DELIVERABLE 2.2

Report on emissions and material footprints associated with capital stock dynamics in an input-output framework

Main Authors

Della Bella, Simone

Jiang, Meng

Disclaimer

This report was written as part of the CircEUlar project under EC grant agreement 101056810. The information, documentation and figures available in this deliverable were written by the CircEUlar project consortium and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Statement of originality

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

How to quote this document

Della Bella, S. (2025). Report on emissions and material footprints associated with capital stock dynamics in an input-output (CircEUlar Deliverable 2.2)



This deliverable is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0).

CircEUlar

Developing circular pathways for a EU low-carbon transition

Deliverable number	**2.2**
Deliverable name:	Report on emissions associated with capital stock dynamics in an input-output framework
WP / WP number:	Stocks and Flows of Materials, Energy and Emissions in a European Circular Economy /2
Delivery due date:	31/August/2025
Actual date of submission:	31/August/2025
Deliverable description:	An inter-temporal framework will be developed to integrate stock-flow modelling with supply chain input-output modelling and capital stock-flow dynamics. This will build on and extend established accounting frameworks from the System of Environmental and Economic Accounts (used in earlier projects such as FP7 CREEA) as well as previous efforts to endogenise capital at the macro-level in EXIOBASE (based largely on KLEMS databases). The inter-temporal perspective will endogenise capital formation, service and retirement. Explicit representation of technologies describing how capital is produced will start from the early 1990s, initialised by an estimation of residual stocks (from Task 2.1), product lifetimes for capital items, and production capabilities, using probabilistic estimates where possible [NTNU, BOKU].
Dissemination level:	Public
Lead author(s):	Della Bella, Simone
Contributors:	Jiang, Meng (collaboration with CIRCOMOD) Wood, Richard Anders Hammer Strømman
Internal reviewers:	Jihoon, Min Dominik, Wiendhofer

Version log

Version	Date	Issued by	Description	Summary of changes
1	23.08.2025	Della Bella, Simone	First draft	Revised based on internal review comments
2	25.08.2025	Della Bella, Simone	Second draft	Internal review
2.1	28.08.2025	Della Bella, Simone	Third draft	Internal review
3	10.10.2025	Della Bella, Simone	Revised final version	Revised based on feedback from internal reviewers.

Executive Summary

This report makes capital visible in a multi-regional input–output framework by linking EXIOBASE with a cohort-based stock model. Rather than treating gross fixed capital formation as a one-off demand item, the framework follows annual cohorts of capital goods from manufacture to retirement and attributes embodied material and carbon footprints to the sectors and final users that benefit from capital services. The approach is consistent with SEEA accounting.

The results show that capital-related footprints are large and have grown substantially since the mid-1990s. Construction and machinery dominate both materials and emissions; the material perspective further elevates the role of non-metallic minerals such as cement, concrete, and aggregates, while metals are critical for the functional core of machinery. Growth is concentrated in emerging economies from the early 2000s onward, with Europe, the United States, and Japan remaining comparatively stable. Beyond levels and shares, the analysis reveals dynamics that conventional accounting obscures: legacy burdens embodied in existing assets and retirement waves as past cohorts reach end-of-life. Making these dimensions explicit improves the attribution of footprints and clarifies when and where mitigation and circularity measures can be most effective.

The framework developed here provides the evidence base and tooling needed to monitor capital-attributed footprints over time and to explore future pathways. In the next phase, integration with EXIOFutures scenarios will translate macro drivers—demography, technology, energy mixes, and material intensities—into capital-aware indicators and projections. This will enable robust assessments of how demand- and supply-side strategies, including lifetime extension, refurbishment and reuse, material efficiency, and high-quality recycling, change system outcomes over time.

Keywords

Capital formation; Manufactured capital; Cohort-based stock model; Multi-regional input–output (MRIO); SEEA; EXIOBASE; Embodied emissions; Material footprint; Construction; Machinery; Circular economy.

Contents

Executive Summary 4
Keywords 4
List of figures 6
Abbreviations 6
1. Introduction 7
2. Methods 10
2.1. Framework overview and data 10
2.2. Capital in MRIO 10
2.3. Dynamic stock–flow (cohorts). 11
3. Findings 12
3.1. GHG footprints of capital formation 12
3.2. Material footprint of capital formation 14
3.3. Construction capital stock 17
3.4. Machinery capital stock 20
4. Result in prospective 23
4.1. Future use of capital stock in MRIO framework 23
References 24

List of figures

Figure 1 Share of (A) global greenhouse gas (GHG) emissions and material footprints ((B) total,(C) metals,(D) and non-metals) attributable to capital investment (Gross Fixed Capital Formation, GFCF) compared to household consumption and total GFCF, divided by construction, machinery and other assets, 1995–2022. 8
Figure 2 Global GHGs emission of total GFCF, (A) by country, (B) by production sector 12
Figure 3 GHGs footprint per capita by regions. 14
Figure 4 Global Material footprint of total GFCF, (A) by country, (B) by production sector. 15
Figure 5 Total Material footprint (A) by end-use sector (B) by material, 1995-2022. 16
Figure 6 Material footprint per capita by region, 2000 and 2022. 17
Figure 7 Material footprint of Constructions, (A) by end-use sector, (B) by material, 1995-2022. .. 18
Figure 8 Non-Metal footprint embodied in construction stock and inflows, and outflows across different regions. 19
Figure 9 Material footprint of Machinery, (A) by end-use sector, (B) by material, 1995-2022..... 20
Figure 10 Metal footprint embodied in machinery stock and inflows, and outflows across different regions. 21

Abbreviations

CircEUlar	Developing circular pathways for a EU low-carbon transition
EU	European Union
GFCF	Gross Fixed Capital Formation
GHGs	Greenhouse gases
IAM(s)	Integrated Assessment Model(s)
ICT	Information Communication and Technology
KLEMS	K-capital, L-labor, E-energy, M-materials, and S-purchased services
MRIO	Multi-Regional Input-Output
SEEA	System of Environmental-Economic Accounting
UN	United Nations

Report on emissions and material footprints associated with capital stock dynamics in an input-output framework

1. Introduction

Europe's transition to climate neutrality and a circular economy hinges not only on cleaner energy and consumption but also on how the continent invests in, operates, and retires its long-lived capital assets. Buildings and structures, transport infrastructure, energy and ICT systems, industrial machinery and equipment—collectively termed "manufactured capital or physical assets"—involve significant upfront resource use and emissions, shape material and energy flows for decades, and ultimately release substantial outflows at end-of-life (Krausmann et al., 2017). Yet most environmental accounts and many footprint studies still treat gross fixed capital formation (GFCF) as a one-off final demand item, leaving the resulting stocks effectively invisible once installed (United Nation, 2024). This practice obscures three realities that matter for EU policy: first, the legacy emissions already embodied in physical assets providing services today; second, the service-period impacts that accrue while assets operate and are maintained; and third, the retirement waves that will occur as cohorts installed in past decades reach end-of-life. As a result, conventional production-based and consumption-based accounting systematically understates the emissions and materials associated with the goods and services that depend on capital, particularly in service-oriented economies (Berrill et al., 2020; C.-J. H. Södersten et al., 2018).

To illustrate the magnitude of this issue, Figure 1 presents the share of global greenhouse gas emissions and material footprints (both aggregated and split into metals and non-metals) attributable to capital investment, compared to household consumption and other final demand. The four panels show that GFCF accounts for a substantial and growing share of total environmental footprints, in some cases reaching 30–40% of global material use and over a quarter of greenhouse gas emissions. Within GFCF, construction and machinery dominate, representing the largest contributors to both material and carbon footprints. This evidence highlights why capital assets cannot be overlooked in footprint analysis: their scale renders them decisive drivers of resource use and emissions, and understanding their dynamics is essential for designing effective mitigation and circularity strategies.

This report addresses that gap by developing an inter-temporal framework that integrates stock–flow modelling of physical assets with supply-chain input–output (IO) modelling and capital stock–flow dynamics. Building on the System of Environmental-Economic Accounting (SEEA) ((UN) 2014) used in earlier EU projects (e.g., FP7 CREEA[1]), and on prior work to endogenize capital at the macro level

[1] https://cordis.europa.eu/project/id/308552/reporting

in EXIOBASE (C.-J. Södersten et al., 2017; C.-J. H. Södersten et al., 2018)(drawing on KLEMS investment and depreciation statistics), we explicitly represent capital formation, service, and retirement from 1995 onwards. The framework assigns asset-specific lifetime distributions and incorporates production capabilities and technology change; where data are uncertain, parameters are estimated probabilistically. In practical terms, annual cohorts of capital goods are followed from manufacture (and their supply-chain footprints) to end-of-life fates, so that the upstream burdens of capital are attributed to the industries and final users that actually benefit from the services capital provides.

