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RESEARCH AND ANALYSIS

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Global distribution of material inflows to in-use stocks in 2011 and its implications for a circularity transition

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Abstract

Around 40% of global raw materials that are extracted every year accumulate as in-use stocks in the form of buildings, infrastructure, transport equipment, and other durable goods. Material inflows to in-use stocks are a key component in the circularity transition, since the reintegration of those materials back into the economy, at the end of the stock's life cycle, means that less extraction of raw materials is required. Thus, understanding the geographical, material, and sectoral distribution of material inflows to in-use stocks globally is crucial for circular economy policies. Here we quantify the geographical, material, and sectoral distributions of material inflows to in-use stocks of 43 countries and 5 rest-of-the-world regions in 2011, using the global, multiregional hybrid units input–output database EXIOBASE v3.3. Among all regions considered, China shows the largest amount of material added to in-use stocks in 2011 (around 46% of global material inflows to in-use stocks), with a per capita value that is comparable to high income regions such as Europe and North America. In these latter regions, more than 90% of in-use stock additions are comprised of non-metallic minerals (e.g., concrete, brick/stone, asphalt, and aggregates) and steel. We discuss the importance of understanding the distribution and composition of materials accumulated in society for a circularity transition. We also argue that future research should integrate the geographical and material resolution of our results into dynamic stock-flow models to determine when these materials will be available for recovery and recycling. This article met the requirements for a Gold-Gold *JIE* data openness badge described in http://jie.click/badges

KEYWORDS

capital formation, circular economy, industrial ecology, in-use stocks, multiregional hybrid units input–output tables

1 | INTRODUCTION

Global resource extraction has increased from 7 gigatonnes (Gt) in 1900 to 89 Gt in 2015 (Fishman et al., 2016; Haas et al., 2020). Furthermore, a large amount of materials is extracted to produce durable goods that are accumulated by society (IRP, 2019). These materials accumulated as durable goods are called either in-use stocks or built/manufactured capital, and consist of buildings, infrastructure, machinery, and other durable goods (OECD, 2008). Additions to in-use stocks account for almost half of the global resource extraction, while the rest of the materials are used for food and energy purposes (Haas et al., 2015; Krausmann et al., 2017). From an environmental perspective, the production of capital stocks is responsible for around 20% of global CO_2eq emissions (UNEP, 2019) and between 40% and 52% of the material footprint of high income countries (Berrill et al., 2020; Tukker et al., 2014).

The materials stored in in-use stocks can in principle be reintroduced into the economy as secondary materials when these stocks reach their end-of-life (Lanau et al., 2019; Mayer et al., 2018; Pauliuk & Müller, 2014). This reintroduction would be in line with the paradigm of a circular economy (Ellen MacArthur Foundation, 2015; Kirchherr et al., 2017), according to which such a reintroduction would lead to a decrease in primary resource extraction, waste, and emissions (Aguilar-Hernandez et al., 2018; Mayer et al., 2018). Several governments have encouraged the implementation of circular economy measures in order to promote resource efficiency as well as sustainable production and consumption (McDowall et al., 2017). However, most of these policy measures, for example, those proposed in the Circular Economy Action Plan by the European Commission (EC 2020), do not pay attention to inflows to and outflows from in-use stocks as a potential avenue to promote circularity. Keeping track of such material flows is essential for understanding the potential for a circularity transition (Pauliuk et al., 2012; Stahel & Clift, 2015).

Material flows into and from in-use stocks have traditionally been assessed through material flow analysis (MFA), which traces the flow of materials through socio-economic activities (Graedel, 2019; Eurostat, 2013). For example, multiple MFA studies have estimated the inflows and outflows of materials, such as metals (Gorman & Dzombak, 2020; Dong et al., 2019; Pfaff et al., 2018; Miatto et al., 2017; Zeng et al., 2018) and construction materials (Schiller et al., 2017; Marinova et al., 2020; Deetman et al., 2020; Wuyts et al., 2019) in different countries and world regions. More comprehensive MFA have been used to examine the global stock-flow dynamic (Pauliuk et al., 2017b; Nakamura et al., 2017; Wiedenhofer et al., 2019; Krausmann et al., 2018), showing the evolution of the material composition of in-use stocks as well as the amount of waste recycled worldwide.

A few studies have examined the relation between in- and outflows to and from in-use stocks by using an alternative top-down approach: hybrid units and physical input–output analysis (Aguilar-Hernandez et al., 2019; Beylot & Villeneuve, 2015; Hoekstra & van den Bergh, 2006). This approach offers a comprehensive view on the economy and on different economic sectors. For example, the most detailed global, multiregional input–output table in hybrid units (MR-HIOT), EXIOBASE, covers 43 countries and 5 rest-of-the-world regions, with a resolution of 163 sectors and 200 product categories per country/region.

Although inflows to in-use stocks have been studied before in specific countries as well as in the global economy, we believe that a better geographical, material, and sectoral resolution is required to provide insights into the largest opportunities for increased circularity.

This paper aims to quantify the global distribution of material inflows to in-use stocks, and its implications for material circularity. We examine the geographical, material, and sectoral distributions of material inflows to in-use stocks in 2011, using the MR-HIOT EXIOBASE version 3.3.18 (Schmidt & Merciai, 2017; Merciai & Schmidt, 2018) and ancillary World Bank (2020) data. We estimate material inflows to in-use stocks of 43 countries and 5 rest-of-the-world regions for 12 material categories (non-metallic minerals, steel, etc.). At the sectoral level, we estimate the distribution of non-metallic minerals and steel in construction (including building and infrastructure), transport, other industries, and final demand categories. Furthermore, we determine the global material inflows to in-use stocks per country and region in per capita terms (i.e., tonnes per capita), covering different income categories (e.g., high, middle and low income).

In the next section, we describe how material inflows to in-use stocks are represented in the MR-HIOT EXIOBASE. We then present our results for the global distribution of various materials added to in-use stocks in different countries. Based on these results, we discuss the implications of additions to in-use stocks for a global circularity transition and identify key aspects for future work on this topic.

2 | METHODS

2.1 | Material inflows to in-use stocks in the MR-HIOT EXIOBASE

We use the latest version of the global, multiregional hybrid units input–output table (MR-HIOT) of the EXIOBASE database v3.3.18, which includes 43 nations and 5 rest-of-the-world regions (Merciai & Schmidt, 2018; Schmidt & Merciai, 2017). The MR-HIOT EXIOBASE flows are represented in mass, energy, and monetary units.

