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Identifying emission hotspots for low carbon technology transfers

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HIGHLIGHTS

- An accelerated diffusion of existing low-carbon technologies is vital.
- Emission hotspots for low-carbon technology transfer are identified.
- The emission hotspot industries vary for different final products and countries.
- Coal electricity is a recurring emission hotspot for technology transfer.

ABSTRACT

Achieving the <1.5°C warming target is only feasible if carbon emissions peak before 2020. This means that we cannot wait for new breakthrough technologies that significantly alter the production structure of emission intensive industries such as electricity, iron and steel, or transport. An accelerated diffusion of existing low-carbon technologies is vital for achieving a plateauing, followed by a decrease of carbon emissions within the next few years. Data on consumption-based CO_2 emissions raise the awareness of the link between final goods and the environmental pollution caused by upstream production processes. Consumers of final products learn where in the world CO_2 was emitted along the upstream production chain. For producers of final products these data provide benchmarks for total CO_2 emitted in upstream production processes. These are used together with an extended version of the inverse important coefficient methodology to identify 'emission hotspots'. 'Emission hotspots' are defined as countries/industries where a bulk of the upstream emissions occur and where a change in technology brings about the largest decrease in upstream emissions. This knowledge provides a basis for well-targeted technology transfers to clean up the upstream production chain, thus reducing the emission footprint of final goods production. The highest impact overall in a significant number global value chains analyzed here would be replacing upstream use of coal electricity by low carbon electricity. These results support the call of the 'Powering Past Coal Alliance' at the COP23 of ending the use of coal power sooner rather than later.

KEYWORDS

Consumption-based emissions; embodied emissions; low-carbon technologies; technology transfer; technology diffusion; multi-regional input-output analysis

1. Introduction: Emissions and technology diffusion

Achieving the <1.5°C warming target is only feasible if carbon emissions peak before 2020 (Figueres et al., 2017). This means that we cannot wait for new breakthrough technologies that significantly alter the production structure of emission intensive industries such as electricity, iron and steel, or transport. An accelerated diffusion of existing low-carbon technologies is vital for achieving a plateauing followed by a decrease of carbon emissions within the next few years.

An important tool in the Paris agreement to achieve a global diffusion of clean technologies is the UNFCCC Technology Mechanism (CTCN, 2013; Krause, 2015; UNFCCC, 2015, 2011). This mechanism supports the transfer of technologies from developed to developing countries (Shimada and Kennedy, 2015). Such transfers are facilitated by the Technology Executive Committee (TEC) and the Climate Technology Centre and Network (CTCN). However, it is not yet used widely enough to build networks between the recipient and source countries to facilitate technology transfer to a significant extent (Coninck and Sagar, 2015, p. 7). In short: suitable technologies exist, but they need to be increasingly diffused around the world (Piccard, 2016; UN, 2016). This is also supported by the IEA "Bridge Strategy" which aims at employing as much of already existing low-carbon technology as possible as long as new technologies are not yet available. The question remains: how can the technology diffusion process be advanced?

An indirect way to support the diffusion of these technologies from a European perspective are (European) support policies that aid a cost reduction of low carbon technologies (Wiebe, 2016): First, via R&D support and, second, via an increased deployment in Europe and associated learning effects. With decreasing costs, the deployment of low carbon technologies becomes economically viable in more and more countries and thus diffused to these countries. Nonetheless, this indirect mechanism via European-induced cost decreases needs to be complemented by other actions to accelerate the diffusion.

Enhancing environmentally friendly behavior across related economic agents has been thoroughly researched; a prominent focus has been the effect of informing households about their energy consumption vis-à-vis social norms (Allcott, 2011) and identifying competitiveness as a significant component of green supply chain management (Kushwaha and Sharma, 2016; Luthra et al., 2016). This benchmarking gives incentives to improve their own actions compared to those of their peers. To this end, a final-product-based emission accounting scheme is used to inform industries about the emissions embodied in their final products (emission footprints). These are predicated upon industry averages, and can effectively give benchmarks against which establishments in that industry can compare their performance. Such benchmarking can increase pressure on firms to produce more cleanly, and, hence, be an effective means to overcome psychological barriers to climate change action (Stoknes, 2015, 2014; Wackernagel and Rees, 1998). In addition to this ‘reputation-led’ behavior, ‘innovation-led’ and ‘imitation-led’ contributions to green supply chain management have been identified (Testa and Iraldo, 2010). While they cannot find any evidence for ‘cost-led’ contributions, earlier research argues that the pressure to cut costs have already led to very resource efficient manufacturing processes in the 1990s (Orsato and Wells, 2007).

As little as half a decade ago, very few assessments of embodied carbon existed due to a lack of measurement concepts and tools (Lee, 2012). The measurement of embodied carbon includes not only the direct environmental impact at the final production stage or during the consumption phase, but it also includes all upstream production processes, the environmental footprint. Two main ways to calculate this environmental footprint exist nowadays: bottom-up life-cycle assessment (LCA) at the product-level and top-down environmentally extended multi-regional input-output analysis (EE MRIO) at the industry level. Of course, various blends of these two extremes have also been used (Cooper, 2003; Suh and Huppes, 2005; Tukker et al., 2009). LCA is more detailed (product-specific) and requires extensive data when a range of products, and not just one or two, are considered. EE MRIO is less-detailed, but valuable in assessing a large set of industries simultaneously, especially across various countries (see for example (Tukker and Dietzenbacher, 2013)) for an overview of existing datasets (Andrew and Peters, 2013; Dietzenbacher et al., 2013; Lenzen et al., 2013; Timmer et al., 2014; Tukker et al., 2013; Wiebe et al., 2012).

Initiatives have tackled the lack of data and analysis using the LCA approach for few selected industries. These industries are for example the car industry (Kushwaha and Sharma, 2016; Lee, 2011, 2012, Zhu et al., 2011a, 2011b) and more recently also the clothing industry, e.g. (Mair et al., 2016; Parisi et al., 2015; Resta et al., 2016; Roos et al., 2016; Wang et al., 2015; Zamani et al., 2017). However, LCA studies are very labor and data intensive and can, unfortunately, not be applied to every industry in every country in the world.

The focus in this paper is on final-product-based CO_2 emissions calculated using the MRIO approach. The advantage is that the data are available not only for selected industries, or even only selected products within industries, but for all product groups/industries and countries represented in the MRIO database. These data on environmental footprints help to bridge dissonance and psychological distance for producers from a great variety of industries as they become aware of where CO_2 was emitted along the supply chain that produces the goods they require (Stoknes, 2014; Wackernagel and Rees, 1998). This is because consumers/producers feel more responsible for reducing the upstream emissions of ‘their’ final product as opposed to emissions that cannot be readily traced to their behavior. The idea is that such knowledge can be extended to develop a better-targeted low-carbon energy technology transfers from CO_2-consuming to CO_2-producing countries. The emission hotspot analysis identifies industries/countries producing with high emission intensities and that are at the same time supplying a significant amount of the upstream product. Reducing the emissions in these hotspots using existing technologies is usually easier and more cost-efficient than further reducing the domestic emission intensity in countries/industries with already low emission intensity, possibly due to strict environmental policies. Naturally, this can also be applied at the country level, i.e. using consumption-based emission accounts for countries to identify where in the world the general investments into technology, e.g. by development cooperation programs, are necessary to reduce the country's footprints outside its own boarders.

The paper is structured as follows: At first, the data and calculation of final-product-based CO_2 emissions are introduced. Second, the methodology to identify upstream emission hotspots is developed, before discussing options for technology transfer.

