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RESEARCH

Material circularity strategies in the stock-flow-service nexus of buildings, transport, electricity, machinery, furniture, and appliances

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Abstract

Increasing global population and rising levels of wealth are raising demands for services such as shelter and mobility, leading to greater resource use and environmental impacts. Circular strategies can reduce the resources required for these services. However, the potential of circular strategies to reduce material demand is rarely quantified. Here, we present a method to link service, product, and resource use with circular material reduction strategies. We estimate the potential material reductions for shelter, mobility (including transportation infrastructure), spatial and thermal comfort, and supporting assets such as machinery, and energy infrastructure. We provide a review of the current state of the art on circularity strategies and stock-flow-service (SFS) data availability for the sectors of shelter, mobility (including transportation infrastructure), comfort, and supporting assets such as machinery, and energy infrastructure. We then make a first-order assessment of their theoretical potential for primary material demand reductions by linking them in a counterfactual approach. These show that the current global service provision and supporting assets rely on an in-use material stock of 81 tons per person, with 1.2 ton of materials needed per capita and year to maintain this stock. Current circular strategies could reduce primary material flows by 68% in the absence of rebound effects, economic, policy, or behavioral implications. 15% reduction would be achieved through modal shifts and sharing of products, 31% by slowing the resource flows via longer product lifetimes, and 22% by reusing and recycling materials. This analysis and extensive data repository serve as a starting point for more detailed multi-sector future projections.

Keywords Societal metabolism · Product lifetime · Industrial ecology · Material intensity · Resource flows · Circular economy

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1 Introduction

Population growth and rising global levels of wealth drive demand for services like shelter and mobility, increasing the need for energy and manufactured goods. In most countries, welfare has increased in recent decades (Rosling et al., 2018), resulting in lower mortality and improved education, employment, and quality of life. This increased welfare goes hand in hand with a higher provision of services and an associated increase in the use of resources (Wiedenhofer et al., 2024b). The increase in resource use, in turn, has led to increased environmental impacts (Haberl et al., 2020; Wiedenhofer et al., 2020; International Resource Panel and United Nations Environment Programme, 2011). These improvements and impacts, and many more, are tracked within the Sustainable Development Goals (SDGs) framework, which has many indicators to monitor improvements in economic and societal sustainability. This coupling of demand and impact is problematic: the SDGs not only aim for an increase in welfare but also for a decrease in environmental impacts, especially related to climate change.

Strategies to reduce GHG emissions are already being implemented in some regions, such as Europe, with targeted policy like the Fit for 55 policy packages (Schlacke et al., 2022) aiming to further reduce GHG emissions (Intergovernmental Panel On Climate Change (IPCC), 2023) along with the GHG emissions reduction goals of other regions.

One way to achieve decoupling between economic development and environmental impacts is to decouple economic development from resource extraction (Haberl et al., 2020; Wiedenhofer et al., 2020; International Resource Panel and United Nations Environment Programme, 2011). To achieve this, implementation of resource efficiency and circular economy strategies is often suggested (Giljum et al., 2005; Kjaer et al., 2019; Scheel et al., 2020). In its review of the EU's climate policy, its climate advisory board ascertained slow progress towards reducing materials use in the EU. It recommended new and strengthened policies to improve progress to stated circularity and climate targets. (Lima et al., 2023) Ineffective policies are in part due to a limited understanding of the relationship between service demand and resource use and a narrow focus on waste management over product system design and lifetime extension (European Scientific Advisory Board on Climate Change, 2024, Chapter 5, page 82).

The stock-flow-service nexus (Deetman et al., 2020; Haberl et al., 2017; Pauliuk et al., 2021) provides a conceptual approach to translate societal services into material stocks, and from there into material flows and associated environmental impacts. Several studies have used the stock-flow-service (SFS) nexus to determine the levels of material (Streeck et al., 2025a) and energy use for sectors such as buildings (Deetman et al., 2020; Hertwich et al., 2019; Krausmann et al., 2017; Marinova et al., 2020), vehicles (Pauliuk et al., 2021), and electricity infrastructure (Kalt et al., 2021a; Deetman et al., 2018), showing the value and versatility of this concept. The SFS Nexus approach is used to explore future developments in material use, mostly in case studies of individual sectors. Several studies have focused on multi-sector modeling such as residential buildings and passenger vehicles (Pauliuk et al., 2021; Pérez-Sánchez et al., 2024). There has been less modelling of sectors including non-residential buildings, furniture, transportation and electricity infrastructure, and machinery. No study yet combines the SFS of multiple sectors to approach complete economy-wide coverage, in part because a multi-sector data review and harmonization has not been achieved yet.

Circularity strategies aim at reducing resource extraction by keeping resources, once extracted, in use for as long as possible. This is achieved by reusing or recycling of resources, reducing the demand for services, or reducing product stocks by increasing the service provision per product. In principle, this can reduce primary resource extraction, while maintaining the level of service provisioning. Various strategies and proposed frameworks for measuring and implementing circularity exist (Cantzler et al., 2020; Corona et al., 2019; Kirchherr et al., 2017). Although many studies partially investigate these strategies (Haberl et al., 2020; Wiedenhofer et al., 2020; International Resource Panel and United Nations Environment Programme, 2011; Kjaer et al., 2019; Scheel et al., 2020; Wiedenhofer et al., 2025), quantifications of the reduction potential are limited (Pauliuk et al., 2021; Zhong et al., 2021).

The Global Resource Outlook (GRO) published by the International Resource Panel (IRP) (United Nations Environment Programme, 2024) clearly demonstrates the need for more research into circularity potentials. The GRO shows increasing environmental impacts of growing resource use but also the potential for resource savings from using products and providing services more efficiently. The GRO also indicates, by a simplified application of SFS nexus modelling, that applying circularity strategies to buildings, vehicles, and energy systems can already lead to a significant reduction in materials demand without loss of service provision (United Nations Environment Programme, 2024).

Integration of circularity strategies into SFS modelling rarely happens (Haas et al., 2025; Li et al., 2025; Vélez-Henao & Pauliuk, 2025; Wiedenhofer et al., 2025; Wiprächtiger et al., 2023), and from the work where it does happen it usually is a case study of a single country or region and a limited number of product groups. There is a lack of global, standardized, parameterized models for assessing resource reduction potentials of circularity strategies, individually but also collectively.

Quantifying circularity strategies and linking the strategies with the SFS nexus approach is therefore a gap we aim to address with this study. We combine the SFS-nexus with circularity strategies, estimating the potential for global resource demand reduction across multiple services and sectors. We include the services of shelter, mobility, spatial and thermal comfort, and supporting infrastructure such as electricity generation and machinery, representing a high level of sectoral coverage responsible for most economy-wide demand for minerals. Our leading research question is: *How effective can specific circularity strategies be, while maintaining constant service provisioning levels, in reducing global primary materials demand*? To answer this research question, this study consists of two parts:

Reviewing literature and data using the R10 circularity framework for the sectors and services with large material demands.

Explore the maximum of each circularity strategy per sector in a simplified approach to estimate a first-order primary material reduction potential.

For each product group, we use the currently available data for services and products, and the knowledge on their circularity potential. Our multi-sector analysis treats product groups in parallel to highlight differences in material stocks and flows. To systematically address the circular potentials, we use the R10 framework (Potting et al., 2017), one of the more commonly used circularity frameworks, which identifies ten different circularity strategies: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover, and waste/discard. These ten strategies can be aggregated to a typology of narrowing, slowing, and closing the loop (Bocken et al., 2016). We classify the circular R10 strategies of each sector based on how they address resource flows, and how these strategies will affect the resources within the economy.

2 Methods and data

2.1 Identification of the services and their translation into in-use products and materials stocks and flows

The SFS-nexus quantifies the link between service demand, resource stocks (products and infrastructure), and resource flows. Resources are processed into materials and manufactured into products that provide services. The in-use products form the stocks that the provision of services relies on. These stocks have outflows: products entering the waste stage, and inflows: new products. The framework allows for sufficient complexity to analyze circularity strategies: it includes end-use services as well as production, and allows for modelling of recycling, lengthening of lifespan, and changing the composition of products.

Drawing on Whiting et al. (2018) we categorize end-use services and associated product groups to cover a significant share of global material requirements (Table 1). We exclude consumables (food, fuel), focusing strictly on long-lived stocks and their constituent material flows.

With these services, product groups, and product types as a basis we aim to identify the relevant literature and databases following a data categorization described in Supplementary Information SI2.