Material inflows to in-use stocks are represented in the extension of stock additions. This extension shows the gross material inflows to in-use stocks in mass units in intermediate and final demand categories. The extension of stock additions is formally calculated as a residual in a mass

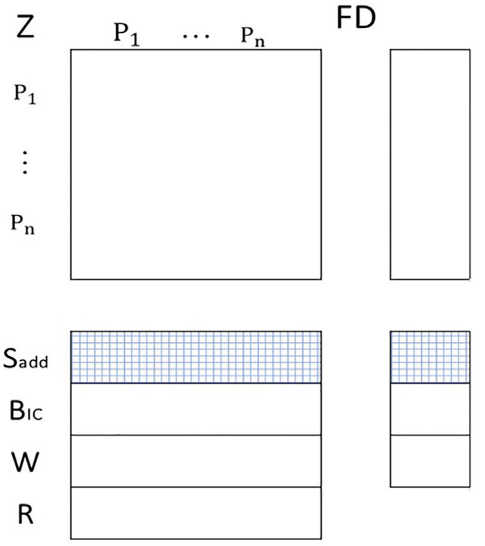

FIGURE 1 Simplified global, multiregional hybrid units input-output table (MR-HIOT). FD = final demand matrix; Z = intermediate demand matrix; P = product or service; R = resource extraction matrix; W = waste supply and use matrix; B_{IC} = dissipative emission matrix; S_{add} = stock additions matrix. Elements in Z and FD are in hybrid units as monetary (i.e., Million Euros), energy (i.e., Terajoules), and mass units (i.e., tonnes). Elements in extensions R, W, B_{IC}, and S_{add} are in mass units. Blue large grid lines correspond the elements represent the material inflows to in-use stocks in mass

balance of resource extraction, waste, and dissipative emissions (Suh, 2004; Schmidt & Merciai, 2017; Mayer et al., 2018), as follows:

$$m + r + w_{rec} = e + b_{IC} + w_{sup} + s_{add}, \tag{1}$$

where m represents the sum of imported materials, r is domestic resource extraction, w_{rec} is recovered or recycled materials, e is material export, b_{IC} corresponds to dissipative emissions and other combustion and biomass residues from industries and final demand, w_{sup} is waste generation, and s_{add} represents material added to stocks[1] (Aguilar-Hernandez et al., 2019). The latter variable conceptually represents the material inflows to in-use stocks, which is the focus of this paper.

Figure 1 shows a simplified representation of the MR-HIOT based on Donati et al. (2020) and Towa et al. (2020). Capital letters indicate matrices of intermediate demand (Z), which includes domestic intermediate demand and international trade in intermediates, final demand (FD), which includes domestic final demand and international trade of final goods and services, extensions of resource extraction (R), waste supply and use (W), dissipative emissions (B_{IC}), and stock additions (S_{add}). The stock additions extension represents the actual manufactured capital of an economy in physical terms, which comprises material inflows to in-use stocks in a specific year. Furthermore, S_{add} is represented as a matrix in which rows are material types (see material_class spreadsheet in Data_S3 in the Supporting Information) and columns cover all industries and final demand categories for each country or region (see industry_class and fd_class spreadsheets, Data_S3 in the Supporting Information). The MR-HIOT EXIOBASE extensions were developed by integrating multiple databases of international institutions, such as the Food and Agriculture Organization of the United Nations (FAO), the International Energy Agency (IEA), Eurostat, and Ecoinvent (Merciai & Schmidt, 2018). In particular, waste extension in the MR-HIOT EXIOBASE was calculated by combining several data sources (see table 2.9 in Merciai et al., 2014) and applying the gap-filling procedure (Merciai & Schmidt, 2018) if there was a lack of data for waste flows.

As the stock additions in the MR-HIOT might be confused with the representation of capital formation in a traditional input–output table, it is important to highlight the main differences between the two accounting systems. In a traditional monetary input–output table, stock additions are represented by gross fixed capital formation (GFCF), which accounts for the economic value of fixed assets used for productive purposes in an economy (Weisz & Duchin, 2006; Södersten et al., 2018a, 2018b). According to the System of National Accounts 2008 (UN, 2009), fixed assets are defined by the asset boundary that differentiate which durable goods are accounted as GFCF and which are not. For example, consumer durables (e.g., washing machines and other home appliances) and small tools (e.g., saws, knives, axes, and hammers) are not accounted in GFCF, despite having a lifetime of more than 1 year (UN, 2009). In contrast, stock additions extension in the MR-HIOT EXIOBASE includes all the material added to the in-use stocks in 1 year, which includes fixed assets plus all the other durable products. This follows the definition of gross stock additions used by the economy-wide material flow accounts (EC, 2001).

2.2 Estimating the global distribution of material inflows to in-use stocks

We use the stock additions extension of MR-HIOT EXIOBASE to quantify material inflows to in-use stocks of 43 countries and 5 rest-of-the-world regions for 2011. This extension contains 12 material categories linked to durable goods added to in-use stocks (see material_class spreadsheet in Data_S3 in the Supporting Information). Algebraically, the total stock additions of material m in country c for year t (i.e., $S^{T}_{m,\,c,t}$) is equal to the sum of material stock additions in industries ($S^{I}_{m,\,c,t}$) plus the sum of materials accumulated in final demand ($S^{FD}_{m,\,c,t}$):

$$S^{T}_{m,\,c,t} = \sum S^{I}_{m,\,c,t} + \sum S^{FD}_{m,\,c,t}. \tag{2}$$

Considering Equation (2), it is important to notice that the accounting of stock additions in the MR-HIOT allows for the allocation of durable goods in industries (as intermediate demand) and final demand categories. This means that the material inflows to in-use stocks can be allocated to each industry as well as to households, non-profit organizations serving households, governments, and GFCF.

To obtain the distribution of stock additions per material type at the sectoral level, we distinguish three categories associated with intermediate demand (i.e., construction, transport and equipment, and rest of industries), and one aggregated final demand category. Stock additions to the construction sector per country and material type ($S^{C}_{m,\,c,t}$) are directly taken from stock additions extension allocating the material inflows to in-use stocks in the construction (including building and infrastructure). For transport and equipment ($S^{V}_{m,\,c,t}$), we use an auxiliary extension of machinery, which comprises the accumulation of transport equipment products (i.e., motor vehicles, trailers and semi-trailers, and other transport equipment) by all intermediate industries. Stock additions to final demand ($S^{FD}_{m,\,c,t}$ as in Equation (2)) comprise the material accumulated in final demand categories, that is, households, non-profit organizations serving households, government expenditures, and GFCF. We distinguish the sum of $S^{FD}_{m,\,c,t}$ from other industries because $S^{FD}_{m,\,c,t}$ includes part of the material accumulated for construction and transport purposes, for example, when households purchase residential housing or private vehicles. Material inflows to in-use stocks for the rest of industries ($S^{R}_{m,\,c,t}$) were calculated as the difference between the total stock additions and the sum of construction, transport and equipment, and final demand categories per country and material type, as follows:

$$S^{T}_{m,\,c,t} = S^{C}_{m,\,c,t} + \sum S^{V}_{m,\,c,t} + \sum S^{FD}_{m,\,c,t} + S^{R}_{m,\,c,t}$$

$$S^{R}_{m,\,c,t} = S^{T}_{m,\,c,t} - \left(S^{C}_{m,\,c,t} + \sum S^{V}_{m,\,c,t} + \sum S^{FD}_{m,\,c,t}\right). \tag{3}$$

