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1. Executive summary

1.1. Key messages

Material stocks play a **key role** in **shaping the flows of resources**:

1. **Globally and in Europe, most materials extracted are used to build up and maintain material stocks**. At a global level, 55% of all material inflows were used for these purposes in 2010 with the trend growing (this value was only 50% between 1970 and 1990, 30% in 1945 and 25% in 1900).[1,2] In the EU27 in 2016, the share of processed materials dedicated to the build-up and maintenance of stocks was 41% (Wiedenhofer et al. (2024)[3]; Wiedenhofer, Grammer, et al. (2025)). Consequently, acting on the size and dynamics of material stocks is likely to have a major impact on the overall resource use of global economy, and of the European Union in particular, and on the sustainability of its economic and social model;
2. **The existence of stocks strongly contributes to the quality of life and to the productivity of our economies** and hence is a strong determinant of the (material and energy) metabolism of our societies (Vélez-Henao and Pauliuk 2023; Krausmann et al. 2020; Tanikawa et al. 2021). Housing, transport, energy transformation and distribution, water provisioning, telecommunications, sewerage services all depend upon the existence of material stocks in the form of buildings and infrastructure. Economic output is almost directly proportional to the size of material stocks, with no change in that ratio evidenced in the EU27 over the period 1990-2016;
3. **Stocks induce resource intensive maintenance and due to their long lifetimes create long-term lock-ins into unsustainable resource-use patterns**. Better understanding socio-economic material stocks and their link to resource flows is hence a key priority for sustainability science and policies;
4. **The continuous expansion of in-use stock has been identified as a major barrier for loop closing**. As long as stocks continue to grow, even very high recycling rates of materials contained in end-of-life products will not be sufficient to close material loops. Consequently, the growth rate of material stocks is of relevance;

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[1] *F. Krausmann, D. Wiedenhofer, C. Lauk, W. Haas, H. Tanikawa, T. Fishman, A. Miatto, H. Schandl, H. Haberl (2017) Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use, Proc. Natl. Acad. Sci. U.S.A. 114 (8) 1880-1885, https://doi.org/10.1073/pnas.1613773114(2017 (Figure A) .*

Krausmann, F., Lauk, C., Haas, W., Wiedenhofer, W., (2018) From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015, Global Environmental Change, Volume 52, Pages 131-140, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2018.07.003 (Figure 2B)

[2] *In 2015, of the remaining 45%, 16.9% is used for technical energy from mainly fossil fuels, 12.5% for feed, 4.9% for direct human food, 5% in extractive wastes in mining and metal processing, and the remainder (6.9%) is used for “other dissipative uses” i.e. products that are consumed and turned into wastes and emissions within one year such as detergents, hygiene products, pharmaceuticals, single-use batteries, lubricants, fertilizers, pesticides, single-use packaging material, etc.*

[3] *All scientific references are listed in Annex E. References of scientific documents*

5. **The largest part of all waste flows – and hence of all potential secondary materials – is end-of-life waste from discarded stocks that date back several decades**. Recent research has shown that large amounts of potential secondary material will become available in the coming years (Streeck et al. 2021); hence, knowledge of, and (in the longer term, action upon) the age, location, material composition and quality of material stocks is essential for effective planning of measures aiming to slow material cycles (maintain, repair, re-use, refurbish), as well as measures aiming to close material cycles (recycling, remanufacture).

A **general pattern** in the material composition of stocks is that **the mass of a material in the stock is inversely proportional to its value**:

- The **large majority (95%) of the mass of materials in stock** is made of **low-value, inert materials** (concrete, aggregates, asphalt, bricks, wood), mainly in **fixed assets**, namely **buildings and infrastructure**. Despite this relative lower value, their geographic location and nature frame the subsequent settlement of population and of economic activities, and their resource use, over the long term;
- A **minority (5%) of the mass of materials in stock** is made of **higher-value materials** (iron & steel, non-ferrous metals, glass, plastics, fibres, paper and other materials) that build up the **mobile, active and high-value assets** of society: vehicles, machinery, appliances, furniture, electric and electronic equipment, paper documents;
- **Critical Raw Materials (CRMs)** have a determinant strategic value and yet **represent only 0.02% of the mass of stocks**.

Geography matters. When the geographic location of a fixed or semi-fixed asset no longer matches that of the population or of the economic activity that it was intended to serve, the corresponding material stocks are lost and must be constructed again elsewhere (thereby generating again also the environmental impacts that were embodied in them). This calls for careful regional planning and anticipation of the movements of population and of economic activities, as well for the convertibility of buildings or infrastructure to new uses or to new locations (e.g. via modular design).

The existing material stock, which was built several decades ago, hardly has incorporated Circular Economy principles in its design. The first (and, to date, only) comprehensive legally-binding legislation aiming at improving the longevity, re-usability and recycling of a specific material good and that entered into force (in August 2023) is the Batteries Regulation[4]. Even there, some key technical requirements still are under development as of the drafting of this report (March 2025).

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[4] *The Regulation (EU) 2024/1781 establishing a framework for the setting of ecodesign requirements for sustainable products – Ecodesign for Sustainable Products Regulation (ESPR) http://data.europa.eu/eli/reg/2024/1781/oj has been adopted but has not yet led to any product-specific Delegated Act for implementation.*

Similarly, the Directive (EU) 2024/1275 on the energy performance of buildings (EPBD) http://data.europa.eu/eli/dir/2024/1275/oj provides for the energy renovation of buildings but is limited to information requirements when addressing material efficiency.

The **longer the lifetime of a material good, the longer it takes for the stock of that material good** to be renewed, and hence **to bear circularity features** when they are made mandatory for new products placed on the market. This gives value to early adoption of ecodesign requirements bearing for long-lifetime, high-impact goods, such as buildings or infrastructure.

The contribution of the existing stock to the supply of recycled materials for the manufacturing of new products can be high when the stock is stable (i.e. when the mass of materials leaving the stock matches that of materials entering the stock), **but is low in periods of strong growth of that stock** (in that case, the flow of outgoing materials corresponds to the end-of-life stocks dating back many years, which is much smaller than the demand for new materials in the current year). This is exemplified by the case of batteries for the traction of electric passenger cars over the period 2020-2050 over which the substitution of Internal Combustion Engines by electric motors is anticipated to take place.

1.2. Conceptual perspective on material stocks

Socio-economic material stocks refer to long-lived physical assets such as buildings, infrastructure, machinery, and vehicles that form the biophysical foundation of societies. These stocks provide essential services, including housing, mobility, nutrition, water and energy supply, hygiene, and healthcare. It is estimated that two-thirds of all Sustainable Development Goals (SDGs) directly or indirectly depend on infrastructure, which constitutes the majority of material stocks. However, statistical analyses showed that patterns of built structures (settlements and infrastructures) co-determine levels of per-capita final energy demand and CO2 emissions as well as Domestic Material Consumption (DMC) and the material footprint almost as strongly as per-capita GDP.

