where Austria was used as the origin country. In all cases, the factors were adapted with the relation of the emission intensity of the production country to the LCA-data-related country. The transport emissions for imports were calculated by taking average transport means for different regions and transport distances to Austria. For exports, no transport was calculated as these emissions are not relevant for the CBE. In a next step, this topic will be pursued to show advantages of Austrian products for the destination countries. As a result, the GHGs for imports, exports, and the national production were received for every product. Finally, the emissions of the consumption of products are calculated with the following equation:

$$\text{Consumption of products} = \sum \text{National production} + \sum \text{Imports} - \sum \text{Exports}$$

The used LCA data, however, are generally based on physical units and are related to the provision of products only, neglecting the use phase (e.g., electricity, fuel, heating), comprising partly disposal as far as it is included in LCA data. For providing the total CBE, those coming from the use of products were supplemented by using information about electricity consumption, heating, and fuel consumption reported in the national emission inventory of Austria (Zechmeister et al., 2015). The following section explains the most important steps necessary for this approach in detail.

2.1 Determination of the scope based on LCA-data availability

First, the scope was defined to manage this detailed approach. All products Austria is importing and exporting and producing domestically are included in this analysis. But, to limit the scope to a manageable extent, an appropriate level of detail was selected. The Combined Nomenclature (CN)-classification of the foreign trade was used, distinguishing between 2-digits (aggregated), 4-, 6- and 8-digits (disaggregated). The main source for LCA data was the Ecoinvent database (version 3.2, Wernet et al., 2016), from which attributional LCA data were collected. If no appropriate factor was available in Ecoinvent, GEMIS was used instead. Additionally, data from producing companies were used in cases of missing

CN 2-digit	CN 4-digit	CN 6-digit	LCA-availability
Meat	Meat of bovine animals,	Carcases or half-carcases of bovine animals, fresh or chilled	red meat, live weight (Ecoinvent)
	Meat of swine	Fresh or chilled bovine cuts, with bone in	swine for slaughtering (Ecoinvent)
	Meat of sheep or goats	Fresh or chilled bovine meat, boneless	sheep for slaughtering (Ecoinvent)
Coffee	Coffee	Coffee	Coffee (Ecoinvent)
	Tea	Decaffeinated.	
	Mate	Roasted coffee	
	Vanilla	Coffee husks and skins	
Dairy Products	Milk and cream, not concentrated	Milk and cream of a fat content by weight of <= 1%	skimmed milk, from cow milk (Ecoinvent)
	Milk and cream, concentrated	Milk and cream of a fat content by weight of > 1% but <= 6%	cream, from cow milk (Ecoinvent)
	Buttermilk	Milk and cream of a fat content by weight of > 6% but <= 10%	buttermilk, from cow milk (Ecoinvent)
	Butter	Milk and cream of a fat content by weight of > 10%	butter, from cow milk (Ecoinvent)
Beverages	Water	Waters, incl. natural or artificial mineral waters and aerated waters	Xtra-TrinkwasserDE-2000 (Gemis)
	Beer made of malt	Mineral waters and aerated waters	Beer (World Wide Fund For Nature)
	Wine of fresh grapes	Ordinary natural water	Wine (World Wide Fund For Nature)
	Ethyl alcohol		Ethanol, without water (Ecoinvent)
Wood and articles of wood	Wood in the rough	Coniferous wood in the rough	roundwood, primary forest (Ecoinvent)
	Fuel wood	Red meranti in the rough	roundwood, secondary forest (Ecoinvent)
	Wood charcoal	Tropical wood	roundwood, meranti (Ecoinvent)
	Hoopwood	Oak "Quercus spp." in the rough	roundwood, paraná pine (Ecoinvent)
Salt, Sulphur, Earths and stone	Salts, incl. table salt and denatured salt	Crude dolomite, not calcined or not sintered	Sodium chloride (Ecoinvent)
	Sulphur of all kinds	Calcined or sintered dolomite	Sulfur (Ecoinvent)
	Kaolin and other kaolinic clays	Dolomite ramming mix	Kaolin (Ecoinvent)
	Dolomite, whether or not calcined or sintered,		Dolomite (Ecoinvent)

Fig. 2 Exemplary illustration of the LCA availability and the selection of product levels

data and to check the results. LCA data include all emissions along the life cycle from raw materials up to the considered product (Jungbluth, Nathani, Stucki, & Leuenberger, 2011; Lenzen et al., 2006). Thus, it is important to use appropriate factors for the products in line with the respective processing depth to calculate the emissions in a correct way. Best representative LCA-based emission factors for each of the products were selected, looking at the description of the corresponding LCA data especially concerning system boundaries and cut-offs. As emission factor, the IPCC 2013 Global Warming Potential (GWP) 100 was used directly including all GHGs (e.g., CO_2, CH_4, N_2O), illustrated as CO_2 equivalents (equ).

Emissions from land use and land use change, however, are not covered in this analysis.

The choice of the appropriate level was mainly driven by the heterogeneity of products and their emission intensities as well as the availability of LCA data. In Figure 2 the procedure for selecting the appropriate level of detail is shown for some product groups. The first three columns show different levels of detail from the highest (2-digit) to much lower aggregation (6-digit, corresponding always to the first 4-digit only). The last column (LCA availability) shows the most appropriate LCA data for the respective product groups. For the purpose of illustration, different LCA data exist for meat, making a distinction between various animals reasonable (e.g., beef). The CN-4-digit reflects exactly this kind of differentiation (illustrated as the bolded frame in Figure 2). In contrast, the 2-digit level would be too aggregate as the differences in the 6-digit cannot be reflected in LCA data. For other product groups, however, the more aggregated (e.g., coffee) or more disaggregated digit (e.g., wood) may be more appropriate due to less, respectively, higher LCA differentiation. Overall, a product list consisting of around 1,000 products was created and can be found in Table S1 in Supporting Information.

2.2 Attribution of products to their production stages based on the processing depth

The products under consideration were further analyzed for their appropriate position in the production chain (=production stage). This attribution was inevitable to avoid double counting, as the used emission factors comprise all life cycle emissions up to the considered good. Throughout the project, four different process steps were distinguished, raw materials, basic materials, intermediates and final products, to overcome this double counting threat. Thus, the following question had to be answered for every product: Are they further processed and part of a final product or are they final products themselves? The attribution was mainly derived from the description of the products available in the foreign trade statistics. In this context, the higher levels of detail (e.g., 6- or 8-digits) were sometimes used to get more detailed information about the product, especially concerning its processing depth. Furthermore, every product was analyzed for required inputs and outputs to build a correct and complete production chain. In some cases, the corresponding outputs were missing. It especially emerged for raw materials (e.g., vegetables, stones), for which an essential part is not processed, but rather used directly as final products. For these products the respective part was counted twice as raw material and product to depict the emissions in every production stage in a correct and complete way. The final CBE, however, consist of those emissions of final products only in order to avoid double counting.

2.3 Collection of trade and production data in physical units

Since all products have been attributed to the stages in the production chain, a physical material flow balance was developed. The physical amounts of imported and exported and domestically manufactured products were taken from foreign trade (Statistics Austria, 2018a) and production statistics (Statistics Austria, 2018b) from Statistics Austria mainly. The year 2013 was chosen as it was the most recent year with complete statistical data. Foreign trade is in general well documented and provides all required data for physical and monetary amounts for 246 different countries (additional data can be found in Table S2 in Supporting Information). Challenges emerged for the national production as physical data were often missing due to confidentiality reasons. In such cases, monetary data were used and converted to physical amounts via average prices of similar products, calculated by the relation of physical and monetary data taken from the foreign trade statistics. Additional information from reports of industrial branches and sector-specific literature were used to close data gaps. This was important for products from agriculture and forestry as these data are not included in the national production statistics, but given in reports focusing on agriculture (e.g., BMNT, 2018). Moreover, production statistics data use different units (e.g., kilogram, cubic meter). A harmonization between the different units was done by converting them to kilogram with average weights and densities (Windsperger et al., 2017). Finally, production data could be completed and harmonized so that all domestic material flows in Austria were given in mass (metric tons). As quality indicator, 88% of all quantities were given directly in metric tons, whereby 57% was coming from the national production statistics, 5% was supplemented by data from agriculture and forestry ("Grüner Bericht"), 26% from reports of industrial branches and single companies. The final 12% of all quantities were calculated from monetary values with prices, separated in 7% resulting from different units (e.g., pair, unit) and 5% where physical data was confidential.

2.4 Harmonization of production and trade data

The harmonization of production and foreign trade data is inevitable as these two statistics are illustrated in different classification schemes. To merge these data the correspondence list of Statistics Austria (2017) between the classification scheme of the production statistics (CPA – Classification of Products by Activity) and the foreign trade statistics (CN) was used. An overview of this correspondence can be found in Table S3 in Supporting Information.