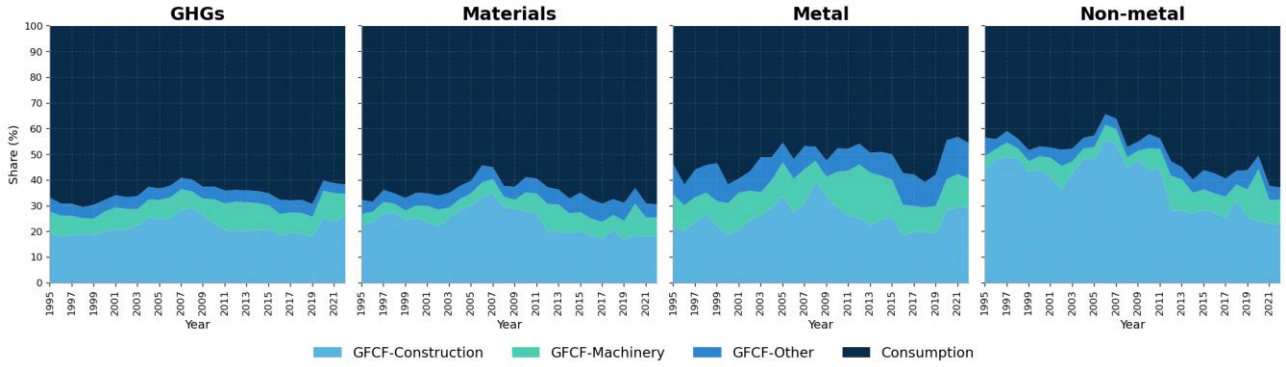


Figure 1 Share of (A) global greenhouse gas (GHG) emissions and material footprints ((B) total,(C) metals,(D) and non-metals) attributable to capital investment (Gross Fixed Capital Formation, GFCF) compared to household consumption and total GFCF, divided by construction, machinery and other assets, 1995–2022.

The approach responds to well-documented limitations of current MRIO practice (Wu et al., 2018). In standard supply-use tables, capital is exogenous: emissions from producing capital goods are accounted for in a separate investment category rather than being reallocated to the products and services that capital helps produce. Prior studies show that distributing capital-related emissions to user industries can substantially change sectoral footprints and shift responsibilities across final demand categories (Jiang et al., 2023; C.-J. Södersten et al., 2020; Xu et al., 2023; Ye et al., 2023). Capital-closure analyses in fast-industrializing economies show that most GFCF-related impacts are tied to domestic construction, but a large remainder is linked to building up manufacturing capacity (machinery and transport equipment) and is partly offshored via global supply chains: for China in 2012, investments drove ~67% of the national material footprint with construction alone >50% and the next-largest share from machinery/transport equipment; globally in 2019, 51% of iron-ore and 67% of copper embodied in capital stocks originated abroad, and 20–37% of capital-related GHGs occurred outside the accumulating economies, while structures still dominated legacy GHGs (>80%) (Jiang et al., 2022; Wang et al., 2023). At the same time, dynamic stock research highlights a conceptual mismatch between accounting depreciation schedules and the physical lifetimes of assets: many assets continue to provide services long after they have been fully depreciated in economic accounts. Ignoring that mismatch can bias scope-3 assessments for firms and mislead policymakers about mitigation timing and circularity potential (Pauliuk & Müller, 2014).

Our contribution is to generalize and operationalize these insights for all major capital asset classes in an EU context. First, we extend EXIOBASE[2] *v3.9.6* (Stadler et al., 2018) with a capital-use representation that keeps capital visible inside the IO system, informed by EU KLEMS (Stehrer,

[2] https://doi.org/10.5281/zenodo.3583070

2019), World Klems[3], LA Klems[4], and national statistics for China[5], Norway[6], Canada[7], and India[8], to allocate asset inflows to user industries. Second, we integrate a cohort-based stock model that traces the evolution of each asset class throughout its service life. This approach applies lifetime distributions (e.g., Weibull or log-normal) to capture the heterogeneity of asset survival patterns and the uncertainty inherent in their retirement. Third, we explicitly represent physical capital assets from 1995 onwards, thereby allowing the associated emission intensities to evolve dynamically in response to changes in energy mixes, improvements in process efficiencies, and shifts in material substitution. Combined, these features provide a framework for consistently attributing the material and carbon footprints embodied in physical capital assets—particularly machinery and construction—to sectors and regions over time, while remaining aligned with the accounting logic of the SEEA framework.

Although the framework is general, its relevance is especially clear for machinery and equipment, which underpin industrial productivity and many low-carbon transitions (renewables, storage, grid equipment, automation). Recent work has shown that machinery production carries substantial metal and carbon footprints at the global scale (Jiang et al., 2023). Integrating such evidence into a European, inter-temporal IO framework reveals where circular economy practices, such as lifetime extension, refurbishment, reuse, and high-quality recycling, can deliver the greatest emission savings and secondary-material supply. The same reasoning applies to buildings and infrastructure (large, long-lived stocks and end-of-life waves), energy systems (rapid technology turnover, evolving emission intensities), transport assets (vehicle fleets and rolling stock), and ICT (fast-changing equipment with rising service demand). By tracking cohorts from 1995 onward, the framework makes visible how yesterday's investments drive today's emissions, how today's purchases lock in tomorrow's operating impacts, and when surges of end-of-life material will arrive—critical information for aligning investment, decarbonization, and circularity targets.

The report provides consistent EU-wide indicators that link capital cohorts to sectoral and final-use footprints across their lifetimes. These insights support the European Commission, Member States, and industry in steering capital investment toward a resource-efficient, climate-neutral economy, while ensuring monitoring indicators reflect how capital accumulates, operates, and retires over time.

[3] https://www.worldklems.net/wkstatistical
[4] http://laklems.net/
[5] https://www.stats.gov.cn/english/
[6] https://www.ssb.no/en
[7] https://www.statcan.gc.ca/en/start
[8] https://www.mospi.gov.in/

2. Methods

This section presents an inter-temporal framework that links a capital-augmented multi-regional input–output (MRIO) model with a cohort-based stock–flow module. The objective is to quantify carbon and material footprint associated with capital formation for all tangible (physical) assets with a focus on constructions and machinery and equipments, and to attribute these burdens to user industries and final demand in a way that is consistent with SEEA accounting logic

2.1. Framework overview and data

For every year t and region r, the workflow unfolds in three steps:

- construct an asset-by-industry capital flow matrix from investment data;
- compute supply-chain footprints of those capital purchases via MRIO
- and follow annual capital cohorts through survival to attribute impacts over time.

The analysis draws on: time-series MRIO tables and environmental extensions—interindustry transactions Z, gross output x, and stressor intensities s; capital accounts disaggregated by asset and industry (e.g., KLEMS-type sources and national accounts); asset-specific lifetime distributions (Weibull or log-normal) derived from the literature (Erumban, 2008; National Bank of Belgium., 2014; Rincon-Aznar et al., 2017; van den Bergen et al., 2009). To initialize the age structure before 1995, we use averages of 1995–1997 technologies and intensities; these spin-up years populate the initial stock but are not reported.

2.2. Capital in MRIO

For each year, the technology coefficient matrix A and the Leontief inverse L are computed as:

$$A = Z * \hat{x}^{-1} \; ; L = (I - A)^{-1}$$

Environmental intensities (row vector or diagonalized as needed): **s** (e.g., kg CO_2eq per monetary output). Supply-chain footprints of any capital investment vector (GFCF) y_{GFCF} are:

$$EF = s * L * y_{GFCF} \; ;$$

To keep capital visible inside the IO system, we identify for each asset class the relevant capital-producing products using a product-to-asset selector M—a binary matrix conformable with y_{GFCF}—and multiplying it element-by-element ($\odot$) to y_{GFCF} to construct asset-specific GFCF vectors:

$$GFCF_a = M_a \odot \; y_{GFCF}$$

These vectors are then disaggregated into a product-by-industry capital flow matrix $\overline{K}$, using the flow-matrix approach developed in previous studies (C.-J. Södersten et al., 2017 and C.-J. H. Södersten et al., 2018). The procedure involves constructing a capital requirement matrix K with the same dimensionality as the inter-industry transactions matrix Z.