The accumulation and maintenance of material stocks require significant material and energy inputs. Net Additions to Stocks (NAS/yr) is a key indicator of stock growth, where an increasing NAS/yr signals accelerating stock expansion, while a decline still indicates growth but at a slower pace. Stock stabilization or 'saturation' occurs when NAS/yr reaches zero. Over the past century, the expansion of material stocks has driven global resource use, rising from 20% in 1900 to nearly 60% today. While stock accumulation is predominant in early industrialization phases, maintenance and replacement become the primary resource demands in mature economies such as the USA and Europe.

A comprehensive assessment of circular economy progress requires tracking material flows across all stages—from extraction and production to final use and eventual repurposing, reuse, or recycling. Accurate accounting of changes in material stocks and the time-lags between material input and end-of-life output is essential for an effective assessment of Circular Economy (CE) policies and for sustainable resource management.

1.3. Status and trends in material accumulation

In 2016, **material stocks in the EU27 amounted to 144 Gt, averaging 325 t/cap. Concrete (49%), aggregates (34%), and asphalt (7%) are dominating the stocks**, with buildings (54 Gt), roads (46 Gt), and other infrastructure (42 Gt) as primary end-uses concentrated in urban areas and transport corridors. Together with bricks and iron/steel (4% each) and wood (2%), these materials cover 99% of total stocks. The remaining 1% include all other materials such as glass, plastics, the large variety of metals, and all minerals listed among the critical raw materials.

In 2016, gross additions to stocks (GAS) amounted to 2.3 Gt/year, with 87% consisting of concrete, aggregates, asphalt, and iron/steel. End-of-life outflows (EoL) of stocks make up for 1.2 Gt/year, representing all discarded products and demolished buildings or infrastructure. In a situation of growing material stocks, the discarded material needs to be replaced on the input-side and thus represents maintenance and replacement of existing structures. Consequently, **in the EU27, 52% of material inputs to stocks (GAS) are used for maintenance and replacement (M&R)**. The example of asphalt shows a higher relative share in EOL as compared to the other materials, highlighting its high replacement rate in roads. The net additions to stocks (NAS) amount to 48% of GAS, confirming overall stock growth.

A Sankey diagram of material flows showed that nearly half of processed materials were used for energy purposes, the other half is material use mainly accumulated in stocks. A minor share of material use (18%) is used and reaches end-of-life stage within a year. Of the 1.6 Gt/yr entering waste management only half is recycled. **The Circular Material Use Rate (CMUR) stood at 12%, underscoring the need for broader circular economy measures.**

While bulk materials, e.g. construction materials, dominate in volume, materials used in smaller amounts such as critical raw materials have high strategic importance and are characterized by higher direct environmental impacts. **The current energy transition boosts the demand for CRMs, which are at the same time facing geopolitical risks in supply as well as challenges in recycling. Hence, the need for circular economy strategies along the full spectrum of 10Rs is evident.** We have to rethink and reduce the size and growth of material stocks, enhanced all activities slowing resource use (reuse, maintain, repair, refurbish, remanufacture, repurpose) before we finally exploit full potential of recycling and recover as the least option.

The empirical evidence presented here indicates that the EU27 is not yet on track. While stock growth has slowed down in particular since 2008, EU27 stocks continue to grow, although they are already at a rather high per capita level. In some EU Member States, however, **there are signs of saturation of per capita stocks**. It is, however, unclear, if the stabilisation of per capita stocks, which in many countries coincided with the 2008 financial crisis is **a lasting phenomenon or only temporary**.

Stocks are key for production and consumption processes and to provide services like mobility, shelter or communication to society. On a global scale, stocks have roughly been growing in unison with GDP (Krausmann et al. 2017). In the EU27 stocks grow at a slower pace than GDP, which means that there is a relative decoupling of stock growth and economic development. In contrast, material inflows to build up and maintain stocks have declined since 2008, i.e. **we observe an absolute decoupling of stock related material flows (GAS/yr) from GDP**. While there is a coupling of GDP and stock development in EU27 countries over time, income (GDP/cap) seems not a good predictor for the level of (per capita) stocks across EU27 Member States and we find countries with very high income with lower per capita stock levels than countries with lower income. Obviously other factors have a strong influence on the stock level. The role of e.g. urbanisation, population density or climate conditions for the level of per capita stocks requires further investigation. Over time **we observe considerable improvements in the aggregate energy and CO2 intensity of stocks**, which reflects improvements in the energy efficiency of industrial processes and stock operation and of the decarbonisation of the energy system; however, improvements have slowed down – and in some countries intensities are still high.

1.4. Interlinkages between material stocks and the Circular Economy

The interlinkages between material stocks, and Circular Economy measures, are profound and fundamental. **Including material stocks in the scope of reflection and knowledge is hence a considerable contribution to the effectiveness and comprehensiveness of policies aiming at developing the Circular Economy in Europe**.

The fixed nature of housing, infrastructure and a significant part of machinery results in geographical mismatches of supply and demand, whereby the material assets discarded in one geographic location cannot be re-used in the other geographic location where the demand (population, economic activity) has moved to.

The persistent dispersion in the stock of housing leads to reduced efficiency in the usage of the materials providing the transport, energy, water and data networks supplying these settlements.

Circular Economy measures have the potential to reduce the demand for Basic Metals, Materials and Chemicals (BMMCs), in particular of *primary* BMMCs. The facilities manufacturing these primary BMMCs are likely to be discarded before they are fully amortised, potentially leading to premature write-offs and corresponding financial losses, a phenomenon known as "**stranded assets**". Similarly, the employment of persons in these facilities is likely to be affected as well, if no Just Transition measures are implemented. Whereas the exact share of the production facilities susceptible to become thus "stranded" remains unknown, the total net assets and employment of the relevant sectors provide a first orders of magnitude approximation of the maximum foreseeable impacts.

The development in the EU27 of the **social norms of ownership** investigated (surface of housing per person, number of cars per household, mass per car) **all have moved in the direction opposite to that of material efficiency** over the last decades.

The material efficiency of the stock of productive assets has increased in the case of steel (but not visibly for textiles or plastics), as the result of technological progress embodied in the stock of machinery.

The usage of secondary materials in the EU27 has been stagnating over the last decade. Structured action relying on ecodesign facilitating dis-assembly and a Digital Product Passport conveying appropriate information for the easy recovery of materially homogeneous parts could be a pathway to improve the situation. Further measures include the scale up of recycling and waste management systems, the adaptation of waste regulations to ease handling of secondary materials, as well as a ecological tax reform shifting the burden of taxation towards the usage of primary resources.