2.5 Country- and sector-specific regionalization of emission factors

LCA data are generally available for regions such as Europe or global, only sometimes for selected countries (e.g., Switzerland or Germany). A further aim was to reflect the specific situation of production in the respective countries, which was done through the emission intensity of the energy mix of the different industrial branches in the countries of origin. As databases, the world energy balances from the IEA (2018) and OECD (2018) were used, where data for the industrial energy mix for 14 different sectors (=material groups) and more than 100 countries are given. Those countries, which do not have specific energy mix available, were attributed to countries with assumed similar energy system. The emission intensity of the energy mix was further calculated with emission factors for the respective energy carriers taken from Pazdernik et al. (2015). The intensity of electricity was calculated from the electricity mix. In a next step, the LCA data were adapted with the relation of the emission intensity of the respective country of origin to the LCA-data-related country. Thus, every product had to be attributed to these 14 sectors (it can be found in Table S4 in Supporting Information). As the sectors mainly reflect material groups (e.g., iron and steel, petrochemistry), the attribution was primarily based on the composition and the properties of every product. Final products, which often consist of different kinds of materials, were also attributed to one sector depending on the materials with the highest share in the products. Consequently, emission factors could be derived specifically for relevant countries behind the imports as well as national production and the exports wherefore the Austrian standard was applied (Windsperger et al., 2017).

3. GREENHOUSE GAS EMISSIONS BEHIND CONSUMPTION OF PRODUCTS IN AUSTRIA

The results section shows three different kinds of new insights coming from the applied approach: First, to depict the GHGs along the whole production chain behind national consumption of products including domestic, imported, and exported emissions for every production stage. Second, to illustrate the distribution of different material groups and to identify the main emission relevant products behind national consumption. Third, to show the main trading partners of Austria from an emission point of view including differences in the emission intensity of the production in the respective countries of origin.

3.1 Consumption-based greenhouse gas emissions from raw materials up to final products

The results of the GHGs are illustrated from raw materials (=resources) up to the national consumption of products in Austria (see Figure 3). Basically, the emissions due to national production, imports, and exports are visible for every production stage, as the arrows show the GHGs in million tons (Mt) of CO2equ. The domestic production emissions are visible as a horizontal arrow coming from the respective production stage (e.g., 11 Mt CO2equ for domestic raw materials). The imported emissions come from abroad (e.g., 13.5 Mt CO2equ for raw material import) and the exported emissions go outside (e.g., 1.3 Mt CO2equ for exported raw materials). Next, all emissions occurring in one production stage are merged into a balance of production plus imports minus exports at this stage. The result of the balance is further the input for the next stage in the production chain.

Overall, the emissions due to imported materials and products (121.5 Mt CO2equ) are significantly higher than those of the exports (67.1 Mt CO2equ). The transport, however, is of minor importance for the import emissions (lower than 10%).

As a result of Figure 3, the balance of final products (92.9 Mt CO2equ) represents all GHGs associated with the provision of products consumed in Austria in 2013. This contribution to the final consumption can be divided into 52.8 Mt CO2equ coming from abroad and 71.4 Mt CO2equ being produced in Austria. Concerning national production and exports, only a part of the supply chains comes from Austria, thus, the physical relation between the domestic and foreign supply of materials behind every process stage was considered. For the imported part, the standard in the respective countries from which Austria imports was applied. As a result, about one third of the 71.4 Mt CO2equ associated with domestic final products come from abroad required to supply the domestic consumption. Consequently, the emissions behind final consumption are dominated by imported emissions compared to those of national origin. Emissions due to the use of products (e.g., fuel and electricity consumption, heating) were included as well (37.2 Mt CO2equ), taken directly from the national emission inventory

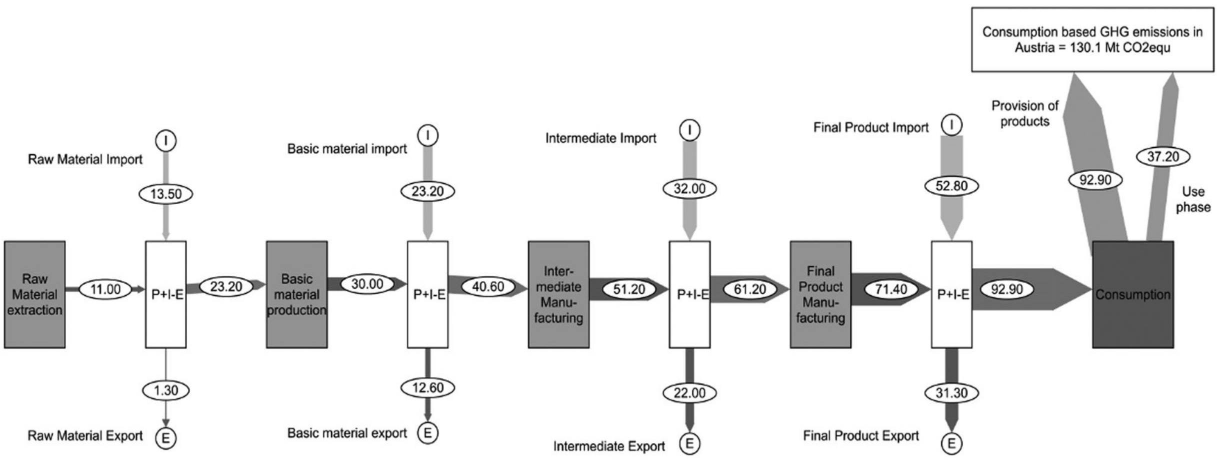

Fig. 3 GHG emissions of the production chain behind consumption of products in Austria in 2013, in million tons (Mt) CO_{2equ}

(Zechmeister et al., 2015). Totally, the CBE of Austria amount to 130 Mt CO2equ in 2013 (see Figure 3), whereby about 93 Mt CO2equ (71%) are emitted along the production chain for providing the products behind the national consumption and only a minor part (29%) comes from the direct use of products. As seen in Figure 3, an emission`s increase along the production chain takes place, as LCA data comprise all emissions behind the production chains up to the considered good. The highest emission increase occurs from raw material provision up to the stage of intermediates. In contrast, the emissions increase from intermediates to final products is comparatively low, as some final products include unprocessed raw materials (e.g., vegetables, gravel) as well, which are not as emission intensive as processed intermediates.

3.2 Main products behind national consumption in Austria

As the previous section has shown, the provision of products is of key importance in the context of Austria's CBE. Thus, detailed information about the most emission-intensive products are needed in order to reduce emissions in the most efficient way. First, the distribution of the emissions to the different material groups is illustrated in Figure 4. In this case the same sectors used for the regionalization were applied. As material groups, the sectors of the energy balances, used for the regionalization with emission intensities.

The distribution of emissions shows that for every production stage three material groups (=sectors) represent more than two thirds of the total provision emissions. In detail, products from "Petrochemistry" are dominating the most production stages, especially in the context of raw materials and basic materials. Besides, products out of "Agriculture and Forestry" are the most emission-intensive raw materials, "non-ferrous metals" products are of main importance for basic materials, products of the "iron and steel industry" are most relevant for intermediates and final products (see Figure 4). The top-10 emission-intensive products of CBE are further shown for every process step (without emissions from the use phase) in Figure 5.

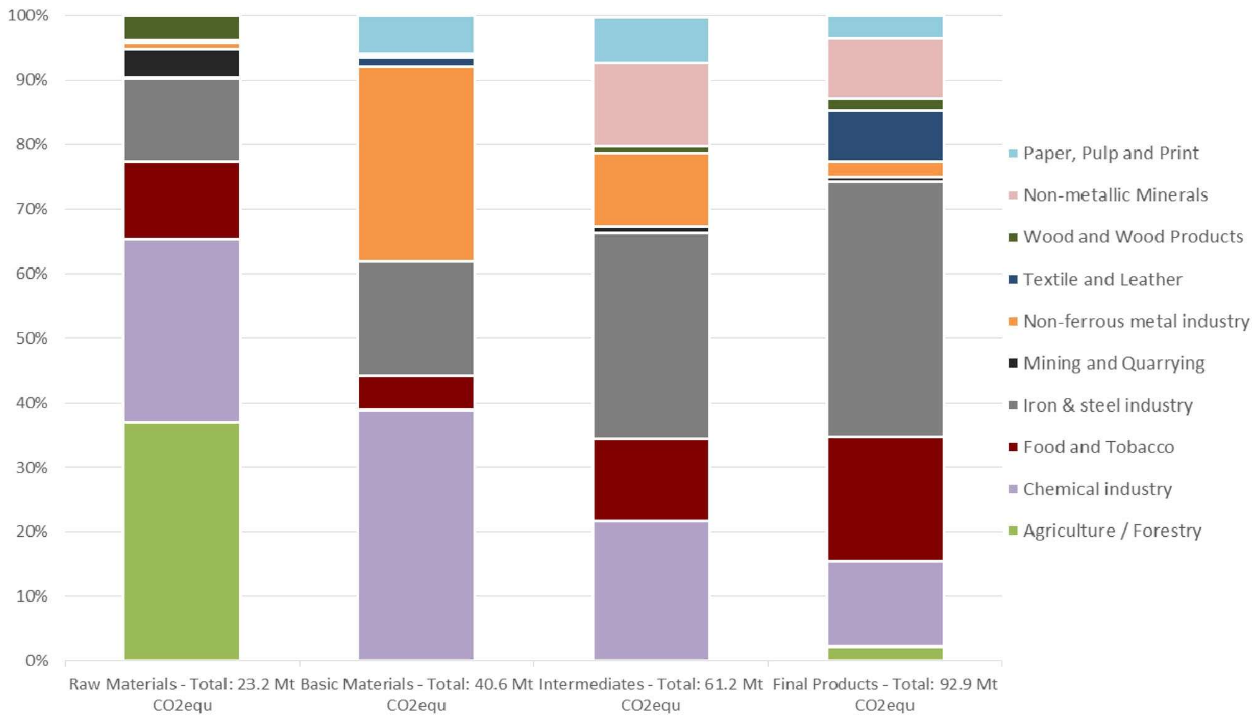

Fig. 4 Distribution of Austria's consumption-based emissions (2013) to different material groups for every production stage

The share of the top-10 products on the total provision emissions is high especially for raw materials (75%) and basic materials (70%), but decreases in the course of the production chain. Intermediates still have a 49% share of the 10 most emission-intensive products, followed by 34% at the step of the final products. This can mainly be explained with the higher diversity of products at the end of the production chain. Looking at the respective production stages, it is visible that the origin of the emissions is highly different among the products. Exemplarily, Austria's most emission-intensive raw materials are "petroleum gases," where the imports are dominating. "Milk and cream" is at second position exclusively due to national production. "Iron ores" and "petroleum oils," in contrast, are mainly influenced by imported emissions (see Figure 5).