2.3 Regression analysis

We developed a regression analysis of material inflows to in-use stock with gross domestic product at purchasing power parity per capita (GDP-PPP). In the past, material and environmental indicators have been correlated to GDP-PPP, indicating that affluence is one of the main drivers for environmental pressures (Tisserant et al., 2017; Wiedmann et al., 2015; Aguilar-Hernandez et al., 2019). Furthermore, Krausmann et al. (2017) showed that global material stocks (i.e., total in-use stocks) have increased at a similar rate as the GDP-PPP from 1900 to 2010, and stock productivity (i.e., GDP/material stock) has not changed significantly over the past century. In this paper, it was not possible to establish a relation between GDP-PPP and global material stocks over time, because this requires the development of long time series, which are currently missing in the MR-HIOT. However, material inflows to in-use stocks can be correlated to affluence to identify whether there are major differences of stock additions across different countries in one period. Algebraically, the relation between S_{add} and GDP-PPP is expressed as follows:

$$S_{add}/\mathrm{cap} = \mathrm{k}(\mathrm{GDP}/\mathrm{cap})^{\beta}, \tag{4}$$

$$\log\,(S_{add}/\mathrm{cap}) = \log\,(\mathrm{k}) + \beta \log\,(\mathrm{GDP}/\mathrm{cap}), \tag{5}$$

where S_{add}/cap represents the material inflows to in-use stocks per capita, GDP/cap indicates GDP-PPP, β is the elasticity coefficient, and $\log(\mathrm{k}) = \alpha$ is a constant parameter in the linear model. The elasticity β represents the percentage change in S_{add}/cap when there is a 1% change in GDP-PPP. To distinguish income groups, we used the classification used by the World Bank Atlas method (World Bank, 2019). We matched the 43 countries and 5 rest-of-the-world regions of the MR-HIOT EXIOBASE with 223 countries considered in the World Bank Atlas method (World Bank, 2019). To obtain the income categories for the rest-of-the-world regions in EXIOBASE, we used the average of the per capita income across all countries in

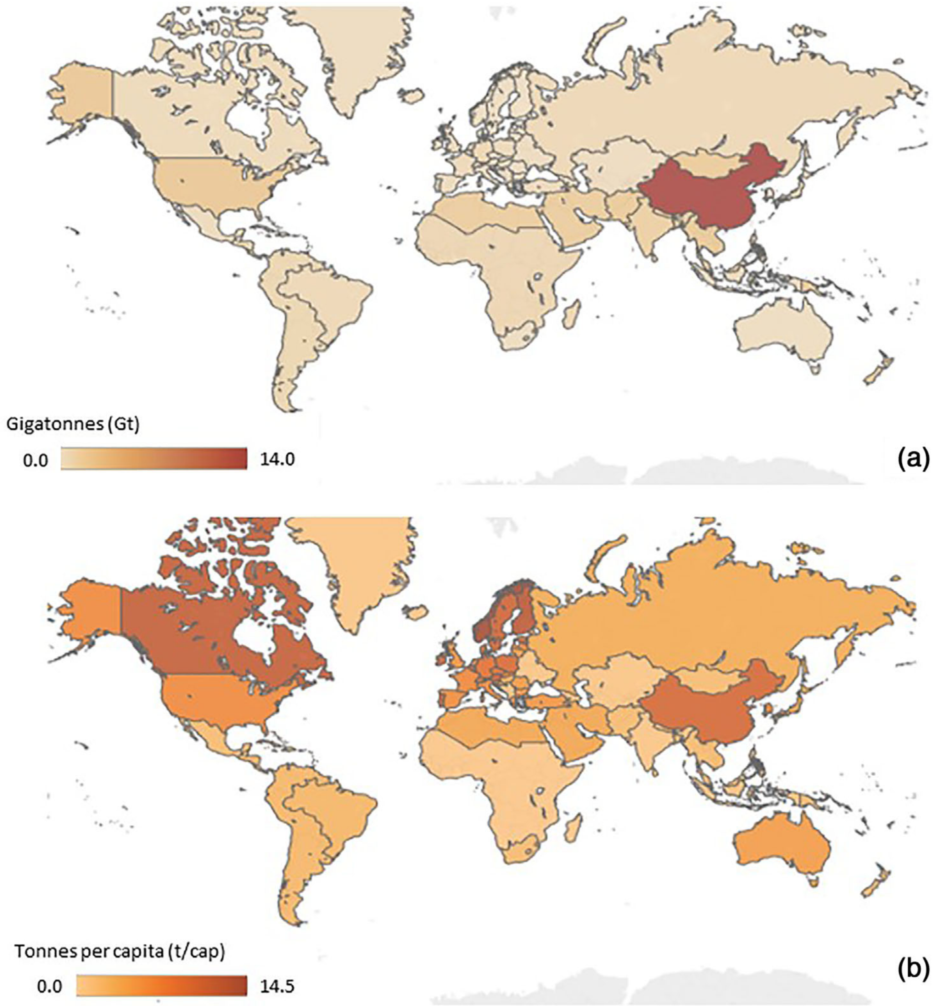

FIGURE 2 Global distribution of material inflows to in-use stocks in (a) absolute values, and (b) per capita for 2011. Total values are in Gigatonnes (Gt), and per capita values are in tonnes per capita (t/cap). Underlying data for this figure are in tab sa_agg_tot of file Data_S2.xlsx in the Supporting Information

the World Bank database associated with the rest-of-the-world regions in EXIOBASE (see country_class spreadsheet in Data_S3 in the Supporting Information).

A detailed list of stock additions classification, the Python code used for the calculation, results, and data validation are available in the Zenodo repository (https://doi.org/10.5281/zenodo.4905938). Some of this information is also available in the Supporting Information for this article.

3 | RESULTS

3.1 | Global distribution of material inflows to in-use stocks

In 2011, the total global stock additions amounted to around 30 Gt. For comparison, this amount represented 40% of global material extraction, while about 54% of materials were extracted for food and energy purposes (which were converted into dissipative emissions from fuel combustion as well as solid organic residues, water, and CO_2 emissions after food consumption); the remaining 6% represented the amount of ordinary waste that was treated by waste treatment sectors in the respective period (Aguilar-Hernandez et al., 2019). Of the global material inflows to in-use stocks, 46% (i.e., 14 Gt) were accumulated in China (see Figure 2a). While high income countries such as the United States, Japan, and countries in the European Union accumulated around one quarter of global stock additions (7.3 Gt), the material inflows to in-use stocks in lower middle and lower income economies constituted 10% (2.9 Gt). The rest of material inflows to in-use stocks (i.e., around 6.1 Gt or 20% of global stock additions) was accounted for by upper middle and middle income regions except China, such as Latin America and the Asian-Pacific region.