Using the SFS framework we quantify services, stocks, and flows, which can be combined to produce intensity variables: the services (for example, person km for transport) are translated into product stocks (for example, number of cars) by an *intensity of use* (in this case, using an average km/car per year and an average number of people in a car). The product stocks in turn are translated into material stocks by a *material intensity (global average)*, representing the amount of materials per car at the level of individual materials (as an example having a total weigh of 500 kg and composed of 350 kg of steel, 50 kg of HDPE, 50 kg of glass, and 50 kg of rubber). With Eq. 1 we can thus calculate the product stocks (PS) by dividing the service demand (SD) by the intensity of use (IU). In Eq. 2 the product stock is multiplied by the material intensity (kg of materials per unit of product) to calculate the material stocks (MS). This is done for all product groups. We create a correspondence table to harmonize different product categorizations from different data sources, the intensities of use, and material intensities listed in Supplementary Information SI1.

$$PS = \frac{SD}{IU} \tag{1}$$

$$MS = PS \times MI \tag{2}$$

The product stocks are related to flows. There are inflows into the stock of new products, and outflows of discarded products. These inflows and outflows are driven by two main mechanisms: (1) stock maintenance: each discarded product must be replaced by a new one to compensate for its loss, and (2) stock growth or decline: the number of products in the stock changes over time in response to changing population and per-capita service demand (Wiedenhofer et al., 2015). Product flows can be translated into material flows by using material intensities, which can change due to new product design. For our first-order assessment, we estimate the product flows (Pfl) and material flows (Mfl) by dividing product and material stocks by the mean lifetime (global average) for each product group (Eqs. 3 and 4). The

Table 1 Overview of the services included in this study

Service provisioning	Covered product groups	Common units of service	Product types
Mobility	Passenger transport	Passenger-km	Cars, buses, trains, bicycles, motorbikes, ships, airplanes
	Freight transport	Ton-km	Ships, trucks, freight trains, vans, airplanes
Shelter	Residential	m^2 floor area, # of households	Detached houses, semi-detached houses, high-rise building apartments, low-rise buildings apartments
	Non-residential	Service value added, m^2 floor area	Office buildings, shops, hotels, government buildings, hospitals, schools
Comfort & communication	Furniture	Units/m^2 floor area, # per household	Tables, chairs, bed frames, closets, storage containers, office furniture, couches
	Appliances	# per household, ownership rate	Domestic appliances (washers, dryers, tv sets etc.), office appliances (copiers, printers etc.), electronic appliances (computers, mobile phones etc.)
Supporting services	Transportation infrastructure	km, km^2	Road and rail infrastructure
	Electricity provisioning	GW (power capacity), TWh (energy storage capacity), km (distribution/transmission)	Installations for electricity generation (thermal power plants, wind turbines, solar panels), electricity storage (batteries), electricity distribution/transmission (HV, MV, LV cables, transformers)
	Machinery	Units	Agricultural machinery, industrial machinery

Including sub-sectors per sector, physical units that are commonly used and the services these provide. The product types are a broad overview of what is represented in this study; however, the list is not exhaustive. Further details on all products are in Supplementary Information SI1

resulting product and material flows represent long-run average levels of inflows and outflows, assuming a consistent mean lifetime. This means that growth of SD or PS are not represented in our assessment, making it a what-if scenario, counterfactual to the current state.

$$Pfl = \frac{PS}{meanlifetime} \tag{3}$$

$$Mfl = \frac{MS}{meanlifetime} \tag{4}$$

where SD is service demand, PS is product stocks, MI is material intensity, MS is material stocks, Pfl is product flows, and Mfl are the material flows.

Material inflows into products can be of different origin: they can be primary materials, taken from the environment, or secondary materials, recovered from discarded product flows. As not all products get fully replaced at end of life, we include an additional Equation to account for this. As an example, road repaving happens at end of service life, but not all sub-surface materials get removed (Ebrahimi et al., 2022). For the stocks where this information is available, we use Eq. 5, where the known replaced share of materials is multiplied with the material flow. Within this study it is only applied to transportation infrastructure, due to data availability.

$$Mfl = Mfl \times Materialreplacementrate\% \tag{5}$$

2.2 System definition and data

2.2.1 System definition

Our SFS nexus system is analysed at global level, broken down into ten global regions (IAMC, 2025) (see Supplementary Information SI2, Appendix III for further details). We track service demand development for the service categories and concurrent product groups of Table 1 from 1990 to 2024. The reduction potential of circularity strategies is based on recent data (2020–2024).

2.2.2 Data collection

We performed a semi-structured review (Supplementary Information SI2 pages 3–4), to collect variables for Eqs. 1–4:

- Service provisioning (SD) (Eq. 1)
- Intensity of use (Eq. 1)
- In-use stocks of products and infrastructures (PS) (Eq. 1, 2)
- Material intensity of products and infrastructures (MI) (Eq. 2)

- Lifespans of products and infrastructures (Eq. 3, 4)

Service provisioning data mostly comes from national statistics. Data on the in-use stocks of infrastructures are available from national statistics which was complemented with geospatial based data on the built environment such as roads, and railways. For other variables, we performed an extensive literature search identifying in-use stock databases, studies including lifetime data or material intensities, intensity of use data, and circular strategy quantifications. We report service provisioning, and product stocks on a regional level aggregated from mostly national data. For material intensities and lifetimes, we apply global averages per product group which can be found in Supplementary Information SI2.

All data is stored in the Zenodo data supplement, grouped by data type and end-use sector. The datasheets form the input for the analysis, and each datasheet provides data on the temporal scope, geographical scope, product definition and literature references for the individual data points. The intermediate results (consolidated parameters of the Equations above) are available in Supplementary Information SI2, giving a detailed overview of how we collected the data and which literature and data was collected during the reviewing process, for each product type on the correspondence table. For Eq. 1, we use the datasheets 2_IUS_[Product_group] to represent product stocks and 3_IUP_[Product_group] to represent intensity of use. This is combined with the product-specific material intensity datasheets in 3_MC_[Product_group] to determine the total material content for each product group in Eq. 2. To determine the mean lifetimes used for Eqs. 3 and 4, we gather the high-resolution product lifetime data from the datasheets in the files 3_LT_[Product_group].

2.3 Review and linking circularity strategies to the SFS nexus

A circular economy strategy ultimately aims at reducing the primary material flows. This can be done by increasing the share of secondary flows, but also by strategies that keep the product in use for a longer time, which encourage smaller or lighter products, or even that reduce service provisioning (see Sect. 2.3). We identify and evaluate sector-specific circularity strategies using the R10 framework (Potting et al., 2017), combined with the framework by Bocken et al. (Bocken et al., 2016), who classify these ten strategies into narrowing-, slowing-, and closing. The three categories are used to summarize R-strategies by common features (reduced material demand, prolonging product lifetime, and recovering material after a products lifetime) which can share modelling assumptions, as manifesting per sector (Table 2). A detailed overview of the available strategies

Table 2 Classification of how the circularity strategies found in the studies are categorized according to the Bocken et al. and Potting et al. frameworks

Bocken et al. (2016)	Potting et al. (2017)	Buildings	Transport infrastructure	Vehicles	Electricity infrastructure	Machinery	Furniture	Appliances
Narrow the loop	R0 Refuse	Refuse strategies are not included in this study. All nexuses are quantified for a nominal unit of the service they provide						
	R1 Rethink	Modal shift, more multi family buildings; teleworking	Modal shift public transport; teleworking; narrowing roads	Modal shift public transport; teleworking	Smart grid solutions	–	Sharing of furniture	Sharing of appliances; pay per service; multipurpose appliances
	R2 Reduce	Lightweighting	Lightweighting	Lightweighting	Lightweighting	Lightweighting	Lightweighting	Lightweighting
Slow the loop	R3 (Product) Reuse	Lifetime extension; repurposing buildings	Lifetime extension; repurposing infrastructure	Lifetime extension	Lifetime extension	Lifetime extension	Lifetime extension	Lifetime extension
	R4 Repair							
	R5 Refurbish							
	R6 Remanufacture							
	R7 Repurpose							
Close the loop	R8 Recycle	Component reuse within sector & Recycle	Component reuse within sector & Recycle	Component reuse within sector & Recycle	Component reuse within sector & Recycle	Component reuse within sector & Recycle	Component reuse within sector & Recycle	Component reuse within sector & Recycle
	R9 Recover	Recover strategies are not included in this study						

For each product group we include the primary examples of circular measures. For a full overview and detailed description of the measures see Supplementary Information SI2 is available in Supplementary Information SI2, page 43–49 and appendix IV.