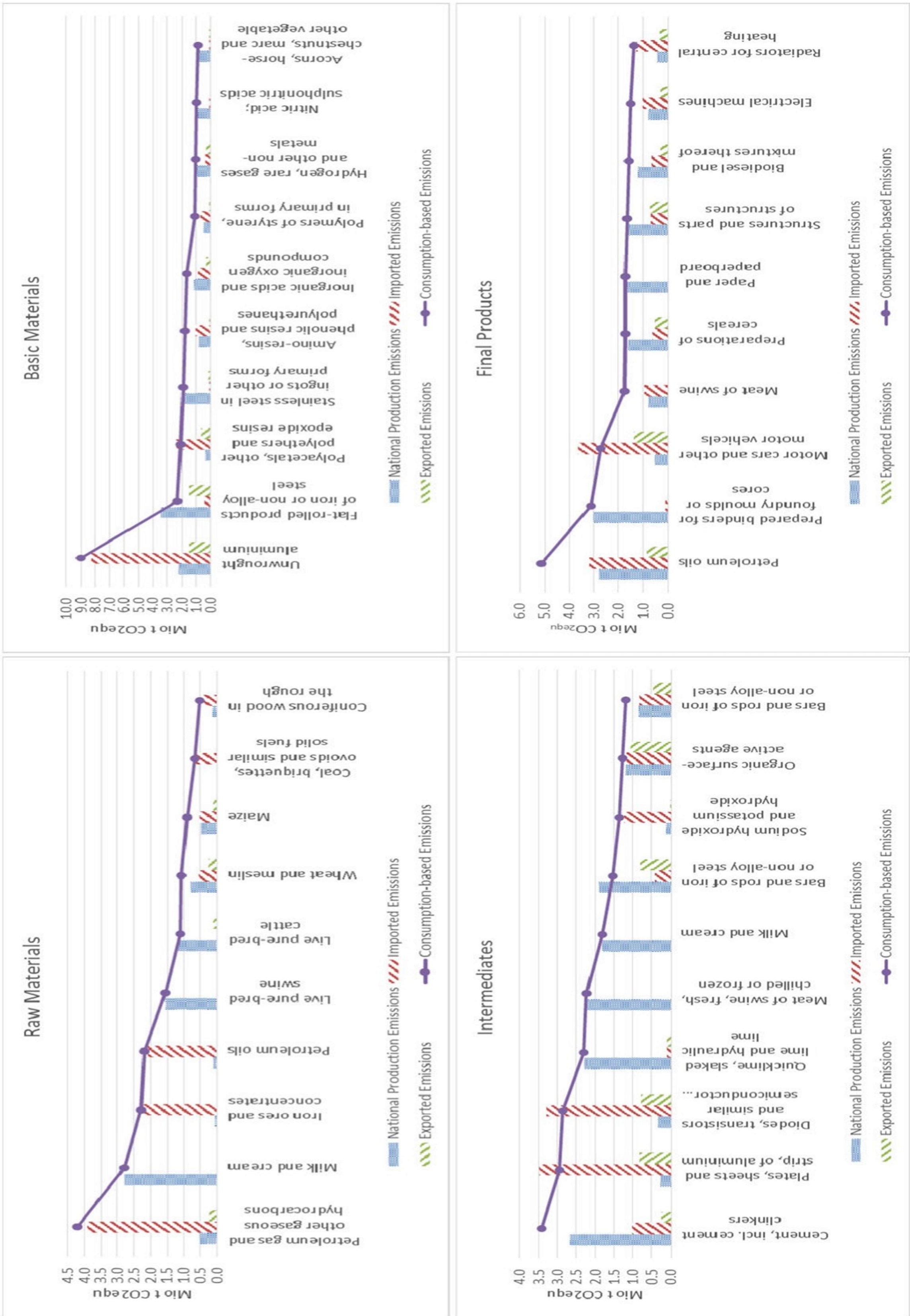

Fig. 5 Main products according to consumption-based emissions (2013) in every production stage, in million tons (Mt) CO_{2equ}. Underlying data provided in Supporting Information S1

3.3 Countries of origin and differences in emission intensities

The last result section depicts the origin of Austria's imports and the destination of Austria's exports including the main differences in emission intensities for production. In general, Austria depends heavily on imports in supplying the products for national consumption and exports for generating added value, respectively. Figure 6 gives a short overview of where Austria import products from and to which countries Austria exports. The most important trading partners are shown separately aggregating all the others together into "other-Europe" and "other non-Europe," selecting the countries from an emission point of view.

As shown in Figure 6, Austria's most important trading partners are countries inside Europe, which is valid both for imports (79%) and exports (75%). In more detail, Germany is the most important trading partner of Austria with 36% of all imports and 35% of all exports. Hereafter, Italy, China, Czech Republic, Hungary, Netherlands, Poland, and Slovakia are further countries from which Austria is essentially importing. For exports, Italy is Austria's second important export country with 10%, followed by Poland, Czech Republic, Hungary, and USA. Nevertheless, it has to be mentioned that in this analysis the countries represent the first level of imports and exports only.

So if Austria is importing final products from Italy, we assume that all goods and

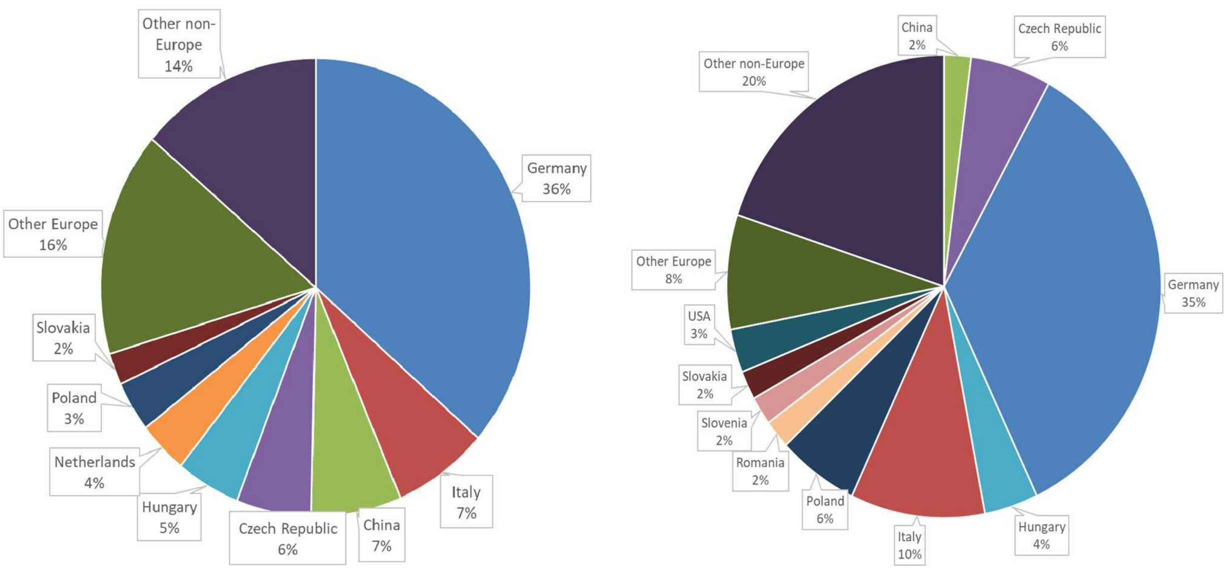

Fig. 6 The origin of Austrian imports (left) and destination of exports (right) in 2013, related to GHG emissions

