Environmental Impacts of Capital Formation

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Summary

The investment in capital goods is a well-known driver of economic activity, associated resource use, and environmental impact. In national accounting, gross fixed capital formation (GFCF) constitutes a substantial share of the total final demand of goods and services, both in terms of monetary turnover and embodied resources. In this article, we study the structure of GFCF and the environmental impacts associated with it on a global scale, and link it to measures of development. We find that the share of GFCF as part of the total carbon footprint (CF) varies more across countries than GFCF as a share of gross domestic product (GDP). Countries in early phases of development generally tend to invest in resource-intensive assets, primarily infrastructure and machinery, whereas wealthier countries invest in less resource-intensive assets, such as computers, software, and services. By performing a structural decomposition analysis, we assess the relative importance of investment structure and input-output multipliers for the difference in carbon intensity of capital assets, and find that the structure of investments plays a larger role for less-developed countries than for developed countries. We find a relative decoupling of the CF of GFCF from GDP, but we can neither confirm nor rule out the possibility of an absolute decoupling.

Introduction

The impacts of infrastructure development are a well-known driver of economic activity and the associated resource use and environmental impacts (Müller et al. 2013; Chen and Graedel 2015). In terms of the carbon footprints (CFs) of nations, capital investments constitute a substantial share of the final demand of goods and services: Hertwich and Peters (2009) assign 18% of global greenhouse gas (GHG) emissions to capital investments. The embodiment of these emissions in the stock of manufactured capital is, however, not necessarily to satisfy the current requirements of a population, but for their future development, and potentially for producing goods for export. Future scenarios of climate-change mitigation will further involve extensive investments in new infrastructure (IPCC 2011).

Understanding the size and composition of the capital is a central objective of industrial ecology (Weisz et al. 2015). Weisz and colleagues (2015) argue that the flow of material and energy from and to the environment generated by the unending process of reproducing manufactured capital defines the whole industrial metabolism, and that reducing its environmental and resource impacts without reducing its function to human well-being is the crucial challenge for long-term sustainability. Pauliuk and Müller (2014) further this line of thinking by identifying different roles of in-use stocks and describe capital stock as not only a means to produce goods and supply services, but also as resource repository, indicator of wealth, and as central part in the social metabolism. Many capital goods are characterized by a long lifetime (several decades/centuries for, e.g., infrastructure, dwellings, power plants, etc.) and static properties (buildings, infrastructure, large machinery, etc.) and, as a result, play important roles as city shapers, consumption couplers, and determiners of the long-term dynamics of the social metabolism.

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Understanding the capital stock is therefore a requirement for understanding the process of economic development, structural change, and the use of resources and could therefore provide valuable insight for further energy and climate research (Pauliuk and Müller 2014).

In the System of National Accounts, infrastructure is treated in a number of ways, one of which is the annual gross fixed capital formation (GFCF)—"the total value of a producer's acquisitions, less disposals, of fixed assets during the accounting period plus certain specified expenditure on services that adds to the value of non-produced assets" (OECD and UN 2009, 198). Fixed assets are assets used repeatedly in production processes for over a year (Eurostat 2008). GFCF accounts for almost 25% of the total global final demand and hence plays a major economic role, but capital stock is also an important constituent in the social metabolism. The GFCF therefore constitutes a flow of long-term investments purposed to build up or maintain production capacity.

While not considering the services that capital provides, the production of capital goods does cause high environmental impacts and is often related to a specific phase of development. In a recent study on the energy use in China, Xie (2014) concluded that energy use associated with GFCF was much larger than for aggregated household consumption, accounting for 49% of the total energy use by final demand category in 2010. Environmental impacts from GFCF are expected to level off as economies mature (Müller et al. 2006; Peters et al. 2007; Pauliuk and Müller 2014; Chen and Graedel 2015), given that building up the capital stock is more energy and resource intensive than maintaining it. Chen and Graedel (2015, 4) talk about goods reaching "saturation levels" in a study estimating historical in-use stocks of various types of capital goods in the United States.

Many countries keep accounts of the total GFCF, but it is seldom specified in which specific industrial sectors the products are invested; conversely, capital inputs are aggregated into one generic entry (the consumption of fixed capital), giving total capital usage, but not by asset type. Economy-wide models are mainly based on national accounts data, and capital accounts are thus structured accordingly. Such data are traditionally reported in the form of supply-use tables (SUTs), but are used in analysis in the form of square input-output (I-O) tables (IOTs). Combining IOTs from different regions yields multiregional (MR) I-O (MRIO) tables (MRIOTs), which can be augmented to include environmental extensions that can be used to calculate environmental impacts from capital.

We wish to assess the environmental impacts associated with global capital formation. Whereas studies on capital goods typically focus on goods and materials associated with construction, we wish to provide a mapping of all types of capital goods produced in the economy as well as of the final use of these goods, in order to obtain an understanding of the functionality of capital investments. We are further interested in linking capital with development by comparing capital investments and the impacts thereof for countries at different levels of development, albeit we do not look at development trajectories of countries over time in relation to the environmental Kuznets curve (Grossman and Krueger 1991), which we discuss in the Supporting Information available on the Journal's website.

In this work, we analyze the CF associated with GFCF. We allocate sectorial specific capital formation to products at the level of detail provided by IOTs, mapping out in which industries and where in the world most GHG emissions are being embodied in the current development of capital stock. By analyzing the structure and calculating the footprints of capital in countries at various levels of development, we are also able to examine whether countries tend to shift away from material- and energy-intensive capital goods as economies develop. We finish by linking our work to potential avenues for future research on the topic.

Methods and Data

Multi-Regional Input-Output

MRIO analysis is a powerful tool for assessing environmental and sustainability impacts of traded commodities and services on a global scale. It is built on a theoretical framework developed by Leontief (1936), which uses previously recorded economic transactions to analyze interdependencies between different sectors of an economy based on records of economic transactions between them. The use of I-O methodology for assessing environmental problems began in the late 1960s and it constitutes the foundations of current MRIO analysis. Environmentally extended (EE) MRIO is widely used today to study global environmental impacts. Wiedmann and colleagues (2011) identify five recently developed projects that have compiled large-scale MRIO databases (AIIOT, Eora, EXIOPOL, GTAP, and WIOD). Tukker and Dietzenbacher (2013) provide a consistent and recent review of the most prominent databases available today, and Moran and Wood (2014) analyze how the choice of database impacts CF calculations. We use I-O analysis to calculate consumption-based environmental impacts, such as CFs, and take the approach of linking capital accounts to the MRIO framework. The basic I-O accounting framework is explained in the Supporting Information on the Web.