1.5. Case studies bearing on barriers and opportunities for circularity created by the existing stock in the construction and the batteries sectors

1.5.1. Rationale for the case studies

The study took a closer look at the barriers and opportunities for circularity in the material stocks of two contrasted categories of products, buildings and batteries:

- **Buildings** are large items (with a cross-section of several tens of metres), made of low-value, chemically inert materials, most of which being non-metallic minerals. They are fixed and designed to last for long periods of time, typically several decades;
- **Batteries** are small items (a few centimetres across), made of high-value, chemically active materials, a large fraction of which being metals and / or Critical Raw Materials (CRMs)[5]. They are mobile and designed to last for shorter periods of time, often a few years, rarely above ten.

Investigating these case studies in greater detail enables a deeper look at two extremes of the stock of anthropogenic materials.

1.5.2. Construction sector

The construction sector heavily relies on materials like concrete, asphalt, and bricks, with EU27 material stocks (buildings, roads, other infrastructure) tripling from 44 to 142 Gt between 1970 and 2016. While initially focused on stock expansion (92% in 1970), the activity increasingly shifted towards maintenance and replacement of stocks now dominating material demand (47% in 2016 as compared to 53% of stock expansion). This underlies the continued and **growing material input required for maintaining stocks and the substantial legacy built stocks represent. This creates a lock-in effect, where current construction decisions persist for decades**. Hence, it takes long to structurally change these stocks, meaning that

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[5] *As defined in the Annex II, section 1 of the Regulation (EU) 2024/1252 establishing a framework for ensuring a secure and sustainable supply of critical raw materials, available at: http://data.europa.eu/eli/reg/2024/1252/2024-05-03*

whatever we construct now will exist for a long time before alternative options can be implemented.

EU policies prioritize recycling and waste management, but sufficiency-based demand-side measures hold untapped potential. Narrowing strategies advocate reducing material use through efficient spatial planning, multifunctional buildings, and sustainable urban designs. Slowing strategies focus on renovation over demolition, extending building lifetimes and reducing resource depletion. Loop-closing strategies promote material recycling and reuse, with modular component recovery proving more effective than recycling. Scientific research highlights sufficiency measures like halting new construction on unbuilt land and reducing per capita floor space as key to cutting material demand and emissions. Renovation and building preservation are particularly impactful. These **strategies can reduce material inputs to construction by 50-60%.**

However, barriers persist. Long building lifespans slow change, while decarbonization efforts often increase material use through energy-efficient retrofits and renewable energy infrastructure expansion. Challenges include a lack of data on buildings design and material composition, leading to inefficient reuse/refurbish/remanufacture. EU regulations now require building renovation passports and digital records to improve traceability. Economic barriers include high deconstruction costs and competition with low-cost virgin raw materials, while political obstacles involve rigid regulations and weak incentives. Cultural resistance to smaller living spaces and risk aversion within the industry further hinder CE implementation.

1.5.3. Batteries sector

The overall stock of batteries in the EU is estimated at 11 Mt in 2021.

In that stock; the **traditional, homogeneous lead-acid batteries represent by far the largest share** (9.7 Mt, i.e. 87.4% of the total) and are used for the Start – Lighting – Ignition (SLI) of Internal Combustion Engines and for fixed industrial applications. This stock is still growing, even if slowly (at a Compound Annual Growth Rate – CAGR of 3.6% over 2006-2021). It is recovered and recycled with an excellent yield, above 95%. This enables the End-of-life Recycling Input Rate (EOL-RIR) in the EU for lead to be among the highest for metals, at 83% in 2022. The consumption of lead-acid batteries is anticipated to remain stable in the EU27 until 2030, with a decrease in SLI being compensated by a growth in fixed industrial applications.

Lithium-ion batteries still represented a small share of the stock of batteries in 2021 (656 kt, i.e. 5.9%), but **this stock is growing extremely fast** (a more than 14-fold increase between 2006 and 2021, i.e. a CAGR of 19%). This family of chemistries is diverse and evolves fast, as the technology improves to increase energy density. This makes its recycling more challenging, even if very high yields are reported in research (between 70 and more than 99%, dependent on material and recycling technology used).

The demand for batteries for the traction of electric vehicles is anticipated to grow very fast, from 238 GWh in 2024 to between 630 GWh and 1,050 GWh in 2030 and a plateau between 1,260 and 1,500GWh in 2035 (i.e. when new cars are anticipated to all be electric). This implies a CAGR between 17.6% and 28.1% until 2030, and then 7.4% between 2030 and 2035. Correspondingly, the stock of batteries will include an increasing, and ultimately dominant, share of Li-ion batteries.

When considering the **active materials present in the stock of batteries** (6.9 Mt in 2021), **lead represents 6.3 Mt, i.e. 91% of the total**. The remaining stock of materials is composed of some **Critical Raw Materials (CRMs)**: Cobalt – Co (6.8% of the stock without lead), Copper – Cu (10.6%), graphite carbon (12.4%) and Lithium – Li (2.9%), all found in Li-ion batteries, but also Manganese – Mn (26.2%), Nickel – Ni (11.1%) and Sb – Antimony (14.9%) present in other chemistries. Other active materials present in the stock include Cd – Cadmium (1.9%) and Zn – Zinc (13.2%).

When considering the **rarity** and the **environmental footprint required by the manufacturing** of these active materials:

- Cobalt (43.8%) and Lead (24.8%) concentrate the bulk of the metric representing the rarity of the active materials present in the stock of EU batteries in 2021;
- Lead (37.6%), Lithium, Nickel and Manganese (ca. 10% each) dominate the metric representing their environmental footprint of the active materials present in the stock of EU batteries in 2021.

The Batteries Regulation acts on the design of batteries and of products using batteries to increase their durability and recyclability, and in parallel increases the market for recycled content in batteries. This coherent framework will increase the compatibility of the future stock of batteries with Circular Economy measures. This is of particular relevance considering the very strong growth being anticipated in the consumption of batteries for electric vehicles.

Considering the fast demand growth for Li-ion batteries and their lifetime, **the share of new batteries that is likely to be manufactured from end-of-life batteries is likely to remain small**. In 2035, this share is anticipated to lie between 3.3% and 4%, even under optimistic assumptions. A balance between the flow of end-of-life batteries and that of new batteries is anticipated to take place after 2050 only, when the last ICE vehicles reach their end of life.

A further hurdle on the path towards circularity of batteries is the current high share (above 50%) of ‘hibernated’ batteries, whose location is unknown.

1.6. Proposed indicators for the monitoring of material stocks

The Table 1-1 below summarises the indicators that have been suggested to monitor material stocks in the EU. It describes what the indicator wants to measure / describe, the indicator used and the data source.