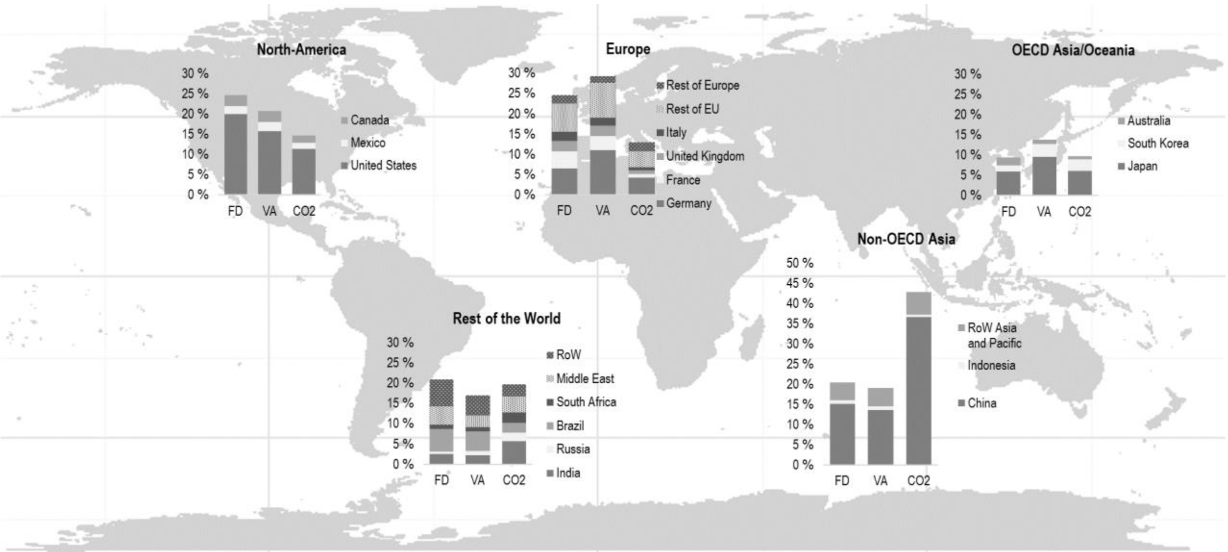
2. Data: Consumption-based and final-product-based emissions

The UNFCCC currently uses a territorial production-based accounting system when assessing emissions. That is, the UNFCCC allocates CO_2 and other greenhouse gases (GHGs) to the country in which they are emitted. Using data from the IEA's publication of CO_2 emission from fuel combustion (IEA, 2015a) and the MRIO EXIOBASE, Figure 1 plots where in the world final demand for motor vehicles occurs, where most of the value is added to the motor vehicles and where the CO_2 is emitted along global value chains.

While North American and European countries account for about 50% of global motor vehicle demand and value added, only 27% of CO_2 associated with motor vehicle production is emitted in these regions. Germany (part of “Europe” in Figure 1) and Japan (part of “other Asia” in Figure 1) each yields 4 percentage points more in product value share than their world demand share (11% VA compared to 7% FD and 10% compared to 6% respectively). This suggests their relatively high involvement in the production chain. Still, their shares as an originator of CO_2 emissions are much lower (4% and 6% respectively), underlining very low polluting in the course of their vehicle-related production activities. This is due either to their engagement in cleaner links of the production chain, or to the use of cleaner production technologies than those used by other countries, or some combination of both. The USA comprises a 20% share in global final demand for motor vehicles, while its share in value added is only 16%, leaving the USA being more of a consumer than a producer. But as in Japan and Germany, its share of CO_2 emissions related to motor vehicle production is comparably small (11%).

In China and India, the opposite is true: their shares in CO_2 emitted along global production chains for motor vehicles are disproportionately high compared to demand and value added shares. China owns a 37% share of all CO_2 emissions, but its shares of final demand and value added are less than half of that. This suggests that China participates in more pollution-intensive stages of the motor-vehicle production supply chain, or that its industries pollute more than their counterparts in other countries. The same holds true for India, which also has a share of related CO_2 emissions that is higher than its world shares of demand and value added for motor vehicles, albeit by a factor of three.

Figure 1: Regional FD, VA and CO2 shares of global demand for Motor vehicles in 2011



Notes: FD denotes final demand, VA value added and CO2 carbon emissions.
Source: Own calculations based on IEA CO2 emission from fuel combustion (IEA, 2015a) *and EXIOBASE3.4. Similar results are found when using the OECD's intercountry input-output table* (OECD, 2015; Wiebe and Yamano, 2016).

The evidence is naturally slightly different for each industry, but the basic picture remains across them all. That is, OECD countries are relatively important consumers and contribute relatively high shares of value within global production chains. Meanwhile non-OECD countries tend to emit disproportionately high shares of CO_2 within the same global production chains. That is, the developed nations close to the technology frontier are essentially exporting pollution to meet their final demands. This fundamental international inequity highlights the importance of linking the social and environmental costs of upstream emissions either to countries in which the final good is produced (final-product-based emission accounting) or in which the final product is consumed (consumption-based emission accounting). The difference is in the allocation of exports of final products to the exporting industry/country or to the importing country. In mathematical terms consumption-based emissions by country and industry are calculated as

$$\mathbf{CO2}_{Cons} = i'\hat{e}(\mathbf{I}-\mathbf{A})^{-1}\hat{\mathbf{Y}} + h' \qquad (1)$$

with $\hat{\mathbf{Y}} = \begin{bmatrix} \hat{y}^{11} & \dots & \hat{y}^{1M} \\ \vdots & \ddots & \vdots \\ \hat{y}^{M1} & \dots & \hat{y}^{MM} \end{bmatrix}$**,** M denoting the total number of countries and $\hat{y}^{kj}$ being the diagonalized final demand vector (either one or the sum of the FD categories) of country j directed at final goods of country k, and h being direct emissions by final demand. $\hat{e}$ is the diagonalized matrix of emission intensities by industry and country and $(\mathbf{I}-\mathbf{A})^{-1}$ is the multi-regional Leontief inverse matrix. In the resulting vector, $\mathbf{CO2}_{Cons}$, entry *(c-1)*M+k* corresponds to consumption–based emissions of country *c*'s demand for goods from industry *k*. Final-product based emissions in contrast are allocated to country where the final product is produced, not where it is consumed. That is the emissions associated with the production of a car by the German motor vehicle industry, which is sold as a final product to Belgium, are allocated to Germany and not to Belgium (where it would be allocated to in case of consumption-based emissions). The mathematical notation for final-product-based emissions is

$$\mathbf{CO2}_{FP} = i'\hat{s}(\mathbf{I}-\mathbf{A})^{-1}\widehat{\dot{\boldsymbol{Y}}} + h' \qquad (2)$$

with $\dot{\boldsymbol{Y}} = \begin{bmatrix} \mathbf{y}^{11} + \dots + \mathbf{y}^{1M} \\ \vdots \\ \mathbf{y}^{M1} + \dots + \mathbf{y}^{MM} \end{bmatrix}$ and $\mathbf{y}^{cd}$ being final demand vector (either one or the sum of the FD categories) of country d directed at final goods of country c. Then $\mathbf{y}^{cP} = \mathbf{y}^{c1} + \dots + \mathbf{y}^{cM}$ is the total demand for final goods produced in country c. Final demand for products in country c would be the "column sum" of the vectors in $\mathbf{Y}$**,** i.e. $\mathbf{y}^{cD} = \mathbf{y}^{1c} + \dots + \mathbf{y}^{Mc}$. Then, entry *(c-1)*M+k* of vector $\mathbf{CO2}_{FP}$ corresponds to final-product–based emissions of country *c*'s industry *k*. This concept adds yet another possible allocation to the existing concepts (Davis et al., 2011) of extraction-based, territorial- and production-based, consumption-based emissions and correcting consumption-based emissions for technology differences (Kander et al., 2015). Recognizing that exporters' technology weighs heavily on the final-product-based and consumption-based emissions, it is important to use different accounting perspectives to identify emission hotspots and, thus, potential partners for technology transfer. As emission intensities in those countries/industries are higher than in the corresponding domestic industry, corresponding mitigation technologies and practices most likely already exist. Transfers of already existing technologies are cheaper than developing new or improving domestically employed technologies that are already comparably energy/emission efficient. If industries (countries) care about the CO_2 footprints of their final products, technology transfers to the 'emission hotspots' can provide a cost-effective way of reducing their footprint.