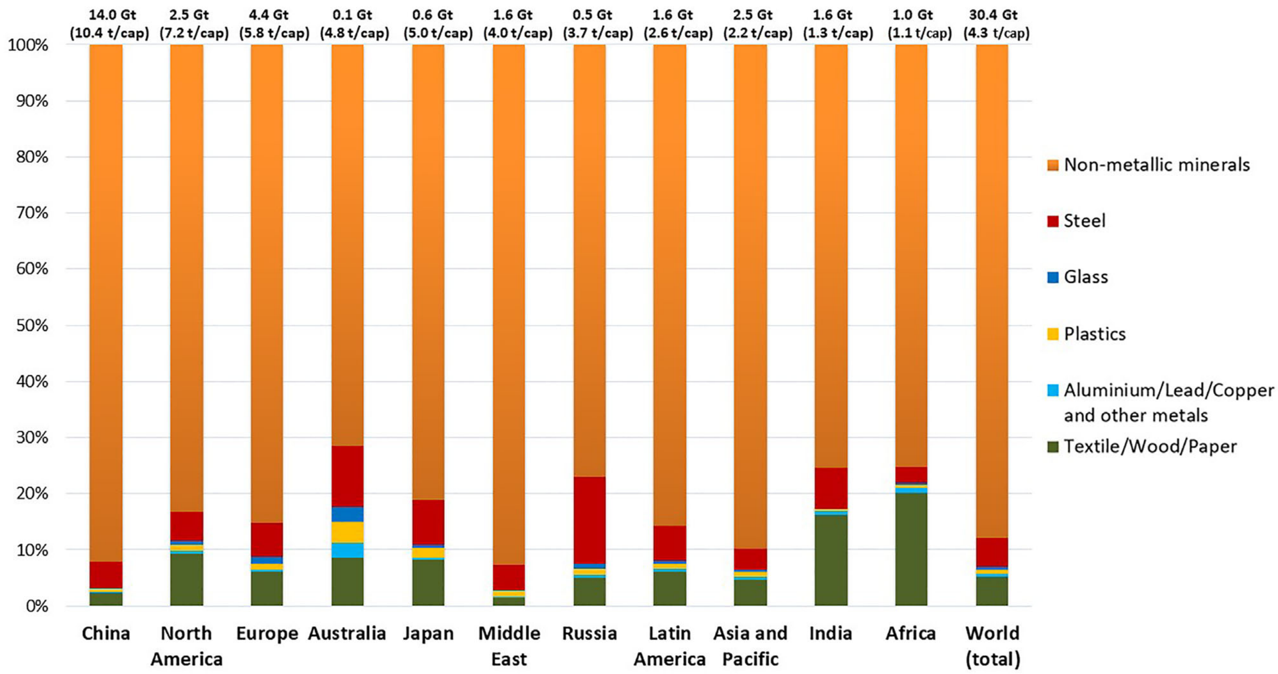

FIGURE 3 Material composition of inflows to in-use stocks for selected regions and countries in 2011. Values on the top of the figure indicate totals in Gigatonnes (Gt). Values between brackets on the top of the figure indicate per capita values in tonnes per capita (t/cap). World (total) represents the sum of all selected regions and countries. Underlying data for this figure are in tab sa_agg_mat of file Data_S1.xlsx in the Supporting Information

In per capita terms, the global material inflows to in-use stocks averaged 4.3 tonnes per capita (t/cap) in 2011 (see Figure 2b). For high income countries, the average value was 7.0 t/cap, with the highest values in Luxembourg (19.1 t/cap), Finland (15.2 t/cap), and Norway (14.7 t/cap). This is a common trend for other material use and environmental indicators, where nations with larger affluence and low population density show the highest values per capita (Wiedmann et al., 2015; Tisserant et al., 2017). A high affluence enables higher investments in capital stock, and countries with a low population density could require, on a per capita basis, comparatively more transport and infrastructure (Tukker et al., 2016). Low population density is also related to a lower density of residential infrastructure (such as detached housing), which requires more material per square meter of residential surface (UNEP, 2017) . In China, the value of material inflows to stocks was 10.4 t/cap, which is twice as large as the global average. However, the evolution of in-use stocks in China is not comparable to the material inflows in high income economies, where high levels of material accumulation have been taking place for over a century. By contrast, in China, high levels of material inflows to in-use stocks have only been observed in the past four decades (Wiedenhofer et al., 2019; Krausmann et al., 2017). With the exception of China, the stock additions per capita in upper middle and middle income economies ranged from 0.9 to 5.2 t/cap. The value in lower middle income and lower income countries averaged 1.2 t/cap, which includes for instance Indonesia (1.5 t/cap) and the African region (1.1 t/cap).

3.2 | Material composition of stock additions

Global stock additions consisted of non-metallic minerals (87.9%), steel (5.2%), wood (4.5%), plastics (0.7%), paper (0.6%), glass (0.5%), other metals (0.4%), and textiles (0.2%). Non-metallic minerals and products include materials such as concrete, asphalt, bricks, aggregates and other durable materials used for buildings and infrastructure (Schmidt & Merciai, 2017). Figure 3 shows the material composition of inflows to in-use stocks for five countries and six selected regions covering different income groups in 2011. Material composition for all the 43 countries and 5 rest- of-the-world regions is available in Data_S1 in the Supporting Information.

The percentage of stock additions consisting of non-metallic minerals ranged from 72% to 92%, depending on country. In general, the share of non-metallic minerals in stock additions was largest in upper middle and middle income economies, such as China (92% of 14.0 Gt), the Asian-Pacific region (90% of 2.5 Gt), and Latin America (86% of 1.6 Gt). Non-metallic minerals represented a lower share of the stock additions in high and upper middle income countries, such as Japan (81% of 0.6 Gt), Russia (77% of 0.5 Gt), and Australia (72% of 0.1 Gt).

Regarding steel added to in-use stocks, there is no noticeable difference between the composition of high and upper middle or lower income regions, except for higher values in Australia (11% of 0.1 Gt) and Russia (15% of 0.5 Gt). For instance, the share of steel in stock additions for North

America (5% of 2.5 Gt) and Europe (6% of 4.4 Gt) were comparable to those in China (5% of 14.0 Gt), Latin America (6% of 1.6 Gt), and the Asian-Pacific region (4% of 2.5 Gt).