Table 1-1: Summary of suggested indicators

Issue of interest	Indicator	Data source(s)
The size, growth, flows and intensity of material stocks	Total stocks in Gt	MISO model
	Stock related flows – Gross and net additions to stock (Gt)	MISO model
The fact that stocks (increasing and/or large size of) lead to future resource consumption to maintain and operate these	Maintenance and replacement flows of stock (equal to end-of-life flows from stocks but from a different angle)	MISO model
The components and environmental impacts of consumption	Domestic material consumption (DMC) by material groups and CO_2 footprint related to material consumption	Eurostat DMC, with environmental impact multipliers from EEA / EIONET work
Examples of the stock related inflow and outflow of certain key materials	Stock-Inflow and -outflow of iron/steel and copper	Eurostat DMC and waste sent for treatment MISO model
Circular economy policy measures / activities designed to (inter-alia) reduce material use, increase longevity of stocks and increase material recovery and reuse	Index of housing surface per person, No. cars per person. Battery demand	Eurostat
	Level of building refurbishment / repurposing	DG ENER observatory of housing in Europe
	CDW recovery	Eurostat
	Modal share (passenger and freight)	Eurostat
	Stocks by end use	MISO model

Source: Own elaboration

2. Introduction

2.1. Purpose of the document

This document is the final report of the project "Investigating material stocks in Europe", performed for the European Environmental Agency (EEA)[6] by a consortium of Trinomics BV[7] (the Netherlands) and the Institute for Social Ecology of the BOKU University[8] (Austria), under contract N° 3504/B2024/EEA.60014. The work whose conclusions are presented in this report was performed between July 2024 and March 2025.

2.2. General objectives of the project

This project "Investigating material stocks in Europe" summarizes the scientific state-of-the-art regarding the nature, magnitude and location of **societal material stocks**, i.e. of stocks of **long-lasting human-made artefacts** (fixed assets such as buildings, infrastructure and machines; long-lasting consumer and professional products such as vehicles, appliances, furniture etc.) in the **European Union**. The project then discusses the interactions between socio-economic material stocks with the **sustainability of our society**, and in particular with the implementation of a **Circular Economy**.

This study is performed on an economy-wide macro-level for the EU27, and by investigating **two contrasting case studies**:

- Construction, and
- Batteries.

The project concludes with a recommendation regarding **indicators** that could be used to monitor the development of material stocks in Europe.

2.3. Structure of the document

The present document is structured as follows.

- **Section 1** 'Executive summary' summarises the main conclusions;
- **Section 2** (the current chapter) provides a general introduction;
- **Section 3** 'Concepts and methods on material stocks, flows, and circularity' exposes the rationale for studying societal material stocks, the methods for doing so and the challenges on the path to collecting and making sense of data;

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[6] *https://www.eea.europa.eu/en*

[7] *https://trinomics.eu/*

[8] *https://boku.ac.at/en/wiso/sec/research/soziale-oekologie*

- **Section 4** ‘Status of EU material stocks 2016’ describes what is known about the nature, the quantities, the geographic location and the form of the materials present in the stocks of long-lasting products and fixed assets in the European Union (EU). It also provides a short comparison of these material stocks with those obtained for other major developed and emerging economies;
- **Section 5** ‘Trends in material accumulation’ describes what is known of the evolution of these stocks over time, over the period 1900 to the latest available year (2016 or later), in relation to the evolution of population and GDP;
- **Section 6** ‘Links between Circular Economy and material stocks – cross-sectoral perspective’ introduces the general features of the links connecting the Circular Economy with material stocks: how material stocks affect (positively or negatively) the implementation of Circular Economy measures, and reciprocally how the implementation of CE measures can affect material accumulation;
- **Section 7** ‘Material stocks: Barriers and opportunities for circularity in the construction and batteries sectors’ explores the barriers that existing material stocks may place on the implementation of Circular Economy (CE) measures, and the opportunities that these same material stocks may provide to the implementation of CE measures, in two contrasting illustrative sectors: construction and batteries;
- **Section 8** ‘Monitoring material stocks – Contribution to the definition of metrics’ provides insights on the indicators that the EEA could consider to obtain and track an objective view of the state and evolution of material stocks in the EU;
- **Section 9** ‘Policy conclusions and lessons learnt’ summarises the overall conclusions drawn from the project for policy and on how to further investigate the impacts of the existence of material stocks of human artefacts on the sustainability of our societies.
- **The Annexes** contain:
  - Annex A: **Methods and data** used to model material stocks
  - Annex B: **Supplementary materials and methods** supporting the section 6 ‘Links between Circular Economy and material stocks – cross-sectoral perspective’;
  - Annex C: **Supplementary materials and methods** supporting the section 7 ‘Material stocks: Barriers to and opportunities for circularity in the construction and batteries sectors’;
  - Annex D: **Fiches** for the indicators proposed in the section 8 ‘Monitoring material stocks’
  - Annex E: **References** of scientific documents
  - Annex F: reference to the **Data files** generated by this project and that contain the numerical values supporting the graphs and conclusions presented in the main part of the document.

3. Concepts, methods and data on material stocks, flows, and circularity

The concept of socio-economic material stocks addresses the long-lived (lifetime larger than one year) biophysical basis of society, from individual buildings, cars, machinery or computers to entire settlements and infrastructure systems.[9] Bodies of humans and animals also represent material stocks; however, most assessments do not include these two types of stocks (just as most energy statistics do not account for food and feed). With lifetimes longer than a year and often even several decades, material stocks accumulate in the socioeconomic system and form an essential part of a society's economy and biophysical basis. Stocks are defined as part of the socio-economic system if they are used, stored, maintained and reproduced by society.

In this report, we use the term 'material stocks' (Haberl et al., 2019). Related, but not entirely synonymous, notions used in the research community include 'artefacts' (Fischer-Kowalski & Weisz, 1999), 'manufactured capital' (Weisz et al., 2015), 'in-use stocks' (Pauliuk & Müller, 2014) or 'technomass' (Inostroza, 2014) (the latter exclude human and livestock bodies by definition).

Material stocks also include products or materials in storage, e.g. most importantly oil bunkers or strategic reserves of energy carriers and critical raw materials, as well as raw materials and semi-finished products such as cereals, metals, timber, etc. Furthermore, it is highly useful to measure additional properties of specific material stocks, e.g., physical and functional units pertaining to service provisioning such as m^2 of living space of buildings, length and capacity of transport infrastructures, or even broader categories such as purpose, economic value or ownership. These services or properties allow for a better understanding of the relevance of stocks for society, the link to socioeconomic activities and human needs, and allow for developing policy measures addressing material stocks to improve their socio-economic and environmental performance (Lanau et al., 2019).

Concerning abandoned and deteriorating buildings, or waste deposited to legal landfills or illegally to nature, two accounting approaches are available. International MFA conventions (Eurostat, 2018; UN, 2017; UNEP, 2021) consider landfills as socio-economic stocks and therefore does not include those in domestic processed outputs to nature. However, the amount of wastes put on landfills is valuable and important information, representing materials at the end of their use phase, a mass potentially available for recycling, or material that has to be dealt with in a way that potential environmental burden from the storage is minimized.