2.3.1 Narrow the loop

We define the reduction of material stocks and flows in the narrowing strategies of Rethink (R_1) and Reduce (R_2). Refuse strategies are excluded for consistency with our objective of exploring a counterfactual to the present situation, meaning that we keep the service provisioning constant. We do this because we explore the what-if scenario of circular strategies on the current level of service provisioning. If we were to include Refuse we would explore a scenario where demand has already shifted, requiring a further exploration of the willingness to reduce demand for services. Rethink is defined as alternative ways of meeting service demand or increasing the intensity of use for current product stocks. The narrowing strategy of Reduce applies solely to the material intensity of products through lightweighting, which can be implemented by reducing the total weight of products through material substitution or structural optimization. Reduce can be applied to specific materials, but we calculate it based on the total material weight in Eq. 6 and 7, unless data is available on material substitution. As an example, for transportation infrastructure the total material weight is 1000 kg, and we find lightweighting estimates of a 10% reduction. This would decrease the total weight to 900kg, with the 10% reductions applied to all materials. When we find material substitution data, for example for vehicles if we have a total weight of 500 kg and replace 350 kg of steel with 250 kg of aluminum, we would calculate it as a total weight reduction of 100 kg but the relative share of materials will also have changed.

$$Mfl_{narrow} = Mfl \times (1 - R_1) \times (1 - R_2) \tag{6}$$

$$R_2 = 1 - \frac{MI_{narrow}}{MI} \tag{7}$$

where Mfl_{narrow} is narrowed material inflows, R_1 is the reduction achievable with Rethink options, R_2 is the reduction achievable with Reduce options, and MI_{narrow} is the lightweighted material intensity.

2.3.2 Slow the loop

R_3–R_7 commonly result in extension of the lifetimes of products, through reuse, second-hand ownership, and so on. In many cases, this lengthening of lifetime is made possible through repair, refurbishment, or renovation. These processes also require materials. However, given the limited data availability on material intensity of slowing strategies, these material inputs are not accounted for. This implies that the effectiveness of slowing the loop strategies can be overestimated. This is calculated as shown in Eq. 8:

$$Mfl_{slow} = Mfl \times \frac{meanlifetime}{extendedlifetime} \tag{8}$$

2.3.3 Close the loop

To determine the potential effectiveness of closing the loop, we apply component reuse and recycling rates extracted from literature. Reuse in this case means reuse of product components, like car batteries or doors from demolished buildings in contrast to product reuse such as reusing furniture which would fall within the slowing classification. Recycling refers to the recovery and subsequent reuse of materials. Recycling rates are material specific. Although reuse rates refer to components rather than materials, in the literature they are nearly always defined at the materials level. Therefore, we express both reuse and recycling rates in terms of materials. To fully explore the potential of these strategies, we use the maximum reuse and recycling rates found in literature. Equation 9 shows what the closing potential is compared to a situation without any reuse or recycling. Where current reuse and recycling rates are above zero, Eq. 9 may therefore overestimate the potential of closing the loop compared to current practices.

$$Mfl_{close} = Mfl \times (1 - componentreuserate) \times (1 - EOLrecyclingrate) \tag{9}$$

While in the case of narrowing and slowing the loop, the reduced material flows refer to the total of primary and secondary materials, in the case of closing the loop the outcome is the reduced inflow of primary materials. We do not account for secondary material, there is no correction with current reuse/recycling rates, no secondary materials between sectors, or material losses. We calculate using the optimistic technical potential found in literature. This potential in reuse and recycling rates means that those components and materials will be replacing primary materials fully.

2.3.4 Combined strategies

We can calculate the potential for each strategy separately but also combine them to assess the maximum potential of a circular economy (Eq. 10). Equation 10 is used for the calculation of the maximum theoretical reduction. To avoid double counting, we first apply the narrowing strategies, then add the slowing strategies, and finally the closing strategies on the resulting flows of the combined narrowing and slowing strategies. This follows the r-ladder by applying the strategies from highest (narrow/rethink), to lowest (close/recycle), exploring the maximum potential in this counterfactual analysis while avoiding double counting. Because this analysis assesses the total theoretical counter-factual potential of the system, we apply these strategies uniformly, making no distinction between interventions targeting newly added inflows versus the existing in-use stock.

$$Mfl_{reduced} = Mfl \times \frac{Mfl_{narrow}}{Mfl} \times \frac{Mfl_{slow}}{Mfl} \times \frac{Mfl_{close}}{Mfl} \quad (10)$$

Finally, we take the $\mathrm{Mfl}_{\mathrm{reduced}}$ to calculate the total circular reduction potential (Eq. 11).

$$Circularreductionpotential = \frac{Mfl - Mfl_{reduced}}{Mfl} \quad (11)$$

We reviewed the literature and compiled data for the circularity strategy parameters of Eqs. 5–10 with the same approach as the SFS variables. In cases where multiple datapoints are available we average the data. The raw data is available on Zenodo as described in Sec. 2.2, and the circularity factors are available in Supplementary Information SI1, and are described in Supplementary Information SI2.

3 Results

3.1 Review of the knowledge on service provisioning, lifetimes of products, and in-use stocks

The data coverage of services varies per sector. For shelter, data availability is extensive, with multiple models estimating service provisioning. However, the level of detail differs by region and product group. For buildings, transportation infrastructure, electricity infrastructure, and vehicles where data exist for different countries across the globe, but more granular data is typically available for Europe. For products like transportation infrastructure and machinery, a variety of unit metrics are used to quantify service provisioning (such as square kilometers, kilometers, lane length, amount of machinery, or total weight of machinery). On the contrary, for buildings, appliances, vehicles, and electricity infrastructure most studies have comparable units across studies. Furniture is the only product group with limited data coverage, found only for the USA and Europe. The main sources of data on services per sector are:

- Buildings (Marinova et al., 2020; Berrill & Hertwich, 2021; Berrill et al., 2021; Enerdata; Mantzos et al., 2018; Pezzutto et al., 2024; Sebi et al., 2013; Yepes-Estrada et al., 2023; Pezzutto et al., 2019; Song et al., 2021; van Oorschot and van der Voet, 2022; van Oorschot et al., 2023; Zhong et al., 2021)
- Transportation infrastructure (Eurostat, 2024; FHWA, 2022; IUC, 2023; Meijer et al., 2018; Nguyen et al., 2019; Rousseau et al., 2022; Van Engelenburg et al., 2024; Wiedenhofer et al., 2024a; World Bank, 2024)
- Electricity infrastructure (Deetman et al. 2018; Song et al., 2021; Arderne et al., 2020; Van Oorschot et al., 2022)
- Machinery and equipment (Song et al., 2021, 1978–2018; Jiang et al., 2023)
- Vehicles (ACEA, 2021; EAFO, 2024; Liu et al., 2020; Mantzos et al., 2018; Schuster et al., 2023; Song et al., 2021; UIC, 2023)
- Furniture (Beijnum, 2021; Ikeda, 2023)
- Appliances (Song et al., 2021; Jiang et al., 2023; Boldoczki et al., 2021; Cabeza et al., 2018; Deetman et al. 2018)

The product stocks currently in use vary widely across the world (Fig. 1). Developed regions such as Europe, North America, Asia–Pacific, and Eastern Asia show higher usage across almost all categories. Developing regions such as Africa and Southern Asia show the lowest levels of use with low building service provisioning, fewer appliances, lower electricity provisioning, and a lower number of vehicles (see SI, Section part A).

Average lifetimes vary for the seven product groups (Fig. 2). Buildings have the longest lifetimes, followed by transportation infrastructure. Transportation infrastructures show the largest spread of lifetimes, from roads having short lifetimes of 10–20 years to bridges and tunnels having longer lifetimes of 75–120 years (see Supplementary Information SI2 for details). Electricity infrastructure also includes long lifetime products such as hydroelectric dams, and cables. Machinery and equipment, appliances, and furniture all having lifetimes that between 5 and 25 years, with appliances having the shortest lifetimes. Main data sources for lifetimes are:

- Buildings (Cao et al., 2019; Deetman et al., 2020; Marinova et al., 2020; Mequignon et al., 2013; Pauliuk et al., 2017; Reyna & Chester, 2015)
- Transportation infrastructure (Bai et al., 2017; Beng & Matsumoto, 2012; Ebrahimi et al., 2022; Huang et al., 2015; Nabizadeh et al., 2018; Schiller, 2007; Svenson, 2014; Wiedenhofer et al., 2024a; Yue et al., 2015)
- Electricity infrastructure (Kalt et al., 2021a; Deetman et al. 2018; Balzer & Schorn, 2015; Harrison et al., 2010; Jones & McManus, 2010; Jorge et al., 2012b; Turconi et al., 2014; Van Vuuren, 2007)
- Machinery and equipment (Centraal Bureau voor de statistiek, 2009; Erumban, 2008; Jiang et al., 2023; Nationale Bank van Belgie, 2014; Nomura & Suga, 2018; Rincon-Aznar et al., 2017; Wang et al., 2023b)
- Vehicles (ACEA, 2021; Schuster et al., 2023; Deetman et al. 2018; Yue et al., 2015, 2015; Aamodt et al., 2021; Allekotte et al., 2020; Banar & Özdemir, 2015; Car-

