Environmental Research Letters

LETTER • OPEN ACCESS

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Environmental Research Letters

OPEN ACCESS

RECEIVED
25 April 2018

REVISED
3 September 2018

ACCEPTED FOR PUBLICATION
14 September 2018

PUBLISHED
5 October 2018



LETTER

# The growing importance of scope 3 greenhouse gas emissions from industry

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**Keywords:** emissions responsibility, multi-regional input–output (MRIO) analysis, life-cycle assessment (LCA), embodied energy, consumption-based accounting

Supplementary material for this article is available online

## Abstract

Carbon reporting is increasingly focussing on indirect emissions that occur in the supply chain of establishments. The GHG protocol, a corporate standard, distinguishes scope 2 (emissions associated with electricity consumption) and scope 3 (emissions associated with other inputs), in addition to scope 1 emissions (occurring directly at the facility or company in question). However, the magnitude and growth trajectory of scopes 2 and 3 emissions at the economy-wide level is unknown. Here we conduct an input–output investigation of indirect carbon dioxide ($CO_2$) emissions for the global economy organized in five sectors—energy supply, transport, industry, buildings, and agriculture and forestry—as defined by the Intergovernmental Panel on Climate Change (IPCC). In comparison to previous work that looks at indirect emissions of consumption, we present the first economy-wide analysis of indirect emissions of gross production. The goal of the work is thus to capture the potential agency different sectors have over supply chain emissions, rather allocating emissions between production and consumption. Between 1995 and 2015, global scopes 1, 2, and 3 emissions grew by 47%, 78%, and 84%, to 32, 10, and 45 Pg $CO_2$, respectively. Globally, the industry sector was most important with scope 2 emissions of 5 Pg and scope 3 emissions of 32 Pg. For buildings, scope 3 emissions of 7 Pg were twice as high as direct emissions. Industry and buildings stood in marked contrast to energy and transport, where direct emissions accounted for >70% of total emissions responsibility. Most of the growth happened in developing countries. The proposed analysis scheme could improve the integration of sector chapters in future IPCC reports.

## Introduction

Direct emissions, e.g. through the combustion of fossil fuels, are those that occur at an establishment. Indirect emissions occur in the supply chain of the establishment in question, i.e. covering all steps in the production of the goods and services delivered to the establishment [1]. When evaluating specific measures or technologies to reduce greenhouse gas (GHG) emissions, the most effective action should consider the potential to address both direct or indirect emissions [2, 3]. Different expert communities have developed a bewildering diversity of terms for indirect emissions, as listed in table 1, which is both a testimony to their importance and an opportunity for a more consistent terminology to ease communication. Among corporations [4–7] and cities [8, 9], the GHG Protocol is a widely accepted standard that defines how to assess direct emissions (scope 1), as well as emissions associated with the supply of electricity, heat, and cooling (scope 2) and value-chain emissions not related to the (direct) purchase of energy (scope 3) [10, 11].

In national and international climate policy making, there is no consistent practice of taking scope 2 or

**Table 1.** Emissions terminology clarification. Expressions akin to direct emissions (territorial, production-based, scope 1) and related to indirect emissions (embodied, consumption-based, scope 2, scope 3, upstream, downstream, carbon footprint).

| Term | Explanation |
|---|---|
| Direct emissions | Emissions directly associated with an activity, a process, or an entity |
| Territorial emissions | Emissions occurring within the territory of a country. Extraterritorial emissions, such as those associated with international aviation and shipping, are not assigned to any entity under this accounting scheme, which is the basis of emissions reporting under the UNFCCC and its Kyoto Protocol |
| Production-based accounting | Direct emissions of entities belonging to a country, including (usually) extraterritorial emissions |
| Scope 1 emissions [59] | Direct emissions of an organization |
| Indirect emissions | Emissions associated with the production of the inputs to an activity or organization |
| | In the IPCC report, only power-plant emissions associated with the production of electricity are accounted for |
| Embodied emissions | Emissions associated with the production of the product in question |
| Consumption-based accounting | Accounting scheme which assigned emissions from production to consumption, i.e. only accounting for the direct and indirect emissions of final consumption |
| Carbon footprint | Direct and indirect emissions associated with a specific product or consumption activity or unit. Most literature only considers the direct and upstream indirect emissions, although life-cycle approaches often assign end-of-life impacts to individual products or consumption activities. In organizational reporting and the Product Environmental Footprint standards [37, 38], the inclusion of downstream emissions is optional |
| Scope 2 emissions | Emission associated with the production of electricity and fuel, following the GHG protocol |
| Scope 3 emissions | Emissions associated with the inputs other than electricity and those associated with the combustion of fuel (those accounted in scopes 1 and 2), and potentially also includes emissions associated with the use of sold products and the commuting of employees |
| Downstream emissions | Emissions associated with the distribution, retailing, use, and waste treatment of products produced by an organization. An optional element of scope 3 and the EC organization environmental footprint [11, 37] |
| Upstream emissions | In most cases, synonym to the summation of both direct and indirect emissions, i.e. those associated with the production of inputs to an organization and the operation of the organization. In the GHG Protocol, this is a part of scope 3 emissions |