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[9] *The concept of stocks is also used in the natural sciences, for example to quantify carbon pools in forests, soils or the atmosphere, or to measure the size of resource deposits. Stocks of natural resources also are valued by economists, who then refer to them as natural capital. Those 'natural' stocks exist without humans investing work into their creation and maintenance.*

3.1. Why do stocks matter? Introduction to material stock accounting

Global societal material stocks have grown rapidly (Krausmann, Wiedenhofer, et al., 2017) and have reached about the same mass as the (dwindling) biomass stocks in plants, animals and other wild-living organisms worldwide (Elhacham et al., 2020; Erb et al., 2018). Beyond this coincidence, material stocks are hugely important for several reasons:

1. A growing fraction of resource use is required to build up and maintain material stocks. Globally, this fraction has risen from about one-fifth in 1900 to now almost 60% (Krausmann, Wiedenhofer, et al., 2017). While building up new material stocks is a major driver of resource use in early phases of industrialisation, maintenance and replacement of structures reaching their end of lifetime, as well as refurbishment of existing structures, requires a rising fraction of resource inputs in later stages of industrialisation, e.g. the USA or Europe (Wiedenhofer et al., 2021).
2. Material stocks are of key socioeconomic importance because specific combinations of stocks and resource (energy, material) flows provide societies with services of key importance for social wellbeing (e.g., dwelling, mobility, nutrition, water supply, hygiene or health care) (Haberl et al., 2019; Haberl, Schmid, et al., 2021; Tanikawa et al., 2021). It was estimated that achieving two-thirds of all SDGs directly and indirectly depends on infrastructures (Thacker et al., 2019), which make up the lion's share of all societal material stocks.
3. Service delivery by stocks usually requires resource flows (e.g., energy or other resources). Roads and cars can deliver mobility services only when energy is available for propulsion, buildings need to be heated, cooled and lit, etc. (Haberl, Schmid, et al., 2021). Size and patterns of stocks therefore co-determine demand for resources. Global statistical analyses showed that patterns of built structures (settlements and infrastructures) co-determine levels of per-capita final energy demand and CO_2 emissions (Haberl et al., 2023) as well as Domestic Material Consumption (DMC) and the material footprint (Duro et al., 2024) almost as strongly as per-capita GDP. These findings corroborate insights from urban studies (Creutzig et al., 2016) and show that effects found at the city level translate to the national scale. The effects of built structures on resource use and emissions are about as strong as those of GDP and act on top of the effect of GDP; other factors often included in such national-scale analyses of determinants of resource use were found to be much weaker. These findings also imply that stocks can lock societies into resource-intensive practices, creating phenomena such as carbon lock-in (Seto et al., 2016) or car-dependency (Mattioli et al., 2020).
4. Processing of material flows in production and consumption processes and the use of material stocks (e.g. the energy required for vehicles, heating/cooling or lighting) are associated with energy use and GHG emissions. The build-up and maintenance of material stocks is hence a key driver of climate change and other environmental problems (Krausmann et al., 2020; Pauliuk et al., 2024). Extraction and processing of

material flows alone currently accounts for55% of global GHG emissions (UNEP, 2024). Hence, the success of climate policies crucially depends on tackling stock growth as a key driver of GHG emissions.

5. Materials stocks and Circular Economy are deeply inter-related: Circular Economy is defined as one 'where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised'[10], which implies in particular that products remain in use, as part of the material stock, for longer periods of time or in a multiple-use approach.
6. The mass balance principle between stocks and flows (see the following chapter) is of key importance for monitoring frameworks aimed at informing sustainable resource use strategies such as the circular economy. From a methodological point of view, it allows triangulation of often inconsistent data sources (e.g. MFA data vs. data from waste statistics for the European circular economy monitoring framework (Mayer et al., 2018)).
7. An economy-wide assessment of progress towards a 'circular economy' needs to consistently trace resource flows through the economy, from import and domestic extraction to production, final use, and eventually re-purposing, re-use or recycling (Charpentier Poncelet et al., 2022; Haas et al., 2015, 2020). This is only robustly possible when changes in material stocks are explicitly accounted for, and the time-lags between the processing of material flows into product stocks, and its (often much) later output as end-of-life material flow are considered. Accurate assessment of the environmental benefits and trade-offs of circularity measures require detailed and comprehensive modelling of material cycles, to fully capture environmental impacts (Korhonen et al., 2018; Pauliuk, 2018).
8. Gross additions to the existing material stock use more than half of the resource consumption in industrialised countries[11]; Similarly, the large quantities of materials currently in the stocks of products and infrastructure in use can become sources of secondary materials once these products and infrastructure reach their end of life.

For all these reasons, a deeper knowledge of the composition and location of material stock, is of relevance for the effective implementation of Circular Economy policies.

3.2. Conceptual approach towards material stocks and flows

Because stocks influence production and consumption patterns over years to decades, they play a crucial role for transformations towards a sustainable circular economy as well as net-zero GHG emissions. For example, safe and affordable housing requires constructing a building and its water and electricity supply networks. In the process, flows of

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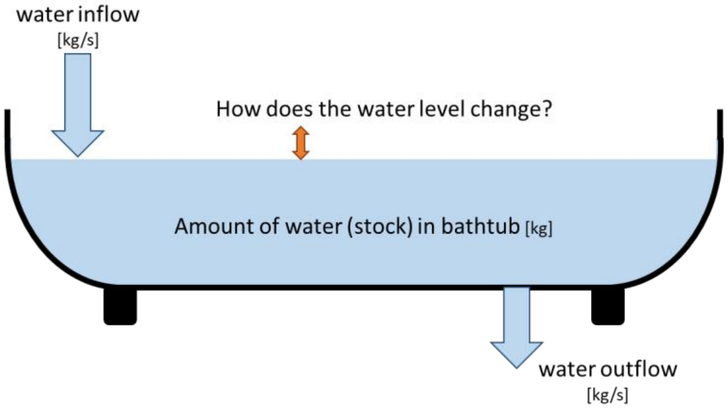
[10] *European Commission (2015) Closing the loop - An EU action plan for the Circular Economy COM(2015) 614 final, accessible at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52015DC0614*

[11] *In the remaining half, one quarter of the resource use provides energy (as food or as fuels) and one quarter is dedicated to the manufacture of short-lived and consumable products.*

construction materials are converted into long-lived material stocks. Then, energy flows are needed to heat and cool living space, based on the thermal performance of the building and the inhabitant's demand for thermal comfort. Buildings also require maintenance, repairs and component replacement. The building's location in relation to the accessible mobility infrastructure, as well as places people want to reach, determines mobility practices of its inhabitants, locking in future energy flows for transport. Those mobility practices then shape the required material stocks and flows in infrastructure systems and vehicles, including upstream energy and material flows in industry and construction. Each use, maintenance and repair causes waste and emissions. At the end of its life, a building might be demolished, causing further waste flows which might be recycled, landfilled, or otherwise disposed of. Correct representation of these processes in economy-wide Material and Energy Flow Accounting (MEFA; Krausmann, Schandl, et al., 2017; Wiedenhofer et al., 2019; Wiedenhofer, Streeck, et al., 2024) and the establishment of consistent accounts hinges on a precise vocabulary and clear conceptualisation of the distinction between stocks and flows, as well as the appreciation of their dynamic interrelationships.