To achieve consistency with EXIOBASE, we convert the KLEMS capital account (K^{KLEMS}) into the EXIOBASE product and industry classifications using concordance matrices: G_p (mapping capital assets to EXIOBASE products) and G_i (mapping KLEMS industries to EXIOBASE industries). In cases where a single KLEMS asset corresponds to multiple EXIOBASE products or industries,

distribution proxies are employed. After applying these proxies and normalizing, we obtain $\overline{G_p}$ and $\overline{G_i}$, which allow us to compute the capital flow:

We convert the KLEMS account K^{KLEMS} to the EXIOBASE classification with the help of concordance matrices G_p (from capital asset to EXIOBASE products) G_i (from KLEMS industry to EXIOBASE industries) . We used distribution proxies when one asset from KLEMS is divided into several product (or industries) in EXIOBASE. After proxing and normalizing we obtain $\overline{G_p}$ and $\overline{G_i}$ that allow us to calculate the capital flow matrix $\overline{K}$ as follows:

$$\overline{K} = \overline{G_p'}\, \mathrm{K}^{KLEMS}\, \overline{G_i}$$

Where $\overline{G_p'}$ denotes the transpose of $\overline{G_p}$. Finally, by compiling the capital flow matrices across all countries and regions, we obtain the capital requirement matrix used in the extended IO framework:

$$K = \overline{K} * \hat{x}^{-1}$$

Complementary IO calculations are employed. Capital (flow) footprints—indicating what was needed to develop the cohorts—are calculated with the following equation:

$$EF_{flow} = s * L * \overline{K}$$

2.3. Dynamic stock–flow (cohorts).

Survival curve. Asset lifetimes are represented with a probability distribution $f_a(x)$ (by asset class a), typically modeled using a log-normal or Weibull function. In our case, we apply the two-parameter Weibull distribution. This distribution is described by two key parameters: the scale parameter, which can be interpreted as the average or characteristic lifetime of the asset, and the shape parameter, which controls how concentrated or spread out retirements are around that lifetime. The data are taken from published sources and differentiated by asset type and using industry to reflect heterogeneous service lives (B. Muller, 2006; Miatto et al., 2017; Müller et al., 2014). The cumulative distribution is:

$$F_a(x) = \int_0^x f_a(y)dy$$

and the survival function, i.e., the probability that an asset of any vintage is still in use at age x, is

$$S_a(x) = 1 - F_a(x) = 1 - \int_0^x f_a(xy)dy$$

Cohort accumulation. Let $EF_{i,p,q}^{flow}(m)$ denote the capital-year environmental footprint of the cohort installed in year *m*, for *region* i, *asset* p, and *sector* q. The portion of that cohort remaining in year n is survival-weighted:

$$EF_{i,p,q}^{survive}(m \to n) = EF_{i,p,q}^{flow}(m) \cdot S_p(n - m + 1)$$

The **stock-accumulated footprint** in year n is the sum over all cohorts up to n:

$$EF_{i,p,q}^{stock}(n) = \sum_{m \le n} EF_{i,p,q}^{flow}(m) \cdot S_p(n - m + 1)$$

3. Findings

In this section, we will examine the results of our modelling. We will begin by analyzing the total capital greenhouse gas (GHG) footprints (or carbon footprint), followed by an exploration of the capital material footprints. Next, we will focus on two critical sub-sectors related to material stocks: Construction and Machinery.

3.1. GHG footprints of capital formation

Figure 2 present the evolution of global greenhouse gas (GHG) emissions embodied in capital formation between 1995 and 2022, disaggregated by producer **country** (A) and by **sector group** (B). Together, they reveal both the rapid overall growth of capital-related emissions and the uneven distribution of these pressures across economic sectors and world regions.

From a global perspective, capital-related GHG emissions more than doubled over the period, rising from around 6 × Gt tons of CO_2 eq. in the mid-1990s to over 13 × Gt tons of CO_2 eq. by 2022. This reflects the expansion of investment in infrastructure, buildings, machinery, and other long-lived assets worldwide, particularly in rapidly industrializing economies. The growth trajectory is not linear: a relatively steady rise through the early 2000s accelerates sharply during the period 2002–2012, coinciding with China's industrial boom and a global wave of infrastructure development. After 2013, growth slows somewhat, with modest fluctuations linked to cyclical downturns (e.g. the 2008–2009 financial crisis, COVID-19 in 2020) but with an overall trend that continues upward. However, a slight dip in global emissions around 2014–2016 partly reflects a slowdown in China's capital-intensive investments (Khan et al., 2017; Zheng et al., 2019), especially in coal-fired energy and infrastructure, combined with the effects of the sharp oil-price collapse of 2014–2015, which dampened global investment and slowed the pace of carbon-intensive capital formation.

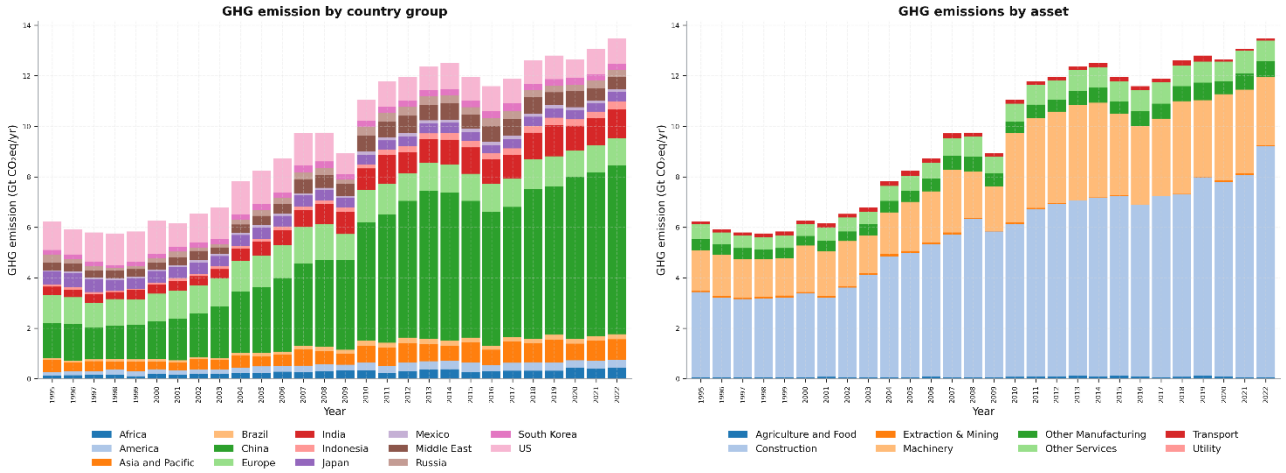


Figure 2 Global carbon footprint of total GFCF, (A) by country, (B) by production sector

The geographical distribution of emissions shows a clear global shift. In 1995, the United States, Europe, and China were already at comparable levels of capital-related emissions, with Japan also contributing significantly. From the early 2000s onward, however, China's emissions increased rapidly, far outpacing all other regions and accounting for more than half of the global total by the

mid-2010s. In contrast, GHGs emissions from the United States and Europe remained relatively stable over the period, while Japan showed little growth.

Other emerging economies, including India, Brazil, and countries in the Asia-Pacific and Middle East, also show steady increases, though at smaller scales. In contrast, emissions linked to Europe, the US, and Japan remained relatively stable or even declined slightly, reflecting slower growth in capital stocks, efficiency gains, and partial outsourcing of carbon-intensive production to emerging economies.

Construction emerges as by far the largest single source of capital-related GHG emissions throughout the period, consistently accounting for around half or more of the total. This dominance reflects the carbon-intensive nature of cement and steel production, combined with the massive scale of global building and infrastructure projects. Machinery is the second-largest contributor, rising steadily over time as manufacturing capacity expanded worldwide. Extraction and mining, utilities, and transport contribute smaller but non-negligible shares, highlighting the diversity of capital goods that embody significant emissions. The strong role of construction and machinery indicates that strategies to decarbonize materials (e.g. cement, steel, aluminum) and to improve machinery efficiency and circularity are central levers for reducing the climate footprint of capital.

Taken together, these findings underline two key insights for EU policy. First, capital-related emissions are not marginal: they represent a large and growing share of total GHG emissions, with construction and machinery as the dominant asset classes. Second, the regional dynamics highlight the importance of global interlinkages: while much of the recent growth stems from emerging economies, these investments are often tied to global value chains and international demand, including exports of goods and services consumed in Europe. This underscores the importance of incorporating capital dynamics into both EU climate strategies and international trade and resource policies, ensuring that mitigation and circularity efforts target the capital goods and sectors that drive long-term system lock-ins.

The per-capita view of capital-related GHG emissions in Figure 3, highlights clear differences across regions and how they evolved between 1995 and 2022. In 1995, the highest per-capita burdens were found in advanced economies such as the United States, Japan, and South Korea, reflecting large and mature capital stocks. Europe also showed relatively high levels, while China, India, and most of Africa and Asia–Pacific remained much lower, consistent with earlier stages of capital accumulation.

