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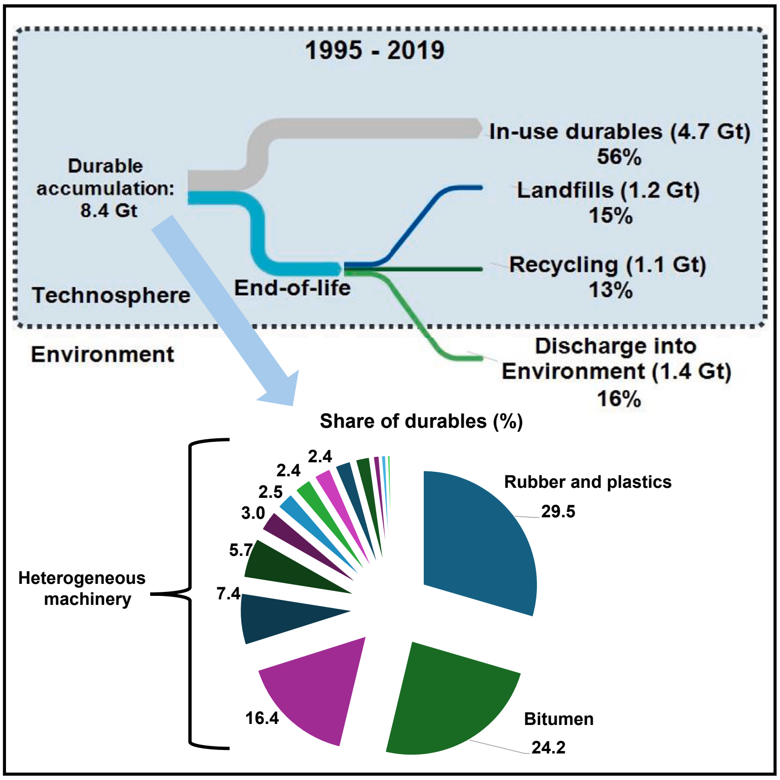
The extent and fate of fossil carbon accumulation in our technosphere

Graphical abstract



Highlights

- Quantified annual fossil carbon addition of 0.4 Gt to durable goods and infrastructure
- The highest proportion of fossil carbon is stored in rubber and plastic products
- 8.4 Gt of fossil carbon accumulated in the technosphere from 1995 to 2019
- Large portions of fossil carbon in landfills can take over 50 years to break down

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In brief

Hidiroglu et al. quantify fossil carbon accumulation in durable goods and infrastructure from 1995 to 2019, totaling 8.4 billion tons, with 0.4 billion tons added annually. A significant portion of this carbon ends up in landfills, where most will take over 50 years to break down. The study highlights that extending product lifetimes and improving recycling can reduce reliance on virgin carbon stocks, while better waste management can limit the long-term environmental impacts of carbon leakage, supporting global climate goals.

Hidiroglu et al., 2024, Cell Reports Sustainability *1*, 100265
December 20, 2024 © 2024 The Author(s). Published by Elsevier Inc.
https://doi.org/10.1016/j.crsus.2024.100265

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The extent and fate of fossil carbon accumulation in our technosphere

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https://doi.org/10.1016/j.crsus.2024.100265

SCIENCE FOR SOCIETY This study examines how much fossil carbon is stored in long-lasting products, such as buildings and infrastructure, using data from 2011 and extending it to cover the years 1995–2019. Over these 25 years, 8.4 billion tons of fossil carbon have accumulated, with approximately 0.4 billion tons added each year, with a huge potential for further contribution to anthropogenic greenhouse gas emissions. A significant portion ends up in landfills, where it can take several hundred years to break down. This presents both challenges and opportunities for managing carbon and achieving climate goals. On one hand, durable goods and infrastructure act as temporary carbon storage. On the other hand, without proper management, much of this carbon will eventually be released into the atmosphere or biosphere.
Enhancing recycling rates and product lifetimes can lower demand for virgin fossil carbon, while better waste management can limit carbon leakage from landfills, preventing long-term environmental harm. These actions are crucial for meeting climate goals and building a more sustainable, circular economy.

SUMMARY

Energy and non-energy use of fossil carbon-based fuels and associated emissions have been extensively studied, but the retention and accumulation of fossil carbon in the technosphere are less understood. This study uses retrospective dynamic material flow modeling to map the flows related to fossil carbon in durables between the years 1995 and 2019 using monetary multi-regional supply-use tables for 1995–2019 and multi-regional hybrid supply-use tables for 2011. In 2011, 91% of the extracted fossil carbon flowed directly to the atmosphere, with 9% accumulating in the technosphere, primarily in construction, manufacturing, and households. From 1995 to 2019, 8.4 Gt of fossil carbon (i.e., 30.8 Gt of CO_2 equiv) accumulated in all human-made artifacts, with most remaining in use and some ending up in landfills, where decomposition exceeds 50 years. This study lays a critical foundation for future research focused on reducing fossil carbon reliance by curbing its inflow and slowing its throughput in the technosphere.

INTRODUCTION

Fossil carbon (FC) is fundamental for sustaining and expanding the current activities undertaken within the technosphere, which refers to the sum of all human artifacts[1–5] and relates to similar concepts such as the Anthropocene[6,7] or the socioeconomic metabolism.[8,9] Fossil fuels play a prominent role in contributing to the growth of the technosphere, dominating the supply of primary energy needs. The total demand for fossil fuels (coal products, crude oil, and natural gas and liquefied natural gas) was 5.6, 4.9, and 3.5 Gt of oil equiv, respectively, in 2019.[10] This translates into 12.5 Gt of FC in total, based on the FC content (FCC) of these products. A considerable share of fossil fuels is used as feedstock (non-energy use) in the industry: 5.1%, 16.7%, and 11.9% of total final consumption of coal, oil, and natural gas, respectively.[11] FC as feedstock is most prominently used in petroleum refineries and the petrochemical industry as an input to industrial and chemical processes for producing materials and intermediate and final goods. These include petroleum refinery products such as various fuels, chemicals, rubber and plastic products (PPs), nitrogen and phosphorus (N-P) and other fertilizers, bitumen, liquid biofuels, lubricants, additives and blending agents, and many other products. In 2017, the total material weight of final products of the petroleum refineries and the petrochemical industry were 4.1[12] and 1.0 Gt,[13] respectively. Among these products, petroleum fuels held the highest share with 61%, followed by other petroleum refinery products with 20%, including bitumen. Petrochemical products such as plastics, rubber, and other forms of fibers contributed 8% to FC feedstock consumption. Fertilizers accounted for 6%, with other chemicals accounting for 5%. All these products have varying degrees of FCC. There are numerous studies on fossil inputs for energy[11,14–16] and non-energy purposes[17–20] quantifying environmental pressures of production and consumption[21,22] in terms of carbon emissions[23–28] and waste streams.[29–32] However, very little is known about the necessary carbon streams used to maintain and expand the global technosphere.

FC has various fates in the technosphere, ending up as gaseous emissions, additions to stocks of durables and non-durables, or discharge to the physical waste stream during production or after final consumption. The biggest share of FC is in refined fossil energy carriers (e.g., gasoline and diesel), naphtha, and lubricants. These types of products are considered as non-durables because they serve as intermediary inputs, with a lifetime of less than a year.[33] By contrast, feedstock FC for materials is used in durable goods such as infrastructure and buildings, machinery, and any manufactured items that persist in the technosphere for over a year.[33]

In the early 1900s, 72% of all extracted materials were used for non-durables; however, this share has been in a steady decline. In the early 1990s, materials used to produce durables surpassed materials used to produce non-durables.[33] The global economy has shifted from a ‘‘throughput’’ toward a ‘‘stockpiling’’ economy, resulting in a reduced share of processed materials culminating in emissions and waste in the atmosphere and biosphere. This proportion decreased from 94% in 1900 to 65% in 2015, while total throughput and total emissions increased considerably within the same time frame. Furthermore, emission and waste streams reached ~1,000 Gt in 2015, with a 27-fold increase compared with 1900.[34] Hence, the environmental pressures from discharging these extracted materials (end-of-life [EoL] emissions or waste) have not been fully realized. Input circularity (share of renewable or secondary inputs over all material inputs) dropped from 43% to 27% in the same period.[34] As the extraction of fossil fuels also saw a sharp rise between 1900 and 2005 with a 12-fold increase,[35] we can expect more FC to be stored in the technosphere as gross addition to stocks (GAS) of durables and non-durables.