Data Used

EXIOBASE

The EXIOBASE database (version 2.2) is based around detailed EE SUTs, trade linked in order to follow global supply chains (Wood et al. 2015). The database consists of detailed MR EE SUTs, as well as symmetric MRIOTs (Eurostat 2008), all for the year 2007. The SUTs have been compiled by gathering information from national and international (e.g., Eurostat, UN) statistical offices, and hence contain detailed accounts from 43 countries, covering 90% of the global gross domestic product (GDP). The remaining countries are accounted for in five rest-of-the-world regions. The EXIOBASE SUT classification contains 163 industries and 200 products, and the symmetric IOTs used here are product-by-product tables

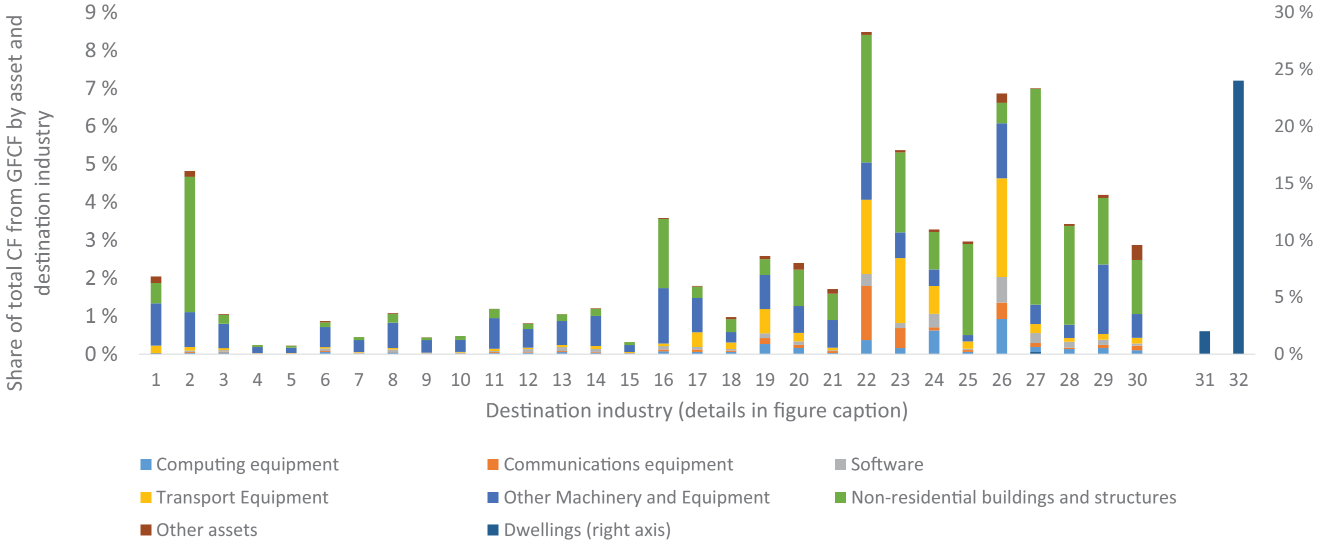

Figure 1 Share of the aggregated CF of the 13 KLEMS countries associated with each asset type and destination industry, 2007. Dwellings are destined almost exclusively to the sectors "real estate" and "other business activities" and are therefore plotted on a separate axis (right axis). All other assets are plotted on the left axis. Industry details: 1, Agriculture, forestry, fishing; 2, Mining & quarrying; 3, Food, etc.; 4, Textiles & leather; 5, Wood & cork; 6, Pulp, paper & publishing; 7, Coke, refined petroleum & nuclear fuel; 8, Chemicals products; 9, Rubber & plastics; 10, Other nonmetallic mineral; 11, Basic & fabricated metals; 12, Machinery not elsewhere classified (nec); 13, Electrical & optical equipment (eq); 14, Transport eq; 15, Manufacturing nec; 16, Electricity, gas & water; 17, Construction; 18, Sale of motor vehicles (mv); 19, Wholesale trade, except mv; 20, Retail trade, except mv; 21, Hotels & restaurants; 22, Transport & storage; 23, Post & telecom; 24, Financial intermediation; 25, Real estate; 26, Renting of machinery and eq; 27, Public admin & defense; 28, Education; 29, Health & social work; 30, Other community & social services; 31, Other business activities (dwellings); 32, Real estate (dwellings). CF = carbon footprint.

according to the industry technology assumption. This, along with the high country resolution, makes it one of the most detailed MRIO database currently available (Tukker et al. 2013). Moreover, one of the objectives of EXIOBASE is that it should be relevant for environmental policy, and one of its benefits for that aim is the availability of interindustry requirement matrices and detailed stressor matrices for agriculture, energy, and resources (Wood et al. 2014).

KLEMS

The EU KLEMS Growth and Productivity Accounts are a set of databases containing inputs and outputs of capital, labor, energy, materials, and services for 25 European countries as well as five non-European (Australia, Canada, Japan, Korea, and United States) (Timmer et al. 2007b; EUKLEMS 2016). Many countries provide highly aggregated capital formation matrices, and the KLEMS database has therefore settled for a low level of industry and asset type detail, including only eight and 32 categories of assets and industries, respectively, which can be seen in figure 1.

Whereas EXIOBASE provides global accounts of GFCF disaggregated over 200 asset types, it only lists the investments as one final demand category. The KLEMS database provides additional information regarding where different types of assets are actually being purchased, which makes it a valuable complement to EXIOBASE. Although it is available only for fewer countries, combining the two databases enables us to assign environmental impacts to different industry sectors.

Methods

Carbon Intensity of Assets

Our research question concerns the structure of capital investments and the hypothesis that countries tend to shift toward less material- and energy-intensive goods as they develop. It is therefore necessary to establish a way to measure the environmental impacts associated with different capital assets. We have chosen the CF as a reference measure for environmental impacts, estimated by the 100-year global warming potential (GWP), calculated according to Intergovernmental Panel on Climate Change (IPCC) guidelines (Pachauri and Reisinger 2007), and expressed in kilograms (kg) of kilograms (CO_2) equivalent (kg CO_2-eq). The procedure to calculate environmental impacts using EE MRIO is explained in the Supporting Information on the Web.