In an industry mapping, an 'emission hotspot' is an industry in upstream partner countries that emits a large share of a country's consumption-based or final-product-based CO_2 and where a change in the technology, i.e. the input structure of the industry, makes the largest difference in embodied emissions. Consumption-based emissions reflect aggregate consumer choices and final product-based emissions the choice of the industry supply chain. Thus, for governments to identify the partner countries for technology transfer, the origin of this country's consumption-based 'emission hotspots' by partner country and by industry is valuable information. If there are specific industry initiatives, it may be more useful to look at the final-product-based emissions in order to trace upstream industries and countries that are emission hotspots.

The research of green supply chain management shows that there are some incentives for reducing upstream emissions (Orsato and Wells, 2007; Testa and Iraldo, 2010). Nonetheless, further research in the fields of climate psychology and climate sociology is necessary to show that the knowledge about upstream emissions indeed fosters mitigation efforts taken by consumers and final goods producers. Nonetheless, for those who already care, the data and analysis at hand present where they could start to decrease their own environmental footprint by improving the technologies used in upstream production processes.

3. Methodology: Identifying 'emission hotspots' for technology transfer using an extended version of the inverse important coefficient methodology

Note that any type of emission account of a specific country is dominated by CO_2 emissions related to domestic production and consumption of electricity as well as of the use of fossil fuel products (mainly for transport). These are well-known drivers of total consumption-based emissions that are tackled by domestic policies. That is, they cannot be reduced by ***inter***national technology transfer, rather only via market incentives that encourage technology diffusion ***intra***nationally. The identification of these hotspots (both national and international) is illustrated below using final products of the German motor vehicles industry as an example. This analysis of industry-specific final-product-based 'emission hotspots' can be done for all industries in all countries available in an MRIO.

For identifying 'emission hotspots' for technology transfer, this paper extends the inverse important coefficient approach (Casler and Hadlock, 1997; Hewings et al., 1988; Sonis and Hewings, 2009, 1992). The goal is to identify those industries, where technological change would result in the largest decrease in upstream emissions of the final product. The methodology to identify inverse important coefficients is adapted to also include emission intensities of the industries. The goal is to find the upstream emission hotspot industries j in countries s of industry i (motor vehicles) in country r (Germany). In mathematical terms this is:

$$max_{s,j,\bar{k}} \left(\alpha^{s}_{\bar{k},j} \lambda^{s,r}_{j,i} + e^{s}_{j} \sum_{c} \lambda^{s,c}_{j,\bar{k}} \lambda^{s,r}_{j,i} \right) \quad (4)$$

with $\bar{k} \in K$, the set of industries supplying fuels for combustion, $\lambda^{s,r}_{j,i}$ being the entry of the multi-regional Leontief multiplier matrix $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$, corresponding to industry i in country r and industry j in country s. Here we assume that it does not matter from which country fuel $\bar{k}$ comes, thus when using the index $\bar{k}$ we need to consider that those inputs come from all countries c. $\alpha^{s}_{\bar{k}j}$ denotes the change in the emission intensity of industry j in country s given a change in the input of fuel $\bar{k}$. The size of $\alpha^{s}_{\bar{k}j}$ depends on the current fuel mix of industry j and the emissions related to burning fuel $\bar{k}$ relative to burning the other fuels used by industry j.

The unknown $\alpha^{s}_{\bar{k}j}$reduces to $\mathrm{E}^{s}_{\bar{k},j}$ (see supplementary material), the CO2 intensity of industry j in country s burning fuel $\bar{k}$. Hence, it is necessary to find those industries j in countries s for which a change in the input of fuel $\bar{k}$ has the largest impact on the overall emissions associated with that upstream production step

$$max_{s,j,\bar{k}}\left(\mathrm{E}^{s}_{\bar{k},j}\lambda^{s,r}_{j,i} + e^{s}_{j}\sum\nolimits_{c}\lambda^{s,c}_{j,\bar{k}}\,\lambda^{s,r}_{j,i}\right) \quad (5)$$

As the aim is to identify industry d in country j, the sum over all CO2 relevant products taken

$$max_{s,j}\left(\lambda^{s,r}_{j,i}\sum\nolimits_{k\in\mathrm{K}}\mathrm{E}^{s}_{k,j} + e^{s}_{j}\sum\nolimits_{c,k\in\mathrm{K}}\lambda^{s,c}_{j,k}\lambda^{s,r}_{j,i}\right) \quad (6)$$

The full derivation of this equation is given in the Appendix.

For EXIOBASE3, data for $\mathrm{E}^{s}_{k,j}$ exist (if at all) only for the supply-use framework, i.e. for product k and industry j. The derivation above also holds for in the supply-use framework (Lenzen and Rueda-Cantuche, 2012): k and i are product indexes and j is an industry index. Thus, the corresponding $\lambda^{s,r}_{j,i}$ can just be taken from the product-by-industry part of the compound Leontief inverse $L^{*} = \begin{bmatrix} \mathbf{I} & -\mathbf{B} \\ -\mathbf{D} & \mathbf{I} \end{bmatrix}^{-1}$. The industry technology assumption is underlying this compound Leontief inverse, but this could also be the product technology assumption. As the detailed $\mathrm{E}^{s}_{k,j}$

data are currently not yet available, the preliminary results are based on calculations where $\mathrm{E}_{k,j}^{s}$ is approximated by the corresponding industry average e_j^s for all CO2 relevant products k.

The results do take into account both interindustry and trade relations through the multi-regional Leontief multipliers. Considering these is important to account not only for the emission intensity of the upstream products, but also for the amount of inputs used from industries in other countries during the production of the final goods. In by including these multipliers the emission intensities are weighed by the amount used (see Equations (5) and (6)). Hence, if there is a particularly high emission intensity of a certain upstream industry, but this provides only a very small share of the inputs into final product, the industry will not be ranked among the top industries for technology transfer.

4. Results and discussion: Emission hotspot analysis for selected industries

The results are shown in Figure 2 for final motor vehicles, trailers and semi-trailers produced in Germany, final wearing apparel products produced Italy, and computers produced Japan satisfying final demand in Japan and elsewhere. The results are based on the calculations using Equation (6) and the total reduction potential is defined as the sum over all countries s and products j. The top-left rectangle in each figure corresponds to the solution of the maximization problem. The results are available for all countries and all industries[1].

Regarding the upstream emission reduction potential for the motor vehicle industry, for most of the countries, their own and the Chinese electricity by coal industry offer the highest potential of

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[1] Some results are included in the supplementary material. Please contact the authors for other industries/countries. The results will also be made available on zenodo.org, an open data repository.