3 emissions into account, despite the appreciation of the importance of treating emissions embodied in trade [12]. In the contribution of Working Group III on climate change mitigation to the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) [13], scope 3 emissions were for the first time taken into account in the analysis of drivers and trends on a national level (chapter 5). In the accounting for carbon emissions, it is common to distinguish between production-based and consumption-based emissions inventories. Production-based inventories allocate emissions to the countries where the emissions occur or, in the case of emissions in international waters and airspace, to the country where the owner of the vessel resides. Consumption-based inventories allocate emissions occurring in the production of goods to the countries where the final consumer of the goods resides. In its assessment of consumption-based emissions, which include scope 3, the IPCC relied on newly developed multi-regional input–output models (MRIOs) [12, 14, 15]. Similar consumption-based indicators have been derived from MRIOs for water [16, 17], materials [18, 19], metals [20], land use [16, 21], biodiversity threats [22] and many other indicators, which are commonly labelled under the popular 'footprint' term [2]. MRIOs represent the global value chains (GVCs) connecting production-based emissions to consumption, yet the intricacies of GVC are only now receiving research attention [23, 24], with a focus on economic issues such as trade in value added (TiVA) rather than GHG emissions.

In the sector chapters of the IPCC AR5 report (Ch.7–11), indirect emissions from electricity production were uniformly reported and allocated to sectors [13]. These scope 2 emissions were prominently discussed in the buildings and transportation chapters but received less attention in the sector chapters on energy, industry, and agriculture, forestry and other land use (AFOLU). Decision makers in companies and cities understand that their mitigation and other actions influence scope 3 emissions and perceive some power over those emissions [25]. Policy options can be broadened by including measures that address scope 3 emissions [26]. In its analysis of mitigation options in the sector chapters, the IPCC-WGIII did address scope 3 emissions only sporadically, even where trade-offs along the life-cycle were well understood, like in the comparison of transportation modes. The risk of not addressing the different scopes of emissions is potentially inefficient or misguided policy. Trade-offs may not be sufficiently captured, e.g., between the direct emissions from combustion engine vehicles and the indirect emissions of electric vehicles in power stations and battery factories [27]. Mitigation in one sector may cause emissions in another sector. At the same time, opportunities may be overlooked, such as reducing electricity use or creating products requiring less energy-intensive materials [28].

If the IPCC did account more systematically for indirect emissions, what would such an accounting look like? How would this such an accounting be achieved? What are the issues that a more complete analysis of indirect emissions would address?

Scope 1 is sufficient to understand where emissions occur. The rationale for considering scopes 2 and 3 is that users of electricity and steel also have an opportunity to reduce emissions associated with electricity generation and steel production by using these inputs more efficiently or replacing them with other inputs that cause lower emissions. Conversely, they may increase those emissions, e.g. by replacing a gas stove with an electric one. The hesitation to use scopes 2 and 3 in emissions accounting is that my scopes 2 and 3 emissions are the scope 1 emissions of the power-plant and steel factory, respectively—accounting for them as both here and there implies a double counting. One hence must understand, as the IPCC implicitly does with its consideration of emissions from power generation, that accounting for scopes 2 and 3 emissions is an accounting for emission reduction opportunities. There is a shared responsibility along the supply chain for these emissions, which previous analyses have interpreted as partial responsibility [29–31], but which we count as both parties being responsible.

In the corporate world, scopes 2 and 3 GHG emissions are evaluated using process-based life-cycle assessment (LCA) [11, 32]. On a macro-scale, input–output analysis (IOA) has become widely employed to quantify emissions embodied in trade and carbon footprints through the allocation of production-emissions to consumption [12, 33, 34]. The approaches are structurally equivalent. The most important differences are in the scope and resolution. LCA can capture specific production conditions and inputs, such as the choice of a company of electricity supplier, while IOA reflects the average of a specific industry sector in the chosen country. IOA more easily avoids double counting of emissions at the macro level by allocating production-emissions only to final demand (consumption that does not produce any market based output), whilst LCA is often used to quantify the quantity of emissions along various stages of the supply chain [35, 36]. Scope 3 may address upstream emissions related to the inputs to production, downstream emissions related to the use of the products produced, as well as emissions related to commuting of employees [11]. According to the organization environmental footprint guidelines of the European Commission [37, 38], the inclusion of upstream emissions is mandatory while the inclusion of downstream emissions is optional. In the context of this paper, scope 3 refers to upstream emissions only.

The objective of this study was to provide a global picture of scopes 1–3 emissions of sectors, using the sector classification of the IPCC mitigation report, the life-cycle perspective of LCA, and the macro-economic coverage of IOA. Despite the large number of consumption-based accounting or carbon footprint studies, no study that we know of has employed the LCA framing (impacts per unit of product output) to the measure of output at the economy-wide level in IOA because of the double counting issues [29]. The total 'embodied' impact of industrial production will indeed be greater than the total emissions in the economy. This double counting reflects the reality that there are several leverage points at which emissions can be reduced; a coke producer can install $CO_2$ capture equipment, a steel producer can move to a direct-iron reduction process not requiring coke, a construction firm can move to build wood-frame instead of steel-frame buildings and a housing company can refurbish an existing building instead of replacing it with a new building. All those companies have the power to avoid the emissions caused by the production of coke.

Our approach traces the flow of embodied carbon through the economy and can be used to identify which sectors have the most influence over the full supply chain of emissions. Gallego and Lenzen [29] have proposed a method of shared responsibility that can also be used to identify the influence of sectors over the supply chain while at the same time avoiding the double counting. Their method is one of allocating responsibility according to a subjectively determined distribution among consumers and producers; it does not calculate scope 2 and upstream scope 3 emissions.