In order to be able to compare assets with one another, we calculate the global GFCF of an asset a, denoted $\overline{GFCF}_a$, as well as the global CF of that GFCF, denoted $\overline{CF}_{GFCF_a}$, and then calculate the share of these measures from the global total GFCF and the CF of the global total GFCF, respectively. In other words, we have:

$$\alpha = \frac{\overline{GFCF}_a}{\overline{GFCF}_{tot}} \tag{1}$$

and

$$\beta = \frac{\overline{CF}_{GFCF_a}}{\overline{CF}_{GFCF_{tot}}} \tag{2}$$

Table 1 Asset types whose GFCF account for more than 1% of the global GFCF and their share of the global GFCF, their respective share of the global CF from GFCF, and the resulting carbon intensity (the ratio of these two shares)

Asset	*GFCF share (%)*	*CF share (%)*	*Carbon intensity (%)*
Construction work	49	59	121
Machinery and equipment n.e.c.	10	12	111
Motor vehicles, trailers, and semitrailers	6	6	99
Computer and related services	6	1	23
Real estate services	3	1	20
Other business services	3	1	29
Other transport equipment	3	3	104
Wholesale trade and commission trade services, except of motor vehicles and motorcycles	2	1	31
Medical, precision, and optical instruments, watches, and clocks	2	2	73
Office machinery and computers	2	2	92
Radio, television, and communication equipment and apparatus	2	2	77
Electrical machinery and apparatus n.e.c.	2	3	148
Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motorcycles parts . . .	2	1	43
Furniture; other manufactured goods n.e.c.	2	2	116
Retail trade services, except of motor vehicles and motorcycles; repair services of household goods	1	1	40
Fabricated metal products, except machinery and equipment	1	2	138

Note: GFCF = gross fixed capital formation; CF = carbon footprint; n.e.c. = not elsewhere classified; the darker shading in the carbon intensity column indicates the five most carbon-intensive asset types and the lighter shading indicates the five least carbon-intensive asset types (out of the 16 types analyzed).

To establish a measure of carbon intensity, we calculate the ratio β / α for each asset a and characterize assets as "dirty" if the ratio is above one and "clean" otherwise. We perform these operations for the asset types whose individual GFCF account for more than 1% of the global GFCF, which entails 16 of the 200 assets (summarized in table 1).

Structural Decomposition

In order to determine why a certain country's capital formation has a high or low carbon intensity, we have performed a structural decomposition analysis (SDA). Whereas a typical SDA studies the evolution of a variable over time by separating the changes in the constituent parts (Dietzenbacher and Los 1998), we wish to compare the value of a variable across different countries. Synchronic cross-country decomposition involves certain additional problems that do not occur in chronological decomposition within a single region. Instead of breaking down a continuous time derivative into annual snapshots, the decomposition is a pure counterfactual comparison between two (unrelated) states. This can potentially lead to large residuals because of the large variations in the explanatory factors attributed to inherent differences between countries, such as GDP, energy mix, relative prices, and, to a certain point, structural comparability (Zhang and Ang 2001). For instance, a study by Chung (1998) concludes that 18% of the difference in CO_2 emissions between China and South Korea is attributed to the residual. This residual increases as the variations among countries increase, and the effect on the residual attributed to each variable depends on the variables' specific change patterns, as is explained in detail by Hoekstra and van Den Bergh (2002). In general, Zhang and Ang (2001) describe some of the prevailing methods for tackling the issue of residual, and conclude that perfect decomposition techniques, that is, techniques that leave no residual, are to be favored over conventional techniques when performing cross-country comparisons, but it must be noted that the handling of the residual is performed mathematically, and that the concept of SDA is not uniquely defined. For further details on the performances of various SDAs as well as discussions about nonuniqueness issues, see, for instance, Dietzenbacher and Los (1998); De Haan (2001); Ang and Liu (2007); De Boer (2008); Ang and colleagues (2009); and Wood and Lenzen (2006). In our approach, we avoid many of the uniqueness problems by only decomposing two variables. Reference values have been normalized to reduce the interaction effects caused by the residual, which, in turn, is evenly distributed among the interaction terms, as is done in the refined Laspeyres method (RLM) (Sun 1998; Owen et al. forthcoming).

In this SDA, we wish to decompose the CF $\mathbf{d} = \mathbf{s}_{\mathbf{CF}}\mathbf{LC}$ into two factors: the multiplier $\mathbf{q} = \mathbf{s}_{\mathbf{CF}}\mathbf{L}$ (where $\mathbf{L}$ is the Leontief matrix and $\mathbf{s}_{\mathbf{CF}}$ is the emissions coefficient matrix for CF, both described in detail in the supporting information on the Web); and the capital expenditure factor $\mathbf{C}$, in order to assess which of these factors is the predominant one for each country (analogous to the study by Alcantara and Duarte [2004]). The multiplier $\mathbf{q}$ shows emissions by country of origin of final good (dimension 9600), whereas $\mathbf{C}$ is a matrix of country of origin of final good, by country of consumption (dimension 9600*48).

The CF has been selected as a measure of environmental impacts for the analysis. The CF multiplier q is expressed in kg CO_2-eq per million Euros (MEur), and when multiplied by the capital expenditure $\mathbf{C}$ we obtain total impact in kg CO_2-eq. The goal of our SDA is to calculate how much the CF $\mathbf{d}$ of each country deviates from the average by adding the respective contributions of $\mathbf{q}$ and $\mathbf{C}$ to the deviation (similarly to Alcantara and Duarte [2004]):

$$\Delta \mathbf{d} = \Delta \mathbf{q}\mathbf{c}_{\text{country}} + \mathbf{q}\Delta \mathbf{c} + \Delta \mathbf{q}\Delta \mathbf{c} \tag{3}$$

where $\Delta \mathbf{q} = \mathbf{q}_{\text{country}} - \mathbf{q}_{ref}$, $\Delta \mathbf{c} = \mathbf{c}_{\text{country}} - \mathbf{c}_{ref}$ and $\Delta \mathbf{q}\Delta \mathbf{c}$ is the residual, which is, in turn, allocated to the delta terms (see below, and Sun [1998]). In these terms, the "country" and "ref" attributes refer to the individual country values and reference values, respectively. That is, $\mathbf{q}_{ref}$ describes reference multiplier values and $\mathbf{c}_{ref}$ represents a reference investment structure. This means that a positive $\Delta \mathbf{d}$ implies that a country has a higher CF than the average. Residual values for each country can be found in the Supporting Information on the Web. We are interested in the impact caused by a certain country, and thus defining capital asset j that country k purchases from country i, we wish to recalculate the product-by-region-of-origin multipliers to product-by-region-of-consumption multipliers. We first reshape $\mathbf{q} = Q_{j,k}$ and then calculate product-by-region-of-consumption multipliers as:

$$\overline{Q_{j,k}} = \frac{\sum_i^{48}(Q_{i,j}C_{i,j,k})}{\sum_i^{48} C_{i,j,k}} \tag{4}$$