The estimation of stocks and outflows in relation to product lifetimes poses a significant challenge, a concern frequently emphasized in prior research. Numerous studies have explored the impact of different assumptions regarding product lifetimes on material stocks,[36,37] future emissions associated with EoL flows,[38–40] and their implications for prospective recycling options.[31,41] Additionally, previous research[42,43] has analyzed the comparative advantage of adopting top-down versus bottom-up approaches in estimating EoL flows. Top-down approaches utilize a range of data, such as annual time series material production data, economic input-output tables, and lifetime distributions of products to estimate material stocks. By contrast, the bottom-up approach involves quantifying the number of products within a defined boundary, later to be multiplied by the material intensity of materials under inspection. An in-depth examination and comparative analysis of the results derived from both approaches are detailed in Hirato et al.[43]

Considering the ongoing debates revolving around resource scarcity, vulnerability and dependency, and the circular economy,[44,45] the increasing volume of materials stockpiling in the technosphere provides an additional challenge for the transition toward a circular economy. Prior studies utilized the material flow analysis (MFA) framework to quantify and compare global flows of materials,[35,46] stocks,[47–52] and emissions and waste[33,34] in the technosphere. Some MFA-based studies focus on specific materials, such as retained carbon for Japan,[53] global carbon flows and stocks,[50] steel,[54] aluminium,[55,56] nickel and chromium,[57] chemicals,[58] and their circulation at a global level. Yet, we do not know the amount of FC contained in GAS of durables and non-durables, FC accumulation hotspots, and to what extent they stay in different parts of the technosphere before they are finally discharged to their final destination.

In this study, we aim to comprehensively map all major flows of FC in the global production and consumption network for 2011 by conducting MFA based on a global multi-regional hybrid supply-use table (EXIOBASE MR-HSUT and extension accounts: http://www.doi.org/10.5281/zenodo.10148587). Subsequently, we estimate the FC stored in durables in the global technosphere, i.e., infrastructure, machinery, and other durable products. To achieve this, we extrapolate our results for 2011 to cover the entire period, using monetary supply and use tables (Exiobase MR-SUT: http://www.doi.org/10.5281/zenodo.5589597) for the period 1995–2019. Finally, we estimate the annual EoL flows by employing a top-down approach based on the inflow of in-use durables and lifetime distributions per durable type. These outflows are categorized into different waste treatment methods, informed by the global average of waste treatment statistics per durable type. Finally, our study quantifies the projected time it will take for the FC contained in EoL durables to be released into the environment.

RESULTS AND DISCUSSION

FC flows and pathways

In order to understand how much FC accumulates in our technosphere in a year, all FC entering and leaving our economy has to be tracked: FC initially enters in the form of coal, crude oil, and natural gas and liquefied natural gas, then goes through industrial transformation and finally ends up in different FC pathways, either as emissions, in durables and non-durables, or as waste. Following the definitions provided in the introduction, products designed for intermediary use are classified as non-durables. Subsequently, we consider products with a lifespan over a year and not integrated into another product as durables. For this analysis, we do not take process losses into account and introduce input and output balances to deal with imbalances in our flow model. The Sankey diagram in Figure 1 shows the flow of FC in the global technosphere, which is an aggregated

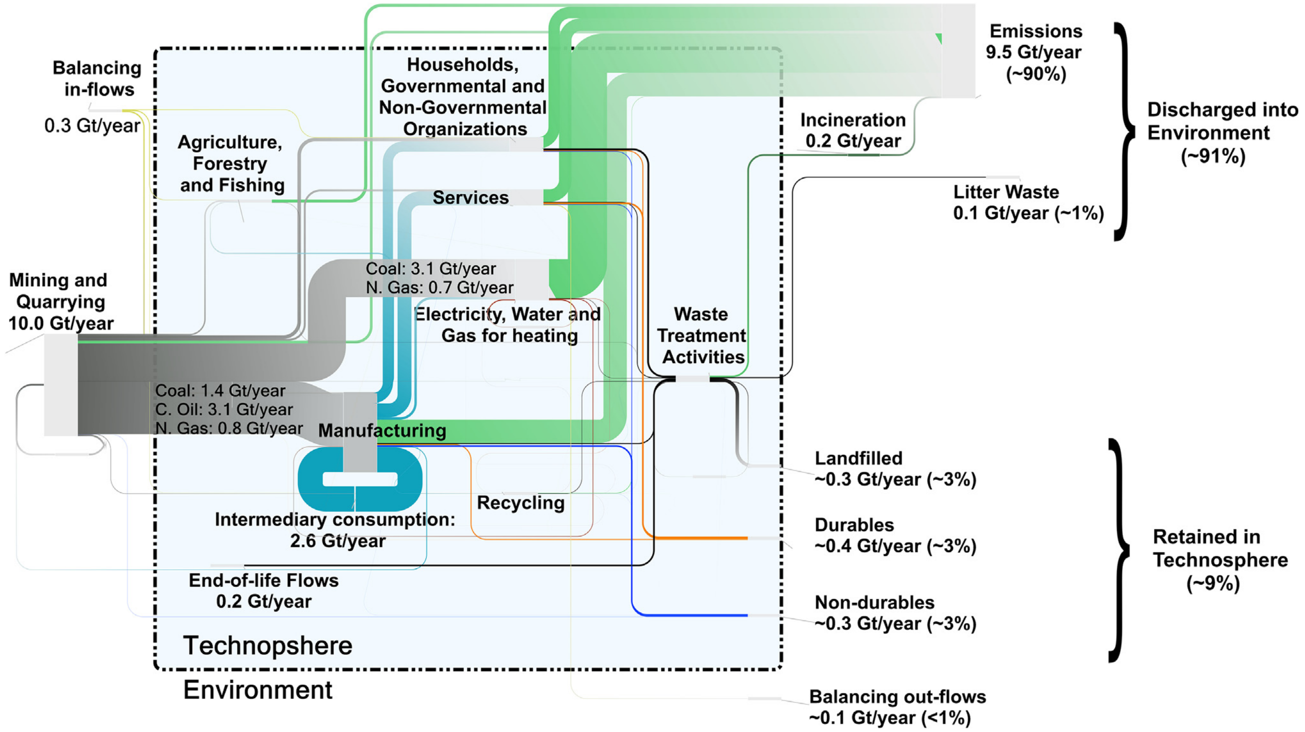

Figure 1. FC flows in the global technosphere in mass units (Gt/year) for 2011, based on Exiobase MR_HSUT and extension accounts related to final demand, emissions, waste supply, and motor vehicle use

Pathways of FC include emissions, accumulation as durables or non-durables, and waste treatment categories (incinerators, landfills, and litter waste). Extracted fossil energy carrier flows are indicated in gray and balancing flows in light yellow. On the right-hand side, intermediary consumption is depicted in light blue, emissions in green, durables in orange, non-durables in dark blue, and waste in black. See extended Figure S1 for higher granularity of sectors.

representation based on detailed input-output tables with 164 sectors and 48 countries/regions.

Energy carriers such as coal, crude oil, and natural gas (and liquified natural gas [LNG]) provide the highest FC input. The left-hand side of Figure 1 shows that the total amount of FC in extracted fossil fuels was ~10.0 Gt/year in 2011 (from coal, oil, and natural gas). The highest share is supplied through coal products (~48% of FC in energy carriers), then crude oil (~31%), and the remainder through natural gas and LNG. In terms of fossil energy carriers, the bulk of FC from coal products (72%) is used for electricity, water, and gas services, 23% in industrial sectors, including manufacturing and forestry, agriculture, and fisheries, and the remainder flows to households and governmental and non-governmental organizations (2%), service sectors (1%), and waste treatment sectors. FC contained in crude oil is sent to petroleum refineries (~97% of extracted crude oil) for further refinement and converted to many different types of fuels. FC from natural gas is distributed among the following sectors: 40% of the demand is for manufacturing and agriculture, forestry, and fisheries; 35% for electricity, water, and gas supply; 12% for households; 7% to service sectors; and 5% to extraction sectors for mining purposes. Finally, EoL flows represent previously purchased durables that have finalized their lifespan and are subsequently disposed of as waste.

The manufacturing sectors utilized more than half (~5.3 Gt/year or 53%) of FC that entered the technosphere as energy carriers in 2011. Within manufacturing, a considerable portion of the intermediary use of FC (3.6 Gt/year or 68%) was integrated in the final products, highlighting its integral role in production processes across various industries. Petroleum refineries utilized 82% of the embodied materials, followed by the coke oven sector with 15% and the rest distributed among other manufacturing sectors. The remainder of the FC in energy carriers (1.7 Gt/year) was utilized for other intermediary consumption. Further details on the decomposed inter-sectoral flows and the embodiment of FC can be found in the supplemental information sections "extended figure 1" and "extended figure 2." The remaining 47% of energy carriers (4.7 Gt/year) were mostly utilized in electricity, water, and gas supply, constituting 81% of this portion. The rest flowed into the service sectors, mining and quarrying, and agriculture, forestry, and fishing.