By 2022, emerging economies—most notably China—experienced sharp increases in per-capita emissions as rapid urbanization and infrastructure expansion deepened capital intensity. In contrast, Europe and Japan show flat or slightly declining trends, while the United States remains among the highest per-capita emitters but with only modest growth. The overall result is a partial convergence, although substantial disparities persist, with low-income regions still far below the levels of high-income economies.

For the EU context, these trends emphasize both the need to decarbonize construction and machinery domestically, and the importance of engaging with rapidly industrializing regions whose growing capital-related emissions are strongly linked to global value chains and European demand.

Tracking per-capita emissions alongside totals is crucial to distinguish genuine efficiency improvements from mere scale effects of population and investment growth.

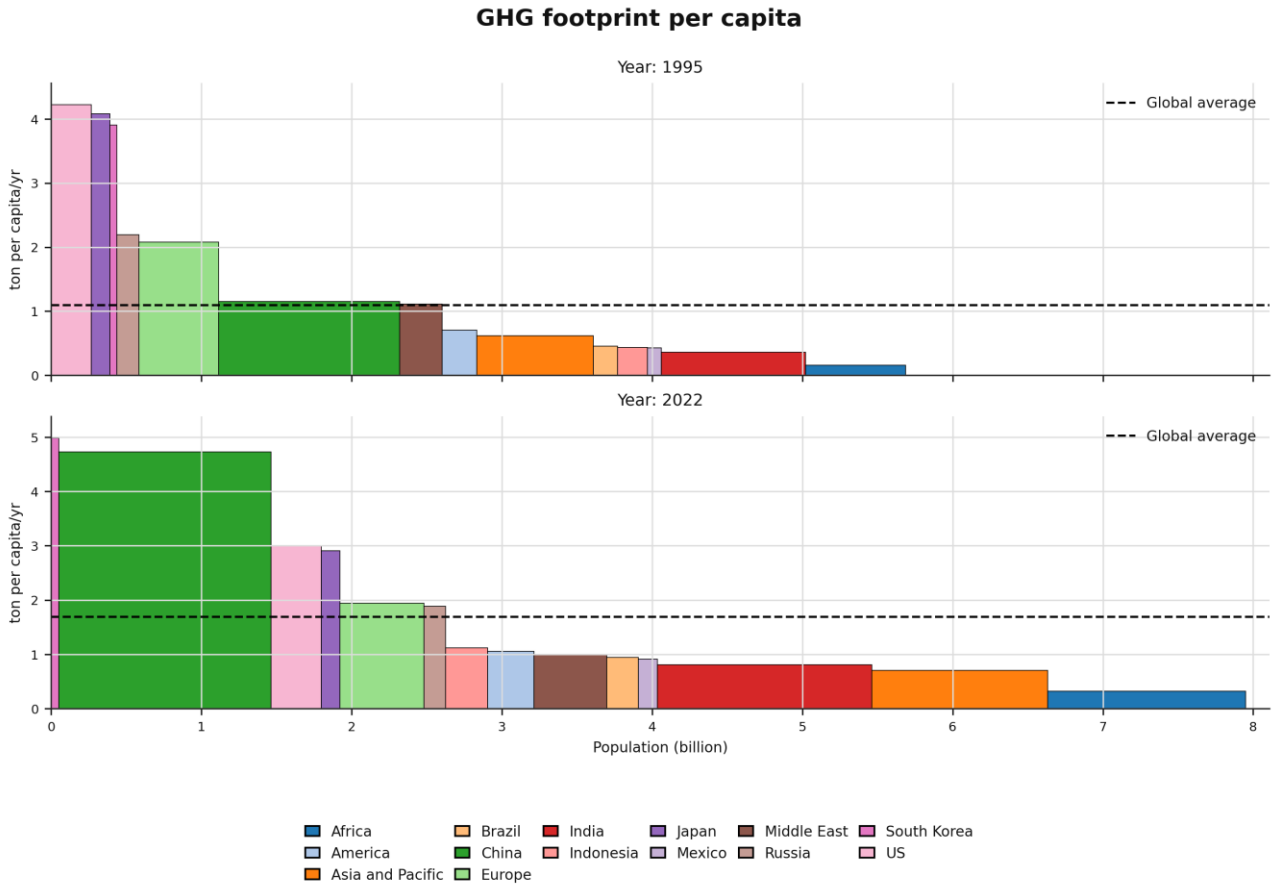


Figure 3 GHGs footprint per capita by regions.

3.2. Material footprint of capital formation

Figure 4 present the evolution of the global material footprint associated with capital investment between 1995 and 2022. As with GHG emissions, both absolute and per-capita perspectives are shown, with results disaggregated by country group, sector of asset origin, and by type of material. Together, they highlight the scale and distribution of resource use embodied in capital, as well as the dominant roles of construction and machinery in driving long-term demand.

In terms of material footprints, the overall trajectory closely mirrors that of capital-related GHG emissions, with China and other emerging economies driving the bulk of global growth since the early 2000s. The dominance of construction is even more pronounced when measured in material terms, reflecting the mass of cement, concrete, aggregates, and steel embodied in buildings and infrastructure. Machinery also contributes a significant and steadily rising share, while other asset groups such as utilities and extractive equipment remain comparatively minor. The key distinction from emissions is the stronger visibility of bulk non-metallic minerals in the material footprint, underscoring the central role of construction-related demand in shaping global resource use.

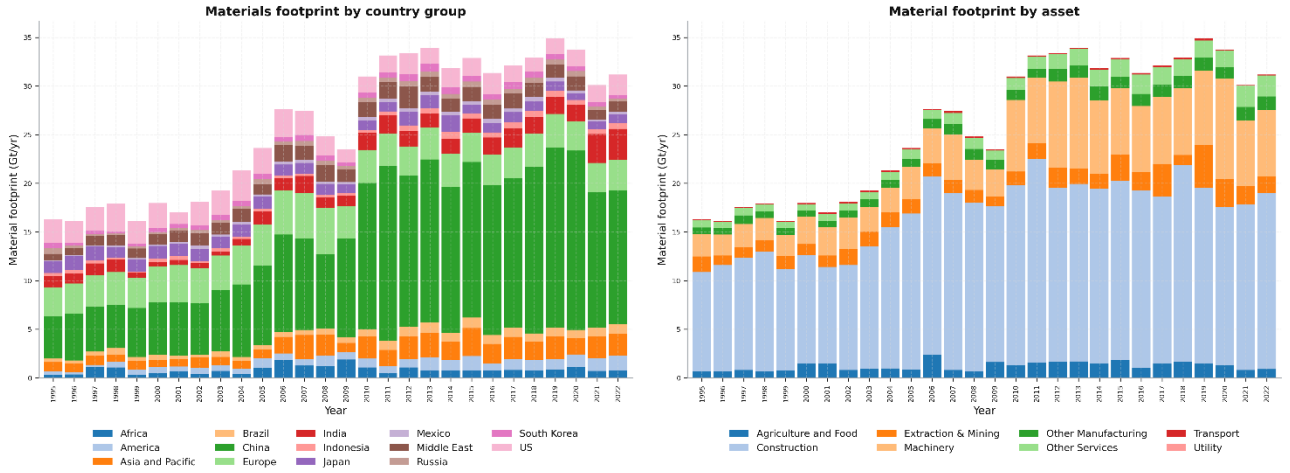


Figure 4 Global Material footprint of total GFCF, (A) by country, (B) by production sector.

The global composition of material use (Figure 5 (B)) confirms the central role of construction-related inputs in capital formation. Non-metallic minerals—cement, concrete, sand and aggregates—dominate the series throughout and account for well over half of total demand in most years. Their trajectory shows a marked step-up in the mid-2000s, a brief dip around the 2008–2009 crisis, a strong rebound through the early 2010s, and then a high plateau with moderate fluctuations. Metals form the second-largest component and rise steadily as machinery and infrastructure expand, especially in rapidly industrializing regions. Energy-related materials and biomass remain smaller but non-negligible components; their contributions are most visible during periods of high fossil-fuel investment and rapid build-out of energy supply infrastructure. Overall, the mix underscores how strongly capital formation depends on mineral extraction, and how non-metallics and metals shape the resource intensity of development.

The end-use breakdown (Figure 5 (A)) clarifies where these materials ultimately provide services to the economy. The largest shares are associated with construction itself and with other services and utilities, reflecting buildings, public infrastructure and network assets that deliver long-lived services. Machinery and other manufacturing together represent the next tier, mirroring the metal-heavy component of the material mix and the continued build-out of productive capacity. Transport contributes a smaller but persistent portion consistent with roads, rail, rolling stock and logistics infrastructure, while extraction & mining and agriculture & food account for comparatively minor shares. The timing of changes is consistent across the two views: the mid-2000s surge corresponds to accelerated urbanization and infrastructure investment; the 2009 dip and quick rebound capture the global crisis and stimulus; and the late-2010s stabilization reflects slower net additions in mature economies alongside continued expansion elsewhere. The temporary softening around 2020 is visible but does not alter the longer-term upward level shift.