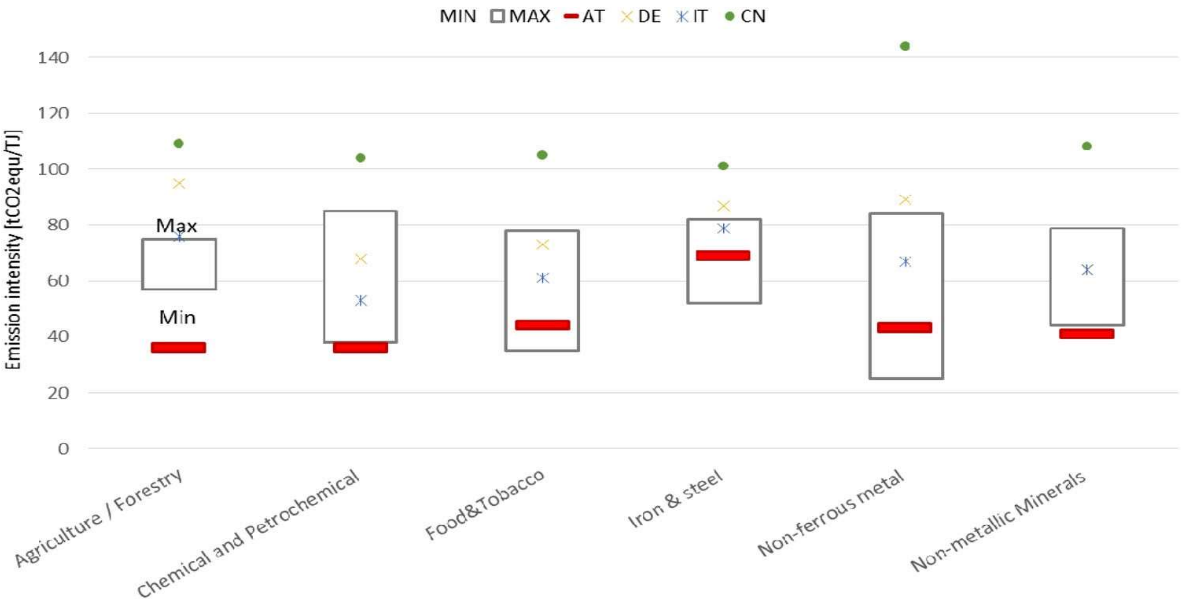

Fig. 7 Range in emission intensities of Austria and its main countries of importation, illustrated for different sectors. Underlying data provided in Supporting Information S1

processes required for the manufacturing of these products take place in Italy. In fact, parts of the supply chains might occur in other countries and are further processed to final products in Italy. This is one main uncertainty which has not been solved in this analysis, especially because of missing information of the real origin on product level in foreign trade statistics. Nevertheless, there may be differences at least in the energy system for producing materials and products. In the course of this approach, the emission intensity of the energy system in more than 100 countries for 14 different sectors was considered to adjust the LCA data to the standard of the energy system in the respective countries. The used emission intensities (in t CO2equ per TJ) are illustrated in Figure 7 for the most emission-intensive material groups (=sectors), based on the results in Figure 4. It shows the range of emission intensities for the three most relevant countries from which Austria is importing. Furthermore, the Austrian standard as well as those of Germany, China, and Italy are shown as well with small symbols, lying sometimes within but also outside the range of the top-3 countries.

Generally, Austria has a comparatively low emission intensity in producing materials and products, at least from the energy

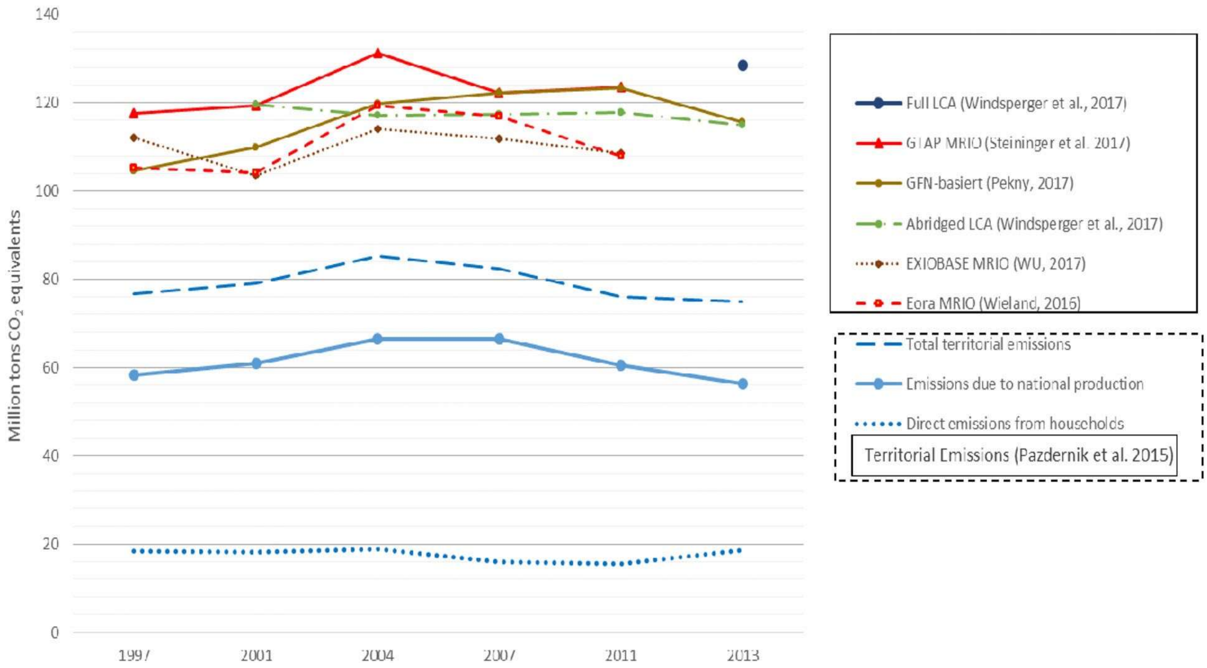

Fig. 8: Comparison of different models applied for calculating Austria's consumption-based emissions. Underlying data provided in Supporting Information S1

point of view. This is mainly due to the high portion of renewable energy carriers, which was slightly increasing to 33.5% in 2016 (Federal Ministry of Sustainability and Tourism, 2017). In contrast, Austria's imports show higher specific emissions per ton than goods produced in Austria (Additional data can be found in Figure S1 in Supporting Information, in comparison to Figure 3). The reason might lie in the dependence on some emission-intensive products, which cannot be produced domestically (e.g., fuel, primary aluminum), or benefit from cost and quality considerations. In detail, Austria shows clearly the lowest emission intensity in "Agriculture/Forestry," "non-metallic minerals," and "Chemical and Petrochemical industry."

The maximum intensity of the top countries is affected by Serbia ("Agriculture/Forestry"), Czech Republic ("Minerals"), and Poland (Chemicals") due to a dominant use of fossil energy carriers. In other sectors such as "Food and Tobacco" (Switzerland), "non-ferrous metal" (France), or "iron and steel" industry (France) some import countries have still lower intensities than Austria, illustrated by the minimum emission intensity in Figure 7. China shows the highest values in all sectors.

4. DISCUSSION

The developed approach leads to GHGs associated with the consumption of products in Austria of 130 Mt CO2equ, which are 62% higher compared to those of the national inventory in 2013. This estimate corresponds generally well with similar calculations based on economic input–output models as illustrated in Figure 8. These studies have reported CBE beginning in 1997 between 105 and 120Mt CO2equ. Until 2004 the emissions increased slightly, followed by a decrease in the following years till 2013. The developed approach, in contrast, shows higher emissions at 130 Mt CO2equ for the year 2013 only.

To sum up the results of this approach, the presented CBE have shown a significant dominance of the emissions behind the provision of products domestically and from abroad, which are clearly higher than those emitted by the direct use of energy carriers. Products from the chemical (e.g., petroleum oils) and metal industry (e.g., aluminum or steel plates) show the highest emissions and should be investigated for measures how to reduce them. This could be achieved through decarbonising the production process or product substitution with climate-friendly materials. Furthermore, the choice of the country of origin may be an appropriate opportunity to reduce emissions of imported products, especially if they are produced with high emission intensity. The found high sensitivity of country- and sector-specific regionalization on the results indicates the magnitude of such measures. From the regionalization of the emissions to the energy system in the producing countries, it became evident that Austria performs comparably very well due to low emission intensity because of a high share of renewable energy carrier in the Austrian energy mix. As this may not be always the case, the special situation should be considered and could reveal distinct potential for improvement. In contrast, it has to be remarked that the regionalization refers only to the countries from which Austria imports and neglects possible supply chains behind, as this information lacks in the foreign trade statistics of Austria. Actually, this is one main weakness of the developed approach, which will be pursued to be improved by a combination with MRIO information allocated to specific products. Additionally, the regionalization primarily relies on the industrial energy mix. This may be appropriate for energy-intensive products, but further data on production structure will be required especially for products from agriculture and forestry.

One further key aspect regarding the use of LCA data is the missing time differentiation of these emission factors. Their update could be improved by implementing the actual situation of energy intensities (energy demand per product unit) in the production sector.