In 2011, the total use of manufactured products amounted to 5.8 Gt/year, with ~2.6 Gt/year of this quantity serving as intermediate consumption across all manufacturing sectors. Within these products, refinery products used for intermediary consumption dominated (1.4 Gt/year) with ~55% (such as the use of naphtha for producing gasoline), followed by coke oven products (~0.5 Gt/year) with 19%, rubber and plastics (~0.4 Gt/year) with ~14%, and the rest of the share attributed to other manufactured products. Among the manufacturing sectors utilizing manufactured products that would be embodied in the final products (1.0 Gt/year), the majority was utilized in petroleum

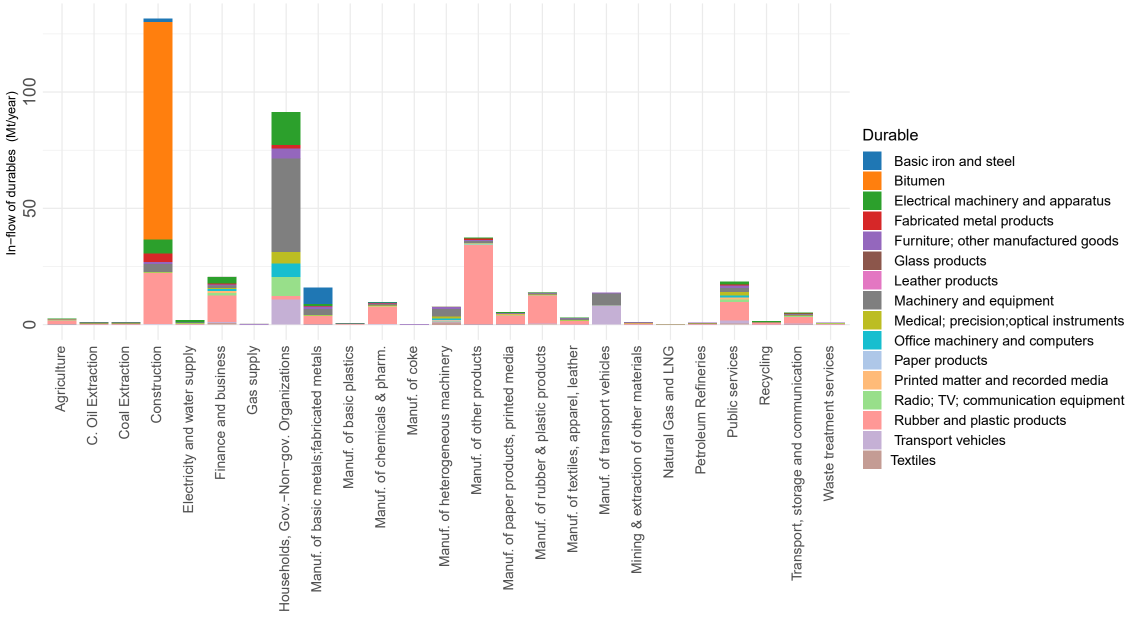

Figure 2. Amount of FC contained in types of durables per aggregated sector (in Mt/year of FC)

All 164 sectors in Exiobase are aggregated to distinguish between 25 different aggregated end-use sectors for ease of display. The details of the aggregation can be viewed in the supplemental information section "Exiobase aggregated sectors." Additional information on the share of materials embodied in final products can be viewed in Figure S2.

refineries, constituting 49% of the total. This was followed by the rubber and plastics (including basic plastics) industry with 33%, and the remainder of the intermediary consumption of manufactured products was distributed among various manufacturing sectors.

The top right part of Figure 1 shows that in 2011, ~91% of the FC in the technosphere was released into the environment, with ~9.5 Gt/year of FC (~34.8 Gt/year of CO_2 equiv). 99% of this amount was in the form of gaseous emissions, whereas the remaining 1% was discharged to the environment due to unmanaged waste (0.1 Gt/year). The highest contribution to FC emissions came from electricity, water, and gas supply services, contributing ~42% of FC emissions, followed by manufacturing sectors with 25% of the FC emissions. The remaining emissions were produced by service sectors (~14%); households and governmental and non-governmental organizations (12%); and waste treatment sectors (~2%—mostly from incinerators). These outflows constitute the overall flows from the technosphere to the environment, linked with environmental damage caused by anthropogenic activities.

The remaining ~9% of FC persisted within our technosphere, constituting ~1.0 Gt/year of FC. These are categorized into three distinct pathways: ~0.4 Gt/year of FC (~3%) was integrated into gross addition to stocks of durable goods, ~0.3 Gt/year (~3%) was disposed of into landfills after reaching the end of their lifetime, and ~0.3 Gt/year of FC (~3%) represented the change in stocks of non-durables. If all this FC stored in products in that year had been oxidized, the CO_2 emissions, based on the stoichiometry of CO_2, would be ~3.7 Gt/year CO_2 equiv. This amount was almost equal to the CO_2 emissions of the EU-28, the third-highest greenhouse gas (GHG) emitter in 2011, with 3.8 Gt of CO_2.[59] Of course, this amount represents a hypothetical contribution, as this FC stock is only slowly released into the atmosphere. On the other hand, this stock addition is only for 1 year and adds to the FC accumulation over time.

It is important to emphasize that our mass-flow diagram encompasses three distinct waste streams within the technosphere, each relevant to FC products. When FC products end up in landfills, we assume that they remain confined within the boundaries of the technosphere. By contrast, the use of incinerators and instances of mismanagement of waste result in the discharge of FC into the environment.

Distribution of FC across durable goods and consumers

In 2011, the overall FC stored in durables was estimated as 0.4 Gt/year (or ~3.7% of the FC in Figure 1).

Figure 2 displays the sectoral breakdown of annual gross FC addition in different durable goods in 2011. Additionally, the breakdown of materials embodied in final products as a percentage share can be viewed in the supplemental information section "extended figure 2" (Figure S2). We have chosen to depict the share of materials rather than the absolute amount.

We observed the highest FC accumulation in buildings and infrastructure through construction, accounting for 34% of the gross addition of all FC-relevant durable goods into stocks. The largest contribution to this amount came from bitumen, with 93 Mt/year, constituting 24% of accumulated durables in 2011. Following in decreasing order, manufacturing industries contributed with 28% to GAS of durables (108 Mt/year), followed by households and governmental and non-governmental

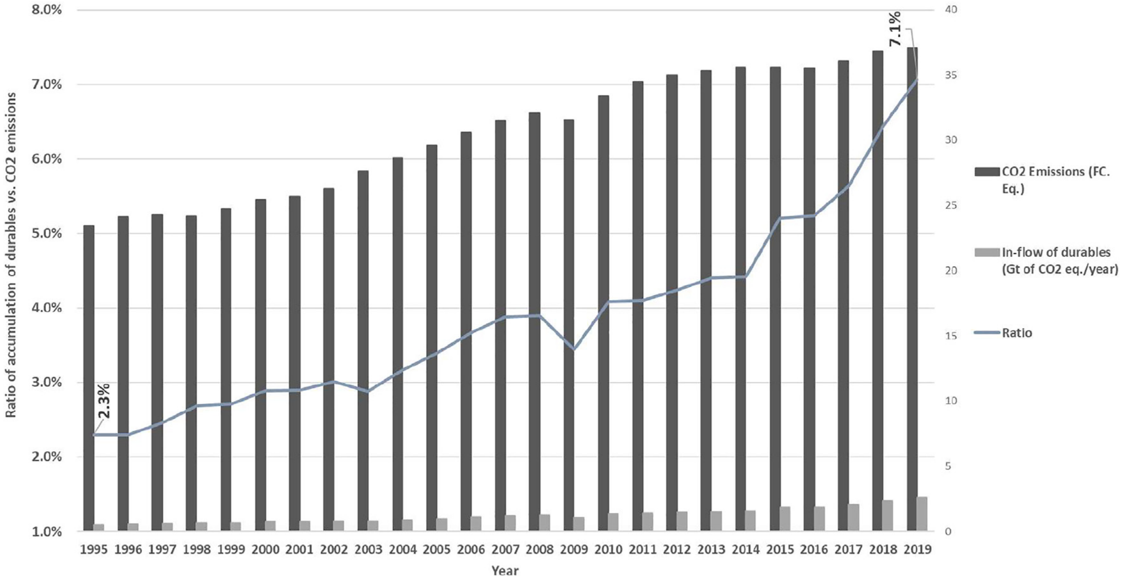

Figure 3. Fossil carbon in global annual CO_2 emissions (Gt/year) versus annual addition of fossil carbon in durables (Gt/year CO_2 equiv) for 1995–2019

The ratio (%) indicates the fraction of durable in-flows versus global annual CO_2 emissions, both in Gt/year CO_2 equiv per year.

organizations (24%). The remaining accumulation is attributed to the service sector; the extraction, mining, and quarrying sectors; electricity, water, and gas supply services; agriculture, forestry, and fisheries; and finally the recycling and waste treatment sectors.

The highest contribution to FC accumulation in durables was through rubber and PPs with ∼114 Mt/year (∼30%), followed by bitumen (∼24%), machinery and equipment (∼16%), electrical machinery (∼7%), transport vehicles (∼6%), and radio, TV, and communication equipment (∼3%). The remainder of the accumulation in durables (∼14%) is distributed among the rest of the durables.