This calculation provides a weighted average multiplier for product-by-region-of-consumption, weighted according to the level of capital consumption from the region of origin. We further then only consider the expenditure by product-and-region-of-consumption:

$$C^*_{j,k} = \sum_i^{48} C_{i,j,k}. \tag{5}$$

In order to calculate a global reference value of multipliers for the SDA, taking just the average of all 48 countries for each j would result in a skewed reference multiplier $Q_{j,ref}$, given that it would imply an equal distribution of the production of asset j over all 48 countries, which is clearly not realistic. Therefore, in order to obtain reference multipliers that reflect the composition of the global final demand, the multipliers $\overline{Q_{j,k}}$ are weighted over the purchasing countries as well:

$$\overline{Q_{j,ref}} = \frac{\sum_k^{48}(\overline{Q_{j,k}}C^*_{j,k})}{\sum_k^{48} C^*_{j,k}} \tag{6}$$

Investments are summed over origin country and normalized by GDP according to:

$$\overline{C_{j,k}} = \frac{C^*_{j,k}}{GDP_k} \tag{7}$$

The reference value for investments is obtained by taking the average:

$$\overline{C_{j,ref}} = \frac{\sum_k^{48} \overline{C_{j,k}}}{48} \tag{8}$$

The subtraction $\Delta Q_{j,k} = \overline{Q_{j,k}} - \overline{Q_{j,ref}}$ then provides information on how carbon intensive the production of asset j in country k is compared to the norm, that is, the reference value. Likewise, the subtraction, $\Delta C_{j,k} = \overline{C_{j,k}} - \overline{C_{j,ref}}$, provides information on whether country k invests more or less in asset j than the norm, that is, the reference value. Distributing the residual in keeping with the RLM, we obtain, for the GFCF of each country k, the following contribution to CF:

$$\Delta d_k = \sum_j^{200}\left(\Delta Q_{j,k}\overline{C_{j,k}} + \frac{1}{2}\Delta Q_{j,k}\Delta C_{j,k}\right) + \sum_j^{200}\left(\Delta C_{j,k}\,\overline{Q_{j,k}} + \frac{1}{2}\Delta Q_{j,k}\Delta C_{j,k}\right) \tag{9}$$

The first term gives the contribution to the global CF that stems from country k's multipliers, weighted by country k's investment in that asset. The second term gives the contribution of country k's investment structure, weighted by the multiplier. The sum hence gives a measure of total environmental contribution of GFCF for country k.

Combining KLEMS with EXIOBASE

In order to combine the capital specifications in KLEMS together with the detailed economic and emissions data of EXIOBASE, we need to make the KLEMS capital accounts compatible with EXIOBASE. First, we convert the KLEMS capital data from national currencies to Euros using yearly averages of exchange rates (XE 2015). For the years preceding the introduction of the Euro, the first official exchange rates were used (analogously to Timmer et al. [2007a] for the development of the KLEMS database). Second, we disaggregate the eight asset types in KLEMS into the 200 product categories of EXIOBASE, using a concordance matrix $\mathbf{G}$ that maps the asset types from KLEMS to relevant product categories in EXIOBASE. When KLEMS products map to more than one EXIOBASE product, the values are disaggregated and distributed among the different destinations using a proxy $\mathbf{p}$ is needed. We use total GFCF values from the existing EXIOBASE data as proxy values. We normalize the concordance matrix to avoid double counting; that is, the sum of the shares that each asset assigns to EXIOBASE product categories should amount to one. We obtain a new matrix $\mathbf{G}_{\mathbf{new}}$ calculated as such:

$$\mathbf{G}_{\mathbf{new}} = (\widehat{\mathbf{Gp} + \delta})^{-1}\mathbf{G}\hat{\mathbf{p}} \tag{10}$$

The circumflex attribute on $\mathbf{p}$ implies a diagonalized vector, and δ is a threshold value that prevents singularities. Multiplying the 8-by-32 matrix of national GFCF values $\mathbf{C}_{\mathbf{KLEMS}}$ with $\mathbf{G}_{\mathbf{new}}$ gives a new 200-by-32 matrix of national GFCF values for each KLEMS country. To make it compatible with EXIOBASE, we need to distribute the GFCF values over all regions to form a 9600-by-32 matrix $\mathbf{C}_{\mathbf{EXIO}}$. KLEMS does not provide information about which country the capital assets are purchased from, and we therefore again use EXIOBASE proxies to distribute the GFCF expenditures of the KLEMS countries across the 48 EXIOBASE regions (the majority of assets are assigned domestically; see table A6 in the supporting information on the Web). To calculate the CF from each asset, each column from $\mathbf{C}_{\mathrm{EXIO}}$ is diagonalized:

$$\mathbf{d}_{\mathrm{m}} = \mathbf{s}_{\mathrm{CF}}\mathbf{L}\widehat{\mathbf{C}_{\mathrm{EXIO}_{\mathrm{m}}}} \tag{11}$$

where $\mathbf{C}_{\mathrm{EXIO}_{\mathrm{m}}}$ is the 9600-by-1 vector of capital expenditure that is used by industry m. This results in a 1-by-9600 matrix of CF for each KLEMS country and industry, that can then be summed asset-wise to obtain a 1-by-200 matrix corresponding to EXIOBASE products or aggregated further to KLEMS asset classification as is shown in figure 1.

Results

Size of Gross Fixed Capital Formation

In 2007, GFCF accounted for 24% of global final demand, both in terms of value and GHG emissions. Figure 2 shows that the share of GFCF varies across countries, from 17% to 44% in terms of value and from 14% to 57% in terms of CF. In general, the GFCF is more carbon intensive than the average for countries with a high share of GFCF, whereas for countries with a low share of GFCF, the reverse is true. The calculations have been performed for the 43 countries covered by EXIOBASE, but only the 22 most populated countries are displayed in the graph, as well as the world average. The countries are ordered by GDP per capita (at purchasing power parity [PPP]) and the data are for the year 2007. China stood out as a large investor, with nearly 45% of the final demand going toward building up the capital stock, and other countries' shares were below 29%, with no apparent correlation between GDP per capita and share of investments. The countries with the lowest GDP per capita had carbon-intensive investments and the richest countries had less carbon-intensive investments. It is interesting to see that of the seven BRIC (Brazil, Russia, India, and China) and MINT (Mexico, Indonesia, Nigeria, and Turkey) countries present in the analysis, six have higher shares of CF than GFCF (IND, CHN, IDN, BRA, MEX, and TUR), of which four are substantially higher (IND, CHN, BRA, and TUR). This suggests that an accelerated increase in emissions can be expected as less-developed countries reach higher levels of development.