5. CONCLUSION

This article presents, for the first time, the calculation of Austria's consumption-based GHGs at a detailed product level by combining physical material flows with LCA-based emission factors. The emission intensity of the energy system in the countries of origin was used for adapting the LCA data to the respective country. The applied approach provides, in general, more details for calculating GHG emissions behind national consumption than previous input–output methods because of more disaggregation and higher accuracy concerning product specificity. It further helps to identify the real drivers behind the induced emissions and to plan measures and future strategies on how to reduce them. As the results have shown, the emissions due to the provision of products consumed in Austria are of much higher importance than the use of products. Consequently, structural changes in the supply of products, for example, by striving for a more conscious procurement of products considering sustainable conditions at the respective production sites are one possibility to reduce these emissions. The substitution of emission-intensive products with more climate-friendly ones or increases in the lifetime coming from a promotion of high quality may be other strategies. But, it is necessary to regularly prove the feasibility and potential consequences and repercussions of such strategies to achieve the desired effects and avoid potential rebound effects. Finally, this approach may also be conducted in other countries, whereas first of all the availability of required industry data has to be checked. It would also be possible to calculate not only GHGs, but also some other environmental impact categories like acidification (SO2equ), as the attribution of LCA data was still made and various categories are available in LCA databases. To conclude, there is still need for improvement and future research especially on the knowledge of the truncated picture of the supply chains (e.g., behind imports), which has not been solved in this approach. For this purpose, a link to MRIO data might help to address this problem, as these models have a better picture of the international interlinkages behind traded products. In more general, this climate assessment of single products works only with adequate and actual emission factors. Unfortunately, the availability of actual LCA data is one key challenge that has to be tackled in future, as the current approach makes use of large assumptions regarding the adjustment of the emission intensities based on the energy mix only. In this context, the incorporation of the energy intensity (energy per produced good) in the production sector would be an interesting possibility for updating LCA data.

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CONFLICT OF INTEREST

The authors have no conflict to declare.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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5.3 Summary of the main results

This article has presented for the first time an approach, which is capable of accounting for all “direct” and “indirect” emissions. Thus, the greenhouse gas emissions induced by the national consumption of products are visible as well. To show the practicability of this approach, the case study of Austria serves as a reference system. In the following section, the procedure of this approach will be summarized.

The article started with an in-depth investigation of the national statistics in Austria to define the scope. The foreign trade statistics were chosen as the best suitable, as it is structured into different aggregates, ranging from highly aggregated (2-digit) up to more disaggregated product descriptions (4-, 6- or 8-digit). To manage the great diversity of products, the most appropriate product-level was chosen. The main criteria therefore were the emission intensity of products, analyzed by life cycle based emission factors from LCA-databases (e.g. Ecoinvent). Thus, the respective product levels depended primarily on the heterogeneity of emission factors within product groups as well as on the availability of emission factors.

Overall, around 1,000 products were defined, which were further attributed to the single steps in the supply chain. This step is of main importance if LCA-data are used to avoid double counting, as LCA-based emission factors mainly comprise impacts along the whole life cycle up to the considered good. In this case, four process stages were defined: raw materials, basic materials, intermediates and final products. Furthermore, this process stages allow to trace material flows and greenhouse gas emissions along the whole life cycle.

Once the respective products were attributed to the single process stages, data for national production, imports and exports were collected in physical units. The national foreign trade and production statistics as well as further literature (e.g. industrial reports) were therefore analyzed. As both statistics show different product classifications, a harmonization was necessary. Finally, the differentiation between the emission intensities of countries in producing goods was done by a country- and sector-specific regionalization. The energy mix of 14 different sectors was therefore analyzed for more than 100 countries. This was necessary, as LCA-data mainly correspond to regions (e.g. Europe) or some specific countries (e.g. Switzerland), but are not available for various countries in the world.

In general, the results of this approach have shown that consumption of products in Austria leads to about 60% more emissions than those of the national inventory. The main part of these emissions come from the provision of products both domestically and abroad. This is one inherent difference as the national inventory, which is focused on national activities only, publishes higher emissions through the use of products. (e.g. fuel consumption, heating, etc.). Thus, it is visible that the manufacturing of products imported to Austria increases the consumption-based emissions of Austria dramatically. The results further show the development of greenhouse gas emissions along the whole supply chain. A clear increase can be observed, which underlies the principle of LCA, as the impacts of the whole life cycle are covered. The single process stages have shown a similar relation as the emissions induced by imports were always higher than those of exports.

When looking at the real drivers of emissions, it is important to distinguish between the process stages. Regarding raw materials, resources from agriculture and forestry show the highest portion on the total emissions, followed by the petrochemical resources. The chemical industry shows further the highest emissions for basic materials, whereas in the iron and steel industry the intermediates and final products are responsible for the main part of emissions. For fulfilling the claim for detailed information on product-level, the most emission-intensive products were depicted in a next step for every single process stage in the supply chain.

The most emission intensive raw material was therefore petroleum gas, whereby the emissions mainly are induced due to imports. The same dominance of imports ca be observed for petroleum oils and iron ores. In contrast, agricultural resources such as milk or animals (e.g. cattle) are dominated by domestic emissions. For basic materials, unwrought aluminium has clearly the highest emissions, whereas the manufacturing abroad shows the highest portion.

Regarding intermediates, there is greater diversity of emission intensive products, as products from different material groups show high emissions (e.g. cement, lime, aluminium plates, diodes and transistors, milk, meat). The most emission intensive final product is petroleum oil, but there are products from various material groups with significant emissions as well (e.g. meat, paper, cereals).

Consequently, this part of the results has shown that there is a great diversity regarding the most emission intensive products, depending on the respective process stage and the origin of emissions. The origin of imports and exports was investigated as well and depicted Germany as Austria's most relevant trading partner. Overall, the main part of imported and exported emissions are related to European countries.

But, it was mentioned that those countries represent the first level of imports only. If products were imported to Austria, the whole supply chain was calculated with the emission intensity of this country, neglecting that some parts of the supply chain have occurred elsewhere. Finally, the results section of this article focused on the differences between the emission intensity of countries in producing goods. This analysis showed a unique insight. In almost all material groups the emission intensity of Austria was clearly lower than those of countries Austria is importing from. Thus, from an energy point of view, producing in Austria emits quite lower greenhouse gas emissions than manufacturing abroad.

6 DISCUSSION AND CONCLUSION

6.1 Discussion of the results

This thesis has tried to shed light into the need and possibilities for accounting consumption-based greenhouse gas emissions on a detailed product-level. In this context, two kinds of results were presented. First (article 1), the importance for greenhouse gas emission accounting from a consumption-based perspective by having an in-depth look at detailed product level to uncover both direct and indirect emissions. Additionally, guidelines for implementing such an encompassing emission accounting were elaborated as well in this first part of the thesis. Second (article 2), the development of a new approach, which is capable to account for all direct and indirect emissions is presented. Thus, the greenhouse gas emissions induced by the national consumption of products shall be visible. To show the practicability of this approach, the case study of Austria served as a reference system.

In the following section, the main results shall be summarized and discussed in a broader scientific context to allow a better interpretation of the main insights of this thesis. In the first part, the demand for a consumption-based emission accounting on product-level was analyzed. This analysis answered the question if product-specific information behind emissions generate additional value compared to previous accounting approaches. As a result, several studies (e.g. Bruckner et al. 2009, Wiedmann 2009, Sato 2012, Lininger 2015, Lutter et al. 2016) have mentioned that the common high aggregation level especially of economic input output models require such information on a more detailed product-level. Besides, the use of physical instead of monetary data as basis for emission calculation was one further key demand for future research. An encompassing literature review was further done to get an overview of the existing emission accounting approaches from a consumption-based perspective and their capability to address product-specific information on a physical level. This review has shown that none of these approaches is able to account for all of the identified main analysis criteria (cf. Table 1 in the first article). The LCA-based approach on the one hand, allows an accounting on product level, but is limited to imports and exports. National production activities are mainly included from available statistics in this approach (Jungbluth et al. 2011, Dittrich et al. 2012, Lutter et al. 2016). On the other hand, environmentally extended input output models (EEIO) have their strengths in tracing supply chains across country borders, as they can include multiple regions (multi-regional input output models - MRIO). Nevertheless, these models have limitations in the high sector aggregation and the use of monetary data as basis for emission calculation (e.g. Giljum et al. 2013, Pinero et al. 2015, Eisenmenger et al. 2016).

The last section of the first part, the elaboration of the key challenges including proposed solutions, was also the starting point for the second part of this thesis, the development of a new product- and technology-specific approach for accounting greenhouse gas emissions due to national consumption of products. The application for the case of Austria of course, did not show the country's consumption-based emissions for the first time (e.g. Munoz and Steininger 2010), but the greenhouse gas emissions could herewith be traced on the level of single products along the whole life cycle. This was not possible on that detailed level before. On the one hand, this bottom-up information allows for the identification of the most emission intensive steps in the supply chain, to what extent the raw material extraction, the commodity production as well as the final product manufacturing are responsible for a country's consumption-based emissions. On the other hand, the source of emissions is visible as well, concerning both the origin (e.g. imported or domestically) and the product groups (e.g. chemical or mineral products). Of course, this kind of information can be delivered by current approaches as well, but especially the high sector aggregation does not allow recommendations e.g. concerning climate-friendly procurement and reduce the quality due to average emission factors.

Consequently, the development of this new approach was in fact a scientific challenge, as the need for an encompassing approach was confirmed in the course of this thesis as well. Nevertheless, its application for the case of Austria has shown that there are many assumptions and uncertainties needed associated with such a complex approach. The main challenges were still mentioned in the second article, but will be explained and discussed in a broader scientific context in the following section. This shall help to interpret the possible impact of implementing such an approach in other countries or deriving specific mitigation measures.