Taken together, the category and end-use figures point to clear priorities for policy and industry. Because non-metallic minerals and metals dominate, material-efficiency levers in construction (clinker substitution, low-carbon binders, secondary and better-graded aggregates, structural optimization, design for adaptability and reuse) and machinery/manufacturing (lifetime extension, refurbishment, modular design, high-quality recycling of steel and non-ferrous metals) will deliver the largest gains. On the demand side, steering public and private investment in utilities and services

toward renovation over new build, improving space and asset utilization, and embedding circular procurement can curb primary material demand without compromising service provision.

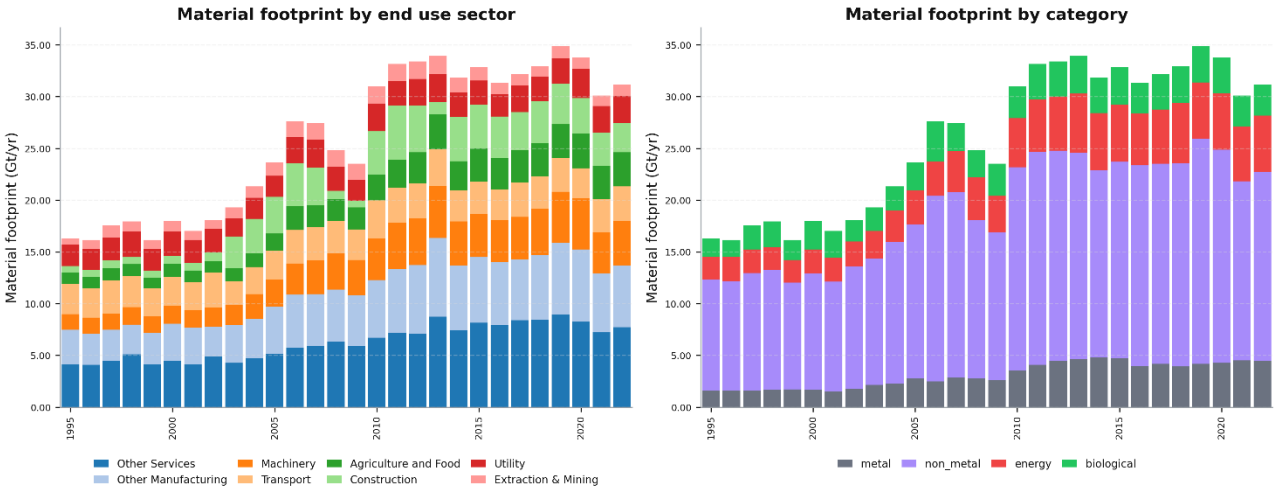


Figure 5 Total Material footprint (A) by end-use sector (B) by material, 1995-2022.

The per-capita view reveals persistent but shifting disparities between regions. In 1995, the highest per-capita material footprints were observed in Japan, the US, and Europe, reflecting mature capital stocks and high levels of infrastructure per person. By 2022, China's per-capita material footprint had risen sharply, approaching the levels of advanced economies, while India, Africa, and other emerging regions remained significantly lower, though on gradually increasing trajectories. Japan and Europe show slightly declining per-capita footprints, consistent with stabilising stocks and some efficiency improvements, while the US remains among the highest.

A comparison of per-capita material and carbon footprints shows additional nuances. While the overall regional ranking is similar, there are differences in relative positions. For example, in 2022 the Asia-Pacific region exhibits about three times the per-capita material footprint of Africa, but only about twice the GHG footprint. This points to structural differences in material production and use: higher material intensities in Asia are linked to large-scale capital formation, but with somewhat lower GHG intensity per unit of material due to differences in production technologies and energy systems. Conversely, in Africa and other resource-exporting developing regions, relatively smaller material footprints may coincide with higher GHG intensity in specific sectors, reflecting reliance on carbon-intensive energy sources or extractive industries.

These differences highlight the role of regional energy systems, industrial structures, and natural resource extraction in shaping the relationship between material and GHG footprints. They also point to the importance of considering not only the scale of capital-related material demand, but also the emissions intensity of production across regions. For developing regions, however, data availability and consistency remain a limitation, as statistics are often incomplete or scattered. This underlines the need for cautious interpretation and the value of improving data coverage to better capture emerging trends.

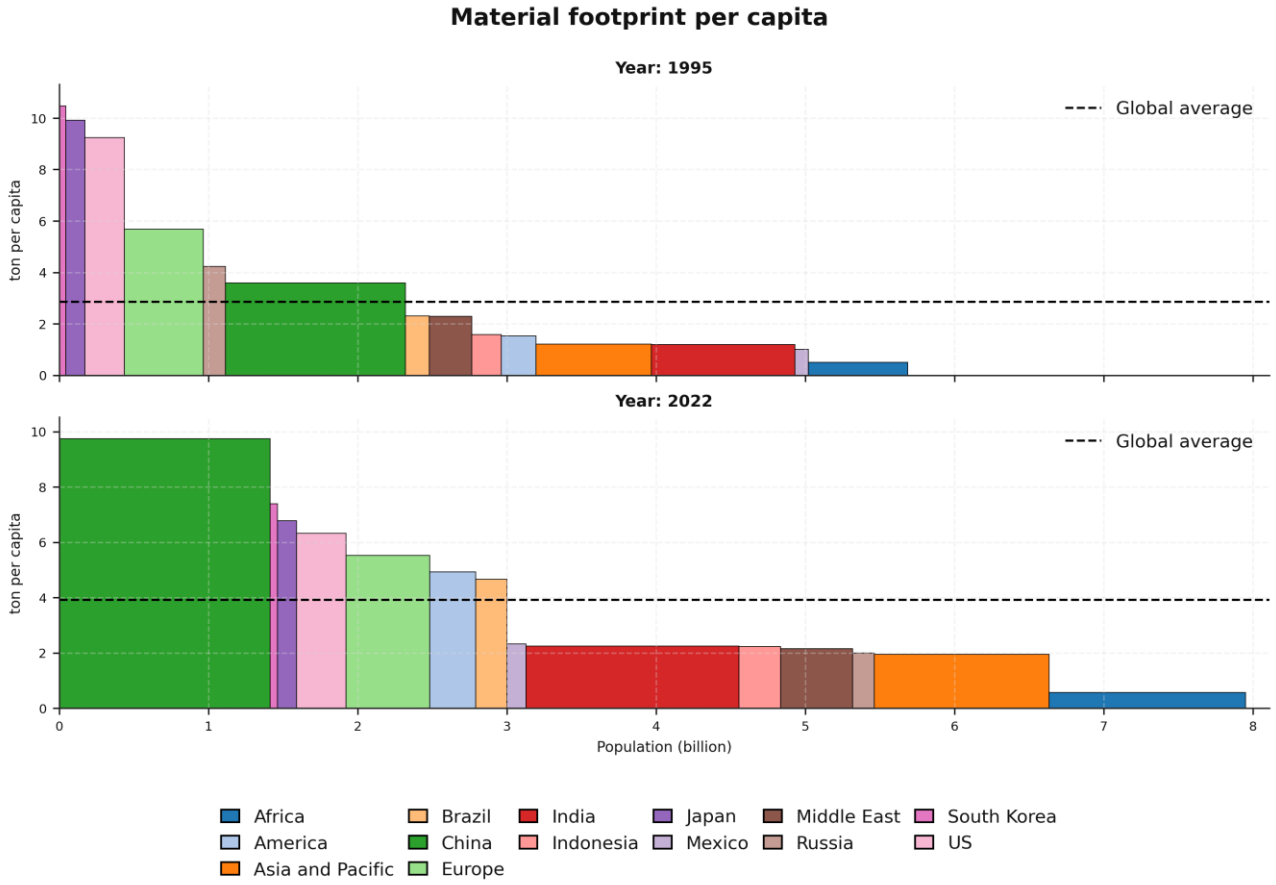


Figure 6 Material footprint per capita by region, 2000 and 2022.

3.3. Construction capital footprint stock

Construction is the single largest driver of the material footprint of capital, as shown in Figure 7. Globally, the construction-related material footprint increased significantly from the early 2000s, with a pronounced surge during the boom years of infrastructure and urban expansion. This trend was temporarily disrupted by the 2008–2009 financial crisis but rebounded quickly, reaching a high and fluctuating plateau from the mid-2010s onwards. This stabilization reflects the maturing investment profiles of industrialized economies, where infrastructure build-out has largely been completed and new flows increasingly serve replacement rather than expansion.