FC accumulation in durables amounted to 8.4 Gt (or about 30.8 Gt CO_2 equiv) between 1995 and 2019

Considering the increase in global fossil fuel use and GHG emissions throughout 1995–2019, we compare FC as GAS of durables in relation to the increase in global production and CO_2 emissions. We have selected this time period based on data availability, and our intention is to observe the extent of accumulation of FC over a longer time frame. Here, we only present FC accumulation in GAS of durables. Viewing Figure 3 in combination with Figure 4, related to EoL flows for the same period, reveals every facet of what happens to FC throughout its life cycle. We assume a fixed ratio of value added to durable production per sector (based on the full granularity of 163 sectors of the Exiobase monetary multi-regional supply and use tables for the period 1995 to 2019).

Next, we observe the relative size of FC in durables compared with annual global fossil-CO_2 emissions to see the potential contribution of carbon stored in infrastructure, buildings, and other durables to climate change. Figure 3 shows the estimation of FC addition to the technosphere in durables in Gt/year CO_2 equiv between 1995 and 2019. We select 2011 as our base year and extrapolate our observation of FC accumulation in durables for other years utilizing Exiobase 3 monetary use tables. We first convert the monetary tables from current to constant prices, setting 2011 as the base year. Current prices were converted to 2011 prices by deflating value added, and then we carried out the extrapolation based on the rate of change in value added per sector per country.

Over the period 1995 to 2019, the estimated cumulative FC in GAS of durables was ∼8.4 Gt (or ∼30.8 Gt CO_2 equiv), excluding the annual discharge of these durables. This amount is considerable, given that it amounts to ∼93% of the annual CO_2 emissions in 2019, with 33 Gt of CO_2.[59] In 1995, the ratio of annual FC addition in durables (Gt CO_2 equiv/year) to global annual CO_2 emissions was 2.3% and increased to 7.1% in 2019. In other words, the pace of FC accumulation in stocks of durables has increased throughout this period.

Infrastructure, durables, and landfills act as temporary FC storage

Figure 4 displays how much EoL FC will end up in waste streams: collected for recycling (including recycling losses), burned in incinerators, ending up as litter in the biosphere, or stored in landfills by the end of 2019 for all cohorts accumulating between 1995 and 2019.

Between 1995 and 2019, cumulatively ∼3.7 ± 0.8 Gt of FC (∼44% of FC in GAS of durables from 1995 to 2019) was discharged to waste streams based on the EoL time of buildings, infrastructure, and other long-term products accumulated. Out of this total amount that enters the waste streams, ∼33% of the FC (1.2 ± 0.3 Gt) resides in the landfills as durables, ∼32%

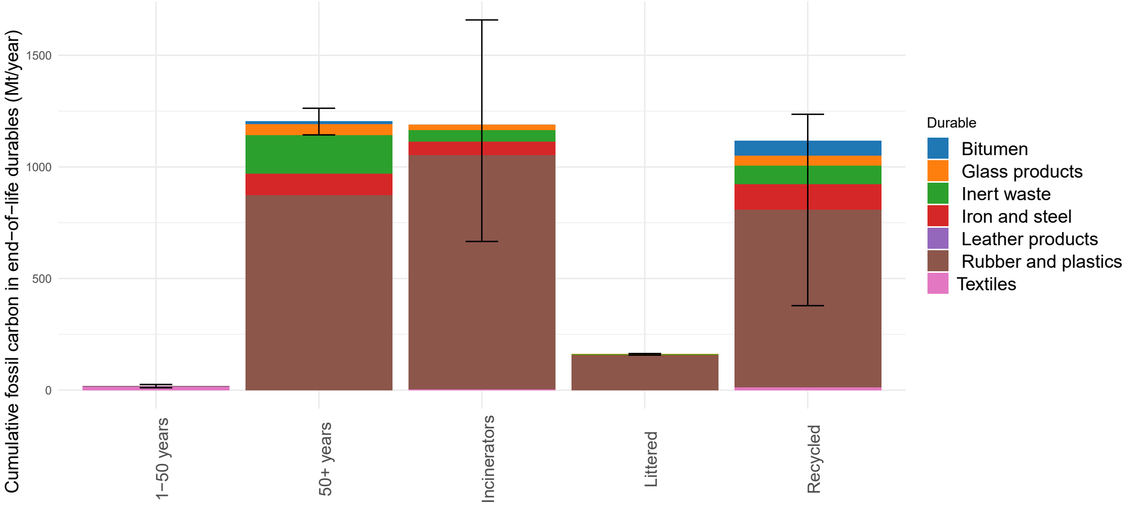

Figure 4. Different waste treatment options for end-of-life waste between 1995 and 2019

Products with different landfill residence times are displayed separately on the leftmost two columns. All end-of-life flows to waste treatment are based on the estimated cumulative gross addition to stocks in the period 1995–2019 and waste treatment statistics per durable type and country of treatment. Error bars indicate uncertainty based on Intergovernmental Panel on Climate Change (IPCC) ranges for the fossil carbon content of products. The inert waste category consists of various products that correspond to the waste category "oils and hazardous waste." Extended Figures S3 and S4 provide further information on end-of-life flows from different cohorts and the breakdown of annual end-of-life flows per cohort.

is incinerated (1.2 ± 0.2 Gt), 28% is recovered for recycling (~1.1 ± 0.3 Gt or ~30%), and the rest is litter or disposed of in open landfills (0.16 ± 0.03 Gt).

Based on our estimation on FC in GAS of durables in the technosphere between 1995 and 2019, we see that 84% (~7.0 Gt) ended up within the confines of the technosphere. We display the results of the retrospective dynamic MFA diagram in Figure 5, depicting the fate of FC in durables by the end of 2019. Figure 5 represents the mass-flow diagram of the fate of gross-accumulation of FC displayed in Figure 4, based on waste treatment statistics we employ (further details provided in section estimation of EoL FC durable flows to waste streams and to the atmosphere/biosphere in 2020).

We further estimate that ~29% of the remaining 4.7 Gt of FC in durables will not have reached their EoL stage by 2050 (~1.4 Gt of FC), still persisting within our technosphere. Revisiting the estimation of Haas et al.,[34] 35% of the processed materials did not end up as gaseous emissions or liquid or solid discharge in 1900–2015. We find FC retention in stocks of durables (57% as of 2019) to be much higher compared with retention of all materials in stocks.

These findings indicate that infrastructure, durables, and landfills act as long-term carbon storage and delay the realization of related environmental effects. The bulk of the FC that enters landfills stays there for more than 50 years. Approximately 98% of the FC entering landfills within the period of this study as durables take more than 50 years to decompose, with only textile and leather waste requiring less than 50 years to decompose. For example, glass products require ~400 years to chemically break down in landfills,[60] whereas PPs either decompose over a very long period due to the vast majority of plastics' precursor monomers being non-biodegradable[61] (requiring more than 500 years), or mechanically break down into micro-plastics through external effects such as sunlight and heat.[61] Thus, landfills act as FC storage, postponing the effects of FC discharge either into the atmosphere as GHGs or as solid or liquid discharge into the biosphere for several decades, depending on landfill conditions and the respective materials (waste materials such as glass, plastics, and metals are considered to be inert[62]). We do not account for biodegradable plastics, as they account for less than 1% of plastic production in 2019.[63]

As heterogeneous machinery consists of different materials, the lifetime of its components is also not homogeneous as each material fraction has its own lifetime and decomposition characteristics. Here, we treat heterogeneous machinery and motor vehicles regarding all incorporated FC-relevant materials. We choose to do so, as the average lifespan of materials varies based on different end-uses for the same type of materials. We only decompose EoL flows from heterogeneous machinery and motor vehicles while allocating the flows to different waste treatment methods. This approach results in uncertainty regarding the distinction of "plastics" and "rubber and PPs," which we aggregate into one category in Figure 4. The product category "inert waste" includes various types of waste materials, yet none of the products that fall under this category are considered durable. Thus, the fraction attributed to inert waste seen in Figure 4, indicates the amount of FC that is discharged from machinery and motor vehicles to waste streams and persists in landfills for over 100 years.[64]

Because it takes a longer time for coated paper to decompose in landfills compared with paper without coating,[65] we assume that such paper products will have a longer time required in landfills to decompose. In this regard, we still rely on waste treatment statistics for paper products when allocating EoL flows to related

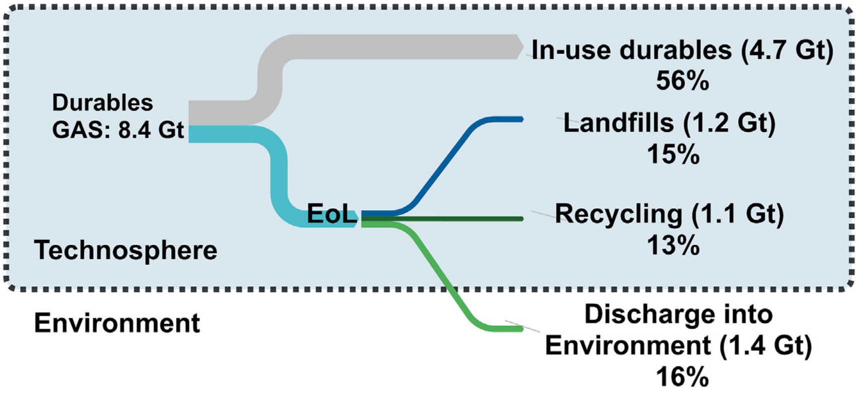

Figure 5. Fate of FC in GAS of durables between 1995 and 2019

waste streams. However, when determining the fate of FC in paper products, we aggregate them with PPs and display together in Figure 4.