By quantifying both upstream and direct emissions, our approach answers the question: what is the scope of sectors to influence $CO_2$ emissions directly or indirectly through changes in their supply chain? We apply a Leontief demand-pull model to industrial production, as well as final demand, using a global, MRIO model. Consumption-based emission accounts focus on the indirect emissions of final consumers; this study addresses the indirect emissions of producers. We introduce the carbon flow table to display the sector origin of scope 3 emissions and hence the interconnectedness of the different sectors. We find that the industry sector dominates scope 3 emissions and investigate whether splitting up the industry sector would provide further insights.

## Methods

The analysis was conducted with the EXIOBASE 3.4 MRIO model, describing the world economy disaggregated into 200 products produced and consumed in 43 countries and six aggregate regions, covering a time series from 1995 to 2015 [39, 40]. Product-by-product symmetric input–output tables were used. $CO_2$ emissions from combustion were treated like production factors in a Leontief demand-pull model, as is common for carbon footprint calculations [3, 41]. Other emissions were not addressed because $CO_2$

from land use change is difficult to ascribe to products in the input–output table and the emissions of methane, nitrous oxide and other GHGs are more uncertain and were not available for the most recent years. Results for estimated $GWP_{100}$ GHG emissions are provided in the supporting information available online at stacks.iop.org/ERL/13/104013/mmedia.

This work used a simple endogenization of the consumption of capital goods, which is the same in magnitude as the augmentation approach described by Lenzen and Treloar [42]. It assumes that each economy has one uniform capital product, the production of which is described by the current year's gross fixed capital formation vector of final demand. We normalized the gross fixed capital formation vector and multiplied it by the consumption of fixed capital required for the production each product to obtain a flow matrix of products required to replace the capital consumed by production processes in the given year. Net capital formation was calculated as the difference between gross fixed capital formation and the consumption of fixed capital by each country, and retained in the final demand, so that the total output vector $x$ remained unchanged. The consumption of fixed capital was set to zero, so that total inputs to production also remained unchanged. See supporting information for more details. The largest impact of the inclusion of capital was on the carbon footprint of services, in particular real estate services, the rental of machinery and equipment, and public services like education and health care.

The following derivation of Leontief multipliers shows that multipliers applied to intermediate inputs trace the flow of embodied carbon through the economy, counting it at each stage of production. Indirect emissions are the $CO_2$ embodied in inputs from other sectors [43]. In an input–output system, production of products is described by the production balance in the column of the input–output table, where inputs $z_{ij}$ are required to produce a volume $x_j$ of products $j$. The market balance in the row of the input–output table describes the use of product $i$ as intermediate input to produce products $j$ and types of final consumption $k$, $x_i = \sum_i z_{ij} + \sum_k y_{ik}$. The emissions embodied in the output of a production process are defined as the sum of the direct emissions occurring in the process and the emissions embodied in the intermediate inputs of the process (figure 1). If $m_i$ is the emissions embodied per unit input $i$, the direct emissions in the production of $j$ are $f_j$, and the embodied emissions per unit output $x_j$ are given by $m_j$ (noting that the same emissions can be included in $m_i$ as $m_j$), we can write the balance of embodied carbon of each individual production process as

$$f_j + \sum_i m_i z_{ij} = m_j x_j \quad \forall j. \tag{1a}$$

If $m_i = m_j \;\; \forall i = j$, the equation can be written in matrix form as

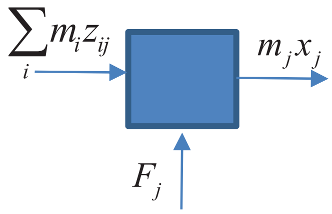


**Figure 1.** Balance of direct and embodied emissions in a single production process. $z_{ij}$ presents the input of products $i$ used in the production of $j$, $xj$ the production volume of $j$, $Fj$ the direct emissions, and $mi$, $mj$ the embodied emissions per unit product in both inputs $i$ and output $j$, respectively.

$$\mathbf{f} + \mathbf{mZ} = \mathbf{m\hat{x}}, \tag{1b}$$

where lower-case letters signify vectors and capital letters matrices. The hat indicates a diagonal matrix. Right-multiplying equation (1b) with $\hat{x}^{-1}$ and replacing $\mathbf{s} = \mathbf{f}\,\hat{\mathbf{x}}^{-1}$ and $\mathbf{A} = \mathbf{Z}\,\hat{\mathbf{x}}^{-1}$, i.e. the coefficient matrices, we obtain

$$\mathbf{m} = \mathbf{s}(\mathbf{I} - \mathbf{A})^{-1}. \tag{2}$$

The logic inherent behind such a calculation is that each sector in an input–output table produces a homogenous good, which has the same cradle-to-gate emissions whether it goes to intermediate or final demand. For a homogenous good, the factor inputs and their associated emissions must be the same.

The embodied flows of carbon across production activities and to final demand are hence obtained as, respectively,

$$\mathbf{E_Z} = \mathbf{\hat{m}Z} \tag{3a}$$

$$\mathbf{E_y} = \mathbf{\hat{m}y}. \tag{3b}$$

$\mathbf{E_Z}$ and $\mathbf{E_y}$ are matrices or vectors with the same dimension as $\mathbf{Z}$ and $\mathbf{y}$, respectively, and can be read in the same fashion as $\mathbf{Z}$ and $\mathbf{y}$, only that they represent the flow of embodied carbon rather than the flow of monetary values (embodied value added). In $\mathbf{E_Z}$, a column indicates that input of embodied carbon in the form of intermediate purchases to a sector, a row indicates the destination. If $\mathbf{E_Z}$, $\mathbf{E_Y}$, and $\mathbf{f}$ are combined, we get a carbon flow table displayed in table 2, which can be read like an input–output table, only in units of carbon rather than monetary value.