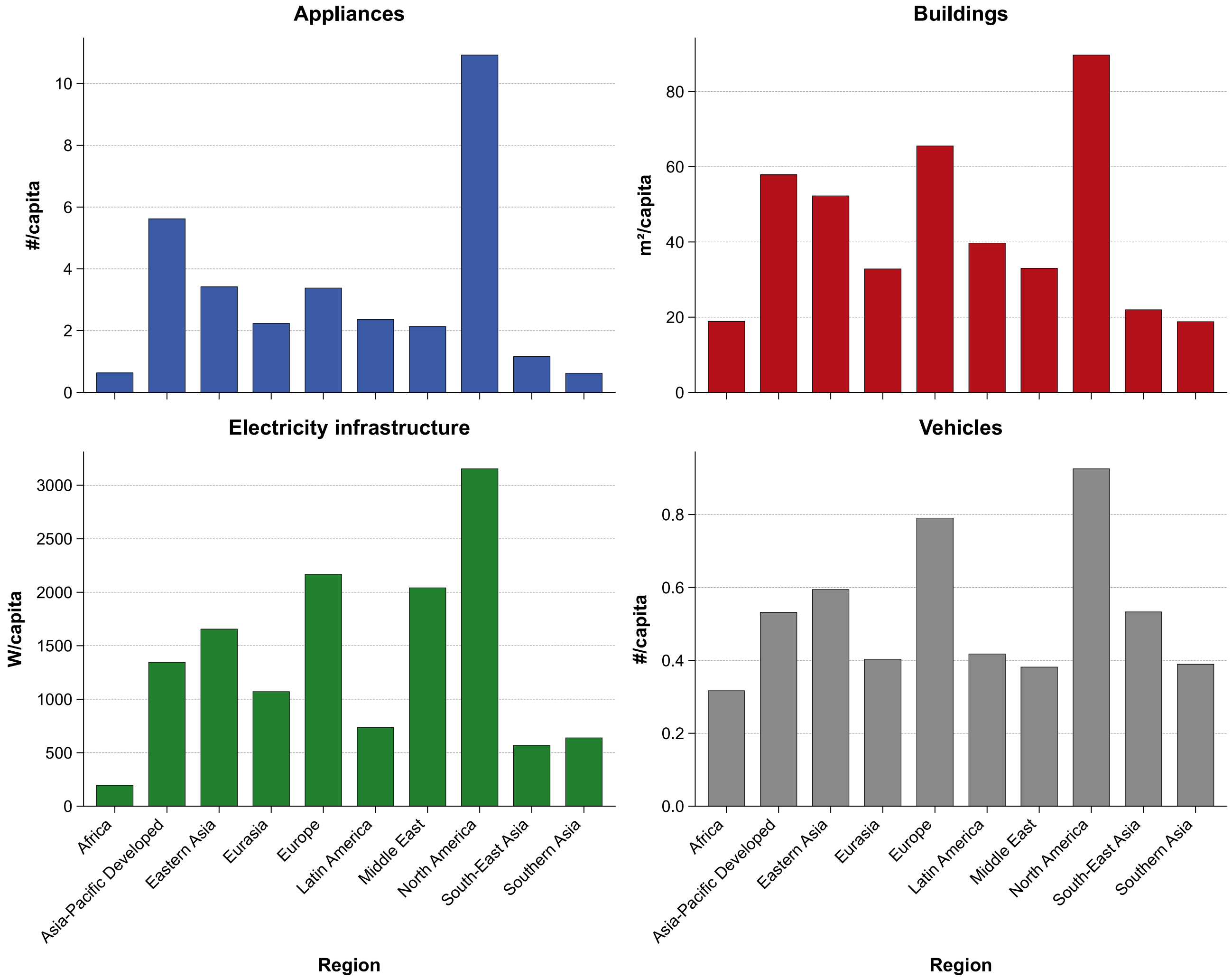

Fig. 1 Current (most recent data available between 2020 and 2024) per-capita product stocks by the ten global regions for Appliances, Buildings, Electricity infrastructure, and Vehicles. Appliances are measured in number of appliances per capita, Buildings in floorspace (m$_2$) per capita, Electricity in Watt generation capacity per capita, and Vehicles in number of vehicles per capita. More details about category definition are available in Table 1 and Supplementary Information SI1

ranza et al. 2022; Chen et al., 2022; Chester & Horvath, 2010; Cox & Mutel, 2018; Das et al., 2022; Del Pero et al., 2015; Delogu et al., 2017; Gassner et al., 2018; Hao et al., 2011; Horvath, 2006; International Energy Agency, 2018; Iyer & Badami, 2007; Iyer et al., 2023; Jakub et al., 2022; Kerdlap & Gheewala, 2016; Khalili et al., 2019; Li & Yu, 2017; Lie et al., 2021; Liu et al., 2016, 2020; Mao et al., 2021; Merchan et al., 2020; Sen et al., 2020; Shahraeeni et al., 2015; Shinde et al., 2024; Sopha et al., 2016; Tang et al., 2019; Taptich et al., 2016; Tong et al., 2015; Virág et al., 2022; Walsh et al., 2008; Weinert et al., 2008; Zenith et al., 2020; Yeow et al., 2022; Zhang et al., 2016; Zhou et al., 2016; Zhu & Lu, 2023)

- Furniture (Beijnum, 2021; Box, 1983; Ikeda, 2023; Wiprächtiger et al., 2022)
- Appliances (Jiang et al., 2023; Deetman et al. 2018; Centraal Bureau voor de statistiek, 2009; Erumban, 2008; Nationale Bank van Belgie, 2014; Rincon-Aznar et al., 2017; Wang et al., 2023b; Liu et al., 2020; Amatuni et al., 2023; Baldé et al., 2015; Forti et al., 2018; Jaco Huisman et al., 2017; Wang et al., 2013)

These differences in lifetimes have large implications for the relationship between the stocks (Fig. 3) and the annual turnover flows into and out of the stock (Fig. 4). The heaviest in-use stocks with longest lifetimes (buildings and transport infrastructure) have long turnover times. Vehicles, machinery, appliances, and furniture have a faster stock renewal, implying that technological change may diffuse much faster. Circular strategies that extend product lifetimes, such as reuse and refurbishing of in-use products, therefore have a

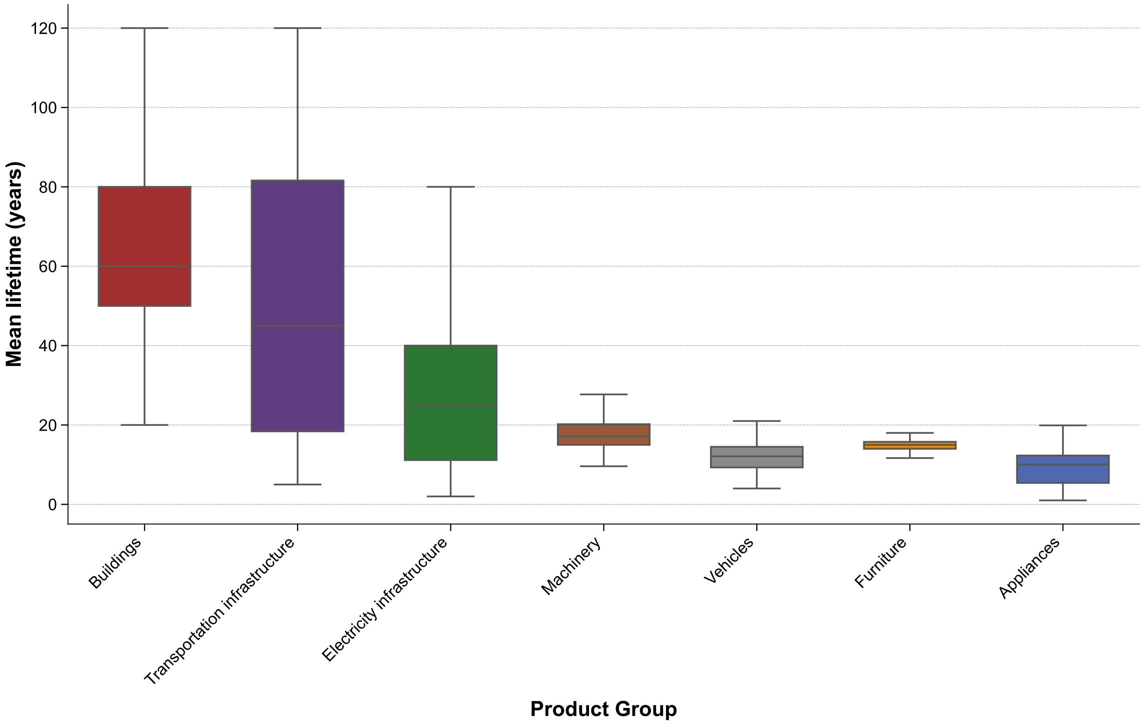

Fig. 2 Boxplot of the various product groups from the mean lifetimes included in this study. On the y-axis the mean lifetime in years and on the x-axis the boxplot for each product group. The data can be found in Supplementary Information SI1

dual effect: demand for new products is reduced, but also the time required for the diffusion of changed product characteristics (such as higher efficiency, or higher mass per product) becomes longer.