It is important to mention that landfill residence time of different waste materials is highly dependent on landfill and climate conditions.[60] Considering the landfill and climate conditions in the region of disposal would yield more accurate results in terms of the landfill residence time of durables.

Conclusions and implications

An increasing share of FC is retained in the technosphere each year, in durables, buildings, and infrastructure from 1995 to 2019. After the retained FC completes its lifetime in temporary capital stocks, it follows one of two pathways. It may remain in the technosphere, by being collected for recycling as secondary inputs to industrial processes, or stored in landfills, where it will most probably remain for at least 50 years without any chemical breakdown. Alternatively, it can be discharged to the environment by being burned in incinerators for energy recovery, therefore released to the atmosphere, or may end up as litter waste in instances of mismanaged waste. Hence, highlighting the factors that affect the fate of FC holds important implications amid global efforts to mitigate our dependency on fossil fuels and reduce emissions and environmental impacts of waste.

One important factor is the lifetime of products, which effectively delays the FC throughput in the technosphere. Based on our calculations, we observe that extending the product lifetimes by 50% reduces waste streams by 15% between 1995 and 2019 (supplemental information section "local sensitivity test" and Figure S4). One other factor that delays the discharge of FC into the environment is the recycling rate of each product/material. Increasing the recycling rate of each product by 5% and 10% results in ~5% and 18% less FC in waste streams within the same period, respectively (supplemental information section "local sensitivity test"; Figure S5). This may contribute to curbing our reliance on FC as feedstock to some extent. Moreover, it is crucial to further investigate the spillover effects associated with substituting FC feedstock with bio-based alternatives within the technosphere. This includes examining the land and water resources utilized in the shift from FC feedstock to biomass and understanding the implications of this transition on land use, particularly in relation to food production. This investigation is vital for comprehensively assessing the environmental and socio-economic impacts of such a shift.

Therefore, we highlight the importance of current initiatives toward a circular economy to reduce the inflow and throughput in our global economy and require a shift toward more sustainable and environmentally responsible practices, with the ultimate goal of mitigating the adverse impacts of human activity on our planet through closing material loops. Contrary to a wide emphasis on individual behaviors, such circular initiatives should increasingly focus on stock accumulation in industrial sectors as well as households. In addition, specific policy measures aimed at containing the materials in landfills and minimizing the solid or liquid discharge from landfilled waste could diminish the environmental impact related to landfilled FC and act as FC "sequestration" in our technosphere.

Data and methodology

Exiobase 3 hybrid-MR-SUT

In order to achieve sectoral FC mass balances, all FC inputs (in tons of FC equivalent) to sectors (including materials, fossil energy, and intermediary products) and FC outputs (waste, emissions, and final products) have to be taken into account. Exiobase 3 MR-HSUT[66,67] (v3.8.2) proves to be useful for exerting mass MFA on FC globally,[68] with data from 43 countries and five rest-of-the-world regions for the year 2011. Flows in this hybrid data are represented in any of the 3 units: mass (in tons), monetary in million Euro (EUR) in current prices, and energy in terajoule (TJ). In total, there are 164 different sectors and 200 products and services per country in the Exiobase 3 dataset (see supplemental information section "results" for the detailed list of sectors/products and countries). In addition, numerous extensions, such as emissions, waste supply and use, and heterogeneous machinery supply and use, have been developed for Exiobase 3.[66] In order to estimate the FC in durables from 1995 to 2019, we used the Exiobase 3 MR-SUT framework based on waste-input-output and hybrid IO approaches, similar to Cimpan et al.[69] This dataset covers 163 sectors, with the gas manufacturing sector excluded. Supplemental information summarizes the detailed list of the datasets, their size, and units. Figure 6 shows the properties of different accounts.

We first start by converting the Hybrid-MR-SUT and extension accounts to FC equivalent by the following:

- Let FCC^U be the FCC matrix, initially a 200 × 1 vector, expanded to 9,600 × 1, assuming the same FCC for all countries and regions in Exiobase. Similarly, FCC^E (66 × 1) and FCC^W (19 × 1) were created for emissions and waste supply matrices (also used for motor vehicles), respectively.

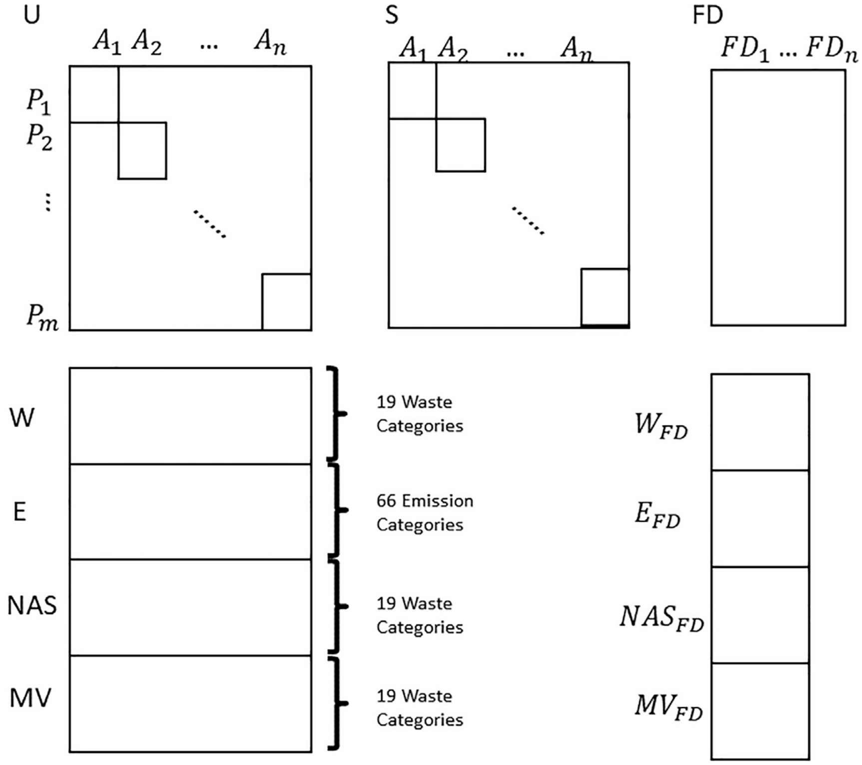

Figure 6. Structure of Exiobase 3 MR-HSUT and extension accounts

U, use matrix; P_n, product or service; A_k, activity or sector; FD, final demand; W, waste supplied by industries; E, emissions by activities; MV, extension account of motor vehicles sector showing MV production. Datasets depicted with subscript FD indicate extension accounts for final consumers. FCC denotes the matrix holding fossil carbon content of each product (9,600 × 1), and EoL (9,600 × 48) denotes end-of-life flows from durables. Variables n, k, l, w, and e are used to denote products (200 × 48), industries (164 × 48), final demand categories (6 × 48), waste types (19 × 1), and emissions categories (66 × 1), respectively. U and FD matrices have hybrid units: mass (tons), monetary (MEuros), and energy (terajoules [TJ]). The rest of the datasets have mass units (tons).

- Let U and FD denote the use table and final demand matrix, with dimensions 9,600 × 7,872 and 9,600 × 288, respectively. The operation involves scaling U and FD by FCC^U (both U and FD have the same row dimensions). The scaling operation is carried out as follows:

$$U^{FCC} = U * FCC^U \qquad \text{(Equation 1)}$$

where * denotes the matrix row-scaling operation. Therefore, U^{FCC} has dimensions 9,600 × 7,872. Similar to the operation carried out in Equation 1, FD matrix is converted to FCC equivalent, yielding FD^{FCC} with dimensions 9,600 × 288. FCC matrix also serves as a filtering matrix, removing all unnecessary flows in MJ and MEuros. The country aggregation is denoted as:

$$F_{n,k} = \sum_{j=0}^{47} \sum_{i=0}^{47} U^{FCC}_{(200j+n,164i+k)} \qquad \text{(Equation 2)}$$

where variable i and j are the country index, n is the product, and k is the sector index. The summation in Equation 2 removes country resolution from the data, with each data point being in FC mass. The final matrix only has global sectors, with dimensions 200 × 164. Sectors with similar activities/products were only grouped together for ease of display; all calculations were done according to full granularity of sectors, as reported in Exiobase 3. The breakdown of the grouped sectors (supplemental information section "Exiobase aggregated sectors") and the related FCC of each product (as a % of the total weight of products) (supplemental information section "calculation of FCC for HSUT products") can be found in the supplemental information.