When MRIOs are used, the carbon flow matrix will describe both international trade and domestic trade. The carbon flow matrix can hence also be used to add up emissions embodied in international trade, although this topic is not explored in this work. The calculations presented in this work produce annual carbon flow tables (dimension 9800 × 9800) accounting for up to 200 products produced in and sold to each of the 49 countries or regions. To obtain the presentation in table 2, flows were aggregated across countries and from the 200-product detail to the five IPCC sectors, with the sector aggregation provided in the supporting information. In addition, direct emissions resulting from the fuel combustion by

**Table 2.** Table of embodied carbon flows through the world economy. Direct and embodied GHG emissions in an aggregated input–output table describing the world economy in 2015, displaying the production-based accounts of combustion-related $CO_2$ emissions of IPCC sectors in the last line and the consumption-based accounts of carbon footprints in the last column.

| Pg CO2 | Energy | Transport | Industry | Buildings | AFOLU | Consumption |
|---|---|---|---|---|---|---|
| Energy | 3.9 | 0.4 | 8.5 | 0.7 | 0.5 | 5.4 |
| Transport | 0.2 | 0.9 | 1.7 | 0.3 | 0.1 | 3.6 |
| Industry | 0.9 | 0.5 | 23 | 4.7 | 0.5 | 16 |
| Buildings | 0.3 | 0.2 | 2.4 | 1.2 | 0.1 | 5.9 |
| AFOLU | 0.02 | 0.02 | 0.9 | 0.1 | 0.4 | 0.7 |
| Direct | 14 | 4.8 | 9.2 | 3.1 | 0.5 | |

consumers in buildings and cars were added to the buildings and transportation sectors, respectively. End of life emissions are associated with the consumption of waste services, which are reported by industry/final consumer, but not directly allocated to individual products. Downstream emissions can be calculated via the Ghosh model, which could give insight into responsibility down the supply chain, but provides a different policy question to that which we take here [29].

The calculation of $E_z$ includes counting for emissions at multiple stages along the supply chains (e.g. emissions from steel production will be included, as well as the embodied emissions of the use of steel in the car). Just like one sectors' scope 1 emissions are another sectors' scope 3 emissions, the total emissions $E_z + E_y$ are counting each unique emission multiple times in the supply chain. Hence $E_z > E_y$ (or $f$). As opposed to $E_y$ or $f$, $E_z$ thus does not sum to the total global $CO_2$ emissions, but the matrix instead shows the level of emissions that each industry has agency over along the full upstream supply chain. For a discussion of potential misuses of double counting in other applications, the reader is referred to Lenzen [36]. The greater the difference between the sum of $E_z$ and total emissions, the more production activities are involved in the production of a product. The unit of accounting here is the establishment level as defined in the United Nations System of National Accounts. We account output, and hence embodied emissions, at the boundary of an establishment. Of note, if an establishment was disaggregated into multiple stages, then the level of disaggregation would impact the quantity of double counting [36]. Hence the importance of keeping to statistical quantities in the analysis.

## Results

### Indirect versus direct emissions per sector

In 2015, indirect (scopes 2 and 3) emissions from fossil fuel combustion in the supply chains of all sectors totalled 55 Pg $CO_2$, up from 30 Pg in 1995, growing 83% (figure 2). In comparison, direct emissions have grown by 47% in the same period. In the OECD, direct emissions increased by 4% and indirect emissions by 20%; in non-OECD countries, direct emissions doubled while indirect emissions grew by two-and-a-half fold (figure 3). The increasing importance of supply chain emissions indicates that intermediate producers can have a much greater influence on emissions than before. The industry sector as defined by the IPCC, which includes everything from slaughterhouses to tour operators, had by far the largest indirect emissions of 37 Pg. The building sector indirect emissions were 10 Pg, three times as high as direct emissions. The indirect emissions for the energy sector were about one third as large as the direct emissions, and those of transport were two fifths of direct emissions when driving by consumers is included in the direct emissions. For AFOLU, indirect emissions were almost three times as high as direct emissions, a picture that changes dramatically when emissions of $N_2O$ and $CH_4$ are included (see SI).

Direct $CO_2$ emissions increased by 47% between 1995 and 2015, scope 2 emissions increased by 78%, indicating the increasing importance of modern energy carriers. Scope 3 emissions increased by 84%. The importance of scope 3 emissions increased particularly in the industry sector, but also in buildings, transport, and energy (figure 2). The increases were largest in the developing countries (figure 3; figure S3 for GHGs). The rise of scope 3 emissions was particularly rapid in China's industry sector, although a similar trend appeared in other countries, as the example of Brazil in figure 3 indicates. In OECD countries, the development was different, as both energy sector and industry's scope 3 emissions peaked in 2007 and declined after that. This development, while exposed to more fluctuations, was apparent also in individual countries such as the US and Germany (figure 3). In 1995, the ratios of scopes 3 to 1 emissions were 1.1 for OECD countries and 1.2 for non-OECD countries. By 2015, these had grown to 1.3 and 1.5, respectively. While the growth in importance of scope 3 emissions was most marked in developing countries, it reflects a structural change that happened all over the world.