3.2 Quantification of materials stocks & flows

Figure 3 shows the variation in the combined mass of materials per capita over time for the in-use stocks of seven product groups, calculated using the average of the reviewed and harmonized material intensities from:

- Buildings (United Nations Environment Programme, 2024; Song et al., 2021; Liu et al., 2020; Breunig et al., 2022; CEU. JRC., 2022; Chen & Shi, 2012; Haberl et al., 2021; Han & Xiang, 2013; Heeren & Fishman, 2019; Huang et al., 2013; Lederer et al., 2021a, 2021b; Li et al., 2023; Liu et al., 2019; Miatto et al., 2023; Wang & Graedel, 2010; Wang et al., 2015; Xiao Yaxin and Yang Jianxin, 2016; You et al., 2011; Zhang et al., 2015)
- Transportation infrastructure (Alzard et al., 2019; Haberl et al., 2021; Han & Xiang, 2013; Hasan et al., 2020; Heeren & Fishman, 2019; Huang et al., 2013; Li et al., 2023; Liu et al., 2019; Mao et al., 2020, 2021; Nguyen et al., 2019; Ren et al., 2022; Rousseau et al., 2022; Song et al., 2021; Wang & Graedel, 2010; Wiedenhofer et al., 2024a; Yue et al., 2015)
- Electricity infrastructure (Bödeker et al., 2010; Arvesen et al., 2018; Elshkaki & Graedel, 2013; Capellán-Pérez et al., 2019; Kis et al., 2018; Tokimatsu et al., 2018; Luderer et al., 2019; Wang et al., 2023c; Rietveld et al., 2019; Månberger & Stenqvist, 2018; United Nations Environment Programme, 2024; Pacca & Horvath, 2002; Jorge et al., 2012a; Bonou et al., 2016; Turconi et al., 2014; Chipindula et al., 2018; Dones et al., 2007; Jones & McManus, 2010; Valero et al., 2018; Li et al., 2020; Kalt et al., 2021b; Ashby, 2013; Vidal et al., 2013; Beylot et al., 2019; Deetman et al., 2021; Ferroukhi et al., 2017; Siemens; Moss et al., 2013; Van Oorschot et al., 2022)
- Vehicles (Delta, 2014; Finkbeiner & Hoffmann, 2006; Danilecki et al., 2017; Cherry et al., 2009; Hawkins et al. 2013; Schneider et al., 2023; Hawkins et al. 2013; Roy et al., 2019; Carranza et al., 2022; Liu et al., 2023; Zeng et al., 2020; Liu et al., 2020; Schuster et al., 2023; Sullivan et al., 2013; Danilecki et al., 2021; Habermacher & Althaus, 2011; Li et al., 2023; Deetman, 2021; Wang et al., 2023a; Wernet et al., 2016a, 2016b; Spielmann et al., 2007; Kelly & Winjobi, 2020; Sullivan et al., 2015; Iyer et al., 2023; Hans-Jörg Althaus & Gauch, 2010)
- Appliances (Boldoczki et al., 2021; Gensch & Blepp, 2015; Balde et al., 2015; Deetman et al. 2018; J. Huisman et al., 2007; Liu et al., 2020; Seyring et al., 2015; Oguchi et al., 2011; Otterbach & Fröhling, 2024; Peeters et al., 2015; R. Hischier et al., 2007; Song et al.,

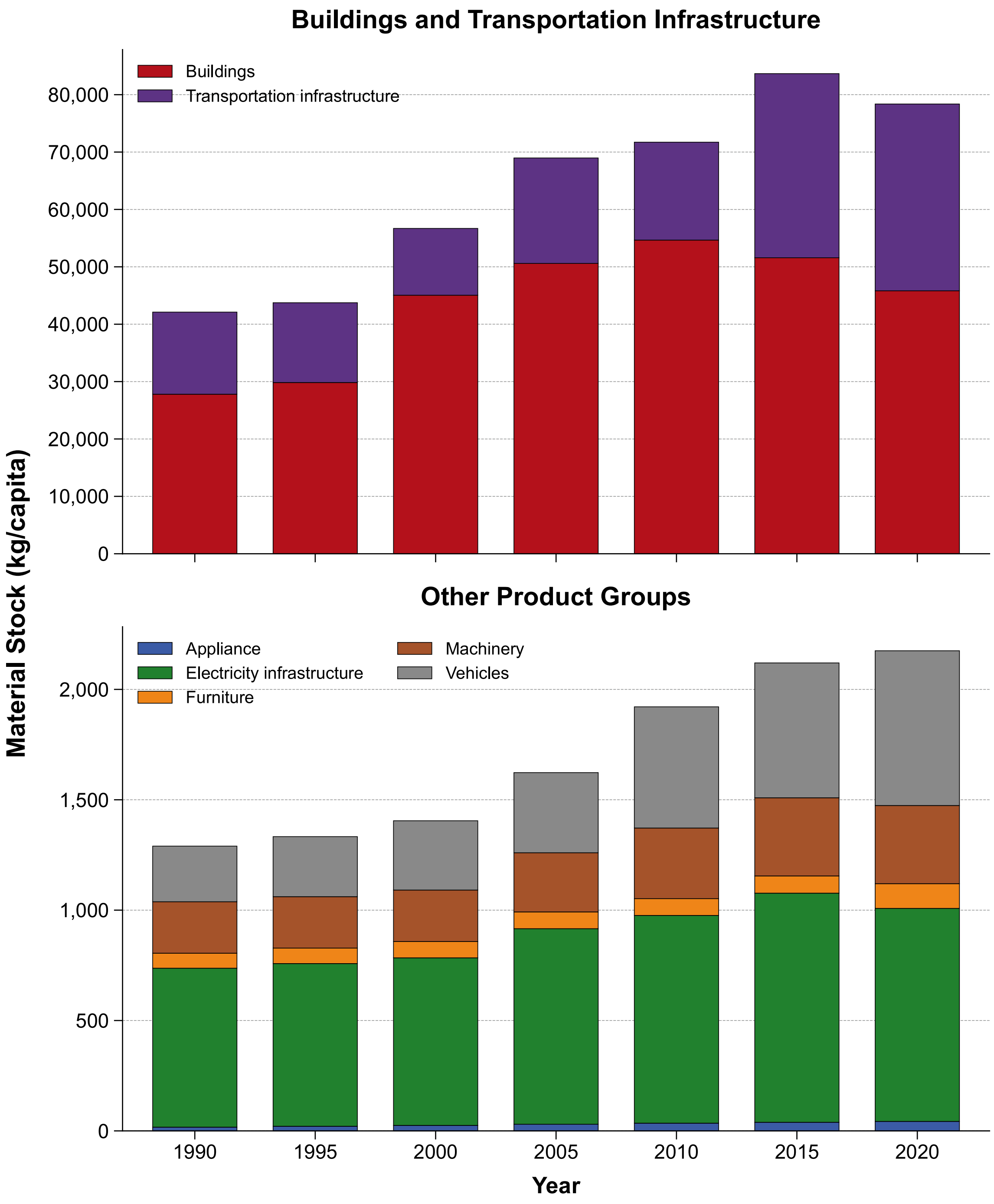

Fig. 3 Total materials stocks for the covered product groups split over time into buildings, and transportation infrastructure, global per capita average. The other product groups consisting of Appliances, Electricity infrastructure, Furniture, Machinery and Vehicles are then shown separately below. The data can be found in Supplementary Information SI1

2021; Sun et al., 2022; von Gries & Bringezu, 2022; Zeng et al., 2020)

- Machinery (Guillén-Lambea et al., 2021; Hitachi, 2023; Li et al., 2023; Liu et al., 2019; Mantoam et al., 2020; Rassõlkin et al., 2020; United Nations Environment Programme, 2024; Volvo, 2025; Wernet et al., 2016a; Zeng et al., 2020)
- Furniture (Beijnum, 2021; Ikeda, 2023)