- Availability of the physical material flows

The basis for this product- and technology-specific approach is the adequate availability of physical data. They are used instead of monetary data because of the assumption of proportionality between physical and monetary flows (Jungbluth et al. 2011, Sato 2012a, Giljum et al. 2013). The physical flows from import, export and national production are further attributed to distinct steps in the supply chain and results in a material flow balance from raw materials up to final consumption. The material flows for Austria (2013) are illustrated in Figure 6.

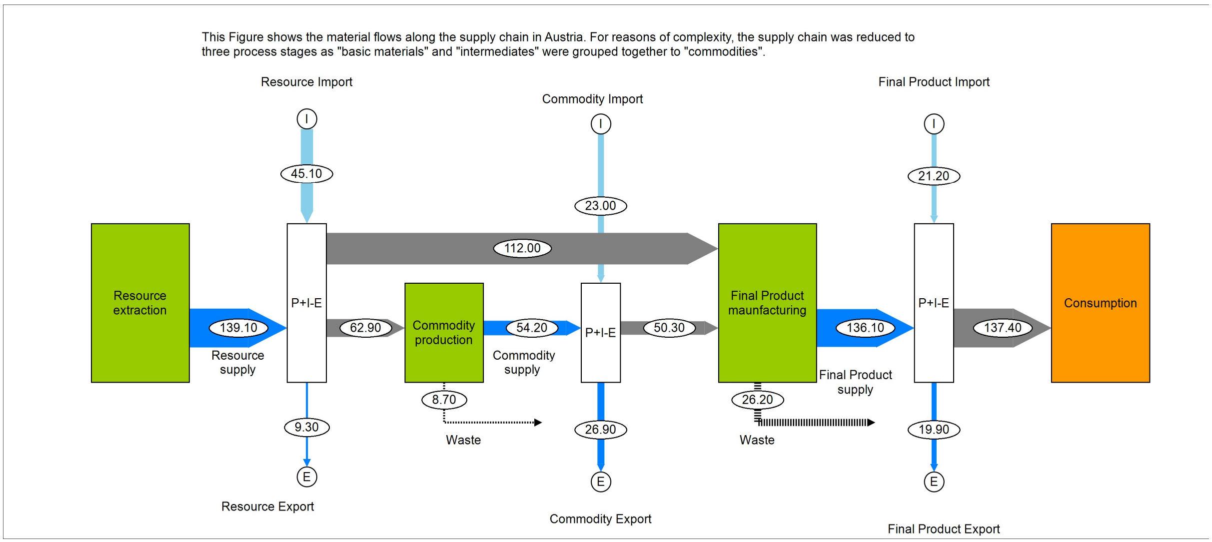

Figure 6: Physical material flows behind Austria's consumption in 2013, in Mio. tonnes (adapted by Windsperger et al. 2017)

The availability of adequate statistics is one precondition for a successful implementation of such an encompassing approach. Fortunately, Austria has good and detailed statistics for both the foreign trade and the national production (Statistics Austria 2018a and 2018b). As a result, before applying such an approach to other countries, the availability of production and foreign trade data has to be analyzed.

- Actualization and availability of appropriate LCA-data

The approach developed in the course of this thesis is based on physical material flows, which are hereafter combined with LCA-based emission factors. Meanwhile various databases are available for life cycle data (e.g. ecoinvent, GEMIS, Gabi), but there are still limitations, as mentioned e.g. in Dittrich et al. (2012).

The availability of appropriate emission factors decreases along the supply chain, as in common final products are too manifold in their quantity. Furthermore, the continuous actualization (e.g. due to changing electricity intensities or efficiency improvements) of emission factors is another big challenge for quality assessment. In Figure 7, the variations between emission factors are illustrated for steel products concerning origin and time. The big differences between the single emission factors emphasize the requirement to differentiate for both the origin country and the temporal development. The latter is especially important for incorporating technological advances.

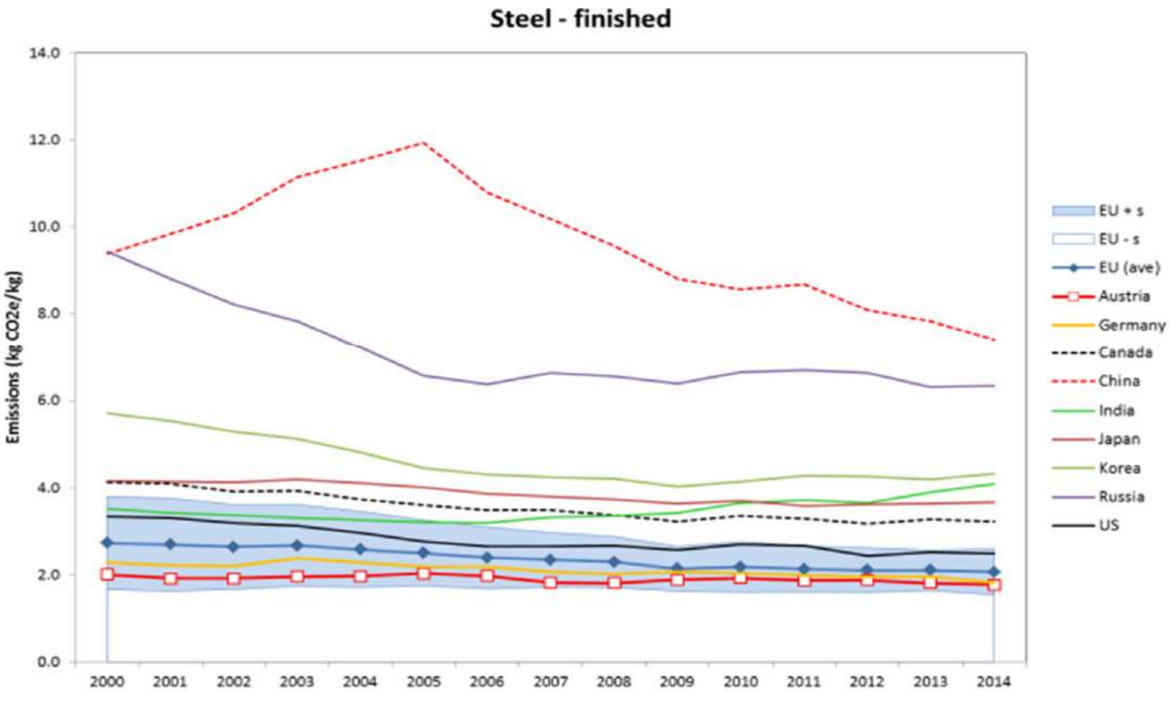

Figure 7: Sensitivity of emission factors on the example of steel products (Windsperger et al. 2017)

Another aspect is shown in subsequent Figure 8, where some selected emission factors are divided into the main emission sources. This illustration clarifies the importance of choosing the most appropriate emission factor for the respective product and to avoid aggregation as much as possible.

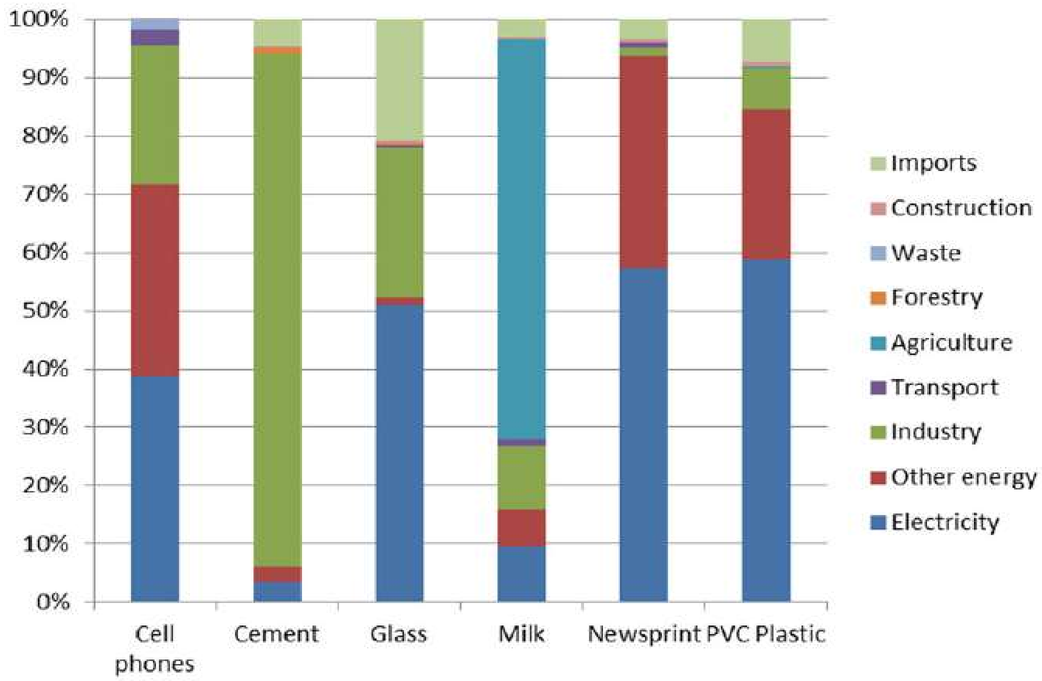

Figure 8: Distribution of selected emission factors to the kind of pollutant (Windsperger et al. 2017)

- Truncated picture of the supply chains

The second article showed that the consumption-based emissions of Austria are about 60% higher than those reported in the national inventory (Pazdernik et al. 2015). The comparison of those two approaches is illustrated in subsequent Figure 9, from which it is obvious that the provision of imported products is of main importance from an emission perspective. Although the emissions induced by exports are subtracted for Austria's consumption-based emissions, the net-imports prevail clearly.