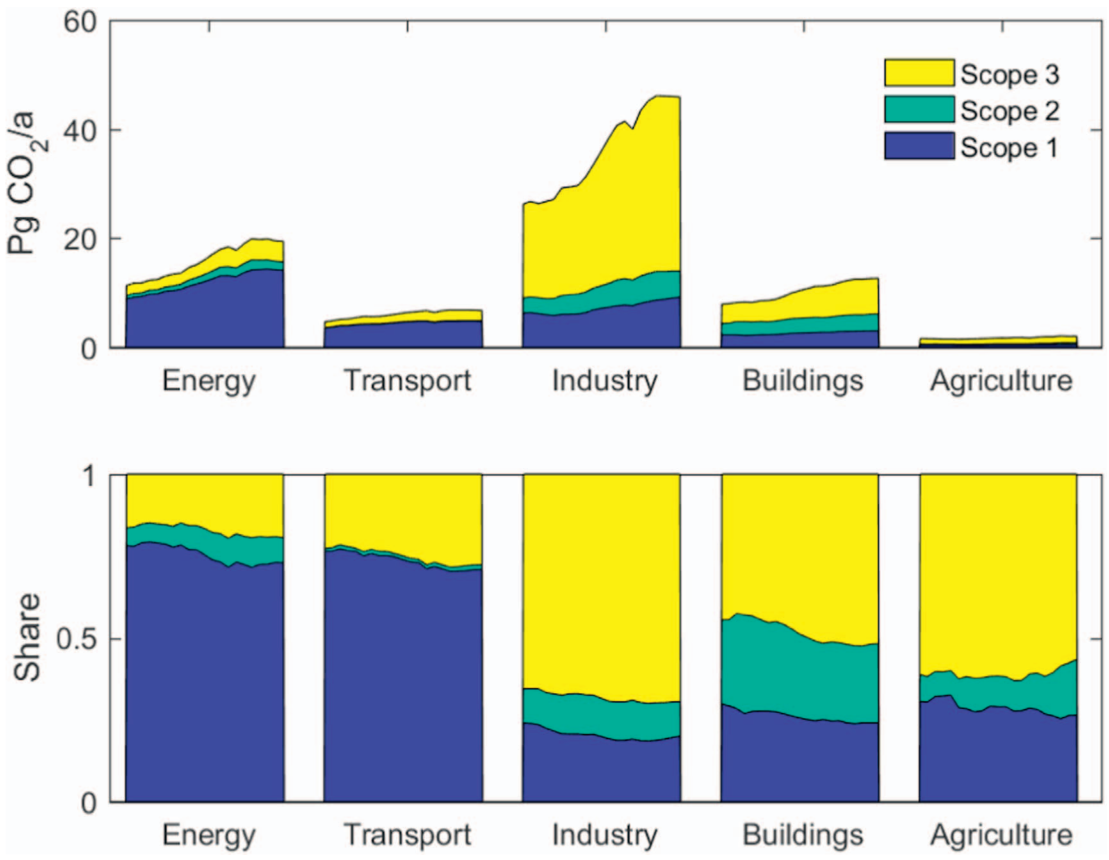


**Figure 2.** Scopes 1–3 emissions of the five IPCC sectors over the period 1995–2015, calculated using EXIOBASE 3.

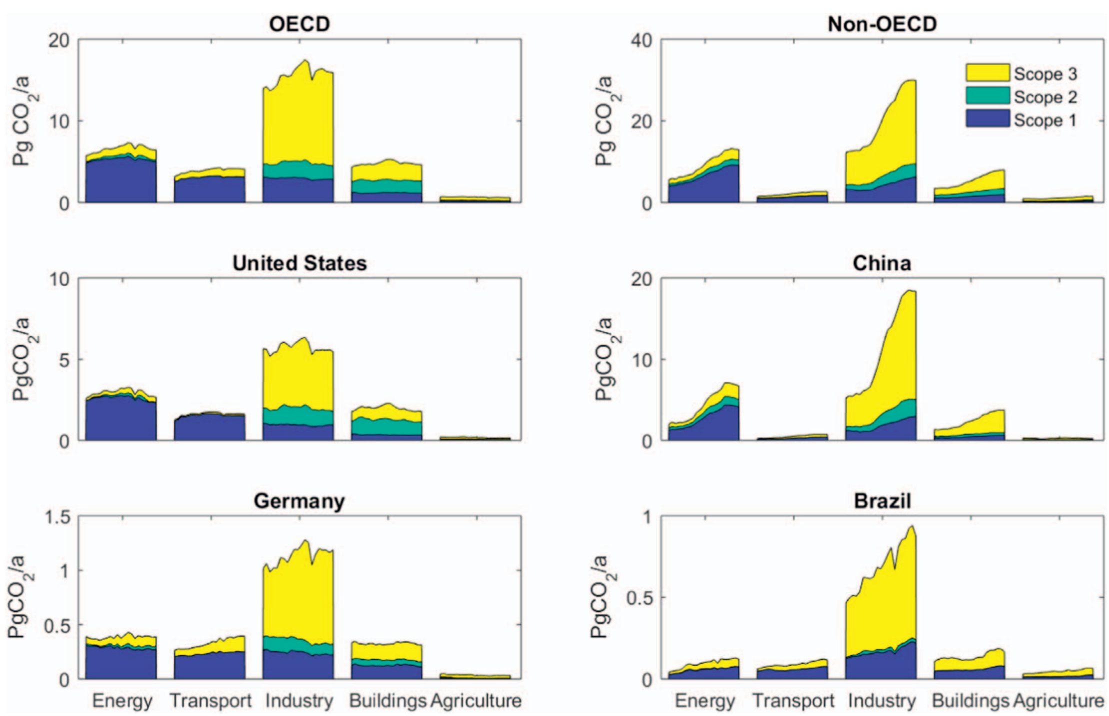


**Figure 3.** Scopes 1–3 emissions of OECD and non-OECD countries, and of selected countries. The figure indicates the rapid rise of scope 3 emissions in developing countries, while industrialized countries appear to stabilize and even decrease their emissions.