Nature of Gross Fixed Capital Formation

Using the KLEMS database, we are able to identify the use of different capital assets per destination industry. Figure 1 shows the CF of GFCF, distributed across destination industries. It has been calculated based on the average nominal investments over the accounting years 1995–2007, for the 13 KLEMS countries that provide full capital accounts. Residential structures are almost exclusively destined to the real estate industry and are therefore plotted on a separate axis. They account for one quarter of all GHG emissions from capital. Nonresidential construction investments stand for another 27%, which means that assets from the construction sector account for slightly over half of the total CF from capital. Investments of service sectors involve all asset types, with significant contributions from software, communications, and computing equipment. Even though the latter types of equipment have lower carbon intensities, investments of the service sectors are responsible for a large share of the total CF of GFCF. The "transport and storage" sector has the largest share of impacts after "real estate activities," followed by other service sectors such as "public administration," "renting of machinery and equipment and other business activities," and "post and telecommunications." All manufacturing sectors account for small shares of the CF. The KLEMS countries are considered to be developed countries (World Bank 2015a; IMF 2014), and the results would probably differ if the same disaggregation were available for developing countries.

We have broken down the CF of GFCF at the asset and country level, yielding 9,600 asset-country combinations, and found that the 20 largest national assets account for 61% of the global CF of GFCF (see table S2 in the supporting information on the Web). The top ten accounts for over half of the CF, and assets related to construction work constitute eight of these ten assets. China is present in three of the top ten assets per CF (construction work, machinery and equipment, and motor vehicles), with construction work in China accounting for 27% of the global CF from GFCF. The case of China has been studied extensively (e.g., Gregg et al. 2008; Guo and Fu 2010; Wei et al. 2007; Minx et al. 2011; Weber et al. 2008; Xie 2014; Liu et al. 2013; Lin and Sun 2010). The production of cement and steel constitutes the main source for the large share of China's CF originating from capital formation. Chinese energy consumption is the highest in the world (World bank 2015b), and 17% of it comes from the steel industry alone (2008 figure, Lin et al. [2011]). It has been argued, however, that this peak in emissions for countries in similar stages of development as China is expected to recede as the countries reach a certain level of wealth (Pauliuk and Müller 2014), and we will therefore study how capital investments change as economies mature.

Carbon Footprint as a Function of Wealth

In order to answer the research question concerning whether or not increasing wealth leads to investments in cleaner capital assets, we plotted the GFCF and CF of GFCF of EXIOBASE countries as a function of GDP per capita (PPP) (figure 3a and figure 3b, respectively). The increase in investments seems to have an elasticity over one, but the trend is different for the CF of investments. Although the second graph showing CF per capita contains more outliers, the slope is not as steep and decreases with increasing wealth. This was indeed confirmed when fitting the curves; the highest coefficient of determination (or adjusted R^2) was obtained with a power law fit, with power coefficients p of above one for figure 3a and below one for figure 3b.

To relate the trends observed in figure 3a and 3b, figure 3c displays the inverse of carbon intensity, or amount of capital formation per unit emissions, which has a similar trend as GDP per capita. The division between the countries at different levels of GDP per capita is clear.

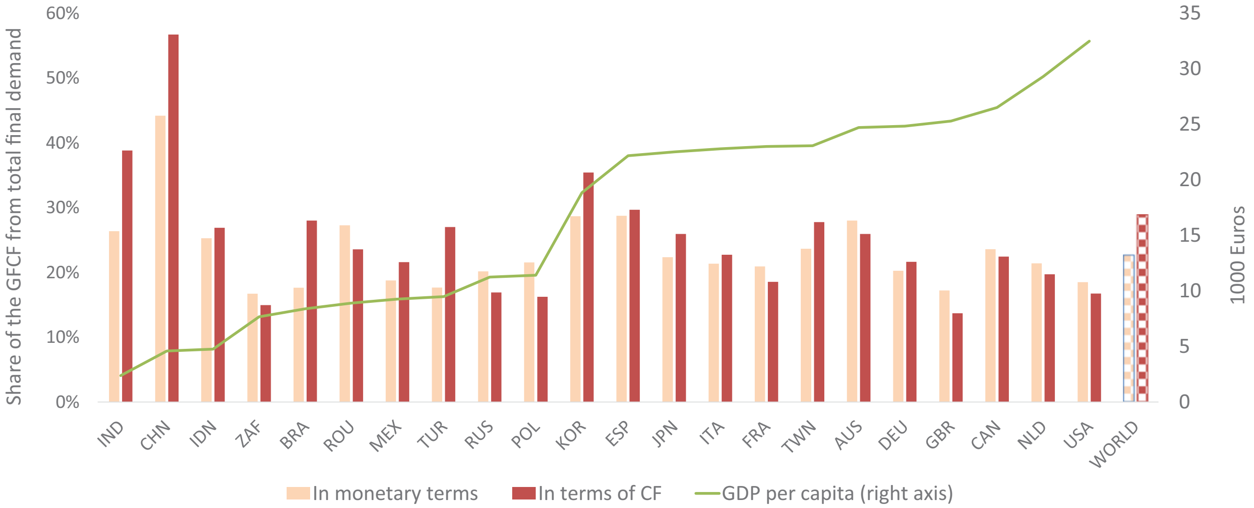

Figure 2 Share of the GFCF from the total final demand, in monetary terms as well as in GWP, for the 22 most populated countries from EXIOBASE2. ISO country codes: IND = India; CHN = China; IDN = Indonesia; ZAF = South Africa; BRA = Brazil; ROU = Romania; MEX = Mexico; TUR = Turkey; RUS = Russia; POL = Poland; KOR = Korea; ESP = Spain; JPN = Japan; ITA = Italy; FRA = France; TWN = Taiwan; AUS = Australia; DEU = Germany; GBR = United Kingdom; CAN = Canada; NLD = Netherlands; USA = United States of America. GFCF = gross fixed capital formation; GWP = global warming potential; ISO = International Organization for Standardization.

Two factors can explain the discrepancies between figures 3a and 3b. The first factor relates to our research question about the structure of capital investments, that is, whether there is a structural shift to less energy-intensive capital goods as countries develop. The second factor is linked to the energy used in the production of the capital assets. The CF of capital goods purchased by a country is directly dependent on the way they are produced, that is, on the electricity mix of the producing country, and for some sectors (e.g., steel and cement production) of process emissions and other energy sources (Guo and Fu 2010; Schneider et al. 2011). These two factors can both amplify each other (e.g., a country that purchases energy-intensive assets that are produced using electricity from coal-fired power plants) or offset each other (e.g., a country that switches from carbon-intensive assets produced with electricity from nuclear power to less carbon-intensive capital assets produced in a country with predominantly coal-based electricity generation). Hence, it is interesting to analyze the outliers from figures 3a and 3b in detail to assess why they deviate. To identify these outliers, we have investigated seven countries each at both ends of the scale in figure 3c—the countries with the least carbon-intensive (green box in figure 3c) and most carbon-intensive capital investments (red box in figure 3c), henceforth referred to as group A countries and group B countries, respectively. Using data from EXIOBASE, we have looked at the nature of capital investments (i.e., asset types) as well as their production country. We then selected the five most (in red) respectively least (in green) carbon-intensive assets (defined according to the method chapter and summarized in table 1) and calculated the shares of these assets that the GFCF (in monetary terms) from the countries in group A and B account for (on a national scale), as well as the average across each country group (figure 4).