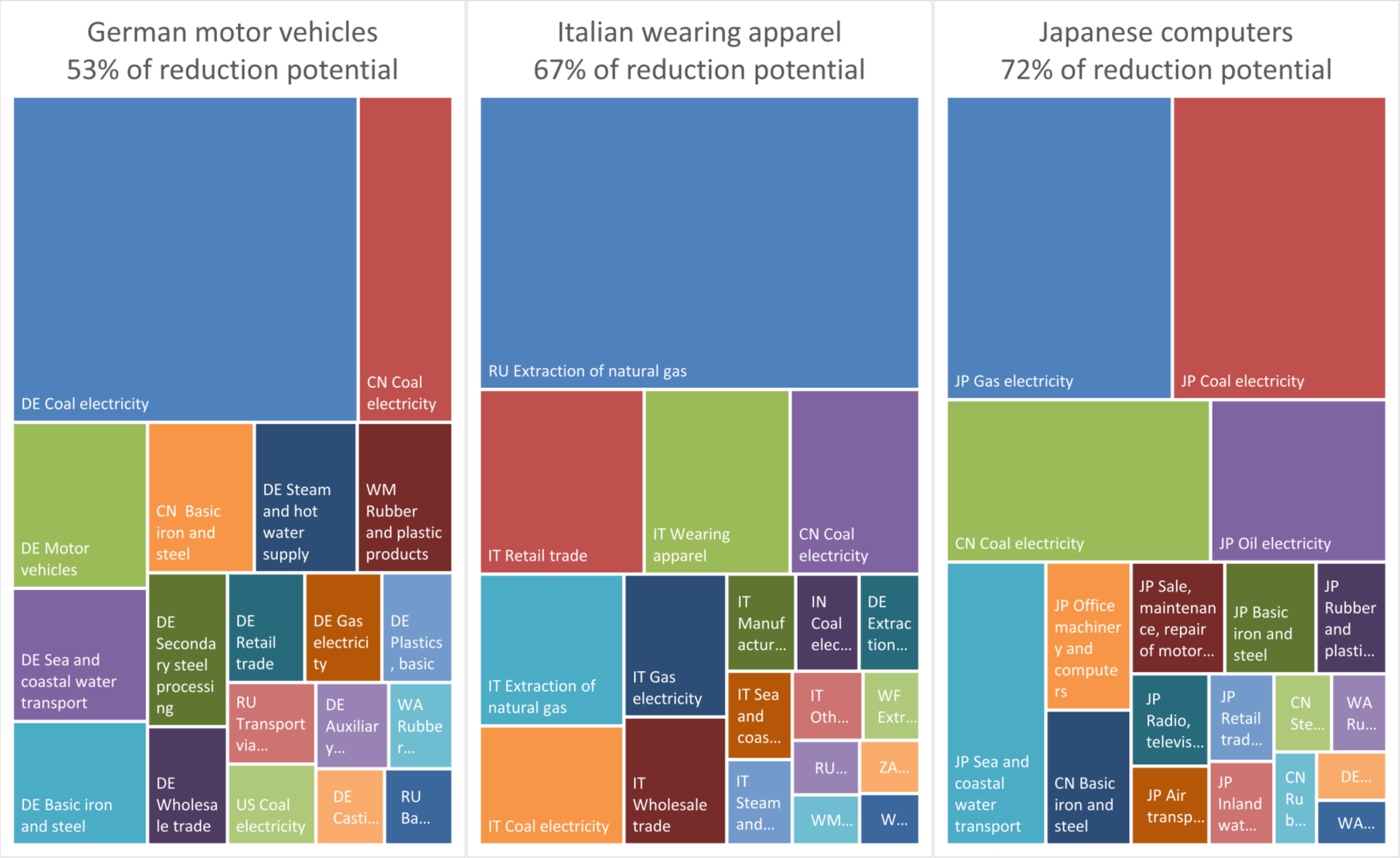
reducing upstream emissions. Germany’s electricity by coal and rubber and plastics production in the Middle East also offers potential to reduce embodied emissions for other European countries. Other upstream industry/country combinations that are common across producer countries are the Chinese iron and steel industry as well as Chinese manufacture of rubber and plastics products and the Russian steel industry. Most of the green supply chain management studies in this field find that a significant share of the emissions embodied in their products stems from (coal) electricity use. But those mostly only look at scope 1 and scope 2 emissions, which is not sufficient (Lee, 2011, 2012).

From the second panel, it is visible that the upstream production potentials in the wearing apparel industry are slightly different. In addition to the energy industries in various countries retail and wholesale trade play a significant role. Other research with a global MRIO approach shows that the share of CO2 emissions embodied in European consumption originating from the BRIC countries (Brazil, Russia, India and China) has increased with the energy and resources industry being the largest contributor (Mair et al., 2016), which is exactly in line with our findings. The LCA studies (Resta et al., 2016; Roos et al., 2016; Wang et al., 2015) unanimously identify ‘spinning’ and ‘weaving’/’fabric production’ as the most carbon intense process in clothing production. This is due to the high use of electricity at these production stages. However, their estimation of the contribution of the ‘distribution’ stage, which corresponds to wholesale and retail trade in the EXIOBASE classification, is lower.

For final products of the Japanese computer industry, the first four industries with the largest reduction potential are fossil fuel electricity industries in Japan and China, as visible in the third panel of Figure 2. These four alone add up to 40% of the total reduction potential. This indicates that production processes of intermediate inputs into computers are very electricity intensive and that the shortage in electricity production in Japan due to the shutting down of all nuclear plants in 2011 had initiated a switch to fossil fuel electricity plants. In addition, the rubber and plastics industry in Japan, China and other Asian countries also exhibit significant reduction potential.

For all of these products it becomes clear that greening the domestic electricity industry has a very large impact on the emissions embodied in the final product. Other industries that occur often are rubber and plastics (for both motor vehicles and computers) as well as industries related to iron and steel production. This is unsurprising, as these industries are generally energy intense industries. However, these results show which downstream final product producers are inducing the production and related emissions in the upstream industries, thus providing a clear link on where and how technological change through technology transfer to upstream production processes has the largest impact on embodied emissions. One of the major advantages for industries/enterprises of engaging in low carbon technology transfers, be it renewable energy technologies or energy efficiency improvements, are the lower energy costs in the future. If upstream products are produced with less fossil energy, they also become cheaper (once the initial investment costs have been repaid).

Figure 2 Upstream industries with largest reduction potential (in % of total reduction potential)



5. Conclusions for technology transfer

The single most often listed industry in all upstream emission hotspots is the coal industry. This means, a change in the inputs of this industry leads to the largest decrease in upstream emissions. Changing the inputs into this industry, however, needs to be reinterpreted in this context. In contrast to many other more aggregated industries, the electricity industry in EXIOBASE is already disaggregated into its major technologies. Thus, even though coal electricity plants may have some emissions saving potential, technological change here actually is the use of a different electricity producing technology. This finding of replacing coal electricity with low-carbon electricity support the call of the “Powering Past Coal Alliance” at the COP23 in November 2017 of ending the use of coal power rather sooner than later (Department for Business Energy & Industrial Strategy, 2017). The natural general starting point would be for industry initiatives to support low-carbon electricity technology transfers, of course, among others, more specific to the industry.

For the technology transfer to be successful, certain prerequisites in the receiving country are necessary, such as the openness to receive the technology as well as the capability to deploy and use the new technologies (Wurlod and Eaton, 2015) as well as a credible policy mix supporting the new technologies and giving the investors some security. Technology transfer should be seen in their broadest definition, that it is not limited to the transfer of/investment in the new hardware, but it also encompasses training and knowledge transfer, R&D support and collaboration, energy efficiency improvements and related management practices (e.g. green supply chain management (Diabat and Govindan, 2010)) as well as other innovation strategies (Coninck and Sagar, 2015). In this way, the clean technologies further contribute to structural change, new industrialization patterns and hence an enhanced economic development (Günther and Alcorta, 2011; Mathews and Tan, 2016, 2014). These additional indirect effects can also be analysed using the MRIO approach.