A bathtub may serve as heuristic example (Figure 3-1). The amount of water in the tub at any point in time (i.e. the stock of water) depends on the in- and outflows of water over time. Usually, one will seal the outflow and control the inflow of water per second [kg/s] to establish the desired water table enabling one to take a bath, i.e. the sum of the inflow over a few minutes required to fill up the tub will be equal to the stock accumulated at the desired water level. As water temperature drops over time, or if the outflow leaks, one may again open the outflow and refill the tub with hotter water. At any point in time, the stock will be equal to the sum of all inflows minus all outflows (assuming we start with an empty tub in the beginning).

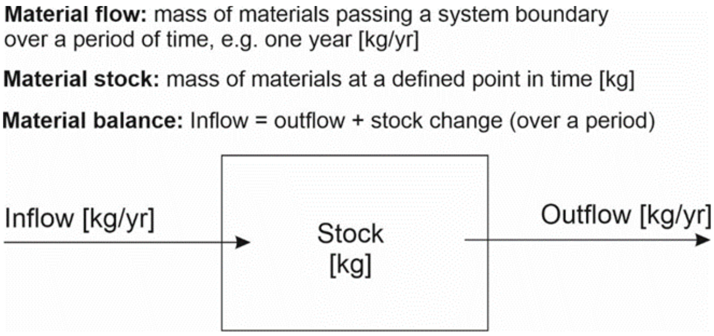
Figure 3-1: Stock-flow relationships at the example of a bathtub.



<u>Source</u>: Own elaboration

Because stocks and flows are systemically related, this relationship is the basis of all system-dynamic stock-flow models. Still, stocks and flows are fundamentally different concepts. A stock is an entity persisting over a prolonged period of time and they are usually measured at a point in time, for example at the end of a year. A flow characterises a process occurring over a defined time span, e.g., per year, or per second. Stocks and flows cannot be measured in the same units, i.e. they are *incommensurable*. The mass of material stocks within a defined system boundary is measured using the SI unit kilogram [kg]. By contrast, flows either crossing the socio-economic system boundary or occurring between socio-economic processes are measured as kilograms per time period, usually as kilogram per year [kg/yr]. Changes in stocks over time therefore depend on the relation between inflows and outflows (Figure 3-2).

Figure 3-2: Definition of material stocks, flows, and their relationship (material balance)



Material flow: mass of materials passing a system boundary over a period of time, e.g. one year [kg/yr]

Material stock: mass of materials at a defined point in time [kg]

Material balance: Inflow = outflow + stock change (over a period)

Let us assume we are interested in stocks at two points in time t_1 and t_2, e.g. in two consecutive years, and the flows over the period between those points in time. Let us denote stocks at different points as $S(t_1)$ and $S(t_2)$ and the inflows and outflows in the respective period $(t_2\text{-}t_1)$ as I_1 and O_1, then:

$S(t_2) = S(t_1) + I_1 – O_1$

For sake of simplicity, it is useful to assign the variable $S(t_2) – S(t_1)$ its own name. This variable denotes change of the stock over the reference period $(t_2\text{-}t_1)$, in MEFA usually one year; hence it is a flow variable. If measured continuously, it would be the first derivative of the function describing changes in stock over time, but MEFA usually works with years, i.e. we need a discrete formulation, e.g. kg/yr. Because most material stocks grow over time, in MEFA, this variable is usually >0. Accordingly, it is often called Net Additions to Stock (NAS/yr), despite the fact that it can sometimes also have negative values.

The mass balancing principle (a direct corollary of the First Law of Thermodynamics) implies that:

NAS/yr = Inflow/yr – Outflow/yr, respectively Inflow/yr = Outflow/yr + NAS/yr (Figure 3-2).

Table 3-1 gives definitions and explanations of the main stock-related indicators from ew-MFA also used herein. Data on resource use as implemented in economy-wide-MFA

(Fischer-Kowalski et al., 2011; Krausmann, Schandl, et al., 2017; Wiedenhofer et al., 2019; Zhu et al., 2023) has traditionally focused on inputs of raw materials into the economy, and outputs of waste and emissions back to nature, without quantifying the interrelated stocks. However, a comprehensive accounting of both stocks and flows, under consideration of stock lifetimes and resulting time lags between a specific material input and its later output as end-of-life material and waste potential is key to systematically cover all material flows, and to understand potential future pathways for resource use, material stock dynamics, waste and emissions.

Table 3-1: Material stock related flows and their definition in economy-wide MFA (Eurostat, 2018; Lanau et al., 2019; UNEP, 2021) and the dynamic material stock-flow model MISO (Wiedenhofer, Streeck, et al., 2024) used in the empirical parts of this report