The results are clear: The share of dirty assets is substantially higher for the group B countries (between 60% and 90% of the GFCF, with a group average of 77%) than for the group A countries (between 47% and 61%, with an average of 57%). Conversely, the share of clean assets is larger for the group A countries (between 19% and 27%, with an average of 23%) than for group B countries (between 1% and 8%, with an average of 4%). This finding supports the hypothesis regarding the evolution of investments with increasing level of wealth. Plotting the calculated carbon intensity of the countries in group A and group B as a function of their GDP per capita does indeed suggest such an evolution, as can be seen in figure A3 in the supporting information on the Web. It should be noted that this categorization of dirty/clean assets is not entirely candid, in the sense that some dirty investments may occur to ensure a cleaner development. For instance, the construction of wind power plants or hydropower dams require substantial amounts of dirty construction assets. Such an asset disaggregation would be interesting, but lies beyond the scope of this article and the data available in the national accounts.

Investment Structure versus Multiplier

To assess the effect of the multipliers, we performed an SDA (described in the *Methods* section) in which we calculated how much the CF of each country's capital investments deviated against a reference value. The contributions of multipliers and investment structures were calculated separately in order to explain the deviations. The results can be seen in figure 5, where countries are ordered by increasing GDP per capita (PPP). Countries with higher GDP per capita tend to purchase their investments of the same asset type from cleaner suppliers,

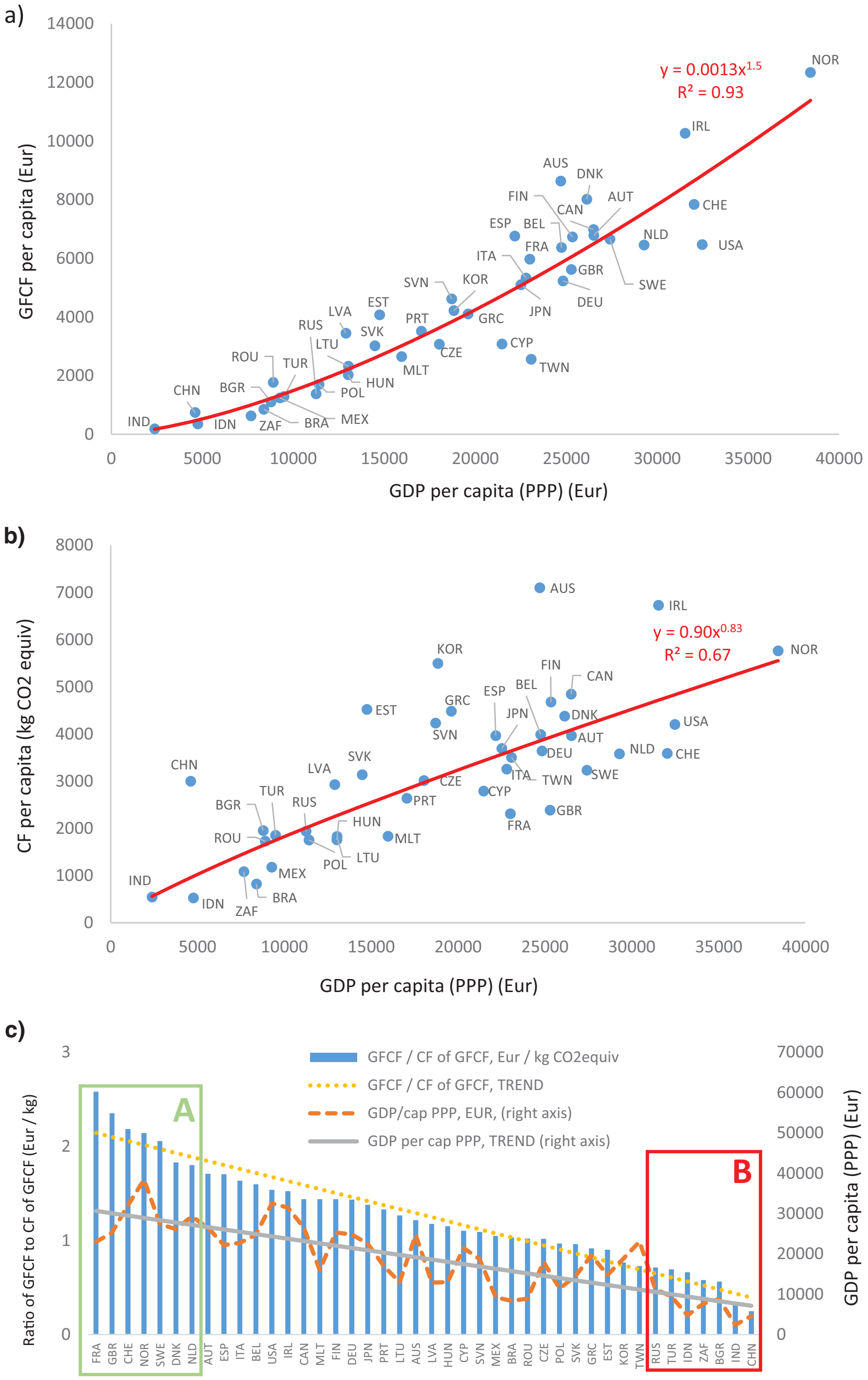

Figure 3 GFCF and CF stemming thereof. The first two graphs display GFCF and CF from GFCF as a function of GDP per capita (PPP), respectively, and the third graph shows the ratio of the two. ISO country codes: FRA = France; GBR = United Kingdom; CHE = Switzerland; NOR = Norway; SWE = Sweden; DNK = Denmark; NLD = Netherlands; AUT = Austria; ESP = Spain; ITA = Italy; BEL = Belgium; USA = United States of America; IRL = Ireland; CAN = Canada; MLT = Malta; FIN = Finland; DEU = Germany; JPN = Japan; POR = Portugal; LTU = Lithuania; AUS = Australia; LVA = Latvia; HUN = Hungary; CYP = Cyprus; SVN = Slovenia; MEX = Mexico; BRA = Brazil; ROU = Romania; CZE = Czech Republic; POL = Poland; SVK = Slovakia; GRC = Greece; EST = Estonia; KOR = Korea; TWN = Taiwan; RUS = Russia; TUR = Turkey; IDN = Indonesia; ZAF = South Africa; BGR = Bulgaria; IND = India; CHN = China. CF = carbon footprint; Eur = Euros; GFCF = gross fixed capital formation; GDP = gross domestic product; ISO = International Organization for Standardization; kg CO_2 equiv = kilograms of carbon dioxide equivalents; MEuro = million Euros; PPP = purchasing power parity.