Calculating the footprints using MRIO analysis gives industry averages and is, therefore, especially interesting for industry networks, where multiple enterprises would like to collaborate to reduce the industry-wide footprints. While individual enterprises can better assess their specific footprint through LCA, they can use MRIO analysis in two ways: First, to estimate the emissions that are truncated in an LCA (using hybrid methods) and, second, as benchmarks, i.e. to compare their performance to the industry average. Thus, the results presented here should be seen as complements to existing analyses (Schneider et al., 2014; Tarne et al., 2017; Zimmer et al., 2017) and initiatives, such as the European Automotive Working Group on Supply Chain Sustainability[ii] or the Sustainable Businesses unit of the European Apparel and Textile Confederation[iii].

[ii] http://www.csreurope.org/european-automotive-working-group-supply-chain-sustainability-1

[iii] http://www.euratex.eu

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ABBREVIATIONS

CO2 carbon dioxide, FD final demand, LCA Life cycle analysis, MRIO multi-regional input-output, VA value added

Mathematical Appendix

Let M denote the total number of countries, h be direct emissions by final demand, $\hat{e}$ be the diagonalized matrix of emission intensities by industry and country and $(\mathbf{I}-\mathbf{A})^{-1}$ be the multi-regional Leontief inverse matrix. Final-product-based emissions are calculated as

$$\mathbf{CO2}_{FP} = i'\hat{s}(\mathbf{I}-\mathbf{A})^{-1}\hat{\dot{\boldsymbol{Y}}} + h' \tag{A1}$$

with $\dot{\boldsymbol{Y}} = \begin{bmatrix} \mathbf{y}^{11} + \cdots + \mathbf{y}^{1M} \\ \vdots \\ \mathbf{y}^{M1} + \cdots + \mathbf{y}^{MM} \end{bmatrix}$ and $\mathbf{y}^{rs}$ being final demand vector (either one or the sum of the FD categories) of country r directed at final goods of country s. $\mathbf{y}^{rP} = \mathbf{y}^{c1} + \cdots + \mathbf{y}^{cM}$ is the total demand for final goods produced in country c. Final demand for products in country c would be the “column sum” of the vectors in **Y,** i.e. $\mathbf{y}^{rD} = \mathbf{y}^{1r} + \cdots + \mathbf{y}^{Mr}$. Then, entry *(r-1)*M+k* of vector $\mathbf{CO2}_{FP}$ corresponds to final-product–based emissions of country *r*’s industry *k*.

The goal is to find the upstream emission hotspot industries j in countries s of industry i (motor vehicles) in country r (Germany). Final-product-based emissions of one product unit of i (this excludes direct emissions from final demand as these are zero in case of motor vehicles) are calculated as

$$\mathbf{CO2}_{FP}[r,i] = \textstyle\sum_{s,j} e_j^s \lambda_{j,i}^{s,r}, \tag{A2}$$

with $\lambda_{j,i}^{s,r}$ corresponding to entry of country s industry j and country r industry i in the Leontief inverse matrix

$$\mathbf{L} = (\mathbf{I}-\mathbf{A})^{-1} = \begin{bmatrix} \lambda_{11}^{11} & \cdots & \lambda_{1N}^{1M} \\ \vdots & \ddots & \vdots \\ \lambda_{N1}^{M1} & \cdots & \lambda_{NN}^{MM} \end{bmatrix}. \tag{A3}$$

The change in final product based emissions then is

$$\Delta\mathbf{CO2}_{FP}[r,i] = \Delta\left(\textstyle\sum_{s,j} e_j^s \lambda_{j,i}^{s,r}\right) = \textstyle\sum_{s,j} \Delta\left(e_j^s \lambda_{j,i}^{s,r}\right) = \textstyle\sum_{s,j}\left(\Delta e_j^s \lambda_{j,i}^{s,r} + e_j^s \Delta\lambda_{j,i}^{s,r}\right). \tag{A4}$$

The emission hotspot industries are those industries j country r for which a technological change, i.e. a change in the corresponding input coefficient combined with a change in emission intensity results in the biggest change in $\mathbf{CO2}_{FP}[r,i]$. Using (Casler and Hadlock, 1997) for the decomposition of the change in the Leontief coefficients $\Delta\lambda_{j,i}^{s,r} = \sum_k \sum_l \lambda_{j,k}^{s,r} \Delta a_{k,l}^{r,s} \lambda_{l,i}^{s,r}$, the maximization problem can be phrased as

$$max_{s,j} \Delta\left(e_j^s \lambda_{j,i}^{s,r}\right) = max_{s,j}\left(\Delta e_j^s \lambda_{j,i}^{s,r} + e_j^s \Delta\lambda_{j,i}^{s,r}\right)$$

$$= max_{s,j}\left(\Delta e_j^s \lambda_{j,i}^{s,r} + e_j^s \sum_{c,k} \sum_l \lambda_{j,k}^{s,c} \Delta a_{k,l}^{c,s} \lambda_{l,i}^{s,r}\right) \tag{A5}$$

Only changes in input coefficients in industry j in country s lead to changes in the emission intensity $e_j^s$of industry j in country s (the emission intensity depends on the use of emission relevant inputs that are burned during production processes). If there is no change ine_j^s, i.e. $\Delta e_j^s = 0$, the first term vanishes. Thus, it is continued as

$$= max_{s,j} \begin{cases} \Delta e_j^s \lambda_{j,i}^{s,r} + e_j^s \sum_{c,k} \lambda_{j,k}^{s,c} \Delta a_{k,j}^{c,s} \lambda_{j,i}^{s,r} & if\ \Delta e_j^s \neq 0 \\ e_j^s \sum_{c,k} \sum_{s,l} \lambda_{j,k}^{s,c} \Delta a_{k,l}^{c,s} \lambda_{l,i}^{s,r} & if\ \Delta e_j^s = 0 \end{cases} \tag{A6}$$

A change in any input coefficient can lead to a reduction in upstream emissions, as this can be achieved through a switch of intermediate products supply from a more emission intense to a less emission intense industry. But, as only possibilities for emission saving technological change are considered, the case of $\Delta e_j^s = 0$ is dismissed.

Not all input coefficients have an impact on the emission intensity of industry j in country s. Only those input coefficients corresponding to the industries that supply fuels for combustion, a subset K of the set of all industries, determine the emissions of industry j in country s. Thus, the maximization problem reduces to

$$max_{s,j} \mathbf{\Delta}\left(e_j^s \lambda_{j,i}^{s,r}\right) = max_{s,j}\left(\mathbf{\Delta} e_j^s \lambda_{j,i}^{s,r} + e_j^s \sum_{c,k\in \mathrm{K}} \lambda_{j,k}^{s,c} \mathbf{\Delta} a_{k,j}^{c,s} \lambda_{j,i}^{s,r}\right). \tag{A7}$$

Before solving this maximization problem, the change in the emission intensity, $\boldsymbol{\Delta}e_j^s$, corresponding to the changes in the different input coefficients, $\boldsymbol{\Delta}a_{k,j}^{c,s}$'s needs to be determined.

Depending on the set-up of the MRIO or MRSUT table, only one or possibly different combustible energy fuels are supplied by industry/product group $k \in \mathrm{K}$. In the OECD ICIO (Wiebe and Yamano, 2016) the relevant ISIC Rev. 3 industries are 'C *Mining and quarrying*', 'D23 *Manufacture of coke, refined petroleum products and nuclear fuel*', and 'E *Electricity, gas, and water supply*'. These industries are too aggregated for a detailed analysis of substitution possibilities between different energy carriers. For that, a further breakdown of the industries, using the IEA Energy Balance data (IEA, 2015b), is necessary.