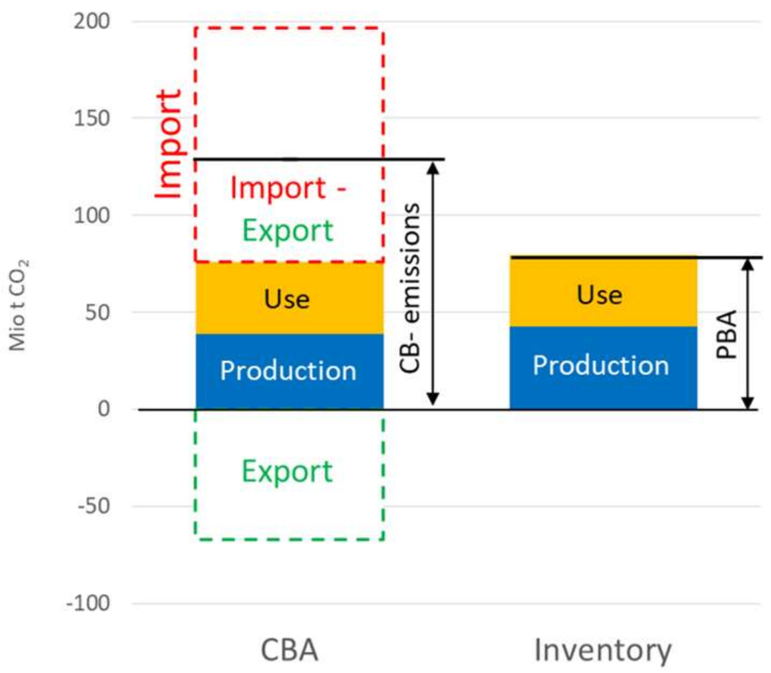

Figure 9: Consumption-based emissions (CBA) vs. Inventory-emissions of Austria in 2013

As a result, it would be necessary to have an in-depth view on the supply chains behind those imports. But, this is one of the main weaknesses and limitations of the developed approach, as the respective foreign trade statistics does not provide information of those supply chains. In a globalized world, however, it is likely that the provision of Austria's imports does not occur in those countries completely, but rather imports to the producing country are required to produce imports to Austria as well. These missing international interlinkages are often called truncation errors. The avoidance of such errors is one main strengths of economic input-output models (Giljum et al.2013, Tukker et al. 2020). Consequently, one promising attempt could be to incorporate this information behind the supply chains of imports from input-output models. However, the distinct aggregation levels will remain as main challenge, which has to get solved in future.

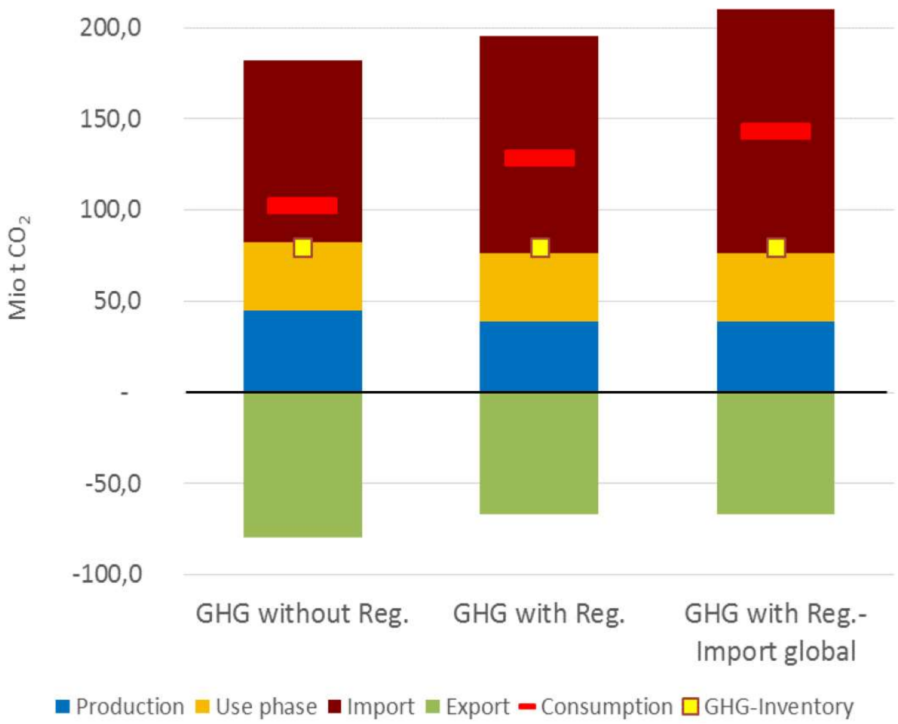

Figure 10: Sensitivity analysis for the consumption-based emissions in 2013 concerning the country-specific regionalization:

GHG without Reg.	*Greenhouse gas emissions without regionalization*
GHG with Reg.	*Greenhouse gas emissions with regionalization*
GHG with Reg.-Import global	*Greenhouse gas emissions with regionalization and global raw material and commodity imports*

Nevertheless, despite of the limitations concerning global supply chains, a sensitivity analysis shows at least the regional influence on the results and emphasizes the need for improvement and future research. Three versions were calculated, whereby the consumption-based emissions of Austria range between 100 and almost 150 million tonnes CO_{2eq}. In detail, the lowest emissions are achieved by using the emission factors as they are available in LCA-databases (GHG without Reg.). The emission factors mainly represent single countries or regions like Europe or rest of the world (Wernet et al. 2016). The greenhouse gas emissions with regionalization (GHG with Reg.) represent adjusted emission factors to the emission intensity in the respective country and sector (see chapter „country- and sector-specific regionalization of emission factors“ in article 2). The version with global supply chains (GHG with Reg. – Import global) and the assumption of worldwide trade for raw materials and commodities means that additionally to the regionalization raw material and commodity imports are calculated with average emission factors from outside Europe. As those results are significantly higher, it was confirmed that production within Europe is more climate-friendly than in the rest of the world (Windsperger et al. 2017).

- Country-specific regionalization of emission factors

As still mentioned, available emission factors from LCA-databases focus on production sites in specific countries. Thus, they mainly do not allow the comparison of distinct countries. The globalization, however, has led to global supply chains and goods and products are traded between countries with very distinct production conditions and emission intensities of the respective energy system. Therefore, the emission factors vary significantly, as shown in Figure 7. Figure 8 has further confirmed that at least for some product groups the underlying energy system has main influence of the product-specific emission intensity. Thus, those emission factors may be sensitive to possible changes in the electrical or industrial energy system (Windsperger et al. 2017).

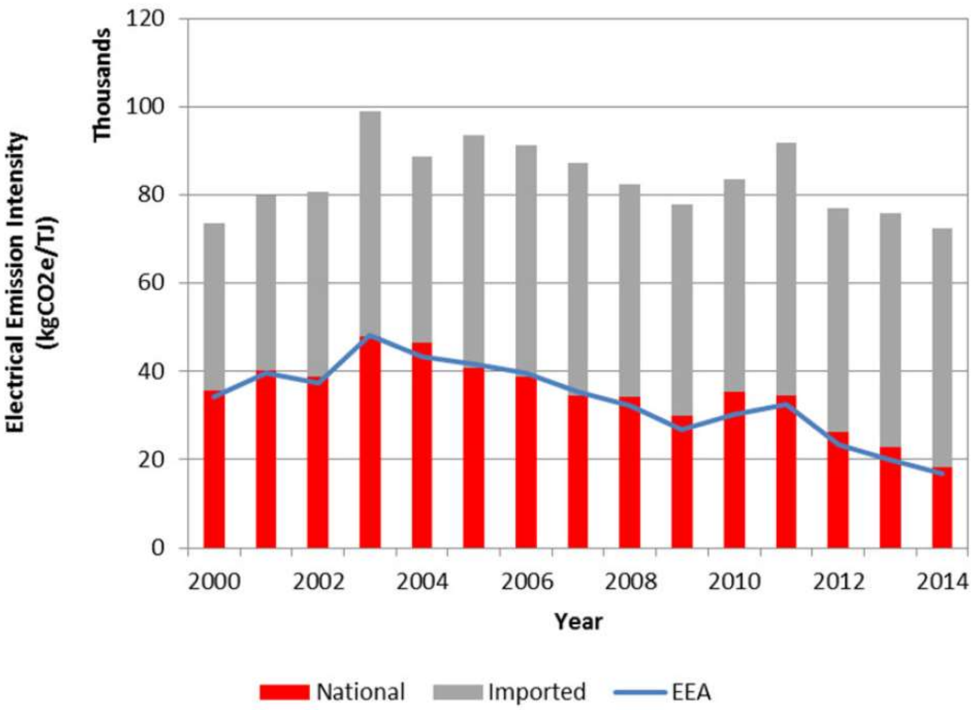

Figure 11: Development of the electrical and industrial energy emission intensity from 2000 to 2014 for Austria, calculated by the EEA - European Environment Agency (Windsperger et al. 2017)

A country-specific regionalization will help to avoid such calculation errors. The emission factors are therefore adapted to the emission intensity of the energy system in the respective country of manufacturing (cf. see chapter „country- and sector-specific regionalization of emission factors“ in article 2). The development of the Austrian emission intensity behind electrical generation is illustrated in Figure 11. It shows that the Austrian intensity has decreased by almost 50% from 2000 to 2014. In contrast, the emission intensity of Austrian electricity imports has increased at the same time and compensated the domestic reductions. This development emphasizes again the requirement for a consumption-based perspective, as imported activities are of main importance besides domestic activities.