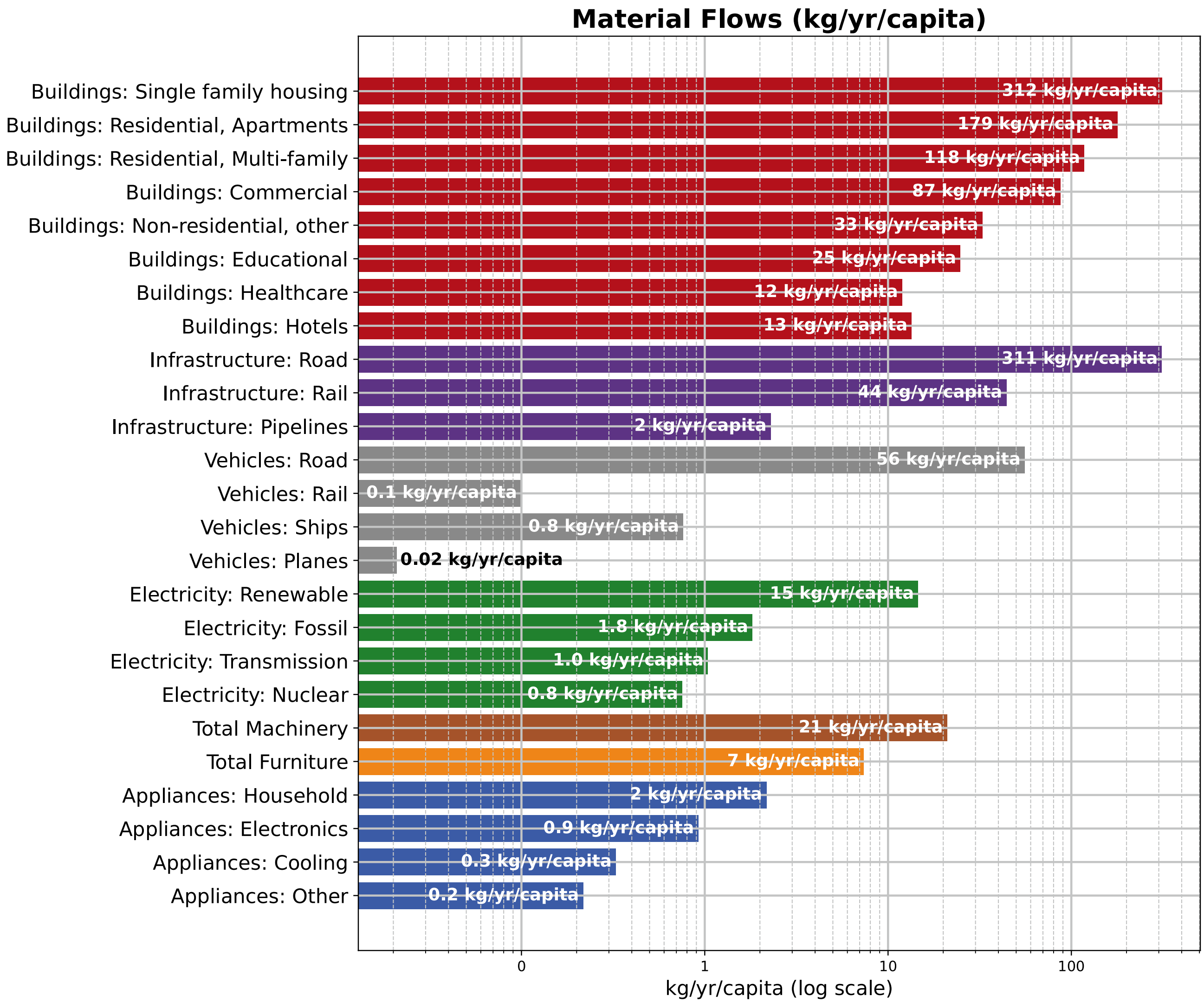

Fig. 4 Average material flows (constant service scenario) in a stationary nexus in kg per capita for the current situation on a log scale of each product group. Buildings and infrastructure are the products with the highest materials usage (reds and purples) with roads and residential buildings accounting for most of the materials in mass. In this counterfactual system we assume a steady-state nexus, meaning the flows both represent the inflows and the outflows. The per capita value is calculated by dividing the total flows/yr by the total global population, not the user population of each product. The data can be found in Supplementary Information SI1

Figure 3 shows that transport infrastructure and buildings account for 97.5% of total mass currently in the stocks of the covered products. Excluding buildings and transport infrastructure, electricity infrastructure, vehicles, and machinery emerge as the most substantial remaining stocks, while furniture and appliances represent significantly smaller shares (see Supplementary Information SI1 for further details). Some product groups, such as buildings and electricity, decrease for 2020. We notice that several datasets do not report beyond 2019 yet, the datasets that do report beyond 2019 are apparently on the lower end.

We find a total of 81 t/capita of materials in stocks currently, compared to 145 t/cap in 2016 from Wiedenhofer et al. (Wiedenhofer et al., 2024b) and 115t/cap in 2010 from Krausmann et al. (2017). These studies take a different approach based on inflow-driven top-down economy-wide material flow accounting, while our results are achieved through a bottom-up approach of major but not all end-use sectors, such as also used by (Streeck et al., 2025a) who found around 88 t/cap globally and regionally ranging from 19 t/cap in Africa to 193 t/cap in Western Europe. While our results have more detail than the inflow-driven estimates, it is likely that the total coverage is less. For example, our bottom-up material coverage may be incomplete (e.g., some aggregates may be omitted), as well as product coverage (e.g., uses of concrete in industrial, infrastructural, and military applications are not covered). It shows that there is a gap in bottom-up approaches such as ours, and Streeck et al. (2025a).

Material flows (Fig. 4) are calculated as long-term averages in a steady-state system (Service demand constant). Buildings generate the largest flows. For roads, we adjusted literature-based lifetimes (typically 10 years) to account for the fact that only the top 20% of material (the wearing course) is typically replaced, while sub-surface aggregates remain in place (Ebrahimi et al., 2022).

3.3 Circular measures and resource reduction potential

Table 3 shows the inventory of quantifiable circularity measures from literature and data. Each sector is represented by a single value, but when product-specific values are available we apply the product-specific value (see Supplementary Information SI2).

3.3.1 Narrowing the loop

For rethink (R_1), we find mostly modal shift strategies that imply a more intensive use of products and infrastructures. For buildings, we calculate a shift to more multi-family housing, and for vehicles, a modal shift to public transport is included in addition to an increase in teleworking. It decreases the need for single-family housing and cars but increases the need for multi-family housing and public transport. This results in a 4% reduction for buildings and a 6% reduction for vehicles. We assume these changes in mobility also affect transportation infrastructure, therefore limit the changes of transportation infrastructure caused by vehicle demand to 25% of the actual vehicle demand change. In addition, we estimate a narrowing of the width of local roads based on van Engelenburg et al. (2024), and developments in road safety and urban planning. For electricity infrastructure, we include smart grid measures. Estimates for smart grid material reductions range between 3 and 59% through decreasing losses, peak demand shifting, and load shifting (Barbato et al., 2015; International Energy Agency, 2023; Razo-Zapata et al., 2016; Santos et al., 2022). For these measures we apply a 20% reduction which is conservative, as many studies state only a single intervention and do not consider the cumulative effect of decreasing losses in the network, peak demand and load shifting. For appliances, we model Rethinking strategies that aim to increase the number of sharing appliances and introduce payment systems so washing- and drying appliances are used more efficiently. We apply a 12% reduction for appliances with the potential for shared appliances such as washing machines as found in literature, and dryers estimated at around 20% (Bressanelli et al., 2021; Wasserbaur et al., 2020), and other appliances limited to 10%.

For R_2 we focus on lightweighting options, reducing material intensity. The literature shows reductions of 10–35% across most sectors. For buildings, lightweighting usually looks to reduce steel and concrete content, resulting in an average 15% reduction. For vehicles, more aluminum and plastics are assumed to be used instead of steel, resulting in an 18% weight reduction. For furniture, lightweighting is possible, on the one hand by using different (lighter) materials, and on the other hand by reducing the amount of materials through a leaner product design. Similar options exist for some appliances, but data availability is more problematic for this product group, therefore we make a rough estimate of an overall reduction of 10%.

3.3.2 Slowing the loop

Slowing the loop (strategies R_3–R_7) aims at lifetime extension of products. When no literature estimate is available, we use the technical lifespan reported for a product as the theoretical maximum for that product (See Supplementary Information SI1 for lifetime extension per product category). Lifetime extension often is associated with additional material inputs for repair, refurbishment and renovation; however our literature review has not found sufficient data to include such inputs in our assessment, repair, and refurbishment on appliances (Fatimah & Biswas, 2016; Nasr, 2018), and renovation on buildings (De Silva et al., 2023; Mohammadiziazi & Bilec, 2023) is available but the coverage is usually single products and thus the material costs of lifetime extension are excluded from this study.