The percentage of stock additions consisting of biomass durable products (e.g., textile, wood, and paper) varied from 2% to 20%, and the contribution of biomass to stock additions was higher in lower middle and lower income regions (e.g., India and African countries) than in other economies. The high share of biomass durable goods in lower middle and lower income regions is due to a large amount of wood stock additions (see sa_agg spreadsheet in Data_S1 in the Supporting Information), which can be associated with the use of wood materials for construction purposes.

The percentage of stock additions consisting of plastic materials ranged from 0.4% to 4%, with a larger proportion of plastics added to in-use stocks in high income countries (e.g., North America, Japan, and European countries). The fraction of glass in stock additions ranged from 0.1% in India to 3% in Australia. The fraction of other metals (including aluminum, copper, lead, and other precious metals) ranged from 0.3% to 3% of the total inflows to in-use stocks, without any trends across income classes.

3.3 | Sectoral distribution of inflows to in-use stocks

Figure 4 shows the distribution of the major material inflows to in-use stocks (i.e., non-metallic minerals, and steel) in 2011 across four sector categories: construction, transport and equipment, the rest of industries, and final demand categories. As explained in Section 2.2, stock additions in construction comprise built environment and infrastructure, and the values were directly retrieved from the stock additions extension in the construction category. Transport and equipment comprise motor vehicles, trailers and semi-trailers, and other transport equipment, which are accounted in an auxiliary extension of the MR-HIOT EXIOBASE.

Stock additions to final demand represent the material accumulated in final demand categories (e.g., households and government expenditures) as part of the material accumulated for construction and transport purposes, as well as other durable goods. This includes, for example, material accumulated when households purchase private cars, as well as repair services for the vehicles. Thus, construction and transport categories exclude all the materials added to the built environment and transport purchased by the final demand category that is not accounted as GFCF. Ideally, stock additions in final demand would be allocated to certain product or sector categories. However, the current structure of the MR-HIOT does not allocate the share of stock additions in final demand per product category. This is a limitation that is addressed in Section 4.2.2 as further research.

The category rest of industries was estimated by calculating the difference between the total stock additions and the sum of construction, transport and equipment, and final demand categories (see Equation 3, Section 2.2.). Although more sectoral disaggregation is desirable, the selected economic activities are among the most relevant for circular economy policies as construction and transport are considered two of the major contributors of resource use (Tukker et al., 2016; Haas et al., 2015; Ellen MacArthur Foundation, 2015).

More than 90% of the inflow of non-metallic minerals to in-use stocks was accumulated in the form of buildings and infrastructure (see non-metallic spreadsheet in Data_S1 in the Supporting Information). This finding confirms the conclusions of previous studies regarding the importance of circular strategies in the construction sector (Jacobi et al., 2018; Jiang et al., 2019; Krausmann et al., 2018).

Steel accumulated by construction activities ranged between 16% and 46% of total steel added to in-use stocks (see steel spreadsheet in Data_S1 in the Supporting Information). Likewise, the fraction of total steel added to in-use stocks accumulated in the transport sector ranged from 1% to 14%. However, as the final demand category also allocates material accumulated in construction and transport equipment, the share of steel in construction and transport is expected to be larger than the sectoral distribution shown here. Steel stock additions should include part of the direct purchases of households in the construction sector and the transport sector, such as housing and private cars. The sum of steel stock additions in final demand, construction, and transport varied between 64% and 86% of total steel stock additions.

These results are similar to those reported by Müller et al. (2011), whose outcomes for six high income countries in 2005 showed that 60–70% of total steel stock additions were accumulated in the construction sector and the transport sector (see Data_validation, and Table S2 in Appendix in the Supporting Information). For a more comprehensive comparison, a further development of MR-HIOT is required to disaggregate the material stock addition of final demand categories in accordance with the classification used by MFA studies. A detailed comparison with previous MFA-based studies is available in Data_validation in the Supporting Information.

The aggregated results are also similar to those reported by previous MFA studies, such as Haas et al. (2015) and Wiedenhofer et al. (2019) (see Data_validation and Section S2 in Appendix in the Supporting Information). This means that the results of the MR-HIOT approach are comparable to those of MFA studies; nevertheless, some improvements are still required in the MR-HIOT system, which we will discuss as further research in Section 4.2.

3.4 | Relation between material inflows to in-use stocks and affluence

The cross-country regression analysis of material inflows to in-use stocks and GDP-PPP showed a positive correlation between stock additions and the degree of economic development (see Figure 5). A change of 1.0% in GDP-PPP could lead to a change of 0.8% in material inflows to in-use stocks