## A flow table of embodied carbon

The flow of embodied $CO_2$ through the economy is displayed in table 2. The table is aggregated from a more detailed table consisting of 200 products for each of 43 economies and six aggregate regions. The table is organized like an input–output table. The column shows the source of (embodied) emissions, the row the destination. The bottom row represents the direct emissions, which are the basis of current climate policy. The right-most column represents the consumption-based accounts, which is the allocation of direct emissions to final consumers. It has received a fair amount of attention in recent climate policy discussions. The sum of both is equal. Direct emissions from fuel consumption by households have been allocated to buildings and transport both in the direct emissions row and the consumption column. The table shows that for energy, the most important source of indirect emissions were other parts of the energy sector. An example of these indirect emissions is the emissions from oil and gas production when oil and gas are further refined or combusted for electricity production. The most important destination of embodied emissions was industry, which absorbed half of the emissions embodied in products of the energy sector. A little more than one quarter went to consumption. In the transport sector, the direct emissions of private vehicles contributed about 2.2 Pg, about 35% of total emissions. Industry absorbed one quarter of the total emissions of the transport sector, as the row indicates. Half of the transport sector's total emissions were associated with consumption. By far the largest number in the table is the flow of industrial products to the production of industrial products, 23 Pg. It appears as if industry was trading with itself, some form of circular flow. In reality, industry includes long supply chains, as a more disaggregated presentation shows (table S1 in the supporting information). For example, the emissions occurring during iron mining are first embodied in the input of the iron and steel industry, which is further passed on to metal products, and from there to car production and further to taxi services. About 35% of emissions embodied in industry went to final consumption, and 10% went to buildings. For products of agriculture and forestry, the most important destination is industry, which includes food processing, followed by final consumption.

## Rapid growth of indirect emissions

When looking at total, direct plus indirect emissions, we see that emissions from the industry sector have increased most in the period of 1995–2015, by 75%, followed by emissions from energy (71%) and buildings (61%). Direct emissions from the energy sector have grown by 59% and the share of the energy sector in direct emissions has increased from 41% to 45%, but scopes 2 and 3 emissions have grown even more rapidly. Potential reasons for this increase in the scopes 2 and 3 emissions of the energy sector are the production of a larger fraction of more refined products such as electricity and gasoline, or additional effort required to extract, transport, and refine available sources, which would suggest decreasing energy return on investment. Indeed, emissions from power plants have doubled from 5.5 to 11 Pg, which explains much of the growth in direct emissions from the energy sector.

## More insight by disaggregating industry

We split the industry sector into extractive industries and material production, manufacturing, and services. In addition, we included food processing and forestry products (lumber) with agriculture and forestry in AFOLU+. This reorganization was motivated by the central role of materials in the industry chapter identified by Allwood and Cullen [28], the overall importance of services to the economy and their unique importance for consumption-based accounts identified by Suh [44], and the role of original equipment manufacturers identified in global supply chains [23]. The move of food processing to AFOLU is justified as dietary change is discussed in AFOLU and has repercussions on the entire supply chain of food. Figure 4 shows that, of the new sectors, materials would have the highest scopes 1 and 2 emissions, while manufacturing would have the highest scope 3 emissions. Services are surprisingly important. The total scope of emissions responsibility of each of the three new sectors would be about the same as those of the buildings sector and larger than transport, which, however, has high direct emissions.

The carbon flow table (table 3) reveals that emissions associated with materials production became embodied mostly in the products of industry and buildings. Industry produces mostly manufactured products sold to final consumers. Materials were the largest contributor to emissions embodied in manufactured products, in total slightly more important than (embodied and direct) emissions from energy. Services drew most evenly on all sectors for inputs and constituted the largest component of consumption-based emissions, higher than buildings (which include direct emissions from heating and cooking), energy, and manufactured products.

Manufacturing and construction can contribute to climate change mitigation through material efficiency measures [45]. While consumption-oriented mitigation efforts often focus on activities with high emissions intensities such as mobility and housing [46], new programmes are needed to reduce the carbon intensity of services. A more detailed sector classification in which the industry sector is broken up into different parts would invite the search for such options, which have received surprisingly little attention to date.