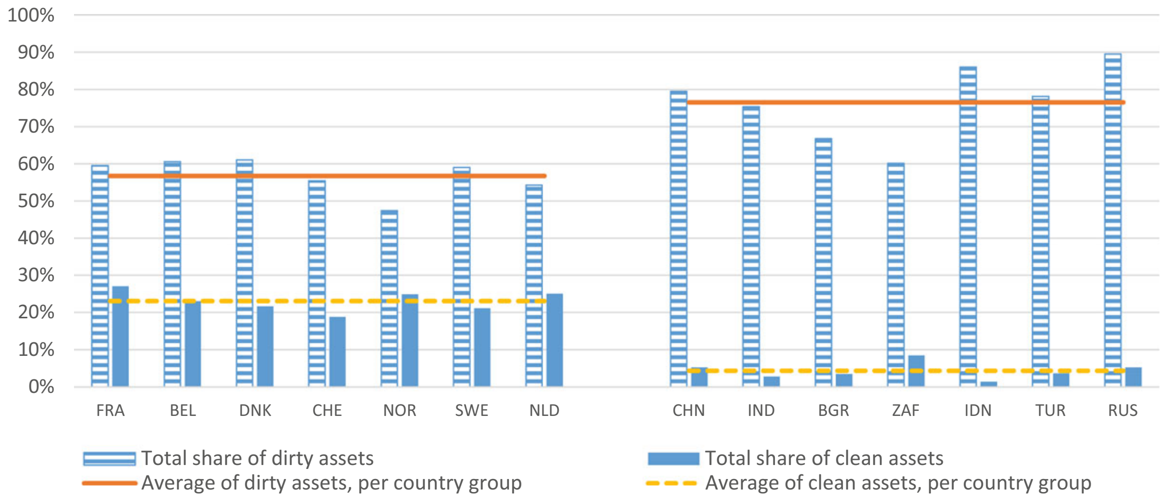

Figure 4 Share that GFCF constitutes of the five cleanest and five dirtiest assets in the countries identified in figure 3c as well as the averages per country group. GFCF = gross fixed capital formation.

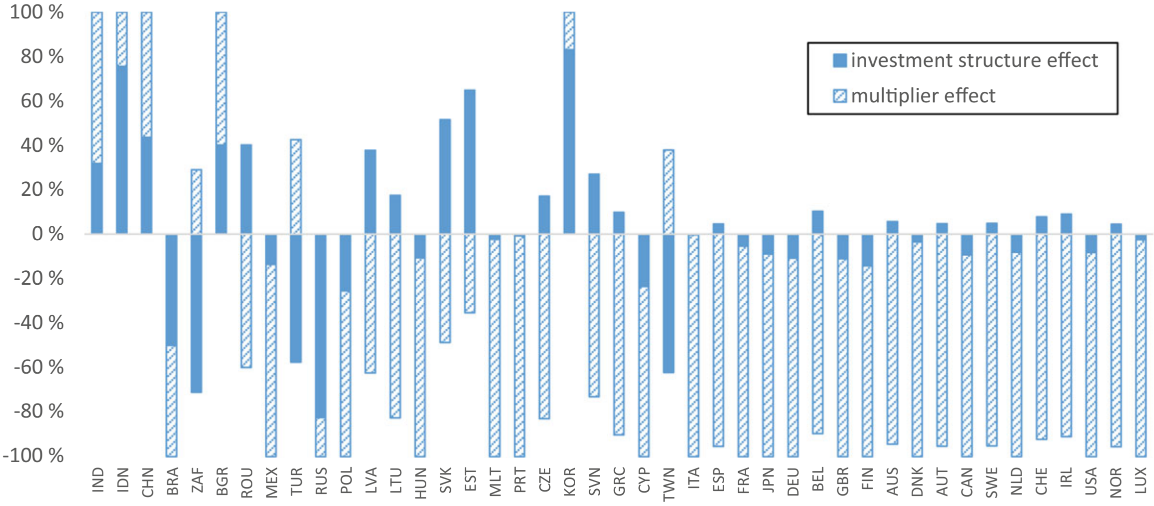

Figure 5 Normalized contributions of multipliers and investment structure to the total deviation of the GWP of GFCF for each country in 2007, ordered by increasing GDP per cap (PPP). The country codes are the same as for figure 3. GFCF = gross fixed capital formation; GDP = gross domestic product; GWP = global warming potential; PPP = purchasing power parity.

which is reflected in the multiplier, and invest in cleaner assets, reflected in the structure of investments. The multipliers explain most of the deviation for high-income countries. For lower-income countries and several middle-income countries, the investment structure has a large effect. For most countries, the aggregated contributions appear smaller than the reference value. This is largely attributed to China's large positive contributions to both investment structure and multiplier.

We also calculated the value added (VA) as well as upstream emissions from capital investments of group A and group B countries, which is summarized in table 2. We see that the VA from GFCF that remains in each country is very similar for both groups, whereas there is a huge difference regarding the upstream emissions. Seventy-seven percent of the CF of investments from group A countries is associated with imports, whereas 67% (on average) of the CF from GFCF from group B countries is associated with domestic production. Table 2 also shows to which countries the CF is outsourced to.

It is well known that one of the loopholes with policies targeting local GHG emissions is the outsourcing of polluting industries from countries with strict emission policies to countries with less-strict policies. This so-called carbon leakage is discussed in several articles (Peters and Hertwich 2008a, 2008b; Babiker 2005; Paltsev 2001). Figure S4 in the supporting information on the Web illustrates the phenomenon for the world's three largest economies; again, the final destination of the VA and CF of the GFCF are plotted, in shares of the respective total (e.g., 52% of the GHG emissions from the total capital investments in the European Union [EU] occur in the EU and the remaining 48% occur outside the EU). In all cases, most of the VA remains in the region, which indicates that a country's capital expenditures tend to profit the country itself. Whereas