In contrast, in EXIOBASE (Tukker et al 2013, Stadler et al forthcoming), the sector breakdown is more detailed, showing the different energy products individually, see Table 1. During the estimation of the environmental accounts of EXIOBASE, a matrix allocating CO_2 emissions by energy product k to industries j will be created, $\mathbf{CO2EPxI}$. It is not differentiated where product k comes from, i.e. whether it is domestically produced or imported. Note that $\sum_{k \in K} \mathbf{CO2EPxI}_{k,j}^s$ is equal to country s industry j's total CO_2 emissions. Using this information country-specific **CO2EPxI** coefficients, $\mathrm{E}_{k,j}^s$, can be calculated by dividing the emissions by the corresponding monetary flow in the aggregated (that is the sum over all import partner countries and domestic flows) intermediate flow matrix $\mathbf{Z}$ of country s:

$$\mathrm{E}_{k,j}^s = \frac{\mathbf{CO2EPxI}_{k,j}^s}{\mathrm{Z}_{k,j}^s}. \qquad \text{(A8)}$$

This in turn gives

$$\mathbf{CO2EPxI}_{k,j}^s = \mathrm{E}_{k,j}^s \times \mathrm{Z}_{k,j}^s. \qquad \text{(A9)}$$

The overall CO_2 intensity of industry j in country s, e_j^s, is

$$e_j^s = \frac{\sum_{k \in \mathrm{K}} \mathbf{CO2EPxI}_{k,j}^s}{x_j^s} = \frac{\sum_{k \in \mathrm{K}} \mathrm{E}_{k,j}^s \times \mathbf{Z}_{k,j}^s}{x_j^s} \qquad \text{(A10)}$$

$$= \sum_{k \in \mathrm{K}} \mathrm{E}_{k,j}^s \frac{\mathbf{Z}_{k,j}^s}{x_j^s} = \sum_{k \in \mathrm{K}} \mathrm{E}_{k,j}^s \, \mathrm{a}_{k,j}^s = \sum_{k \in \mathrm{K}} \mathrm{E}_{k,j}^s \, \mathrm{a}_{k,j}^s \qquad \text{(A11)}$$

Where $\mathrm{a}_{k,j}^s$ are the coefficients corresponding to the aggregated intermediate flow matrix of country s, i.e. $\mathrm{a}_{k,j}^s = \sum_c a_{k,j}^{c,s}$. Thus, the change in e_j^s that results from a change in $\mathrm{a}_{\bar{k},j}^s$ is

$$\Delta_{\bar{k}} e_j^s = \mathrm{E}_{\bar{k},j}^s \Delta \mathrm{a}_{\bar{k},j}^s = \mathrm{E}_{\bar{k},j}^s \Delta \mathrm{a}_{\bar{k},j}^s, \text{ and} \qquad \text{(A12)}$$

$$max_{s,j,\bar{k}} \left(\Delta_{\bar{k}} e_j^s \lambda_{j,i}^{s,r} + e_j^s \sum_c \lambda_{j,\bar{k}}^{s,c} \Delta a_{\bar{k},j}^{c,s} \, \lambda_{j,i}^{s,r} \right) = max_{s,j,\bar{k}} \left(\mathrm{E}_{\bar{k},j}^s \Delta \mathrm{a}_{\bar{k},j}^s \lambda_{j,i}^{s,r} + e_j^s \sum_c \lambda_{j,\bar{k}}^{s,c} \Delta a_{\bar{k},j}^{c,s} \, \lambda_{j,i}^{s,r} \right) \qquad \text{(A13)}$$

Any of the inputs from the CO$_2$ relevant products $k \in \mathrm{K}$ (coming from all countries c) may change. Unfortunately, these changes $\mathrm{a}_{k,j}^s$ s are not independent of each other. There are basically two possibilities

1. A negative change in $\mathrm{a}_{k,j}^s$ is associated with an average positive change in the coefficient of any or all other industries $i \in \{1, \dots N\}$, also including other energy products, possibly more carbon intense then the one in question.
2. A negative change in $\mathrm{a}_{k,j}^s$ is associated with a use of energy carriers that do not emit carbon when being used, e.g. electricity, i.e. a positive change in the input coefficient from the electricity industry.

Nonetheless, the goal is to find out which individual change has the greatest impact, i.e. what needs to be changed about the current technology used. That is, it suffices to compare the same change in any input coefficient $\boldsymbol{\Delta} \mathrm{a}_{k,j}^s$, e.g. $\Delta \mathrm{a}_{k,j}^s = \Delta a_{change} \, \forall_{k \in K, s, j}$, without considering the associated change in other input coefficients. Then the maximization problem reduces to

$$max_{s,j,\bar{k}} \left(\mathrm{E}_{\bar{k},j}^s \Delta \mathrm{a}_{\bar{k},j}^s \lambda_{j,i}^{s,r} + e_j^s \sum_c \lambda_{j,\bar{k}}^{s,c} \Delta a_{\bar{k},j}^{c,s} \, \lambda_{j,i}^{s,r} \right)$$

$$= max_{s,j,\bar{k}} \left(\mathrm{E}^{s}_{\bar{k},j} \Delta a_{change} \lambda^{s,r}_{j,i} + e^{s}_{j} \sum\nolimits_{c} \lambda^{s,c}_{j,\bar{k}} \Delta a_{change}\, \lambda^{s,r}_{j,i} \right)$$

$$= \Delta a_{change} max_{s,j,\bar{k}} \left(\mathrm{E}^{s}_{\bar{k},j} \lambda^{s,r}_{j,i} + e^{s}_{j} \sum\nolimits_{c} \lambda^{s,c}_{j,\bar{k}}\, \lambda^{s,r}_{j,i} \right)$$

$$= max_{s,j,\bar{k}} \left(\mathrm{E}^{s}_{\bar{k},j} \lambda^{s,r}_{j,i} + e^{s}_{j} \sum\nolimits_{c} \lambda^{s,c}_{j,\bar{k}}\, \lambda^{s,r}_{j,i} \right). \qquad \text{(A14)}$$

The target industry for technology transfer is identified by summing over all CO_2 relevant products $k \in \mathrm{K}$:

$$max_{s,j} \boldsymbol{\Delta}\left(e^{s}_{j} \lambda^{s,r}_{j,i}\right) = max_{s,j}\left(\boldsymbol{\Delta} e^{s}_{j} \lambda^{s,r}_{j,i} + e^{s}_{j} \sum\nolimits_{c,k\in \mathrm{K}} \lambda^{s,c}_{j,k} \Delta a^{c,s}_{k,j} \lambda^{s,r}_{j,i}\right)$$

$$= max_{s,j}\left(\lambda^{s,r}_{j,i} \sum\nolimits_{k\in \mathrm{K}} \mathrm{E}^{s}_{k,j} + e^{s}_{j} \sum\nolimits_{c,k\in \mathrm{K}} \lambda^{s,c}_{j,k} \lambda^{s,r}_{j,i}\right) \qquad \text{(A15).}$$

Those industries that are identified as the maximum here are those in the top-left rectangles in the different panels of Figure 2.