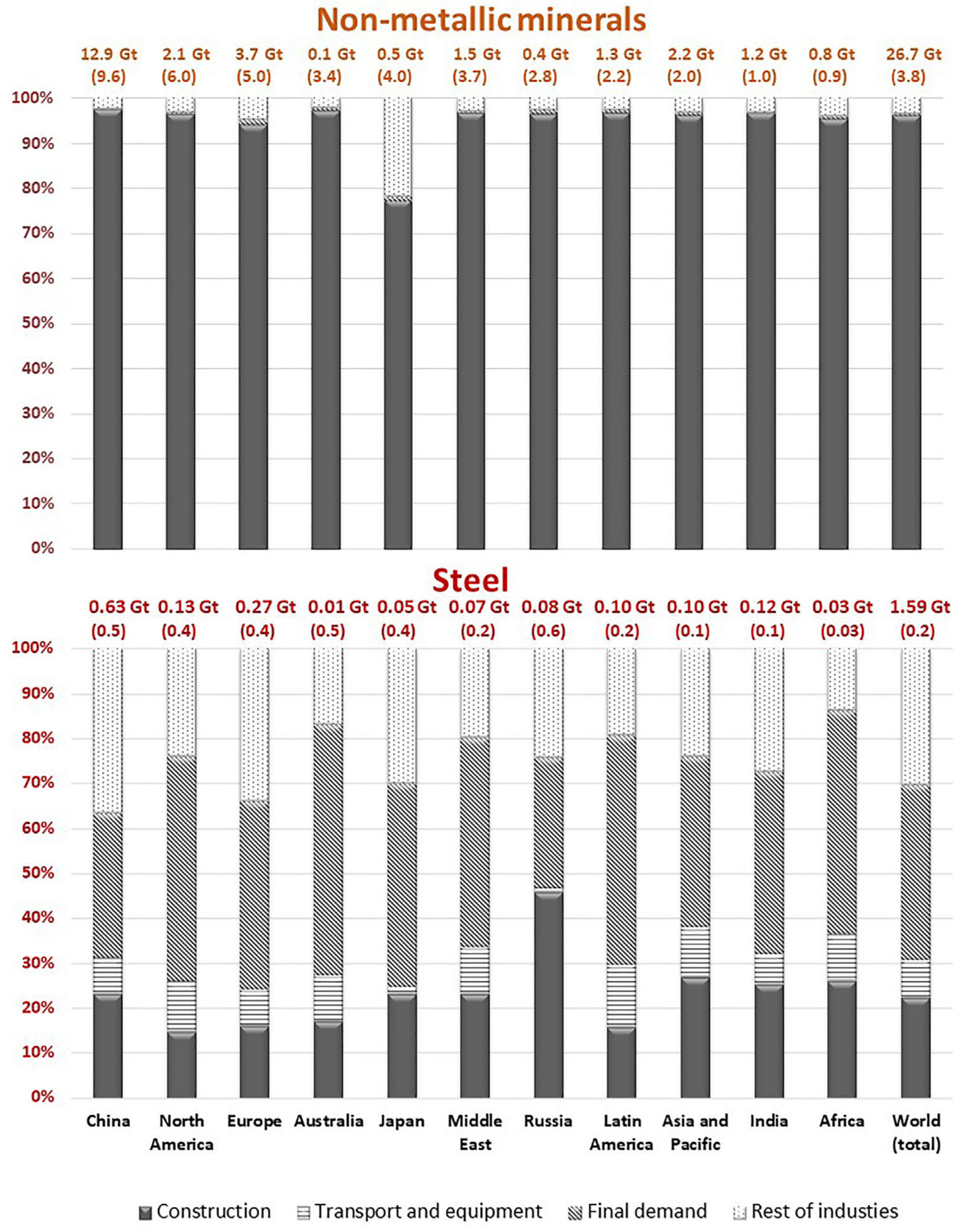

FIGURE 4 Sectoral distribution of inflows to in-use stocks for non-metallic minerals and steel for selected regions and countries in 2011. Values on the top of the figure indicate totals in Gigatonnes (Gt). Values between brackets on the top of the figure indicate per capita values in tonnes per capita (t/cap). World (total) represents the sum of all selected regions and countries. Underlying data for this figure are in tabs non-metallic and steel of file Data_S1.xlsx in the Supporting Information

($\beta = 0.8$). High income and upper middle income economies accumulated more materials because of the increase of affluence, which would imply the availability of more secondary materials from in-use stock removal in the future.

In comparison, some studies have also demonstrated a positive correlation between GDP-PPP, material stocks, and material use, showing similar differences between high income countries and developing world regions (see, e.g., Krausmann et al., 2017; Wiedmann et al., 2015). Despite the lack of time series for the MR-HIOT, we still find a positive correlation between GDP-PPP and material inflows to in-use stocks. It is important to notice that it is still under debate whether the relation between GDP-PPP and stock additions can be used as an indication of drivers for changes in inflows to in-use stocks.

Previous studies have suggested that material use and capital formation is driven by affluence as well as by population growth (Steinberger et al., 2010; Krausmann et al., 2009). Furthermore, more recent studies suggest that the main driver of material inflows to in-use stocks is the rate of stock formation in an economy (Bleischwitz et al., 2018; Haberl et al., 2020; Schaffartzik et al., 2019). For countries with a steady increase in fixed capital, the trend of stock formation is correlated to GDP. However, this relation is not maintained in the case of fast-developing economies, where capital investment grows faster than in other regions (Bleischwitz et al., 2018). For example, the Chinese economy has shown a fast increase in

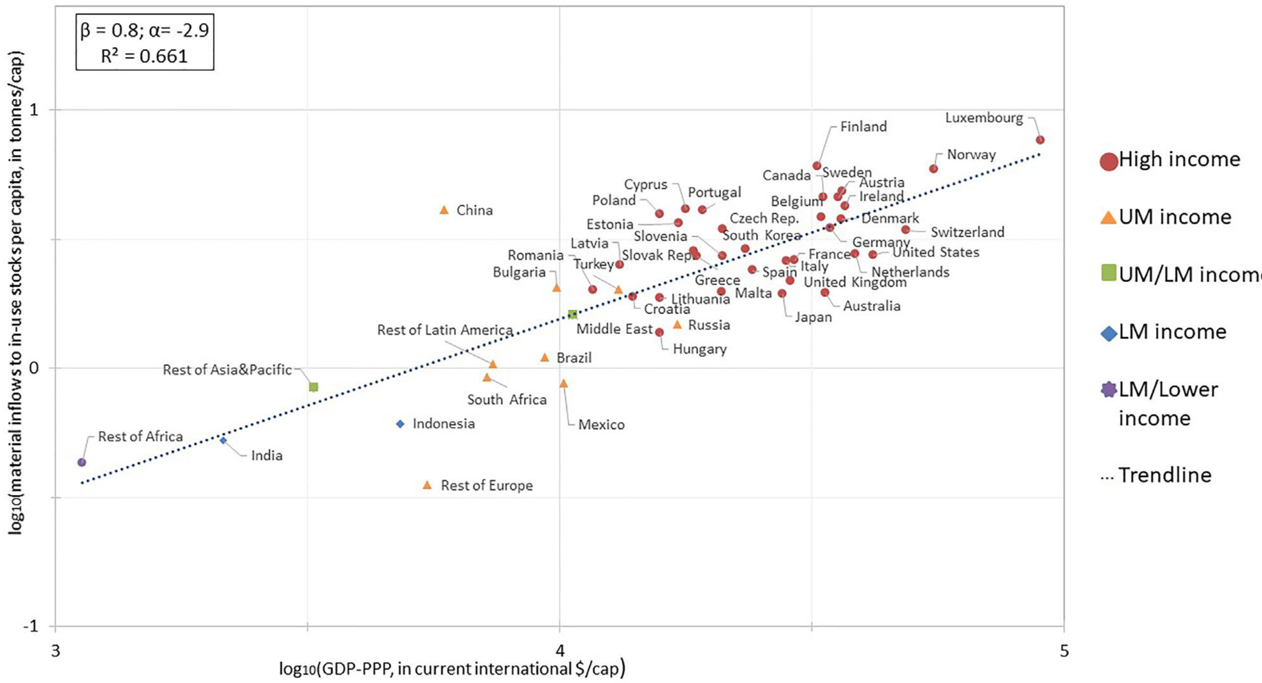

FIGURE 5 Logarithm of material inflows to in-use stocks (in tonnes/cap) over logarithm of gross domestic product, purchasing power parity per capita (GDP-PPP, in current international $/cap). Red circles denote high income countries. Orange triangles indicate upper middle income (UM) countries. Green squares denote upper middle and lower middle income (UM/LM) countries. Blue diamond indicates lower middle income (LM) countries. Purple 6-point star indicates lower middle and lower income (LM/Lower) countries. Dark blue dot line represents the regression trendline, β is the elasticity, α is a constant parameter, and R^2 is the standard coefficient of determination. Underlying data for this figure are in tab regression of file Data_S1.xlsx in the Supporting Information

stock formation, which leads to a higher value of stock additions per GDP-PPP compared to other countries (Song et al., 2020; Soulier et al., 2018; Krausmann et al., 2017). This might explain the observation obtained for China (Figure 5), where the correlation between GDP-PPP and inflows to in-use stocks seems to differ from the correlation found in other world regions. Further data improvements in the MR-HIOT are required to properly analyze the rate of stock formation, which we will discuss as further research in Section 4.2.