Sectoral input-output balance

All flows in this study are in tons of FC, with all mass flows converted to FC based on their FCC (as percentage of weight). The structure of the mass-flow diagram for input-output balance of sectors can be seen in Figure 7.

$$IP + RM = E + W_{disc} + FP \qquad \text{(Equation 3)}$$

Equation 3 provides the most general logic behind achieving sectoral mass balance. The sectoral mass FC I-O balance is obtained by combining different extension accounts provided by Exiobase. In addition to sectoral mass balance, we also look at the mass I-O balance for final products to verify the integrity of flows and FC balance per product. The mass balance equation is formulated as:

$$FP = W_{FP} + C + S; \qquad \text{(Equation 4)}$$

and the relation of waste flows as:

$$W = W_{disc} + W_{FP} + EoL \qquad \text{(Equation 5)}$$

Finally, using Equations 4 and 5, we rewrite Equation 3

$$IP + RM + EoL = E + W + C + S \qquad \text{(Equation 6)}$$

The sectoral mass FC I-O balance is obtained by combining different extension accounts provided by Exiobase. In this regard, flows *IP*, *RM*, *FP*, *C*, and *S* are obtained through using multi-regional hybrid-use tables (MR-HUSE), MR-HSUT related to final demand, and heterogeneous machinery (MV and MV_{FD}) MR-SUT; *E* through extension accounts related to emissions. The waste flows indicated in this I-O representation are W_{disc}, W_{FP}, and EoL. W_{disc} and W_{FP} are obtained by combining MR-HSUTs and waste use extension accounts of Exiobase 3,

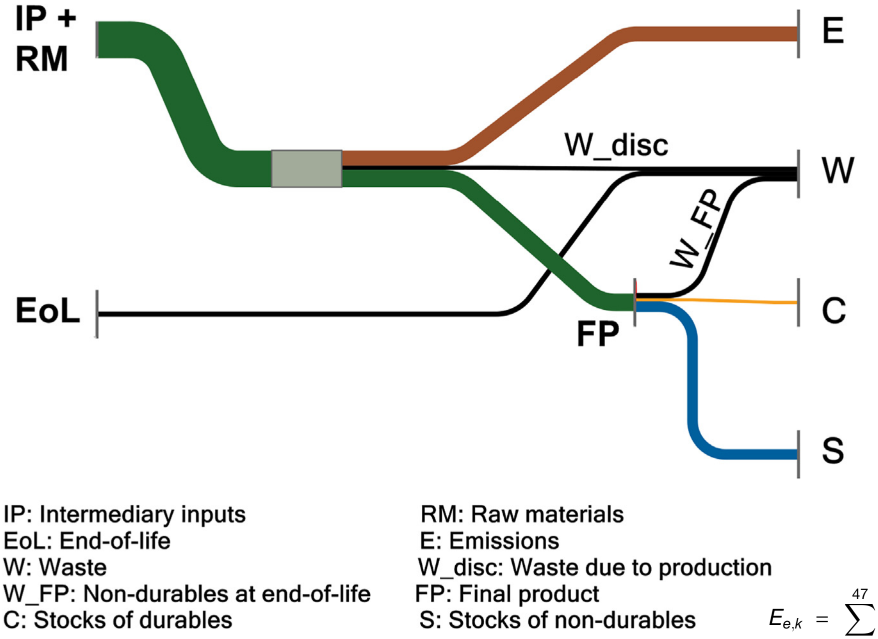

Figure 7. Mass fossil carbon input-output structure of sectors with arbitrary volume of flows

whereas EoL flows for 2011 are quantified using the stocks-to-waste account of Exiobase. EoL for other years, except 2011, is calculated based on imposing the lifetime functions on the products. More details about this calculation can be found in sections "estimation of FC stored in durables" and "lifetime of products and mortality functions."

We also look at each durable product separately and identify the sectors they end up in. For example, we use the following formula for carrying out the filtering and aggregation operations:

$$U^{FCC}_{PP|RS} = \sum_{n=1}^{200}\sum_{k=1}^{164}\left(F_{n,k} * PPI_n * \mathrm{RSI}_k\right) \qquad \text{(Equation 7)}$$

to quantify the total FC stored in PPs that flows into the (petroleum) refinery sector (RS) on a global scale. In this equation, we use $F_{n,k}$, which was displayed in Equation 2, and row-wise and column-wise scales with PP index (PPI_n) and RS index (RSI_k) vectors, respectively. PPI_n (9,600 × 1) and RSI_k (1 × 7,872) are binary filtering matrices that filter out all other information except PPs in rows and petroleum refineries in columns. The resultant matrix is summed over both dimensions. We create specific selection matrices for all aggregated sectors/activities and products. We carry out the same operation in Equation 7 for all aggregated sectors (37 sectors from a total of 164, details in supplemental information section "Exiobase aggregated sectors") and obtain the total FC use in aggregated sectors per aggregated product category.

A similar logic holds for estimating FC in emissions (E), waste streams (W), motor vehicle parts (MV), and GAS of non-durables (S). For example, FC in waste flows with different waste materials discarded by the global petroleum RS is calculated as:

$$W_{RS} = \sum_{i=0}^{47}\left(W_{w,164i+k} * FCC^{W}\right) * RSI_k \qquad \text{(Equation 8)}$$

Equation 8 yields the global waste flows resulting from discarded products in the petroleum RS, in FC equivalent. W matrix (19 × 7,872) denotes waste supplied by all sectors and countries, $\mathrm{FCC}^{\mathrm{W}}$ denotes FCC of waste materials (19 × 1), and RSI_k is the binary filtering matrix (1 × 7,872), as demonstrated in Equation 7. The final matrix is in the form 19 × 1 and is FC equivalent of waste flows, distinguishing 19 different waste types. Similarly, the following equation yields the FC equivalent of GHG emissions from the petroleum RS:

$$E_{e,k} = \sum_{i=0}^{47}\left(E_{e,164i+k} * FCC^{E}\right) * RSI_k \qquad \text{(Equation 9)}$$

The resultant matrix $\mathrm{E}_{e,k}$ has dimensions 66 × 1. Note that not using any filtering matrix would result in FC in global GHG emissions across all sectors. For some sectors, an imbalance in mass I-O flows has occurred on the input side, a total of 0.3 Gt/year. This is mainly due to assuming a fixed FCC for each product globally and harmonizing different environmentally extended tables from Exiobase 3 for different parts of the technosphere. We further discuss this issue in the limitations and assumptions. We deal with this problem as follows: for higher output than input, we achieve mass balance by introducing a so-called "error flow" to rebalance the mass I-O flows. We only observed a significant imbalance on the output side of the electricity generation sectors (which we attributed to the emission flow from the same sector); otherwise, the balancing outflows amounted to 0.06 Gt/year on the output side (0.6%).

Estimation of FC stored in durables

The accumulation of durables in this study involves considering the usage of durable products by sectors and estimating the FCC within various categories of durables. We employ the transfer coefficients matrix[66,70–72] (D_0 matrix) to estimate durable accumulation. The D_0 matrix represents the proportion of inputs of products or materials required for an activity, where these inputs are incorporated into (or contained in) the final products of the same activity/sector. These necessary inputs are quantified based on a life cycle inventory (LCI) approach, details of which can be found in the references listed. Utilizing the D_0 matrix allows us to filter all flows that will be contained in the final product of that sector, hence we end up with products accumulating as capital accumulation in industrial and service sectors. Initially, the D_0 matrix (200 × 164) contained values between 0 and 1, which we then converted to binary digits. We converted all fractions to 1 in the D_0 matrix, assuming that product demand from sectors equals the embodied products/materials in the final products and the capital accumulation. Because the process

Table 1. Share of fossil carbon in all durables, based on Exiobase 3 HSUTs for 2011 and carbon content of products we compiled for this study

Durable product	Share of fossil carbon in durables (%)	Durable product	Share of fossil carbon in durables (%)
Rubber and plastic products	29.5	office machinery and computers	2.4
Bitumen	24.2	iron and steel	2.3
Machinery and equipment	16.4	medical, precision, and optical instruments	2.0
Electrical machinery and apparatus	7.4	textiles	0.9
Transport vehicles	5.8	printed matter and recorded media	0.7
Radio, television, and communication equipment and apparatus	3.0	paper and paper products	0.5
Fabricated metal products	2.5	glass and glass products	0.1

Carbon content for each durable type can be seen in Table S7.

balances that hold for all materials presented in the D_0 matrix do not hold for FC, we choose to treat the matrix as binary. Out of 200 products and services listed in Exiobase, we consider 16 as FC-relevant durables. We create a durable filtering matrix D^f_n with dimensions 200 × 1. By using $D^0_{n,k}$ and D^f_n, we quantify durable accumulation as:

$$F^{dur} = \sum_{n=1}^{200}\sum_{k=1}^{164}\left(F_{n,k} * D^f_n * D^0_{n,k}\right) \qquad \text{(Equation 10)}$$

Equation 10 yields durable accumulation per sector, per durable type, or both, based on the summation operation carried out. Alongside Equation 10, we treat flows of durables into final demand and motor vehicles used by the industry and final consumers as part of this durable accumulation, aligning with the approach in Equation 8. Alongside the durable accumulation obtained through Equation 10, we also quantify addition to stocks of non-durables. Instead of filtering the results for durables with D^f_n, we use the inverse of the said matrix (binary entries reversed) to select non-durable product indices and end up with addition to non-durable accumulation.