Table 1: EXIOBASE3 energy products related to CO2 emissions from combustion: Set K

	No	Product	Code
1	20	'Anthracite'	'p10.a'
2	21	'Coking Coal'	'p10.b'
3	22	'Other Bituminous Coal'	'p10.c'
4	23	'Sub-Bituminous Coal'	'p10.d'
5	24	'Patent Fuel'	'p10.e'
6	25	'Lignite/Brown Coal'	'p10.f'
7	26	'BKB/Peat Briquettes'	'p10.g'
8	27	'Peat'	'p10.h'
9	28	'Crude petroleum and services related to crude oil extraction, excl surveying'	'p11.a'
10	29	'Natural gas and services related to natural gas extraction, excl surveying'	'p11.b'
11	30	'Natural Gas Liquids'	'p11.b.1'
12	64	'Coke Oven Coke'	'p23.1.a'
13	65	'Gas Coke'	'p23.1.b'
14	66	'Coal Tar'	'p23.1.c'
15	67	'Motor Gasoline'	'p23.20.a'
16	68	'Aviation Gasoline'	'p23.20.b'
17	69	'Gasoline Type Jet Fuel'	'p23.20.c'
18	70	'Kerosene Type Jet Fuel'	'p23.20.d'
19	71	'Kerosene'	'p23.20.e'
20	72	'Gas/Diesel Oil'	'p23.20.f'
21	73	'Heavy Fuel Oil'	'p23.20.g'
22	74	'Refinery Gas'	'p23.20.h'
23	75	'Liquefied Petroleum Gases (LPG)'	'p23.20.i'
24	77	'Ethane'	'p23.20.k'
25	78	'Naphtha'	'p23.20.l'
26	79	'White Spirit & SBP'	'p23.20.m'
27	80	'Lubricants'	'p23.20.n'
28	81	'Bitumen'	'p23.20.o'
29	83	'Petroleum Coke'	'p23.20.q'
30	84	'Non-specified Petroleum Products'	'p23.20.r'
31	91	'Charcoal'	'p24.e'
32	142	'Coke oven gas'	'p40.2.a'
33	143	'Blast Furnace Gas'	'p40.2.b'
34	144	'Oxygen Steel Furnace Gas'	'p40.2.c'
35	145	'Gas Works Gas'	'p40.2.d'
36	178	'Plastic waste for treatment: incineration'	'p90.1.c'
37	179	'Intert/metal waste for treatment: incineration'	'p90.1.d'
38	180	'Textiles waste for treatment: incineration'	'p90.1.e'
39	182	'Oil/hazardous waste for treatment: incineration'	'p90.1.g'

REFERENCES

Allcott, H., 2011. Social norms and energy conservation. J. Public Econ. 95, 1082–1095. https://doi.org/10.1016/j.jpubeco.2011.03.003

Andrew, R.M., Peters, G.P., 2013. A multi-region input-output table based on the Global Trade Analysis Project database (GTAP-MRIO). http://dx.doi.org/10.1080/09535314.2012.761953.

Casler, S.D., Hadlock, D., 1997. Contributions to Change in the Input-Output Model: The Search for Inverse Important Coefficients. J. Reg. Sci. 37, 175–193. https://doi.org/10.1111/0022-4146.00050

Coninck, H., Sagar, A.D., 2015. Technology in the 2015 Paris Climate Agreement and Beyond.

Cooper, J.S., 2003. The Computational Structure of Life Cycle Assessment, by Reinout Heijungs and Sangwon Suh. Dordrecht. J. Ind. Ecol. 7, 131–132. https://doi.org/10.1162/108819803322564424

CTCN, 2013. Introducing the CTCN – The Climate Technology Centre and Network. [WWW Document]. URL https://unfccc.int/files/documentation/submissions_from_parties/adp/application/pdf/climate_technology_centre_and_network._introducing_the_ctcn._submitted_by_the_u.s.pdf

Davis, S.J., Peters, G.P., Caldeira, K., 2011. The supply chain of CO2 emissions. Proc. Natl. Acad. Sci. 108, 18554–18559. https://doi.org/10.1073/pnas.1107409108

Department for Business Energy & Industrial Strategy, 2017. Climate Change Minister Claire Perry launches Powering Past Coal Alliance at COP23 - GOV.UK [WWW Document]. Press Release UK Gov. URL https://www.gov.uk/government/news/climate-change-minister-claire-perry-launches-powering-past-coal-alliance-at-cop23 (accessed 11.20.17).

Diabat, A., Govindan, K., 2010. An analysis of the drivers affecting the implementation of green supply chain management. "Resources, Conserv. Recycl. 55, 659–667. https://doi.org/10.1016/j.resconrec.2010.12.002

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., de Vries, G., 2013. The construction of world input-output tables in the WIOD project. Econ. Syst. Res. 25, 71–98. https://doi.org/10.1080/09535314.2012.761180

Figueres, C., Schellnhuber, H.J., Whiteman, G., Rockstr?m, J., Hobley, A., Rahmstorf, S., 2017. Three years to safeguard our climate. Nature 546, 593–595. https://doi.org/10.1038/546593a

Günther, T., Alcorta, L., 2011. Industrial Policy for Prosperity: Reasoning and Approach. UNIDO Dev. POLICY, Stat. Res. BRANCH Work. 2, 1–35.

Hewings, G.J.D., Sonis, M., Jensen, R.C., 1988. Fields of Influence of Technological Change in Input-Output Models. Pap. Reg. Sci. 64, 25–36. https://doi.org/10.1111/j.1435-5597.1988.tb01112.x

IEA, 2015a. CO2 Emissions from Fuel Combustion, CO2 Emissions from Fuel Combustion. {International Energy Agency}, Paris, France. https://doi.org/10.1787/co2_fuel-2009-en-fr

IEA, 2015b. World Energy Balances: Database Documentation - 2015 Revised Edition. Paris, France.

Kander, A., Jiborn, M., Moran, D.D., Wiedmann, T.O., 2015. National greenhouse-gas accounting for effective climate policy on international trade. Nat. Clim. Chang. 5, 431–435. https://doi.org/10.1038/nclimate2555

Krause, K., 2015. The UNFCCC Technology Mechanism.

Kushwaha, G.S., Sharma, N.K., 2016. Green initiatives: a step towards sustainable development and firm's performance in the automobile industry.

https://doi.org/10.1016/j.jclepro.2015.07.072

Lee, K.-H., 2011. Integrating carbon footprint into supply chain management: the case of Hyundai Motor Company (HMC) in the automobile industry. J. Clean. Prod. 19, 1216–1223. https://doi.org/10.1016/j.jclepro.2011.03.010

Lee, K.H., 2012. Carbon accounting for supply chain management in the automobile industry. J. Clean. Prod. 36, 83–93. https://doi.org/10.1016/j.jclepro.2012.02.023

Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013. Building Eora: a Global Multi-Region Input-Output Database At High Country and Sector Resolution. Econ. Syst. Res. 25, 20–49. https://doi.org/10.1080/09535314.2013.769938

Lenzen, M., Rueda-Cantuche, J.M., 2012. A note on the use of supply-use tables in impact analyses. SORT 36, 139–152.

Luthra, S., Garg, D., Haleem, A., 2016. The impacts of critical success factors for implementing green supply chain management towards sustainability: an empirical investigation of Indian automobile industry. J. Clean. Prod. 121, 142–158. https://doi.org/10.1016/j.jclepro.2016.01.095

Mair, S., Druckman, A., Jackson, T., 2016. Global inequities and emissions in Western European textiles and clothing consumption. J. Clean. Prod. 132, 57–69. https://doi.org/10.1016/j.jclepro.2015.08.082

Mathews, J.A., Tan, H., 2016. Lessons from China. Nature 531, 440–442.

Mathews, J.A., Tan, H., 2014. Manufacture renewables to build energy security. Nature 513, 6–8. https://doi.org/10.1038/513166a

OECD, 2015. OECD Inter-Country Input-Output (ICIO) Tables, edition 2015: Access to data [WWW Document]. URL http://oe.cd/icio (accessed 2.2.16).