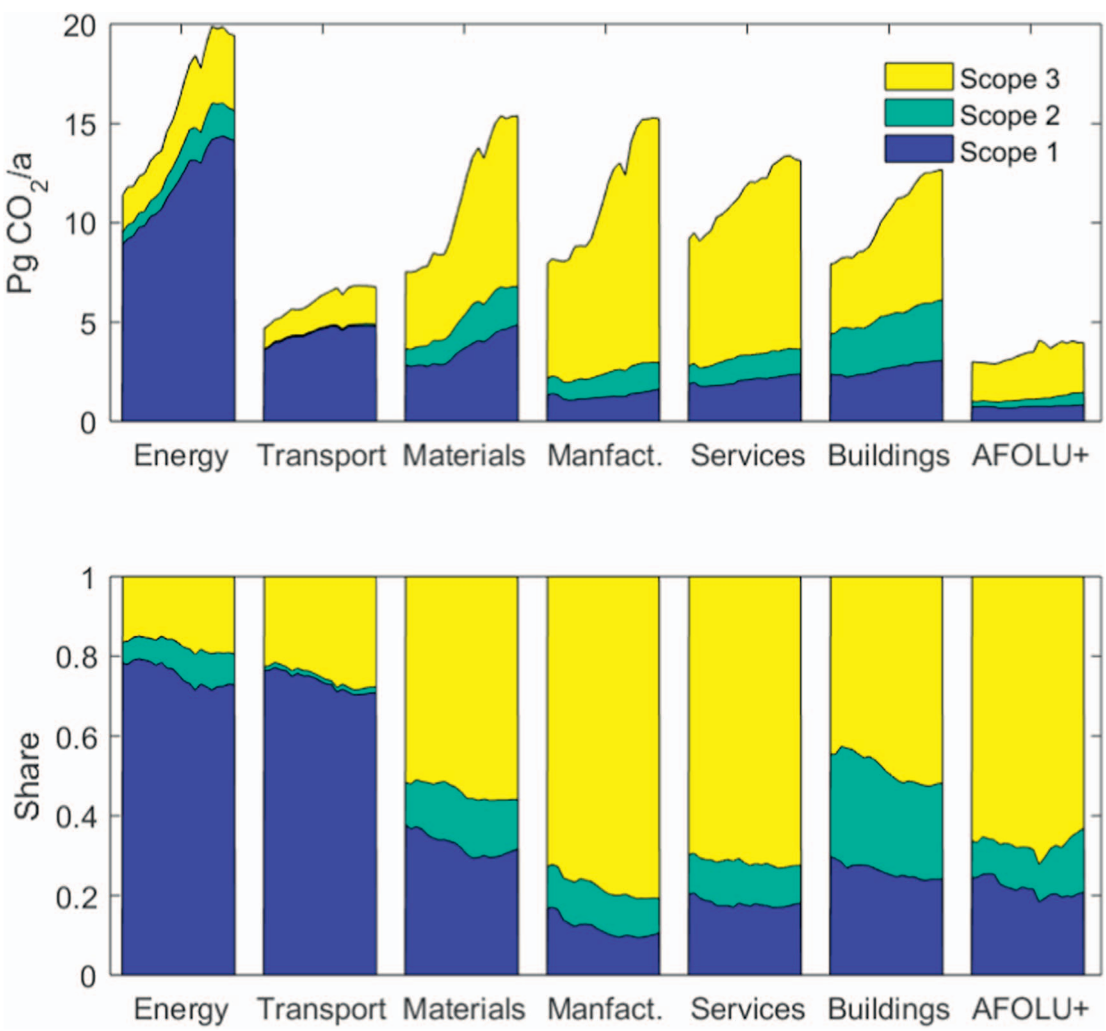


**Figure 4.** An alternative sector classification, in which materials and services are split off the industry sector to form their own sectors and food and forestry products are shifted to an expanded agriculture, forestry and other land use (AFOLU+) sector would result in a more even scope for $CO_2$ mitigation across sectors.

**Table 3.** Embodied carbon flow table through the world economy in 2015 following a more detailed sector classification, in which the industry sector was broken up into materials, manufacturing (industry), and services, and the AFOLU + sector includes the processing of food and forestry products.

| | Energy | Transport | Materials | Manfact. | Services | Buildings | AFOLU+ | Consumption |
|---|---|---|---|---|---|---|---|---|
| Energy | 3.9 | 0.4 | 3.7 | 2.2 | 2.2 | 0.7 | 0.8 | 5.4 |
| Transport | 0.2 | 0.9 | 0.3 | 0.4 | 0.9 | 0.3 | 0.2 | 3.6 |
| Materials | 0.3 | 0.1 | 4.7 | 4.3 | 1.3 | 2.9 | 0.3 | 1.5 |
| Manfact. | 0.4 | 0.2 | 0.9 | 5.4 | 1.8 | 1.2 | 0.2 | 5.1 |
| Services | 0.2 | 0.2 | 0.4 | 0.7 | 2.6 | 0.5 | 0.3 | 8.1 |
| Buildings | 0.3 | 0.2 | 0.3 | 0.4 | 1.6 | 1.2 | 0.2 | 5.9 |
| AFOLU+ | 0.02 | 0.02 | 0.1 | 0.1 | 0.3 | 0.0 | 1.2 | 2.1 |
| Direct | 14 | 4.8 | 4.9 | 1.6 | 2.4 | 3.1 | 0.8 | |

## Discussion

### The implications of indirect emissions for the IPCC assessment

The present analysis shows that indirect emissions are substantial and growing. One may argue that indirect emissions do not matter. In the end, direct emissions need to be reduced; my indirect emissions are somebody else's direct emissions. However, as the treatment of scope 2 emissions by the IPCC illustrates, addressing such emissions systematically reveals a multitude of opportunities both to save energy and avoids problem-shifting. The same logic applies to scope 3 emissions.