The breakdown by end-use sector reveals that the majority of construction's material footprint supports services and utilities, reflecting the embedded materials in buildings, public infrastructure, and utility networks. Construction's own capital requirements also account for a significant share, followed by transport, manufacturing, and—more marginally—agriculture. This wide sectoral distribution highlights the role of both public and private actors in shaping demand for material-intensive assets and underlines the importance of demand-side strategies across multiple sectors, not only within construction itself.

From a material perspective, non-metallic minerals dominate consistently, accounting for more than half of total use throughout the period. These include cement, concrete, sand, and aggregates, which

form the structural backbone of the built environment. Metals constitute the second-largest category of materials that accumulate in capital stocks, and their share has gradually increased over time, reflecting the growing prevalence of steel- and aluminium-intensive construction. Energy-related materials, which appear prominently in the data, do not accumulate in stocks but represent the embodied energy inputs required for constructing and maintaining built infrastructure. Biomass, by contrast, remains a minor component. The sustained dominance of mineral and metal inputs highlights the importance of aggregate demand, clinker content, and structural design in shaping construction's environmental footprint.

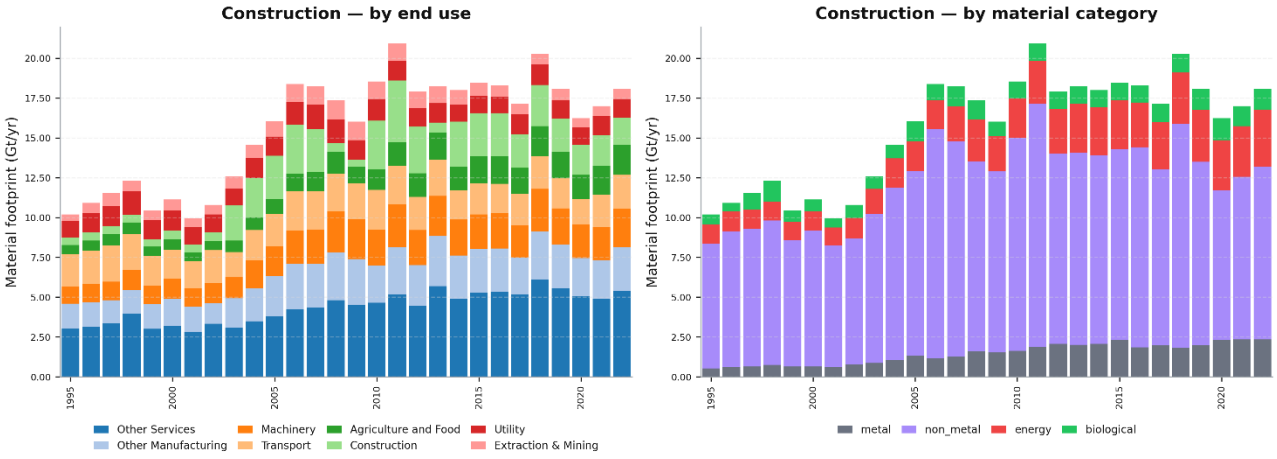


Figure 7 Material footprint of Constructions, (A) by end-use sector, (B) by material, 1995-2022.

Figure 8 provides a complementary perspective by examining regional trajectories of capital footprint stock accumulation and the associated flows of non-metallic materials. Cumulative footprint stock levels differ markedly across regions. China exhibits by far the largest growth, followed by other Asian countries and the aggregate of the US, Canada, and Australia. In these regions, capital footprint stock has expanded rapidly since the 2000s, consistent with urbanization and industrial development. In contrast, Europe and North America show more moderate stock growth, aligned with their earlier infrastructure maturation. Emerging regions such as Africa and the Rest of the World start from lower levels but have recently entered phases of accelerated stock accumulation, indicating growing material demand in the near future.

Flow data highlights the dynamics behind these stock patterns. In regions with fast-growing stocks, inflows dominate, reflecting ongoing construction. In more mature economies, maintenance flows are prominent, and outflows from asset retirement are beginning to rise. This marks a transition toward more circular stock management challenges, where extending the service life of existing assets, improving maintenance efficiency, and recovering materials from decommissioned structures become increasingly relevant. Decline flows, while still limited in scale globally, are

expected to increase as legacy infrastructure built during earlier expansion waves reaches the end of its lifespan.

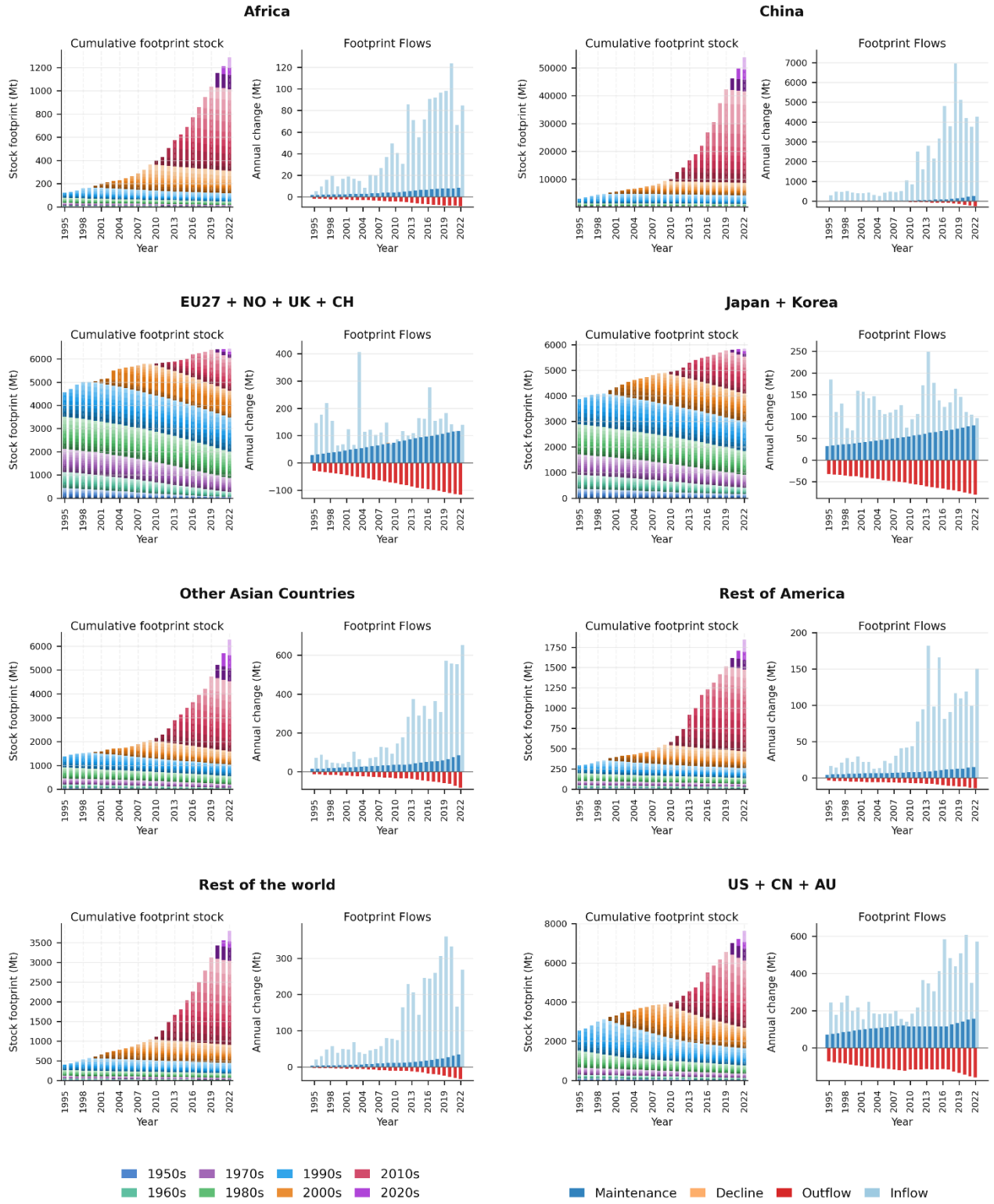


Figure 8 Non-Metal footprint embodied in construction stock and inflows, and outflows across different regions.

These results point to a set of actionable levers for reducing construction's material footprint and enhancing circularity. On the supply side, interventions such as clinker substitution, alternative binders, recycled and secondary aggregates, and high-recycled-content metals can significantly reduce embodied impacts. On the demand and stock side, strategies that extend asset lifetimes, enable adaptive reuse, promote higher space utilization, and reward design for durability and disassembly offer substantial efficiency gains. Importantly, because a large portion of construction materials ultimately support utilities and service-oriented infrastructure, public procurement and planning decisions represent powerful entry points for aligning construction investment with broader environmental and climate goals.