Orsato, R.J., Wells, P., 2007. The Automobile Industry & Sustainability. J. Clean. Prod. 15, 989–993. https://doi.org/10.1016/j.jclepro.2006.05.035

Parisi, M.L., Fatarella, E., Spinelli, D., Pogni, R., Basosi, R., 2015. Environmental impact assessment of an eco-efficient production for coloured textiles. J. Clean. Prod. 108, 514–524. https://doi.org/10.1016/j.jclepro.2015.06.032

Piccard, B., 2016. How Clean Technologies Can Improve Health Worldwide [WWW Document]. UNEP Mediu. A guest post from Bertrand Piccard, Initiat. Chairman, Pilot Sol. Impuls. UNEP Goodwill Ambassad. URL https://medium.com/@UNEnvironment/how-clean-technologies-can-improve-health-worldwide-3b9940cbd3ec#.yhys12vau (accessed 4.13.16).

Resta, B., Gaiardelli, P., Pinto, R., Dotti, S., 2016. Enhancing environmental management in the textile sector: An Organisational-Life Cycle Assessment approach. J. Clean. Prod. 135, 620–632. https://doi.org/10.1016/j.jclepro.2016.06.135

Roos, S., Zamani, B., Sandin, G., Peters, G.M., Svanström, M., 2016. A life cycle assessment (LCA)-based approach to guiding an industry sector towards sustainability: the case of the Swedish apparel sector. J. Clean. Prod. 133, 691–700. https://doi.org/10.1016/j.jclepro.2016.05.146

Schneider, L., Berger, M., Schüler-Hainsch, E., Knöfel, S., Ruhland, K., Mosig, J., Bach, V., Finkbeiner, M., 2014. The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment. Int. J. Life Cycle Assess. 19, 601–610. https://doi.org/10.1007/s11367-013-0666-1

Shimada, K., Kennedy, M., 2015. Potential role of the Technology Mechanism in implementing the Paris Agreement.

Sonis, M., Hewings, G.J.D., 2009. Coefficient Change and Innovation Spread in Input Output

Models. IIOA Work. Pap. Input-Output Econ. WPIOX 09-0.

Sonis, M., Hewings, G.J.D., 1992. Coefficient Change in Input – Output Models : Theory and Applications. Econ. Syst. Res. 4, 143–158.

Stoknes, P.E., 2015. What We Think About When We Try Not To Think About Global Warming - Toward a New Psychology of Climate Action. Chelsea Green Publishing.

Stoknes, P.E., 2014. Rethinking climate communications and the “psychological climate paradox.” Energy Res. Soc. Sci. 1, 161–170. https://doi.org/10.1016/j.erss.2014.03.007

Suh, S., Huppes, G., 2005. Methods for Life Cycle Inventory of a product. J. Clean. Prod. 13, 687–697. https://doi.org/10.1016/j.jclepro.2003.04.001

Tarne, P., Traverso, M., Finkbeiner, M., 2017. Review of Life Cycle Sustainability Assessment and Potential for Its Adoption at an Automotive Company. Sustainability 9, 670. https://doi.org/10.3390/su9040670

Testa, F., Iraldo, F., 2010. Shadows and lights of GSCM (green supply chain management): Determinants and effects of these practices based on a multi-national study. J. Clean. Prod. 18, 953–962. https://doi.org/10.1016/j.jclepro.2010.03.005

Timmer, M.P., Erumban, A.A., Los, B., Stehrer, R., de Vries, G.J., 2014. Slicing Up Global Value Chains. J. Econ. Perspect. 28, 99–118. https://doi.org/10.1257/jep.28.2.99

Tukker, A., de Koning, A., Wood, R., Hawkins, T., Lutter, S., Acosta, J., Rueda Cantuche, J.M., Bouwmeester, M., Oosterhaven, J., Drosdowski, T., Kuenen, J., 2013. EXIOPOL – Development and illustrative analysis of a detailed global MR EE SUT/IOT. Econ. Syst. Res. 25, 50–70. https://doi.org/10.1080/09535314.2012.761952

Tukker, A., Dietzenbacher, E., 2013. Global multiregional input-output frameworks: An introduction and outlook. Econ. Syst. Res. 25, 1–19.

https://doi.org/10.1080/09535314.2012.761179

Tukker, A., Poliakov, E., Heijungs, R., Hawkins, T., Neuwahl, F., Rueda-Cantuche, J.M., Giljum, S., Moll, S., Oosterhaven, J., Bouwmeester, M., 2009. Towards a global multi-regional environmentally extended input–output database. Ecol. Econ. 68, 1928–1937. https://doi.org/10.1016/j.ecolecon.2008.11.010

UN, 2016. SDG Goal 13: Take urgent action to combat climate change and its impacts [WWW Document]. URL http://www.un.org/sustainabledevelopment/climate-change-2/

UNFCCC, 2015. Technology Mechanism - Enhancing climate technology development and transfer. [WWW Document]. URL http://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/TEM/0e7cc25f3f9843ccb98399df4d47e219/174ad939936746b6bfad76e30a324e78.pdf

UNFCCC, 2011. Report of the Conference of the Parties on its sixteenth session: Proceedings. FCCC/CP/2010/7.

Wackernagel, M., Rees, W., 1998. Our Ecological Footprint: Reducing Human Impact on the Earth. New Society Publishers.

Wang, C., Wang, L., Liu, X., Du, C., Ding, D., Jia, J., Yan, Y., Wu, G., 2015. Carbon footprint of textile throughout its life cycle: A case study of Chinese cotton shirts. J. Clean. Prod. 108, 464–475. https://doi.org/10.1016/j.jclepro.2015.05.127

Wiebe, K.S., 2016. The impact of renewable energy diffusion on European consumption-based emissions. Econ. Syst. Res. 1–18. https://doi.org/10.1080/09535314.2015.1113936

Wiebe, K.S., Bruckner, M., Giljum, S., Lutz, C., 2012. Calculating Energy-Related CO2 Emissions Embodied in International Trade Using a Global Input–Output Model. Econ. Syst. Res. 24, 113–139. https://doi.org/10.1080/09535314.2011.643293

Wiebe, K.S., Yamano, N., 2016. Estimating CO2 Emissions Embodied in Final Demand and Trade Using the OECD ICIO 2015. OECD Publishing. https://doi.org/10.1787/5JLRCM216XKL-EN

Wurlod, J., Eaton, D., 2015. Technology diffusion and its problematics: The case of global agriculture (No. 37), Research Paper.

Zamani, B., Sandin, G., Peters, G.M., 2017. Life cycle assessment of clothing libraries: can collaborative consumption reduce the environmental impact of fast fashion? J. Clean. Prod. 162, 1368–1375. https://doi.org/10.1016/j.jclepro.2017.06.128

Zhu, Q., Geng, Y., Sarkis, J., Lai, K.-H., 2011a. Evaluating green supply chain management among Chinese manufacturers from the ecological modernization perspective. Transp. Res. Part E 47, 808–821. https://doi.org/10.1016/j.tre.2010.09.013

Zhu, Q., Sarkis, J., Lai, K.-H., 2011b. Green supply chain management innovation diffusion and its relationship to organizational improvement: An ecological modernization perspective. J. Eng. Technol. Manag. 29, 168–185. https://doi.org/10.1016/j.jengtecman.2011.09.012

Zimmer, K., Fr, M., Ohling, €, Breun, P., Schultmann, F., 2017. Assessing social risks of global supply chains: A quantitative analytical approach and its application to supplier selection in the German automotive industry. J. Clean. Prod. 149, 96–109. https://doi.org/10.1016/j.jclepro.2017.02.041