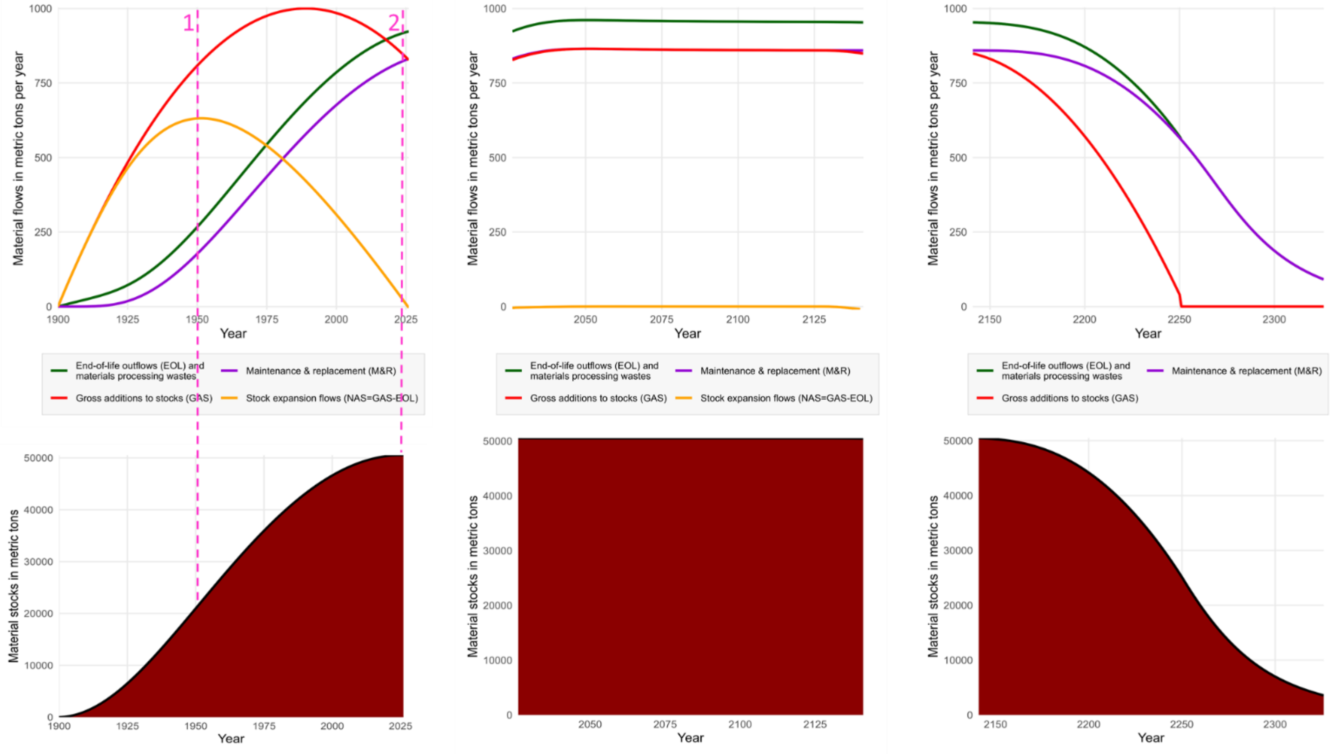
Abbr.	Flow [kg/year]	Explanation
GAS	Gross additions to stocks GAS = NAS + EoL	Measures the total additions of primary and secondary materials to socio-economic material stocks. GAS could be measured by counting all long-lived products built, sold and brought into use within a year (Kovanda 2021; Zhu et al. 2023), which however requires large amounts of data often not available. Alternatively, GAS is also being modelled (Wiedenhofer et al. 2019), using ew-MFA data on resource extraction and trade, industry and recycling statistics, and accounting for unavoidable waste flows during production and construction.
NAS	Net additions to stocks NAS = GAS - EoL	Measures the net-growth of socio-economic material stocks. NAS could be derived from the yearly changes in annual inventories of all stocks, or from known quantities of GAS and end-of-life (EoL) material flows from stocks, for example from waste statistics. Given data limitations for an economy-wide quantification across countries, NAs is alternatively modelled by deducting end-of-life material flows from stocks (EoL) from GAS.
EoL	End-of-life material flows from stocks EoL = Stock * Lifetime Distribution	Covers all material flows exiting the use phase, i.e. all discarded products and demolished buildings or infrastructure. EoL flows could be estimated from waste statistics, which however suffer from widespread data limitations. Therefore, EoL flows are modelled by tracking annual cohorts of materials stocks over their useful lifetime, like a demographic population dynamics model with “births, deaths, and migration”. Different mathematical functions can be used to approximate lifetime ‘survival curves’, most often log-normal or Weibull type distributions.
M&R	maintenance & replacement M&R = GAS – NAS	Maintenance and replacement flows are estimated to understand how much of GAS flows are used to stabilize the already existing material stock and its functions, i.e. via repairs and refurbishments, as well as via replacement construction. M&R flows indicate the lock-in of resource use due to already existing stocks. Ideally, M&R could be measured directly via inventories of functional units across all types of stocks and their related material flows, e.g. m² of useful floor area, length of mobility infrastructure, etc. Due to widespread data limitations for an economy-wide perspective across countries, M&R can also be modelled by quantifying how much of GAS flows are required to keep the material stock, as measured in tons, equal between two years. In this approximation, it is therefore quantitatively equal to total EoL flows.

To gain a deeper understanding of stock-flow dynamics and the economy-wide material flow and stocks indicator utilized in this report, we present stylized results derived from a toy model based on simplistic modelling assumptions. In Figure 3-3, the flow indicators are displayed as line plots in the top panels and the corresponding stocks are shown as area charts at the bottom. The model visualizes material flow and stock patterns across three distinct phases: stock growth (left), stock stagnation (middle) and stock reductions (right). Lifetime of materials follow a log-normal distribution, with a mean value of 50 years. Furthermore, we assumed processing of materials to have a yield of 90%.

In a phase of growing stocks (left two panels), the mass of materials added to in-use stocks (i.e., GAS) is always larger than the mass of materials withdrawn from stocks (EOL – end-of-life or M&R – maintenance and replacement). Consequently, the net additions to stocks (NAS) indicator (NAS = GAS – EOL) is always positive, i.e. growing. The NAS/yr indicates the speed at which material stocks are growing (Fishman et al., 2016; Wiedenhofer et al., 2021), mathematically represented by the first derivative. Therefore, if NAS/yr increases, stock growth is accelerating. If NAS/yr starts to decline (time point 1 in Figure 3-3), stock growth still continues, but at a slower pace. Only if NAS/yr reaches zero, stocks are stabilized or 'saturated' (time point 3 in Figure 3-3). In the present example, gross additions to stocks (GAS/yr) follows a quadratic equation starting in 1900 and increasing to a maximum of 1000 tons/year in 1990. In contrast to NAS/yr, M&R/yr flows follow an s-shaped curve, which represents the increasing need for maintenance and replacement of ageing stocks, e.g., repairs and renovation. With growing stocks, the required M&R/yr is increasing, up to the point where no further stocks are accumulated, i.e. when they are saturated. Then, a relatively steady flow of materials is required for M&R/yr, subject to past dynamics of stock growth. This latter fact reveals the path-dependence given by built-infrastructure that shows the future flows required by in-use stocks. When stocks stagnate (middle panels), GAS/yr equals EOL/yr, resulting in NAS/yr becoming zero.

In a phase where stocks are shrinking, the inflow into stocks (GAS/yr) is always smaller than the outflow (EOL/yr). As materials added to stocks remain in use for several years (according to its lifetimes), end-of-life flows converge towards zero at a much slower pace as compared to GAS/yr.

Figure 3-3: Relationships between material stocks, gross additions to stocks (GAS), end-of-life (EoL) outflows from stocks once these reach the end of their lifetime, and net additions to stocks (NAS).