3.3.3 Closing the loop

Closing the loop strategies focus on component reuse and material recycling. Component reuse is implemented when available. End-of-life recycling is well documented. Most literature on material reuse and recycling is available for single material products such as steel beams or wooden rail sleepers. Using the most optimistic figures available (See Supplementary Information SI2, pages. 43–48), we find that the theoretical maximum recycling rate across most sectors is high, as a large share of the products contain metals that are recyclable. For buildings and transportation infrastructure, concrete limits the recycling potential by its lower recyclability even using the most optimistic estimates.

3.3.4 Global average circular potential

Applying circularity strategies to current material and product flows establishes a first-order counterfactual for maximum reduction potential (Fig. 5). Under the simplified assumptions described previously, narrowing flows offer a potential reduction in total primary inflows of 15%, followed

Table 3 Overview of the material flow reduction potential per strategy per product group in percentage

Circularity strategies	Circular options	Buildings	Transportation infrastructure	Vehicles	Electricity infrastructure	Machinery	Furniture	Appliances
Narrow the loop	R_1	4%	16%	6%	20%	0%	0%	12%
	R_2	15%	0%	18%	2%	0%	17%	10%
Slow the loop	R_3-R_7 (Lifetime extension)	42%	17%	42%	31%	58%	0%	23%
Close the loop	Reuse	22%	2%	20%	22%	20%	50%	32%
	Recycle	40%	16%	82%	35%	81%	36%	59%
Reviewed sources		Ancillo et al. (2021); Bierwirth and Thomas (2019); Deetman et al. (2020); Edelenbosch et al. (2022); Fishman et al. (2021); Hamid et al. (2018); Hertwich et al. (2019); Höjer and Mjörnell (2018); Tserng et al. (2021); United Nations Environment Programme (2024); van Oorschot et al. (2023); Wuyts et al. (2019)	Akerman (2011); Boehm et al. (2021); Edelenbosch et al. (2022); Huang et al. (2015); Keijzer et al. (2015); Moschen-Schimek et al. (2023); Pongiglione and Calderini (2014); United Nations Environment Programme (2024); Van Engelenburg et al. (2024)	Deetman (2021); Edelenbosch et al. (2022); Fishman et al. (2021); Fortes et al. (2023); Hertwich et al. (2019); Norris (2013); Pauliuk et al. (2021); Rodrigue (2020); Soteropoulos et al. (2019); United Nations Environment Programme (2024)	United Nations Environment Programme (2024); Van Vuuren (2007); International Energy Agency (2021, 2024); Deetman et al. (2021); European Parliament (2023); Virtuani et al. (2019); Heath et al. (2020); Ziegler et al. (2018); Ford et al.; Wiser and Bolinger (2019); Dorias and Chivers (2022); Zhang et al. (2007)	Centraal Bureau voor de statistiek (2009); Erumban (2008); Jiang et al. (2023); Nationale Bank van Belgie (2014); Nomura & Suga (2018); Rincon-Aznar et al. (2017); United Nations Environment Programme (2024); Wang et al. (2023b)	United Nations Environment Programme (2024); Ikeda (2023); Beijnum (2021); Wiprächtiger et al. (2022); Cooper et al. (2021); Koch and Vringer (2022); Fu et al. (2023); Susanto and Ilmiani (2018); Palanival Najan et al. (2019); Husein (2021); Curran and Williams (2010); Gelbmann and Hammerl (2015); Ghisellini et al. (2016); Schoonover et al. (2021); Russell et al. (2023); Forrest et al. (2017)	Akande et al. (2020); Alejandre et al. (2022); Anandh et al. (2021); Bigliardi et al. (2022); Brusselaers et al. (2020; Businge and Mazzoleni (2023); Filippas et al. (2020); Govindan et al. (2021); Laitala et al. (2021); Linderhof et al. (2019); Parajuly et al. (2020); Reike et al. (2018); Wasserbaur et al. (2020)

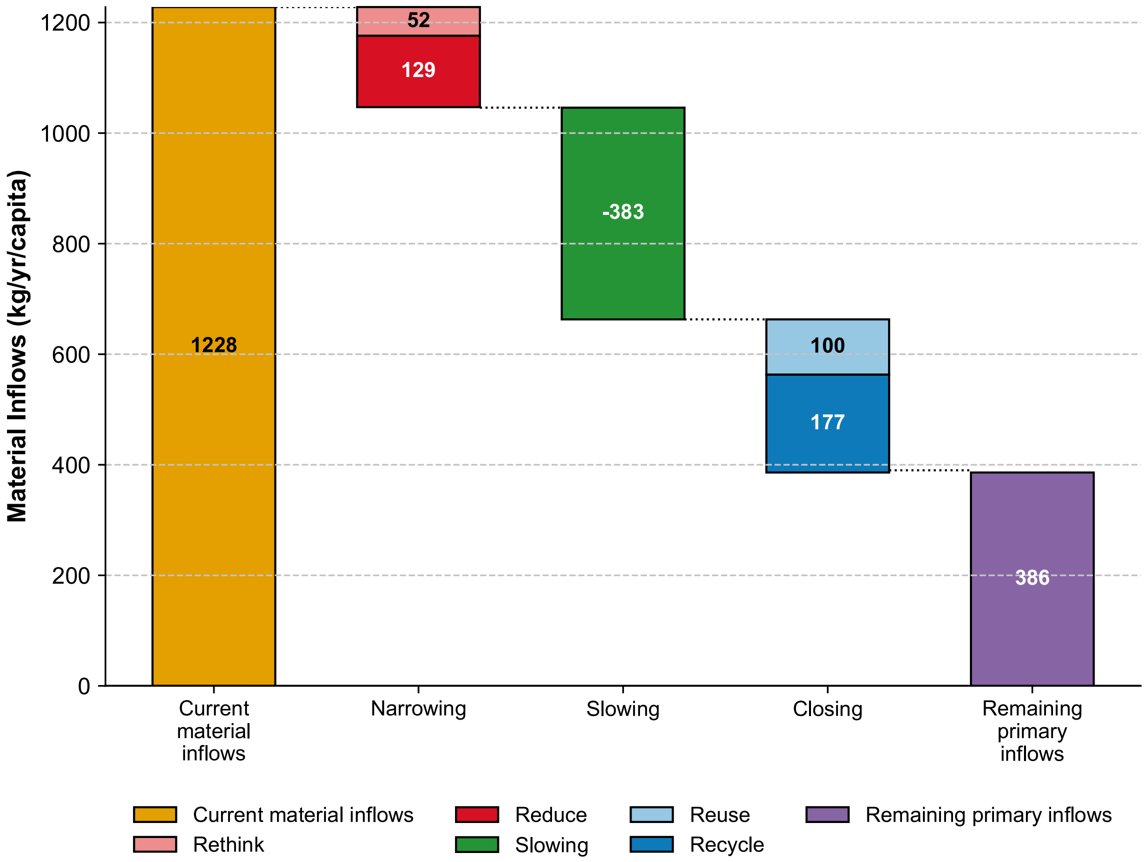

Fig. 5 The current global average materials inflows per capita to maintain a constant service demand shown on the left are about 1230 kg/yr/capita which can be reduced by the circularity strategies Narrowing (red), Slowing (green), Closing (blue), resulting in potentially reduced remaining counterfactual primary inflows (purple) in this counterfactual analysis. The data can be found in Supplementary Information SI1

by Slowing at 31%, and Closing measures contributing a further 22%. Combined, these strategies offer a 68% theoretical reduction.

4 Discussion

4.1 Data availability and uncertainty

Data coverage varies significantly by sector. While buildings, vehicles, and infrastructure have detailed global datasets, furniture requires more research, and appliances are at risk of data obsolescence due to rapid technological shifts (e.g., the transition from VCRs to smartphones). Machinery data remains limited to broad sector aggregates despite its large material stocks and flows.

These issues present challenges in matching data on service provisioning, product stocks material stocks, lifetimes, material intensity, and intensity of use. We addressed gaps by using the correspondence table in Sect. 2.1, but ideally, more detailed service provisioning data for machinery is needed to link between service provisioning, products, and materials. Identifying these data gaps shows that despite the extensive data collection effort, more data on service provisioning, material contents and lifetimes is needed. Especially with current data availability we see an overrepresentation of developed regions and good coverage within European datasets. Using this data beyond a first-order estimate might lead to a Eurocentric bias.

Another limitation we identified is the lack of data on material needs for circularity strategies such as repair, renovation, and refurbishment. These strategies are essential for extending the lifetime of products. We currently only identified repair studies for washing machines. For renovation (van Oorschot & van der Voet, 2023; Mohammadiziazi & Bilec, 2023), the knowledge base is growing, which will allow the future analysis of material requirements of lifetime extension. Especially within developed regions renovation and maintenance might become the main driver of material demand, as the need for new construction reduces (Wiedenhofer et al., 2024a). In addition, there's currently a data gap on the quality of services and products. We classify residential housing by commonly used categories, but not every m^2 is the same. Informal settlements can meet m^2 service demand but have totally different quality and material intensities (Gapminder, 2025; Linares-Capurro et al., 2026).