The temporal development of the industrial energy emission intensity is illustrated in Figure 12. It can be seen that the Austrian and the German emission intensity has decreased continuously in recent years, whereas that of the European mix in contrast has increased. This confirms the relatively low emission intensity of Austrian production compared to those of other countries (cf. Figure 7 of article 2).

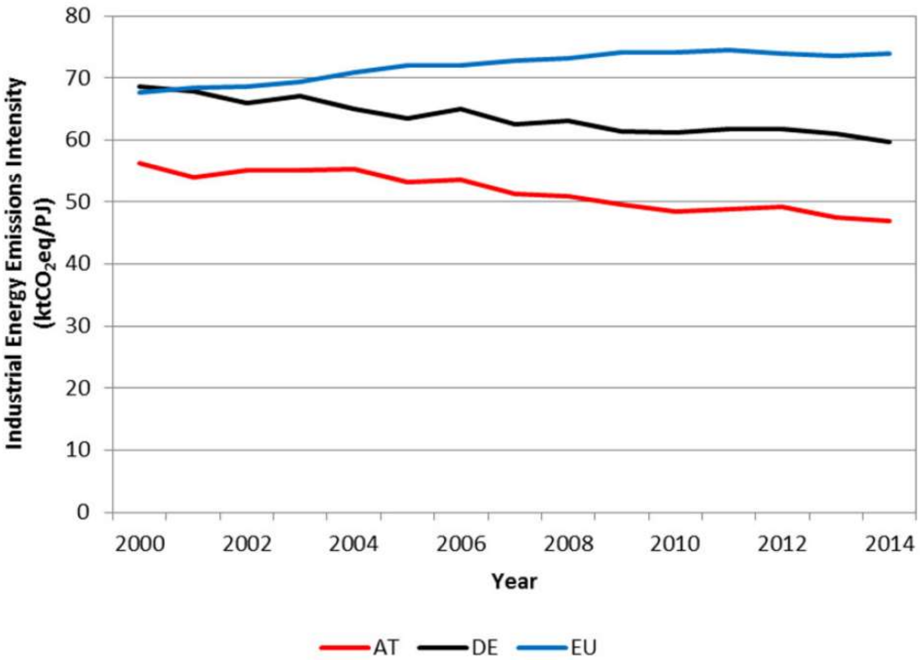

Figure 12: Development of the industrial energy emission intensity from 2000 to 2014 for Austria – AT, Germany – DE and Europe – EU (Windsperger et al. 2017)

Although the regionalization with country-specific emission intensities is one key improvement to conventional emission factors, they do not illustrate the respective production standard completely. The energy system of every sector and country shows the distribution of energy carriers only, but do not answer how much energy is necessary to produce the respective product. This so-called energy intensity has not been addressed yet, but should be part of future research in order to further increase the quality of this approach.

6.2 Conclusion

Climate change research provides clear evidence that the global temperature increases can be only kept below 2°C or 1.5°C, if an encompassing transformation process of our whole society starts immediately (Rogelj et al. 2016). The human impact through our consumption patterns and the supply chains behind are therefore essential drivers responsible for the dramatic increase of greenhouse gas emissions. Up to now, the nationally released emissions from fossil energy carriers through the use of products and services (e.g. driving a car, heating a building) have been in the focus of climate change mitigation. As a result, most strategies for reducing emissions have addressed this essential aspect for tracking national climate targets. But, as climate change is a global challenge, it is not enough to focus on national activities to reduce emissions (according to the UNFCCC-reporting), by neglecting what happens globally. Thus, cross-border effects have to be taken into account as well, especially in times of globalization where international trade has become of increasing importance. Consumption-based emission accounting has evolved in recent years by addressing imports and exports besides national activities (e.g. Bruckner et al. 2009, Munoz and Steininger 2010). Achieving ambitious reductions of greenhouse gas emissions need a comprehensive picture of the sources behind climate impacts, regardless if induced domestically or abroad.

A detailed literature review has shown that there is still demand for an emission accounting on such a detailed level of detail in the scientific community, as consumption-based approaches merely focus on a more aggregated level. However, the analysis has further depicted that various approaches have been evolved dealing with consumption-based greenhouse gas emissions. Although these approaches are aiming at the same in principal, they differ especially concerning system boundaries, calculation principles as well as aggregation levels. Nevertheless, economic input-output models have been established as the most common method for accounting greenhouse gas emissions behind the international trade additionally to the domestic production activity. These models are based on monetary data at sector level, that are combined with aggregated emission factor for the calculation of the greenhouse gas emissions. As a result, such approaches are appropriate for tracing trade flows and the induced emissions along the supply chains, but are restricted in their ability to get product-specific information and are associated with uncertainties in the emission calculation due to monetary data and aggregated emission factors. Of course, there exist other approaches like the LCA-based approach for product assessment, but none of these is capable to include all “direct” and “indirect” greenhouse gas emissions associated with the consumption of products.

Consequently, key challenges of existing approaches and methodical solutions were elaborated to get a first impression how such an approach might look like and what are the main elements. Therefore, the mineral chain in Austria was chosen as case study. First, the definition of an appropriate level of detail for every product was one precondition in order to manage the diversity of products. Furthermore, the definition of the scope was determined by the capability to distinguish between the induced greenhouse gas emissions of the single products. Second, physical data are required for the national production, imports and exports on the level of every single product, which were collected primarily out of national statistics. Third, LCA-based emission factors (e.g. from Ecoinvent database) were used and attributed depending on the product characteristics. Fourth, supply chains were built consisting of different process steps (e.g. raw material, commodity) to avoid double-counting, as LCA-data include the impacts of the whole life cycle. Fifth, the greenhouse gas emissions were calculated by multiplying the material flows with the LCA-based emission factors.

This case study of Austria was a first attempt to account for consumption-based greenhouse gas emissions on a detailed product-level. It was the basis for developing the whole approach, which enables the accounting of greenhouse gas emissions behind the whole supply chains of goods and products induced by national consumption. As globalization is of increasing importance for our whole economy, it was foreseen to distinguish between the origin and destination of goods and products. Origin-specific material flows were therefore developed in order to depict domestically produced, imported as well as exported goods. Furthermore, the whole supply chain from raw materials up to final products was compiled and the material flows were depicted for distinct material groups. The material flows, which are illustrated for every single process step, were further the basis for calculating the greenhouse gas emissions with appropriate LCA based emission factors. To enable the differentiation between the production sites in the single countries, the technology standard in the respective country of origin was considered by including the emission intensity of the energy mix in the respective industrial sector in the LCA-factors of the single products. This allowed the identification of the most climate intensive material groups as well as the most relevant processes within the supply chain. The contribution of imports and exports was visible for every process step throughout the whole supply chain, compared to those of national production. As a result, effects like "carbon leakage" could be estimated.

The results have confirmed that Austria's consumption-based emissions are about 60% higher than those of the national inventory. The provision of products is responsible for the main part of emissions, whereby the provision abroad through imports predominate compared to those produced domestically. This is one essential difference to production-based inventory, where in many cases emissions from the use phase (e.g. fuel use, heating) are dominating. The greenhouse gas emissions thereby increase along the whole supply chain, which corresponds to the principle of LCA where the impacts over the whole life cycle are aggregated. Differences in the emission intensity between the manufacturing in Austria or abroad have further illustrated that the Austrian production causes lower emissions comparing to other production sites in countries Austria is importing from. This product- and technology-specific consideration as well as to trace emissions along the supply chains allows to deduct the most emission-intensive products at every stage in the supply chain and where the emission come from. Consequently, practical emission reduction strategies like climate-friendly procurement could be developed on the basis of the results of this product- and technology-specific approach.

Nevertheless, there are still remaining questions and uncertainties, which should be addressed in future research. One of the most important limitations therefore is the consideration of first level imports only, by neglecting the possible global supply chains behind those imports (e.g. Pomponi and Lenzen 2018). As the incorporation of this effect is one of the main strengths of economic input-output models, possibilities for combining the respective strengths should be investigated in future research. The availability of physical data for imports, exports and national production is one of the main preconditions for applying this approach to other countries as well. The actualization of adequate LCA-data could be of increasing interest in near future, as technological advances will be necessary to combat climate change and achieve actual climate targets. The incorporation of energy intensities besides emission intensities of the energy system is one further objective for improving the current approach. Finally, this new product- and technology-specific approach for accounting greenhouse gas emissions induced by the national consumption of products will hopefully help on the way towards a climate-neutral world, although there are of course still remaining questions which have to get solved in near future.

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