Table 2 Occurrence of VA and emissions from GFCF

	VA from GFCF that remains in the country itself (%)	*Average (%)*	*CF from GFCF that remains in the country itself (%)*	*Average (%)*	*Largest receiver of country's CF from GFCF and share thereof (%)*		*Second-largest receiver of country's CF from GFCF and share thereof (%)*	
FRA	76	**64**	28	**23**	CHN	18	DEU	6
BEL	52		24		CHN	9	RUS	8
DNK	62		25		CHN	18	DEU	9
CHE	67		22		DEU	17	CHN	11
NOR	66		27		CHN	16	RUS	8
SWE	61		17		CHN	18	RUS	8
NLD	63		22		CHN	21	RUS	7
CHN	75	**64**	92	**67**	WWA	2	WWM	1
IND	76		83		WWM	4	CHN	3
BGR	40		48		RUS	14	CHN	8
ZAF	59		69		CHN	10	DEU	2
IDN	72		55		CHN	16	WWA	7
TUR	62		56		CHN	12	RUS	9
RUS	67		68		CHN	12	WWE	3

Note: VA = value added; GFCF = gross fixed capital formation; CF = carbon footprint.

the shares of the CF and VA of China's GFCF that remain in China are similar, the EU and United States outsource a relatively large share of their emissions overseas. In fact, our figures show that 17% respectively 13% of the CF from GFCF in the EU and United States end up in China, which concurs with the results from other studies, such as Shui and Harriss (2006), Peters and Hertwich (2008c), and Yunfeng and Laike (2010). When performing the same analysis for the final demand category corresponding to household consumption, figures are much lower: 10% respectively 5% of the GWP stemming from the EU and the United States' household consumption is outsourced to China.

As discussed above, the carbon intensity of the GFCF depends also on how it is produced, that is, the type of energy source. Hence, the small fraction of domestic emissions from group A countries could also be explained by a cleaner energy mix in the production processes. In order to complement our SDA, we have performed additional calculations to identify the source of the emissions from GFCF. More specifically, we have divided the GHG emissions into three categories: combustion emissions from electricity generation; combustion emissions from other sectors; and noncombustion emissions. Combustion emissions are emissions occurring through the burning of fuel, and noncombustion emissions entail emissions occurring elsewise, including process emissions from cement and steel production, agriculture, and so on. The sum of these three emission categories account for all the GHG emissions, and the share that each category accounts for can be directly applied as an explanatory factor for the multiplier effect described in the SDA. These shares are displayed in figure S5 in the supporting information on the Web.

The results do not indicate any clear trends regarding distribution of CF among the three emission categories. Combustion emissions account for 67% of total emissions (electricity related/nonelectricity related 26% respectively 41%). For comparison purposes, the same analysis has been performed for territorial emissions, displayed in figure S6 in the supporting information on the Web, which does show the expected large variations between countries, partly attributed to electricity mix. This finding implies that when calculating consumption-based impacts, the emission intensity is no longer explained by electricity mix. This does, however, explain, to a certain extent, the disparities observed in table 2 above. Indeed, table S4 in the supporting information on the Web provides an overview of the electricity mix of each of the group A and group B countries, and shows similar distribution between the two groups: 69% of the electricity from the group A countries is carbon neutral, that is, made from nuclear power or renewables, and for four countries the share is over 90%. For group B countries, the share of carbon-neutral electricity is only 25%, and nearly half of the electricity production is coal-based—the alternative with the highest CF.

Discussion and Conclusion

Throughout this article, we have performed various calculations with the purpose of gaining an increased understanding of the structure of capital as well as the environmental impacts associated with it. This has been done for 43 countries and five multicountry regions, thereby covering the global economy. We have presented the total size of GFCF per country and compared it with the CF generated by it, and have also disaggregated investments into both products and sectors in order to obtain a more-detailed mapping of GFCF and the CF stemming from it. By linking GFCF and associated CF to the level of development, here expressed as GDP per capita (PPP), we have shown that investments tend to become less carbon intensive as countries develop. An SDA was conducted to analyze whether this effect was attributed to countries investing in less carbon-intensive assets or simply that assets were produced with cleaner energy sources. By performing regional comparisons of the shares of VAS and carbon emissions that are outsourced versus end up locally, we also confirm the occurrence of carbon leakage in the case of GFCF. Finally, to complete our SDA, we studied the sources of the emissions stemming from countries of interest to assess whether the energy mix could explain the deviations in the SDA.

In 2007, GFCF accounted for 24% of global final demand, both in terms of value and GHG emissions. In general, the GFCF was more carbon intensive than the average for countries with a high share of GFCF, whereas for countries with a low share of GFCF, the reverse was true. By comparing GFCF with the CF of GFCF as functions of GDP per capita, we discovered that the increase of investments as countries become wealthier had an elasticity over one, but that the reverse was true for its CF. Similarly to multiple articles preceding this one, China stood out as an extreme case. It had a much larger share of GFCF than other countries, and its two largest GFCF asset categories accounted for one third of the world's total CF from GFCF.

Upon studying GFCF at the product and industry level and using the additional dimension provided by the KLEMS database, we saw that service sectors were the largest consumers of GFCF, and that countries with the lowest GDP per capita had carbon-intensive investments whereas the wealthiest countries had less carbon-intensive investments, suggesting a trend that concurs with studies such as Shahbaz and colleagues (2013). By analyzing the composition of investments, we saw that this trend could be attributed, at least partially, to the structure of investments, in other words that more developed countries invest more in cleaner assets and that less-developed countries tend to have larger shares of dirty assets in their GFCF. To assess the extent of the asset composition contribution, we performed an SDA in which we calculated how much the CF of each country's capital investments deviated against a reference value and isolated the multiplier and investment structure effects. The analysis showed that the contribution of investment structure was much larger for less-developed countries, and that the deviation of the wealthier countries depended mostly on multipliers. Such information could be of great importance for global emission scenario development as well as local environmental policy making, the latter particularly for developing countries that are expected to get substantially more developed in a foreseeable future. Indeed, we saw that of the total CF from final demand in the BRIC and MINT countries, the share stemming from capital investments is substantially higher than the share that GFCF constitutes in monetary terms.

In this article, we have focused on quantifying the emissions stemming from GFCF, and we have established that, as countries develop, their investments increase uniformly, whereas the marginal emissions from GFCF decrease as they reach higher levels of development. This effect is attributed to the nature of capital investments discussed in the introduction, that is, the combination of the long lifetime and the high carbon intensity of capital assets. Hence, the timing of emissions stemming from capital formation is another interesting topic for the continuation for this work. For instance, it could be argued that environmental impacts from GFCF should be spread over time, similarly to the consumption of fixed capital in national accounts.

The additional dimension provided by the KLEMS database constitutes a valuable asset for future research on the use of capital, both in terms of understanding the interaction between natural capital and human capital, which is crucial for understanding the IM of societies and thereby the global future energy and material requirements, but also in terms of contributing to further methodological development of EE MRIO.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information includes an explanation of the basic input-output framework used in the main article as well as a literature review on the environmental Kuznets curve; also included are additional data results regarding gross fixed capital formation.