4.2 Discussion of the outcomes

When comparing our 81 t/cap of materials stocks and 1.2 t/cap of material inflows with other estimates we find that our stocks our lower than the 145 t/cap (Wiedenhofer et al., 2015) and 115 t/cap (Krausmann et al., 2017) although this is likely a result from the different approaches taken. Our average value of 1.2 t/cap/yr of inflows for maintaining average per capita in-use stocks in a steady state is a plausible estimate and well in line with recent results from the literature on Decent Living Standards (DLS) (Streeck et al., 2025b), who find that *total* yearly DLS-related material consumption ranges from 0.7 to 12.9 t/cap/yr. The main difference is that our study focusses on the stock-maintaining material flows for major end uses at current per capita average, whereas the estimate from Streeck et al., 2025a, b) cover all material groups (biomass, fossil fuels, metals, and minerals), including food and the fossil fuel and biomass for industrial and operational energy.

Circularity strategies, have a large potential to reduce primary resource demand. Our counterfactual analysis shows where impact can be made, with narrowing, slowing and closing the loop strategies having significant reduction potentials. The results indicate that a reduction of almost 70% of primary resource inflow could be possible under the assumptions given, while maintaining the current level of service provision.

Even though the individual options for narrowing the flows (R_1 and R_2) have lower reductions, together they still have a considerable reduction potential. Achieving the high recycling rates of the Close the Loop strategies likely require larger efforts compared to the low-hanging fruit of the Refuse, Rethink, and Reduce measures. The reduction potential of lifetime extension is significant but, as mentioned earlier, may be an overestimation.

When we look at the specific strategies mentioned in Table 2, we see that several of these could become effective already in the short term. For example, the coronavirus period provided evidence that teleworking on a large scale could impact the need for offices and commutes (Ceccato et al., 2022; Hensher et al., 2023; Lu et al., 2022), opening a discussion for rethinking the need for offices. Furthermore, there is technical potential for lightweighting products in almost all product groups. These examples indicate that narrow-the-loop strategies can be effective soon, and without losing service provision. The slowing-the-loop strategies we included combined could result in a 31% reduction in primary material flows. Lengthening lifespan can reduce inflows in the short term but will have a delaying effect on the circularity options targeting the end of life: close-the-loop strategies of component reuse and recycling of materials. Current recycling rates are not achieving what is already technically possible (Graedel et al., 2011), and the technical potential could be increased substantially by a different design of products and materials. The full potential of close-the-loop strategies can thus only be reached in the future, even if implementation starts now.

Finally, due to how this analysis is structured, the feasibility of a total of 68% reduction is optimistic. It does not account for policy, economic, social, or technological barriers to implementation. Additionally, even if the reduction, or any reduction, is achieved we do not account for the rebound effect in this first-order assessment. The study of the rebound effect requires integration with models that have an economic perspective, we acknowledge that our reduction is optimistic. However, a reduction in the need for primary materials for these services could make the resources available for other services if the incentives to reduce them are not changed. Despite these uncertainties, our results do show that aiming for ambitious higher primary material reductions is possible. While critics (Greene et al., 2025; Ottelin et al., 2020; Safarzynska et al., 2023; Yerushalmi & Saha, 2025) argue that rebound effects negate the environmental gains of a circular economy, this perspective ignores the global material gap. In the context of DLS, rebound can be seen as redistributed resource access. Rather than a limitation of circular potential, the rebound effect represents the accelerated closing of the deprivation gap. Once global material sufficiency is reached, the rebound pressure naturally dissipates, allowing circularity to transition from a tool of rapid development to a tool of long-term sustainability. Still, this requires further research, beyond the scope of the presented analysis, including economic, policy, and developmental indicators.

4.3 Implications and future research

Action is needed on multiple institutional levels to achieve the potential shown in this paper. Rethinking strategies such as modal shifts in buildings, vehicles, and infrastructure require changes in urban planning, construction projects and how we currently construct settlements. For consumer goods, consumer choices on the purchase, use and discarding of products are key, although these choices are often influenced by economic and cultural factors. For lifetime extension, proper maintenance is key, and refurbishment may be required, requiring action from users, and governance of the services. For closing the loop, collection and recycling capacity must increase. Prioritizing recycling over primary production because of environmental benefits, simplifying product design, and increasing awareness can contribute to improving reuse and recycling rates. We quantified the potential, but the implementation needs a broader approach dealing with policy, economic incentives, manufacturing, and resource procurement. The circularity measures and data collected can assist with that research.

Circularity strategies differ per region in their applicability. Some regions still require major increases in material stock to provide sufficient services for their entire population. In contrast, regions such as North America, Europe, and parts of Asia and Oceania have already reached such a level of service provision that they can focus less on expansion and more on the maintenance of the service and stock. This requires different implementation pathways of circularity strategies for each region. Future research into the different possibilities as well as challenges for circularity strategies in different parts of the world is therefore important.

The SFS nexus approach has proven to be very useful to establish a link in terms of modelling between societal services and material flows and stocks. We have shown that this approach can be successfully combined with circularity strategies. Our analysis is counterfactual, indicating a maximum theoretical potential of the strategies investigated. In the above we have already indicated the importance of product lifetimes and other dynamic variables. It is therefore important to include those dynamics when developing a dynamic model that is suitable for scenario analysis. With the data we collected for service provisioning, lifetimes, material intensity, and intensity of use, we think sufficient data is available for such a model. Combining dynamic Material Flow Analysis with Integrated Assessment Modelling (IAM), such as used in the Global Resources Outlook 2024 (United Nations Environment Programme, 2024), could be a direction for further development. This would enable a scenario analysis that includes socio-economic development, autonomous changes in demand and product development, and add a temporal dimension to the analysis.

5 Conclusions

Following this counterfactual exploration, we can conclude that there is a large potential for circular strategies. With a theoretical reduction potential for primary material inputs of 68% for circularity strategies, we provide evidence that if circularity strategies are implemented, the need for primary resources could be substantially reduced without reducing service provisioning. At present we are extracting more resources than needed to supply fewer services than we could. Strategies such as increasing the share of apartments or public transport, extending the lifetimes of products, and recycling could be implemented in the short term. For some long-lived products like buildings, bridges, and tunnels, it will take time for the changes to become visible in reduced primary material inflows but for developing regions the implementation of these strategies can be faster and avoid the high consumption rates of the Global north.

Narrowing the loop strategies, although individually only having a limited effect, in combination can have a significant impact. Aiming for a small effect in the modal shift by moving to multi-family housing, increasing public transport, and planning new roads with reduced width, can already make significant impacts without requiring large changes in consumption and use patterns. This could alleviate the pressure on the other strategies, most notably those related to closing the loop. Expansion of the recycling industry takes time and requires a lot of effort.

Although this counterfactual analysis presents an optimistic picture of their reduction potential without accounting for potential rebound effects, policy, technological, or economic barriers, the circularity measures included in this study are already theoretically feasible and could lead to significant reductions in the need for primary resources without reducing our quality of life.

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Author contributions ME: Conceptualization, Methodology, Writing—Original Draft, Writing—Review & Editing, Data Curation, Visualization. PBer: Investigation, Writing—Review & Editing, Supervision. PBeh: Writing—Review & Editing, Funding acquisition, Supervision. SD: Writing—Review & Editing, Investigation, Supervision, Funding acquisition. TF: Writing—Review & Editing, Supervision, Project administration. SP: Investigation, Writing—Review & Editing, Data Curation, Funding acquisition. CH: Investigation, Writing—Review & Editing. EH: Writing—Review & Editing, Funding acquisition. MJ: Investigation. OE: Writing—Review & Editing, Funding acquisition. MZZ: Investigation, Writing—Review & Editing. LK: Investigation, Writing—Review & Editing. PF: Writing—Review & Editing, Funding acquisition. AY: Writing—Review & Editing, Investigation. TV: Writing—Review & Editing, Funding acquisition. AAC: Investigation, Writing—Review & Editing. MH: Investigation, Writing—Review & Editing. EV: Writing—Original Draft, Writing—Review & Editing, Supervision, Funding acquisition.

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Data availability The data that support the findings of this study are openly available on Zenodo at https://doi.org/10.5281/zenodo.15147647 Database name: Material circularity strategies in the

stock-flow-service nexus of Buildings, Transport, Electricity, Machinery, Furniture, and Appliances.

Declarations

Conflict of interest The authors declare no competing interests.

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