Equation 10 yields gross addition of durables to stocks for 1 year only and constitutes the starting point of our analysis on durable accumulation in 1995–2019. Given the variability in durables' lifespans, each durable is assigned a distinct mortality function for discharging the stored FC based on their lifespans (Tables S10 and S11). To calculate the total FC discharge from EoL durables, we multiply the discrete lifetime distribution function (f) for 16 of the FC-containing durables [16 × 99] by the amount of FC stored in each durable, denoted as F^{dur} [16 × 1]. Note that for the period 1995–2019, F^{dur} expands to a dimension of 16 × 25, representing 25 different cohorts of durables.

$$D^{FC} = \sum_{i=1}^{16}\left(F^{dur} * f\right) \qquad \text{(Equation 11)}$$

Equation 11 yields the discharge of FC from FC-durables over 25 cohorts from 1995 to 2019, denoted as D^{FC}. The resultant matrix is restructured into a 16 × 99 × 25 format, representing the aggregate discharge of FC from durables for 99 years into the future, with each year of purchase represented in the matrix's third dimension.

Lifetime of products and mortality functions

Assumptions undertaken regarding lifetime modeling and adopting proper functional forms to represent the mortality function have been discussed in literature.[36,37,39,40,42,73] In Exiobase, the life-time distribution of each product follows a symmetric triangular mortality function.[31,66,68] This function represents the mass fraction of a product that will be discharged over its lifetime, based on a waste input-output approach. If we denote the total mass of any purchased product in a period t as m, and the mass of products discharged as waste as w_t, the ratio (w_t/m) indicates the discharge rate in period t. Exiobase provides discharge fraction information, whereas the remaining fraction is assumed to be retained in the technosphere and will be discharged in subsequent periods. The mortality function we employ in our study follows a delay model, where the outflow in a certain year is based on the function of the inflow in the previous periods.[38]

We obtain the lifespan of products from Exiobase and only consider the average lifespan (L) of products to impose normal distribution for each product ($\mu = L/2$, $\sigma = \mu/2$). We finally normalize the mortality function so that integrating the function over time equals 1. The details of lifespan assumptions, μ, σ, and scaling of the lifetime functions can be found in the supplemental information section "lifetime distribution functions." The lifetime functions we use for our study and the lifetime function used by Exiobase can be found in Figure S5.

Both lifetime functions presented in Figure S5 assume that products primarily release materials during their midlife. The lifetime data in Exiobase 3 encompass 34 products and illustrate their discharge rates over a span of 99 years. Out of these, 16 products contain FC and are therefore considered for this analysis. However, an exception is made for motor vehicles, as Exiobase does not provide specific lifetime information for this product category. In this regard, we estimate the lifetime of motor vehicles and heterogeneous machinery based on the material fractions they consist of, specifically glass, steel, plastics, and inert waste obtained from Exiobase 3. The lifetime functions of these materials were treated in the same way described above and used to determine the lifetime of motor vehicles and heterogeneous machinery. We do not consider all "inert waste" as durable products in this study, but they take part as components in machinery and therefore are included in the final analysis.

Estimation of FC in GAS of durables between 1995 and 2019

After estimating the FC in EoL durables through Equation 11, we extrapolate the gross addition of FC to stocks of durables for 1995–2019, using Exiobase MR-SUT v3.3.18.13 data in monetary units.

Before conducting our analysis, we first deflate the monetary tables, using the deflators per sector and country,[74] and convert the tables to constant prices for 1995–2016. For 2017–2019, we calculate the deflators per sector and country by dividing current prices over constant prices and applying the real gross domestic product (GDP) growth to deflated data of 2016. Therefore, the extrapolation for 2017–2019 is based on the increase in value added in real prices.

We consider GAS of durables (Gt/year) in 2011 for all country sector pairs based on the physical-input-output tables (PIOT) and compare with durable purchases (trillion \$/year) by each sector in monetary-input-output tables (MIOTs). We construct an array v (9,600 × 1) holding the ratio of mass durable production over total money paid by the durable-producing sectors. We multiply array v with the value added in durable purchases for each year using the row-wise scaling operation and estimate the GAS of durables for 1995–2019. For some sectors and countries, array v contained an outlier, with 6 orders of magnitude difference with the average ratio of sectors. These outliers were replaced with data ratios from similar countries with production volumes for the same products. In this regard, we assume that bitumen production in Denmark has the same ratio as bitumen production in Norway. Similarly, the ratio of bitumen production in Cyprus was assumed to be equal to that Malta and the ratio in Slovenia to that in Croatia.

Further details on the share of FC in all relevant durable types can be found in Table 1.

Estimation of end-of-life FC durable flows to waste streams and to the atmosphere/biosphere in 2020

We estimate the EoL FC durable flows into waste streams, as explained in sections "estimation of FC stored in durables" and "lifetime of products and mortality functions." Consequently, we focus on the annual EoL flows throughout 1995–2019. To allocate EoL flows to various waste treatment options, we utilize data on municipal solid waste (MSW) treatment per durable type.[72] These treatment options include open dumps, landfills, incinerators, and unspecified methods. Because composting is not applicable to any of the durables considered here, we allocate the fraction of composted waste to landfills. We employed MSW treatment data for paper, leather, glass, and iron waste taken from Integovernmental Panel on Climate Change (IPCC) Guidelines.[75,76] For plastics,[77] bitumen,[78] and rubber[79] we relied on other sources. Only for the inert waste category did we rely on the weighted global average of waste treatment options for all FC in IPCC guidelines due to lack of data.

After quantifying the influx of EoL FC into landfills, the next step involves determining the duration that durables (and the FC stored in them) remain in landfills before being decomposed or discharged. To analyze this, we utilized the waste reduction model (WARM)[60,80] data source, which provide information on the decomposition time of durables in landfills. Durables were categorized based on their average lifespan in landfills, resulting in two distinct categories: decomposition between 1 and 50 years and decomposition exceeding 50 years.

Analysis of model robustness: Uncertainty and local sensitivity test

Uncertainty analysis

Here, we test our assumption based on the ratio (capital accumulation versus deflated real value added per country and sector), using the socio-economic accounts from the World Input-Output Database (WIOD; http://www.doi.org/10.34894/PJ2M1C) database[81,82] (2016 release) for the basis of the extrapolation of FC in GAS results (nominal value added was converted to real value added for 2011 prices). Based on the resolution of the WIOD database, we have aggregated Exiobase sectors to match WIOD, spanning from 2000 to 2014 (WIOD sectors can be visited in the supplemental information section "WIOD socio economic accounts versus Exiobase aggregated sectors classification"). Our results presented in section "FC accumulation in durables amounted to 8.4 Gt (or about 30.8 Gt CO_2 equiv) between 1995 and 2019" span 1995 to 2019. However, due to lack of data coverage in WIOD compared with Exiobase, we limit our comparison to years 2000–2014. The results of uncertainty analysis can be visited in section "uncertainty analysis" of the supplemental information (Figure S6).

In addition to the ratio, we also plot the uncertainty due to FCC, as indicated in IPCC guidelines. In Figure S6, we present the results related to GAS by relying on Exiobase and WIOD for ratio v on the left, while presenting the uncertainty arising from the IPCC uncertainty ranges regarding FCC of products on the right side of the figure.

We quantify FC in GAS of durables between 2000 and 2014 as 4.5 Gt using WIOD, whereas we quantify this amount as 4.6 Gt using Exiobase, with ~4% difference. Due to the reduced granularity of the sectors in WIOD, we see less fluctuations in our results, possibly indicating a loss in information, while aggregating our results to match the sectoral resolution of the WIOD database.

The total GAS, based on the FCC ranges, deviates our main results by ~2%. Because IPCC ranges do not cover all products that are FC-relevant, there is no substantial change to the results we present in Figure 3. In the next section, we further test the sensitivity of our results for substantial changes in FCC of products.

Local sensitivity test

We leverage Monte Carlo simulations (MCSs) to quantify the uncertainty in our results based on changes in assumed exogenous model parameters. We exert sensitivity analysis on GAS and EoL (Figures S7 and S8) models and compare the changes in the results with the main results we generated for this study. We then display the main results with the 95% confidence interval, using MCS with 10^5 iterations, and compare them with the new results generated with changes in model parameters. We treat each data point as the mean μ of this distribution with uncertainty σ.