3.4. Machinery capital footprint stock

Machinery represents a significant and growing contributor to the material footprint of capital. As shown in Figure 9 global material footprint use associated with machinery production has increased steadily since the 1995, with marked growth after 2005. Peaks in 2010 and 2021 align with periods of intensified industrial investment, often linked to recovery phases following economic downturns. The trend reflects the increasing mechanization of production, logistics, and agriculture, along with the growing complexity of transport and energy infrastructure.

The end-use allocation highlights the wide-ranging economic functions that rely on machinery. The largest shares are associated with the manufacturing sector itself, indicating high levels of intra-sectoral capital formation. Services and utilities also absorb substantial shares, consistent with mechanized operations in infrastructure, energy systems, and maintenance networks. Agriculture and transport follow, reflecting the ongoing mechanization of food production and distribution systems. Notably, construction also emerges as a key end user, particularly in relation to heavy equipment. This broad distribution across productive sectors indicates that machinery is a key enabler of capital productivity and industrial capacity, and therefore an important target for resource efficiency strategies.

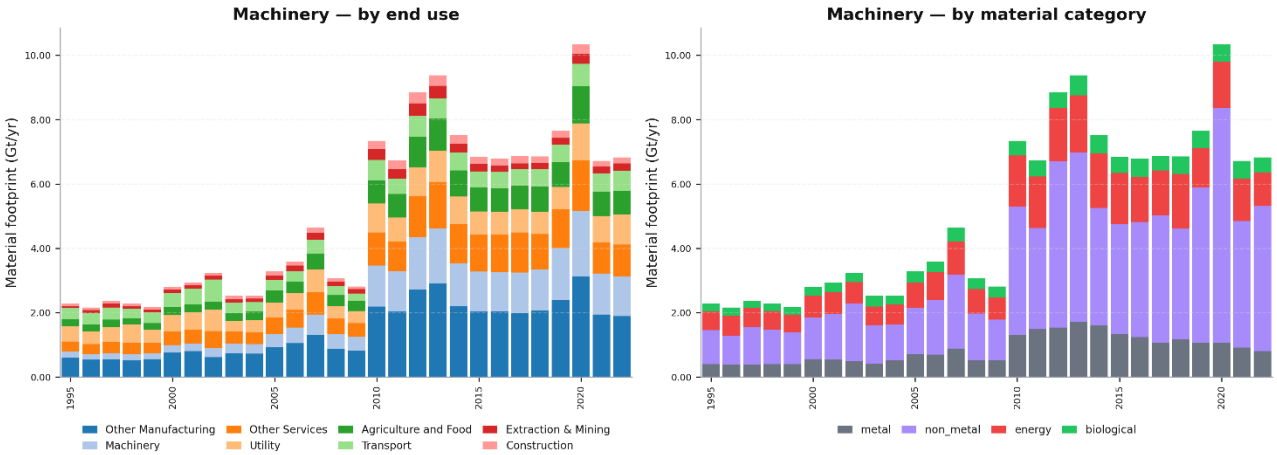


Figure 9 Material footprint of Machinery, (A) by end-use sector, (B) by material, 1995-2022

From a material composition perspective, non-metallic minerals represent the largest category in absolute terms due to the mass contribution of mineral-based components in machinery foundations, housing, and infrastructure-associated equipment. However, when focusing on materials that

accumulate in the machinery stock itself, metals are by far the most critical. They form the functional core of machinery systems, including engines, structural frames, gears, and electronics.

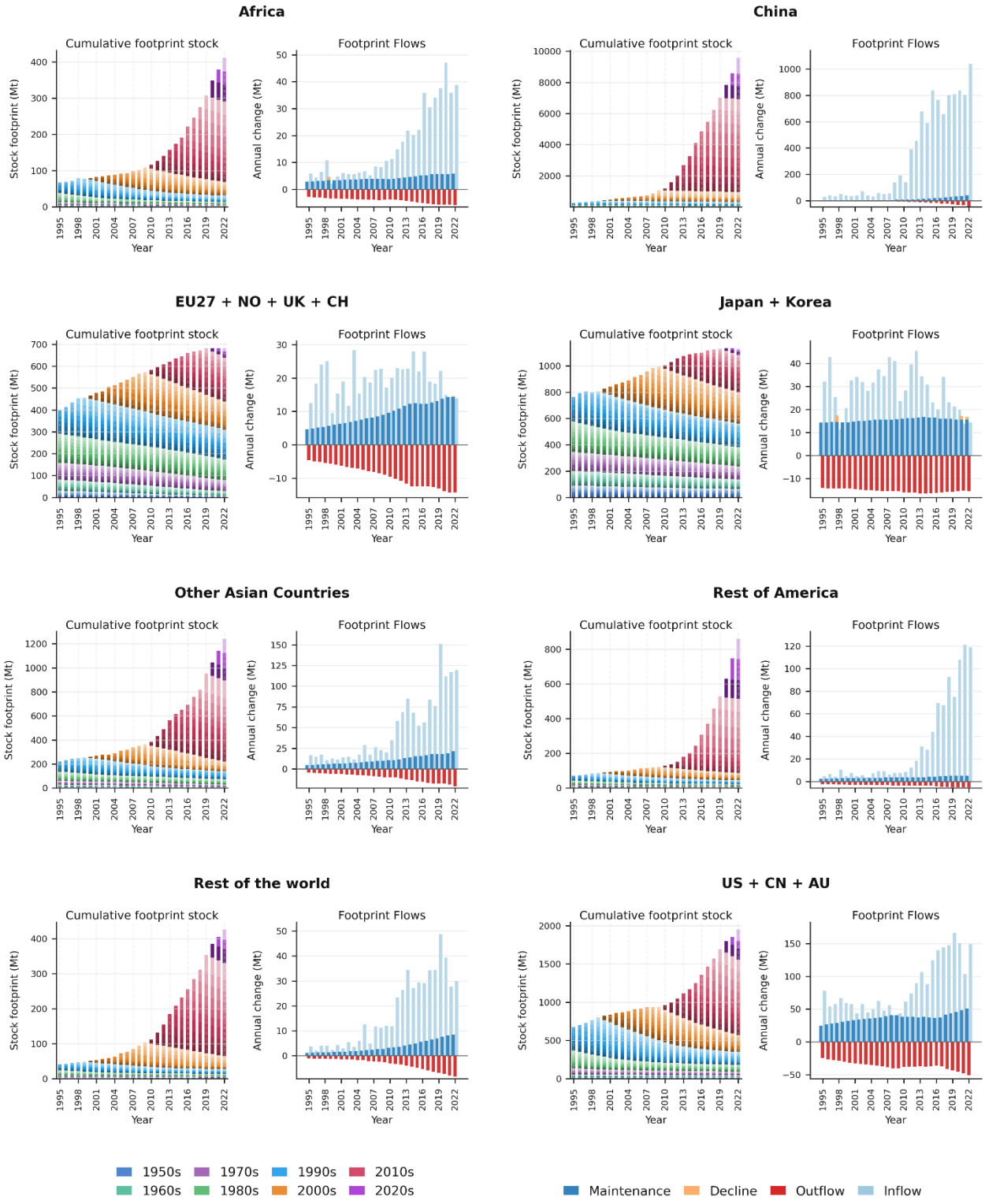


Figure 10 Metal footprint embodied in machinery stock and inflows, and outflows across different regions.

The increasing share of metals over time reflects the rising complexity and integration of machinery components, particularly those made of steel, aluminium, and copper-rich alloys. Energy-related materials are also present in the footprint, reflecting the upstream fuel and feedstock demand associated with machinery production, but they do not accumulate in the stock. Biomass plays a negligible role in this asset category. The prominence of metals in the functional stock reinforces the importance of high-value material stewardship, durability, and design for disassembly in extending asset life and enabling recycling.

Figure 10 provides a regional perspective on metal footprint accumulation and flow dynamics in machinery. The cumulative footprint stock graphs show that China has experienced the most rapid growth, surpassing other regions by a wide margin. This reflects the scale and pace of industrial development and capital expansion over the past two decades. Other regions, including Other Asia, the US + CN + AU group, and Rest of America, also show strong stock growth, indicating widespread machinery deployment in support of economic development and technological upgrading. Europe (EU27 + NO + UK + CH) and Japan + Korea exhibit slower but sustained growth, characteristic of mature industrial systems with a shift toward stock maintenance and renewal.

Flow data highlights the intensity and composition of material dynamics. In rapidly developing regions such as China and Other Asian countries, inflows dominate, driven by new machinery investments. In contrast, mature economies show growing outflows and maintenance-related flows, signalling a transition toward asset renewal and replacement. This creates an opportunity for interventions focused on extending machinery lifespans, enhancing remanufacturing, and improving secondary metal recovery. Decline flows, although still smaller than inflows, are increasing in all regions, pointing to the future importance of reverse supply chains and end-of-life strategies for metal recovery and reuse.