4 | DISCUSSION AND CONCLUSIONS

The purpose of this study was to quantify the global distribution and composition of material inflows to in-use stocks in specific geographical regions, product groups, and sectors, while acknowledging the limitations of the database used in this study, which provides detailed global physical material flows for just one year, that is, the year 2011. In contrast to the existing literature, we provide a higher geographical, material, and sectoral resolution (see data_resolution spreadsheet in Data_validation in the Supporting Information).

In 2011, almost half of the materials added to stocks were accumulated in the Chinese economy, whose per capita stock accumulation value was similar to those reported for high income countries. On average, high income regions (e.g., Europe and North America) accumulated three times more material inflows to in-use stocks than lower upper and lower middle income economies (e.g., Asian-Pacific and African countries). This is comparable to resource consumption patterns at different levels of economic development, which supports the hypothesis that capital formation is a key aspect of material use in a country or region (Jiang et al., 2019). The use of non-metallic minerals and steel constituted almost 95% of all material added to stocks across regions.

Considering the relation between material inflows to in-use stocks and GDP-PPP, the availability of secondary materials will be higher in the future in high income and upper middle income countries. As their current degree of affluence seems to drive more stock additions, this will generate more waste in the future due to stock depletion or removal. Thus, the findings suggest that a circularity transition might occur in high income and upper middle income regions.

Meanwhile, lower middle and lower income regions are still in a phase of capital investment growth and material accumulation. Thus, we could assume that it would require a longer period before there is a source of secondary materials that enables a circularity transition in lower middle and lower income regions.

It is important to notice that the future waste that will become available in countries with high stock accumulation could represent a burden for waste treatment sectors if the materials removed from in-use stocks are not processed in a circular manner. Moreover, there is an increase of international trade of waste (e.g., waste traded from high income countries to be recycled or treated in lower, middle income countries), which raises questions about the spatial scale of waste treatment strategies. This implies that a circularity transition in high income countries (as well as in some upper middle income regions) will not depend only on how much waste is available for recovery or recycling, but also on whether circular strategies consider the spatial dimension of waste management.

There are three aspects to consider regarding the relation between affluence and material inflows to in-use stocks. First, the correlation analysis considers the relation between material inflow to in-use stocks and GDP-PPP, and there is no relation to specific circular improvements (see Section 4.1). For example, at early stages of product design, material inflows to in-use stocks can be designed in a more resource-efficient way and with longer product lifetimes. Second, the correlation analysis does not include the total material stock and stock productivity, which means that the relation between the rate of stock formation and GDP cannot be determined with this data. Third, time series for the MR-HIOT are required to determine whether the differences between countries are driven by the rate of stock formation (see Section 4.2 for further details).

For the stock addition extension in EXIOBASE, it is assumed that each final product has a specific lifetime function (Schmidt & Merciai, 2017). In this way, it is possible to determine which products are supplied and discharged in the same year (i.e., ordinary waste according to Merciai & Schmidt, 2018), and which are accumulated (i.e., material inflows to in-use stocks). Therefore, the logic behind the construction of the MR-HIOT EXIOBASE is similar to the MFA approach (i.e., use of lifetime, product balances, physical data on material extraction, mass balance). An MFA can be performed just by selecting the single material layers in the MR-HIOT EXIOBASE. However, some materials might have to be transformed or reallocated when goods or services are not accounted in mass units but that imply a movement of materials. For example, construction may be accounted in euros and requires a reallocation in mass. Information regarding the reallocation of materials is included in the database (at: https://www.exiobase.eu/).

One of the main differences between MFA and a multi-layer framework such as the MR-HIOT EXIOBASE is that in the latter, all the layers are determined simultaneously combining several data sources, while MFA could be more partial. Another major difference is the time horizon; usually, supply–use and input–output tables (SUTs/IOTs) are a snapshot of the reality, while MFA are performed across several years. Hence it might be a good solution to produce time series of SUTs/IOTs (for more details see Section 4.2.1). Finally, MFA could contribute to improving general multi-layer frameworks by providing more knowledge on specific material properties, which can then be inserted in the balancing routine of multi-layer SUTs/IOTs.

In the MR-HIOT EXIOBASE, it is possible to determine all the raw materials that are embodied in final products using transformation coefficients in the balancing routine (Merciai & Schmidt, 2017). For example, it is possible to derive plastic, glass, and steel embodied into a machinery produced in each country. Thus, the MR-HIOT EXIOBASE can be seen as a multi-layer framework, where each layer includes a specific material, such as plastic, steel, or wood. The team behind the MR-HIOT EXIOBASE plans to make this information available on the website in the near future for anyone who is interested (at https://www.exiobase.eu/).

4.1 | Implications for a global circularity transition

Understanding how much and where materials are accumulated provides valuable information for a sustainable resource management. For circular economy policies, four main circularity interventions have been proposed (Aguilar-Hernandez et al., 2018): closing supply chains (i.e., intervention for materials that are reintegrated into the economy through reuse, refurbishment, or recycling), residual waste management (i.e., end-of-life waste processed by waste treatment sectors), product lifetime extension (i.e., prolonging the lifetime of goods through product design, maintenance, and repair), and resource efficiency (i.e., resource use optimization by producing more output with less input). Further details on the classification of circularity interventions are available in Aguilar-Hernandez et al. (2018).

Regarding material inflows to in-use stocks, the circularity strategy that can be implemented in the shortest term is the design for longevity and resource efficiency. This is because the new material inflows to in-use stocks can be designed for longevity with a right to repair (i.e., policy legislation that enables final user to repair and adjust their own durable products when manufacturers only allow repair and maintenance through their own services), and they can be produced in a more resource-efficient way. In the case of China, for example, both interventions can be applied to the construction sector, which comprised 97% of the total demand of non-metallic minerals and 23% of the total demand of steel. Extending the lifetime of in-use stocks could contribute to decreasing the need for new stock additions, thus reducing resource extraction and waste generation in the future (see, e.g., Huang et al., 2013; Cai et al., 2015) . Furthermore, resource efficiency interventions can reduce the use of primary inputs to provide the same amount of output, which might imply fewer extracted resources per unit of in-use stock. For example, resource efficiency interventions are implemented when the use of materials in construction (e.g., for buildings) is reduced while providing the same amount of product or service (e.g., same floor area). However, the effects of lifetime extension should be assessed from a broader perspective. Keeping older buildings and vehicles in stock could have a negative effect on the overall operational energy efficiency, so trade-offs should be considered in a dynamic and holistic manner, as was indicated in a recent report of the International Resource Panel (IRP, 2020) and by Pauliuk (2020).