- For transportation, the emissions associated with producing vehicles and roads are of comparable magnitude as those associated with producing gasoline or diesel [47] and battery manufacturing would impose substantial emission costs on a transition to electric vehicles [27]. Investigations of high-speed rail, for example, revealed significant impacts related to construction [48]. As distribution of impacts varies among technologies, it is important to take all impacts into account when considering alternatives. Ignoring scope 3 impacts might lead to the promotion of technologies that do not yield the expected emission reductions.
- The building chapter [49] was very much focused on the building as an artefact, not following any economic logic or sector classification. In this paper, the construction sector was included under buildings in addition to real estate services, which includes housing. Such an organization would be more logical. For buildings and construction, scope 3 emissions were larger than scope 2 emissions and may be harder to avoid (tables 2 and 3); decarbonizing electricity production will eliminate emissions associated with electricity consumption but do little to remove emissions from concrete and steel production or the operation of heavy equipment during the construction process. While the buildings chapter of IPCC-WGIII reports was in the lead in addressing scope 2 emissions, it has paid little attention to scope 3 emissions [49].
- A review of the industry chapter indicates that it has a balanced analysis of the wide scope of industries, from basic extractive industries through manufacturing to services, but places its emphasis on the emissions-intensive materials and chemicals sectors [50]. In the summary reports, however, emissions are aggregated and the effects of important structural changes within industry are overlooked. In particular, little heed is played to services, which contribute significantly to the carbon footprints of consumption. An alternative organization might capture three aspects, extractive industries and material production, manufacturing, and services, in separate chapters.
- In the energy chapter, scope 3 emissions associated with the development of energy infrastructure were addressed in AR5 [51] for electricity generation sources and are being systematized now [52]. Similar considerations for other pieces of the energy infrastructure are not likely to reveal large scope 3 emissions, as our assessment of the whole sector shows.
- Consumption and lifestyle aspects of climate change mitigation were most systematically addressed in the buildings chapter, although half of the carbon footprint of final demand is associated with the consumption of products and services produced by industry. The AFOLU chapter addresses dietary change as a mitigation strategy but does not address the analysis of food processing or transport. While such overlaps are inevitable due to the many interactions across sectors, the patchy treatment of final demand is not [53]. The IPCC might choose to have a dedicated chapter on final demand focusing on structural and behavioural aspects, or it could systematically address final demand within each of the sector chapters. Tracing indirect emissions with a global input–output model as presented here will provide a mechanism by which to related emissions and mitigation actions in various sectors to carbon footprints, and to assess the mitigation impact of consumption and lifestyle changes.

We suggest that the IPCC could use the type of analysis presented here to systematically address the interconnections among sector chapters and to identify the potential overlap and synergies of various mitigation strategies, especially those from the demand side. The analysis could be expanded to address the composition of sectors in greater detail, as represented by the national economic accounts. At the outset of the work of the IPCC, there was insufficient information at the global level to effectively use economic accounts, but with the emergence of global multi-regional input–output tables, there are now research tools available to offer the required information. This approach would also allow the IPCC to trace changes in the connections among sectors across time.

Manufacturing and construction can contribute to climate change mitigation through material efficiency measures [45]. While consumption-oriented mitigation efforts often focus on activities with high emissions intensities such as mobility and housing [46], new programmes are needed to reduce the carbon intensity of services. A more detailed sector classification in which the industry sector is broken up into different parts would invite the search for such options, which have received surprisingly little attention to date.

## Emissions embodied in capital goods

Scope 3 emissions include those associated with manufactured capital utilized in the production of energy and products, such as coal mines, vehicles, roads and buildings. Gross fixed capital formation accounted for 25% of the consumption-based emissions in 2015, comparable to the direct emissions from industry. The emissions for manufacturing the capital equipment utilized today occurred in the past. In principle, a dynamic modelling approach of the capital stock [54] and a level of detail in which five to ten different capital goods are distinguished [55] could offer a good assessment of these historical carbon emissions. In practice, the national economic accounts of most countries do not publish such detailed information on the type of capital goods utilized by different sectors. In this work, we have assumed that all sectors use the average capital good produced in the same year, in line with other assessments [56]. Construction, machinery, and vehicles account for two thirds of capital expenditures and their carbon intensity varies little, so that the error introduced through this simplification is not so large [55]. A better analysis of the emissions embodied in different types of capital goods could provide policy makers with a better understanding of the dynamics of emissions related to capital formation and could help identify development pathways for developing countries that are less polluting than the standard model of industrialization. Tracing development dynamics through an explicit representation of the capital stock would require national statistical offices to provide more detailed capital accounts and would benefit if the capital is accounted for in physical units (number, kg etc) as well as the more common monetized valuations.

### Useful for directing further analysis

The use of MRIO tables for the quantification of emissions embodied in products traded internationally [1, 57] and the carbon footprints of final demand is well established [58] and accepted by the IPCC [13]. In this manuscript, we extended the application of MRIO models to quantify indirect emissions of all sectors represented by sector chapters in the IPCC report. With this approach, we could identify important interconnections between different sectors, particularly when dividing the industry sector in materials, manufacturing, and services. We could show that the contribution of materials and manufacturing to the buildings sector was surprisingly important on the global level. Materials contribute as much to manufacturing as energy. The carbon flow table, in particular, provides a new perspective for sectoral carbon accounting and a handy way of gaining an overview at an intermediate level of detail, as soon as one learns how to read it. It provides new insights into the scope of sectors to reduce emissions and may affect our judgement of the merit of mitigation actions. A scopes 2 and 3 analysis of particular economic sectors also chimes with how companies and cities approach the development of their mitigation strategies. The IPCC has so far struggled with properly considering such bottom-up mitigation activities in its assessment of climate change mitigation. The approach presented in this work allows analysist to use at least the same concepts as companies, which would be a starting point for better considering ongoing mitigation activities.

## Data availability

The EXIOBASE MRIO data used to produce the results is from http://exiobase.eu/. The code to reproduce the results is posted on https://github.com/Hertwich/Embodied_C_IPCC_sectors/.

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