The results point to a range of policy and industrial levels. On the supply side, strategies that promote circular design, modularity, and material substitution (especially for critical and scarce metals) can significantly reduce the resource burden of new machinery. On the demand side, shifting from throughput-driven investment cycles to models that prioritise maintenance, performance upgrading, and service-based machinery provision can reduce inflow pressure. Given the concentration of high-value metals in machinery, the sector offers a critical opportunity for implementing advanced circular economy practices and for strengthening Europe’s strategic autonomy in raw materials through improved recycling and product longevity.

4. Result in prospective

4.1. Future use of capital stock in MRIO framework

The work in this report establishes the capital side of the system: we make capital visible inside the MRIO by constructing asset-specific capital matrices and following cohorts through the lifetime of assets. This yields consistent, time-resolved footprints for construction, machinery, and other assets—by sector, region, and material class—and the accounting needed to attribute GHG and material footprint to the final users that benefit from capital services.

The next phase is deliberately forward-looking. We will embed this dynamic capital model in the EXIOFutures scenario engine and run it under SSP-consistent pathways derived from integrated assessment models. In practice, macro drivers (population, income, energy mixes, electrification, process efficiencies, technology and material-intensity trajectories, and transport transitions) will be translated into MRIO terms—levels and composition of GFCF by asset, technology-dependent emission and material coefficients, production technologies, final demand vectors, and, where relevant, trade shares. This integration will produce pathway-sensitive indicators for GHGs and materials at sectoral and regional scales, reveal lock-in risks and end-of-life waves, and quantify how demand- and supply-side measures (lifetime extension, refurbishment and reuse, material efficiency, and high-quality recycling) change footprints over time.

Translating these insights into policy requires a general shift from one-off investment metrics to stock-aware governance. Public and private decision-making can prioritise lower-embodied-impact options and verifiable lifetime performance in procurement and project appraisal; favour renovation and adaptive reuse where they deliver equivalent services with less new material; and support standards that enable maintenance, repair, modularity, and high-value recycling, especially in construction and machinery where most impacts reside. Planning for retirement waves—through better deconstruction practices, reverse-logistics capacity, and secondary-material market development—can turn outflows into reliable inputs and reduce primary extraction. Finally, monitoring and disclosure should incorporate capital-attributed footprints, stock age profiles, and end-of-life forecasts, aligned with national accounts and environmental-economic accounting principles, so that scenario analysis can guide the sequencing of investments and avoid long-lived lock-ins. In short, the scenario linkage turns the capital accounts developed here into a decision tool that connects demand shifts with technology change and supports coherent climate and circularity strategies over time.

References

B. Muller, D. (2006). Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. *Ecological Economics*, *59*(1), 142–156.

Berrill, P., Miller, T. R., Kondo, Y., & Hertwich, E. G. (2020). Capital in the American carbon, energy, and material footprint. *Journal of Industrial Ecology*, *24*(3), 589–600. https://doi.org/10.1111/jiec.12953

Erumban, A. A. (2008). Lifetimes of machinery and equipment: Evidence from dutch manufacturing. *Review of Income and Wealth*, *54*(2), 237–268. https://doi.org/10.1111/j.1475-4991.2008.00272.x

Jiang, M., Behrens, P., Yang, Y., Tang, Z., Chen, D., Yu, Y., Liu, L., Gong, P., Zhu, S., Zhou, W., Zhu, B., & Tukker, A. (2022). Different Material Footprint Trends between China and the World in 2007-2012 Explained by Construction- and Manufacturing-associated Investment. *One Earth*, *5*(1), 109–119. https://doi.org/10.1016/j.oneear.2021.12.011

Jiang, M., Wang, R., Wood, R., Rasul, K., Zhu, B., & Hertwich, E. (2023). Material and Carbon Footprints of Machinery Capital. *Environmental Science & Technology*, *57*(50), 21124–21135. https://doi.org/10.1021/acs.est.3c06180

Khan, M. I., Yasmeen, T., Shakoor, A., Khan, N. B., & Muhammad, R. (2017). 2014 oil plunge: Causes and impacts on renewable energy. *Renewable and Sustainable Energy Reviews*, *68*, 609–622. https://doi.org/10.1016/j.rser.2016.10.026

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., & Haberl, H. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences*, *114*(8), 1880–1885. https://doi.org/10.1073/pnas.1613773114

Miatto, A., Schandl, H., & Tanikawa, H. (2017). How important are realistic building lifespan assumptions for material stock and demolition waste accounts? *Resources, Conservation and Recycling*, *122*, 143–154. https://doi.org/10.1016/j.resconrec.2017.01.015

Müller, E., Hilty, L. M., Widmer, R., Schluep, M., & Faulstich, M. (2014). Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environmental Science & Technology*, *48*(4), 2102–2113. https://doi.org/10.1021/es403506a

National Bank of Belgium. (2014). *Computing capital stock in the Belgian national accounts according to the ESA 2010*.

Pauliuk, S., & Müller, D. B. (2014). The role of in-use stocks in the social metabolism and in climate change mitigation. *Global Environmental Change*, *24*, 132–142. https://doi.org/10.1016/j.gloenvcha.2013.11.006

Rincon-Aznar, A., Riley, R., & Young, G. (2017). *ACADEMIC REVIEW OF ASSET LIVES IN THE UK*.

Södersten, C.-J. H., Wood, R., & Hertwich, E. G. (2018). Endogenizing Capital in MRIO Models: The Implications for Consumption-Based Accounting. *Environmental Science & Technology*, *52*(22), 13250–13259. https://doi.org/10.1021/acs.est.8b02791

Södersten, C.-J., Wood, R., & Hertwich, E. G. (2017). Environmental Impacts of Capital Formation. *Journal of Industrial Ecology*, *22*(1), 55–67. https://doi.org/10.1111/jiec.12532

Södersten, C.-J., Wood, R., & Wiedmann, T. (2020). The capital load of global material footprints. *Resources, Conservation and Recycling*, *158*, 104811. https://doi.org/10.1016/j.resconrec.2020.104811

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., … Tukker, A. (2018). EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *Journal of Industrial Ecology*, *22*(3), 502–515. https://doi.org/10.1111/jiec.12715

Stehrer, R. (2019). *Industry Level Growth and Productivity Data with Special Focus on Intangible Assets*. Vienna Institute for International Economic Studies.

United Nation. (2024). *System of Environmental-Economic Accounting. Ecosystem Accounting* [Statistical Papers]. https://seea.un.org/ecosystem-accounting

van den Bergen, D., de Haan, M., de Heij, R., & Horsten, M. (2009). *Measuring capital in the Netherlands* (No. Discussion paper (09036)). Statistics Netherlands Henri Faasdreef 312 2492 JP The Hague.

Wang, R., Hertwich, E. G., Fishman, T., Deetman, S., Behrens, P., Chen, W., de Koning, A., Xu, M., Matus, K., Ward, H., Tukker, A., & Zimmerman, J. B. (2023). The legacy environmental footprints of manufactured capital. *Proceedings of the National Academy of Sciences*, *120*(24), e2218828120. https://doi.org/10.1073/pnas.2218828120

Wu, X. D., Guo, J. L., Han, M. Y., & Chen, G. Q. (2018). An overview of arable land use for the world economy: From source to sink via the global supply chain. *Land Use Policy*, *76*, 201–214. https://doi.org/10.1016/j.landusepol.2018.05.005

Xu, D., Zhang, Y., & Yang, Z. (2023). From Geospatial to Temporal Separation: A Review on Carbon Accounting Endogenizing Fixed Capital. *Ecosystem Health and Sustainability*, *9*, 0002. https://doi.org/10.34133/ehs.0002

Ye, Q., Krol, M. S., Shan, Y., Schyns, J. F., Berger, M., & Hubacek, K. (2023). Allocating capital-associated CO2 emissions along the full lifespan of capital investments helps diffuse emission responsibility. *Nature Communications*, *14*(1), 2727. https://doi.org/10.1038/s41467-023-38358-z

Zheng, J., Mi, Z., Coffman, D., Shan, Y., Guan, D., & Wang, S. (2019). The Slowdown in China's Carbon Emissions Growth in the New Phase of Economic Development. *One Earth*, *1*(2), 240–253. https://doi.org/10.1016/j.oneear.2019.10.007

For more information: http://circeular.org

And follow us on:

- ***LinkedIn:*** *https://www.linkedin.com/company/circeular*
- ***X:*** *https://twitter.com/circEUlar_mode*

Funded by
the European Union

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

UK Research
and Innovation