First, we quantify the sensitivity of results presented in Figure 3 to isolated effects of change in model parameters. We see that the changes in ratio v (explained in section "estimation of FC in GAS of durables between 1995 and 2019") produce the most significant changes in the model output. When the ratio is increased by

25%, we observe that our results related to GAS between 4.1 and 11.4 Gt, with an approximate change of ~49% and 35%, respectively. Because the pivotal assumption guiding the extrapolation is the ratio *v*, it is to be expected that the model is most sensitive to changes in *v.* Compared with *v*, the model performs more robust results under isolated changes in FCC products. This is mostly because, even in the 1% change in FCC scenario, most products with an FCC higher than 85% cap out at 100% based on MCS results. The variation in the results arising from changes in the rest of the products is comparably smaller. When the variables ratio *v* and FCC are subjected to same amount of change independently (10% increase for each), our model yields more robust results for changes in FCC. These changes affected our results by 24% and 17%, respectively.

Next, we present the sensitivity analysis related to annual EoL flows. In Figure 4, the cumulative EoL flows were displayed. For the sake of this analysis, we display each data point individually.

We investigate the isolated effects of changes in average lifetimes (μ), uncertainty in assumed distributions (σ), and the functional form of the lifetime distribution in the model output. Our model is most sensitive to the average lifetime parameter (μ), similar to previous studies.[83–85] Compared with the main results presented in section "FC accumulation in durables amounted to 8.4 Gt (or about 30.8 Gt CO_2 equiv) between 1995 and 2019," increasing the average lifetime by 50% yields 15% less EoL flows in the waste streams. By contrast, we see that shortening the lifetime by the same amount results in a higher amount of absolute change in the model, with a 47% increase in the EoL flows to waste streams. The policy implications related to product lifetime extensions (PLEs) have found interest in literature.[39,86,87] The uncertainty parameter σ influenced the model output less than μ, with a relative change from the main results with -6% and 4% for -50% and +50% changes, respectively. We finally obtain similar results using Gaussian distribution or the symmetrical triangular distribution with a -2% change in the output, displayed on the rightmost part of Figure S8.

In Figure S9 in the supplemental information section "local sensitivity test," we examine the impact of increased recycling rates on the retention of FC in the technosphere versus its release into the environment. Simulations revealed that enhancing recycling rates of durables by 5% and 10% led to retrospective reductions of 5% and 18% in FC emissions to the environment from 1995 to 2019.

Assumptions and limitations

We merged multiple Exiobase datasets and accounts to apply the FC mass balance of each sector globally. Initially, we assigned FCC to each product based on the fraction of FC relative to the total weight of the product. However, it is important to note that the actual FCC of products can vary significantly within sectors and countries. Due to the unavailability of country-specific data on FCC, our calculations were conducted by aggregating all countries, resulting in a final matrix with products in rows and industries/sectors in columns. To mitigate this limitation, we performed our calculations using the detailed product categories available in Exiobase 3, thereby maintaining the highest granularity possible.

Our analysis acknowledges the susceptibility to aggregation errors, a common limitation inherent to I-O tables. These errors emerge when diverse goods and industries are grouped into broad categories, leading to a significant reduction in granularity. Consequently, such aggregation might yield an oversimplified representation of economic interactions, which may lead to conclusions that do not fully capture the complexities of the underlying data.

This study also contends with the limitations inherent in assuming a static ratio between accumulation of durables and value added for 2011 across the years 1995–2019. Such an assumption neglects the dynamic nature of technological advancements and efficiency improvements that invariably alter production inputs and their efficiency over time. Accordingly, we recognize that presuming a constant ratio of accumulation of durables to value added, as seen in 2011, introduces a degree of uncertainty into our analysis. This limitation is critical for a nuanced interpretation of our findings, given the evolving economic landscape.

In order to estimate the FCC of products and trace the pathways of FC throughout the technosphere, several assumptions were necessary. For PPs, we assumed an FCC of 74%,[88] acknowledging that there can be considerable variations in FCC among different forms of plastics. In addition to plastics, the product category "rubber and PPs" encompasses various rubber- and plastic-based products, with varying degrees of FCC. In this study, we assume a fixed FCC for these products (explanation for calculation in section "rubber and plastic products" in the supplemental information), although in reality, the FCC could vary considerably among different products of the same category. These potential inconsistencies are depicted by the error flow illustrated on the left and right side of the Sankey diagram, which accounts for an error term of 0.3 and 0.06 Gt/year, respectively. This error term arises from the need to rebalance the sectors when there is a mismatch between the input and output of FC.

Similar considerations apply to the waste categories comprising 19 different categories. Each waste category requires the assignment of an FCC, which can vary significantly even among products within the same waste category. This variation is pronounced in the case of the waste category "oils and hazardous materials," as it encompasses a diverse range of FC products in the waste stream, each with its own distinct FCC.

While tracking the FC emissions, a discrepancy was identified in electricity generation sectors, a missing outflow of 0.44 Gt/year (4.1% of the overall FC at the output). This imbalance was mainly due to the use of assumed emission factors for each electricity generation method in Exiobase 3 and the assumptions made regarding the FCC of energy carriers, particularly crude oil and natural gas. We allocated the missing flow to emissions in order to deal with the discrepancy.

The FCC of CO_2 was directly calculated from the molecular weight, taking the FCC of CO_2 as $\frac{Mass_C}{Mass_{CO_2}} = \sim 27\%$.

In the case of heterogeneous machinery, we followed the assumption that the material fractions would be consistent across all machinery worldwide, which may not reflect the actual case. The FCC for this product category was determined based on the global average of material fractions obtained from Exiobase 3 (MR_HSUTs_2011_v3_3_18_waste_coefficients), although the actual FCC may vary depending on the origin of production.

We present the bitumen accumulation under the construction sector in Figure 2. Bitumen is mostly utilized for producing asphalt, later to be used for road construction. Because we do not know the details of bitumen application in the technosphere, we allocate bitumen use in the industry and service sectors to the construction sector. Bitumen used for households and governments and non-governmental organizations is accounted for under the same name in Figure 2.

In the analysis of FC discharge through durables, the lifetimes of durable products are crucial. For instance, plastics primarily used for packaging are assumed to be discarded within a year. However, PPs can have diverse uses[89] and lifetimes,[90] leading to various assumptions.

In allocating EoL flows to MSW treatment methods, we rely on different data sources, encompassing different time periods. While doing so, we assume that the countries' share in treating different durable types would stay constant throughout 1995 and 2019. In reality, share of waste treatment methods is expected to change throughout these 25 years.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for additional resources should be directed to the lead contact, Kaan Hidiroglu (k.hidiroglu@rug.nl).

Materials availability

This study did not generate new unique reagents.

Data and code availability

Data availability

The data were mostly aggregated after calculations for ease of display. The full data may be accessed through the following links:

- Exiobase hybrid-MR-SUT-2011: https://doi.org/10.5281/zenodo.10148587.
- Exiobase 3 monetary MR-SUTs (1995–2019): https://doi.org/10.5281/zenodo.5589597.
- Online repository for intermediary data related to this research: https://doi.org/10.5281/zenodo.14240118.

The following items are additional data that can be found in the online repository related to this research:

- "Exiobase_Monetary_Hybrid_Concordance.xlsx" is the concordance for country orders between hybrid and monetary SUT tables.
- "Lifetime_funct_all_exiobase.xlsx" has the lifetime distribution data of all products considered in the Exiobase dataset.
- "Classifications_v_3_3_18.xlsx" holds the information on the classification of countries, products, sectors, emissions, and waste types.
- "Deflator2011base.xlsx" is the deflator data from Exiobase 3 team for 1995–2016, with base year converted to 2011, also adjusted the countries to the ordering of the monetary dataset.

The description of calculations and dataset classifications are available in the supplemental information.

Code availability

A list of codes can be found in the online repository:

- https://doi.org/10.5281/zenodo.13898916.

The following are the codes used to conduct this research:

- "Durable_Acc_Discharge.m" is the MATLAB code to estimate the discharge of fossil carbon in durables for 1995-2019.
- "MonteCarlo_EoL.m," "MonteCarlo_GAS.m," and "MonteCarloWasteTreatment" are the MATLAB codes for conducting Monte Carlo analysis on results related to end-of-life flows, gross addition to stocks of durables, and waste treatment, respectively.
- "DurablestoWasteTreatment.m" contains the MATLAB code for estimating the treatment of fossil carbon durables in different waste treatment options.
- "capital_calculation.m" contains the MATLAB code for calculating materials embodied in the final products and addition of durables to stocks in sectors.
- "Sector_concordance.m" contains the MATLAB code for aggregating the sectors into aggregated sectors and reading the data.

ACKNOWLEDGMENTS

We acknowledge the contributions of Alessandro Martulli for editing the figures.

AUTHOR CONTRIBUTIONS

Conceptualization, K. Hidiroglu, F.R., S.M., and K. Hubacek; methodology, K. Hidiroglu, S.M., and D.W.; software, K. Hidiroglu and D.W.; data curation, K. Hidiroglu; writing – original draft, K. Hidiroglu; writing – review and editing, K. Hidiroglu, F.R., S.M., and K. Hubacek; supervision, F.R. and K. Hubacek; visualization, K. Hidiroglu; project administration, F.R. and K. Hubacek.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT from OpenAI in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.crsus.2024.100265.

Received: May 31, 2024
Revised: October 9, 2024
Accepted: November 8, 2024
Published: December 20, 2024

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