While residual waste management and closing supply chains are focused on minimizing waste generation, these interventions are more long-term measures in the context of stock additions, where policies can benefit from information about the amount of materials that will be disposed as waste in a specific period. For instance, materials added to stocks in Europe during 2011 will potentially provide 4.4 Gt of materials to be reused or recycled, 85.1% of which are non-metallic minerals, 6.1% steel, 6.0% biomass durable goods, 1.3% glass, 1% plastics, and 0.5% metals (such as aluminum, lead, copper, and other precious metals). However, it is important to notice that closing supply chains and residual waste management also have a role in the short term because a large amount of waste from in-use stock removal is available already now, and this amount will increase in the near future as a result of the large stock additions that have been accumulated in the past few decades.

4.2 | Further research

In this study, material inflows to in-use stocks were allocated in a consistent input–output framework, that is, the global, multiregional input–output table in hybrid units (MR-HIOT) of EXIOBASE. However, there are several shortcomings related to the use of MR-HIOT EXIOBASE for the assessment of the global distribution of material inflows to in-use stocks. Here, we present four main aspects for improving the current analysis, followed by concluding reflections.

4.2.1 | The need for MR-HIOT time series

The MR-HIOT is currently available for just one year. Future research will be needed to develop time series, so that a more dynamic view can be obtained on the global distribution of material inflows to in-use stocks (Pauliuk et al., 2015; Wiebe et al., 2018). This will allow determining the size of the material reservoir of in-use stocks, which until now has only been quantified for individual materials or for a limited number of countries and regions, without a detailed sectoral classification (Pauliuk et al., 2017b; Krausmann et al., 2017). For example, time series of an MR-HIOT could be created using current data advancements of the material inputs, stocks and outputs (MISO) model (Wiedenhofer et al., 2019) and future data development (e.g., from the PANORAMA project (2020)) in order to model the stock-flows dynamic on a high geographical, material, and sectoral resolution.

4.2.2 | The need for allocating material in-flows to in-use stocks to specific economic sectors

The current MR-HIOT resolution has its own limitations. For example, the analysis at the sectoral level (see Section 3.3.) presents an allocation to intermediate and final demand categories, which might be seen as a main drawback because it might obscure a clear allocation of material inflows to in-use stock to functional types of in-use stocks including the sectors that use these stocks (i.e., an allocation to product/service categories). Capital stocks are used by specific economic sectors (including household and government) and form the basis for production capacity and well-being (IRP, 2019; Tukker et al., 2016). However, the MR-HIOT shows stock formation (or GFCF) as a separate entity in a specific year, without allocating in-use capital stock to economic sectors. Södersten et al. (2018b, 2020) demonstrated how investment matrices can be used to integrate such information in IOTs. In combination with information on different age cohorts as described by Pauliuk et al. (2017a) and Sigüenza et al. (2020), these matrices will allow creating dynamic stock vintage models that will determine where and when stock removals will take place. For example, the mean lifetime of a building can vary from 34 to 100 years, depending on the country and region (Deetman et al., 2020). This implies that it takes a long time before material added to construction in-use stocks becomes available as scrap, and hence dynamic stock vintage models are required to determine when the material added to in-use stock in building construction will become available for recovery or recycling.

4.2.3 | The need for more detailed insights into the composition of stock additions

The stock additions extension in the MR-HIOT can be improved by providing more detailed information on stock composition. The current construction of the MR-HIOT allocates additions to in-use stocks to intermediate and final demand categories as part of a mass balance procedure (Merciai & Schmidt, 2018). However, this approach does not allow a connection to be made between the stock additions of different industries and the respective products used by final demand. Ideally, the GFCF should allocate all the material added to in-use stocks in 1 year. However, in the MR-HIOT, there is an issue of using hybrid units (e.g., monetary and mass units) that restricts the estimation of stock additions in physical terms directly from GFCF, as there are some services (such as construction) that account for stock additions in monetary units. A way to address this issue is by developing a concordance matrix that combines product and industry categories to allocate stock additions in mass units, that is, a matrix with industries in rows and products in columns, whose entries are all zeros except where an industry aggregates durable products. Such a concordance matrix can be used to assign material inflows to in-use stocks per product/service, which can be converted into material categories (e.g., non-metallic minerals, and steel) through the use of the transfer coefficients that enable the distribution of material types per product/service (Merciai & Schmidt, 2018).

4.2.4 | Data uncertainty

Another improvement for future analysis is the incorporation of a proper uncertainty analysis, which is important for evaluating the reliability of the data. We did include a data validation through a comparison of net stock additions (i.e., material inflows minus material outflows from in-use stocks) with previous MFA-based studies, which shows similarities when values are aggregated, but also some discrepancies at the country level (see Data_validation in the Supporting Information). A proper uncertainty analysis is still required to understand the reliability of MR-HIOT datasets. There are methods to estimate the uncertainties of multipliers in multiregional input–output tables and to compare different databases (see, e.g., Lenzen et al., 2010; Owen et al., 2014), which can be used as a basis for further uncertainty analysis in the MR-HIOT. This would require an effort to collect data for the model's input as well as the development of statistical methods to propagate standard error through the different modules used in the MR-HIOT EXIOBASE.

4.2.5 | Concluding reflections

We recommend that follow-up research should consider developing time series of a MR-HIOT framework so that a data set is created that works in the same way as dynamic material stock-flow models. The main difference is that the MR-HIOT time series will not focus on a specific material but will cover all material flows and will further discern the products and sectors that create such in-use stocks. Currently, MRIOTs and the MR-HIOT used in this paper present capital investment as a separate demand category, whereas capital investment and in-use stocks should ideally be allocated to the production sectors that use fixed capital. This requires the allocation of capital formation to using sectors, for instance via investment matrices, as elaborated by Södersten et al. (2018b, 2020). In combination with information about the expected lifetimes of in-use stocks, this allocation will allow understanding which material stocks of which composition and in which sectors and countries will become available for material circularity, thus providing a way to identify which circular economy policies will be most effective with respect to time. Finally, the MR-HIOT should be developed along with the integration of uncertainty analysis that ensures the data reliability and future comparison across the body of literature about circularity transition.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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NOTE

[1] It is important to notice that S_{add} refers to gross additions to in-use stocks, which differs from net additions to in-use stocks (i.e., gross inflows to in-use stocks minus material outflows from in-use stocks).

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SUPPORTING INFORMATION

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

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