Source: *Adapted from Wiedenhofer et al. (2021)*

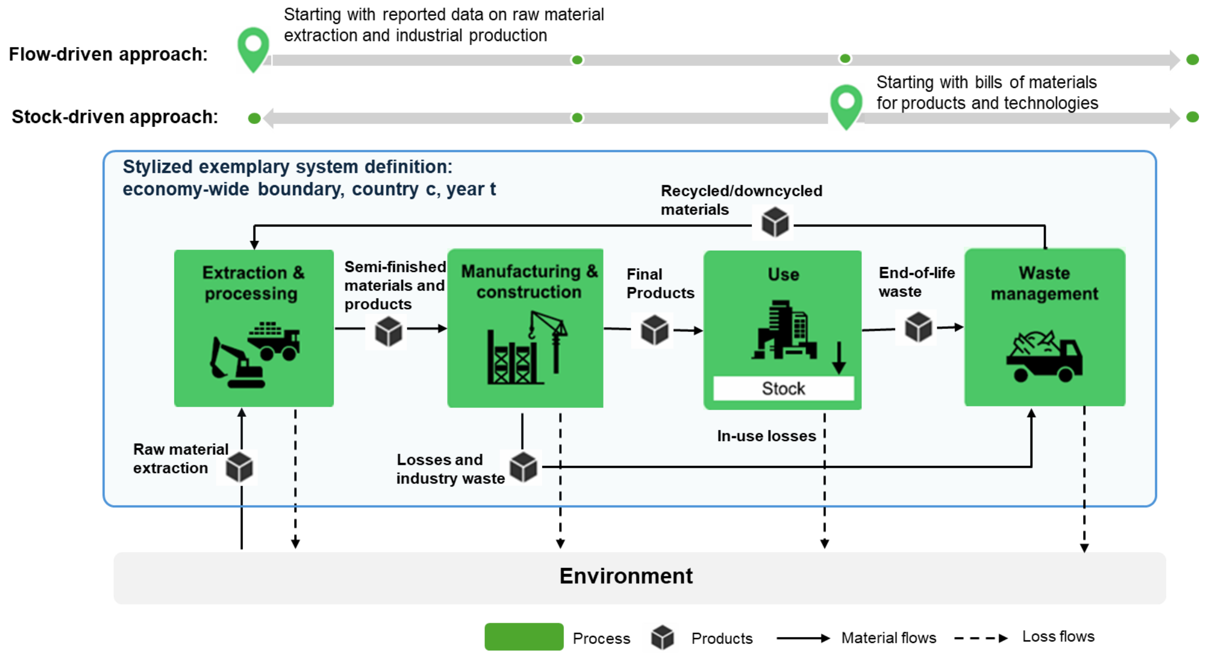
3.3. State of the art: methods and data on stock modelling

Comprehensive material stock accounts have not yet been incorporated in environmental statistics yet, although they are regularly identified as crucial building block for systems-oriented robust monitoring and policy development (Eurostat, 2018; UN, 2017; UNEP, 2021). First estimates of economy-wide net-additions to stocks (NAS/year) have been calculated in early case studies since the 2000's (Bringezu & Schütz, 2001; Kovanda et al., 2007; E. Matthews et al., 2000) and in Eurostat material flow accounts. However, in most economy-wide studies so far, NAS/year was estimated as the difference between material inputs to and material outputs from stocks; only a few studies have attempted direct quantification (e.g., Kovanda et al., 2007). Research on specific substances and materials as well as specific end-uses has advanced rapidly in the last decade (Deng et al., 2023; Lanau et al., 2019). However, on an economy-wide level, progress is slower due to the higher complexity of dealing with multiple material flows and a harmonized system boundary consistently (Wiedenhofer et al., 2019; Wiedenhofer, Streeck, et al., 2024; Zhu et al., 2023).

3.3.1. Methods based on Material Flow Analysis

Material stocks are quantified using the framework of Material Flow Analysis (MFA) (Eurostat, 2018), which is operationalised in static or dynamic models employing top-down or bottom-up approaches (Lanau et al., 2019; Müller et al., 2014; Wiedenhofer et al., 2019). Static MFA provides a system snapshot in time, while dynamic MFA assesses system behaviour over periods of time. Inflow-driven MFA calculates stocks from the accumulation of net-inflows (consumption less discard, the latter quantified by assumptions on the lifetime of materials in socioeconomic use), while stock-driven MFA directly calculates stocks by counting products or functional units (e.g. residential buildings, lengths of roads, etc.) and multiplying them with material intensities (Lanau et al., 2019; Müller et al., 2014). In dynamic MFA, the terms stock-driven and inflow-driven MFA reflect the type of exogenous data used to calculate stocks respectively flows (Watari et al., 2025; Wiedenhofer et al., 2019) (Figure 3-4).

Figure 3-4: Simplified example of an MFA system definition covering raw material extraction, industrial processing, the use phase of material stocks, as well as end-of-life materials, recycling and waste management. Inflow- and stock-driven approaches have different exogenous data requirements and therefore 'start' their estimations at different points in the defined



Source: adapted from Watari et al. (2025)

3.3.2. Inflow-driven ('top-down') models

Inflow-driven ('top-down') models derive material stocks by combining lifetime distributions with data-driven time series of gross additions to stocks over longer periods of time, e.g. annual use of concrete for construction, or sales of cars, and their usual lifetimes. Earliest economy-wide efforts quantified GAS over longer time periods from academic ew-MFA databases enhanced with some industrial production statistics (Fishman et al., 2014; Krausmann, Schandl, et al., 2017; Wiedenhofer et al., 2019, 2021). Very recently, some of the authors presented a novel global database compiling country-level industrial production and trade statistics (Plank et al., 2022b, 2022a), novel methodological advances to delineate end use product groups (Streeck, Pauliuk, et al., 2023; Streeck, Wieland, et al., 2023), as well as a substantially improved version of their dynamic, economy-wide stock-flow model MISO2, which uses this inflow-driven modelling approach (Wiedenhofer et al., 2019; Wiedenhofer, Streeck, et al., 2024). The derived database distinguishes 21 stock-building materials, 14 supply chain processes, 13 end-uses of product stocks (see Annex A. Methods and data on material stock modelling, §10.1.1, for a detailed list of the items) at the national level for 177 countries from 1900-2016 (Wiedenhofer, Streeck, et al., 2024). Efforts are currently ongoing to update to required data to the year 2023 in the Horizon project CircEular, which is coordinated by the Institute of Social Ecology, BOKU University.

3.3.3. Stock-driven ('bottom-up') models

Stock-driven ('bottom-up') models compile data on existing stocks such as vehicles, buildings, roads, power-plants and use so-called material intensities per stock type to calculate material stocks. Using annualized inventories, lifetime distributions and/or end-of-life waste statistics, material flows are then modelled. For example, material stocks in buildings and infrastructure are assessed using maps, cadastral data, results from crowd-sourcing, nighttime lights and other remote sensing technologies (Frantz et al., 2023; Gontia et al., 2019; Haberl et al., 2024; Haberl, Wiedenhofer, et al., 2021; Kleemann et al., 2017; Lanau et al., 2019; Peled & Fishman, 2021; Schandl et al., 2020; Tanikawa et al., 2015). These approaches can focus on any type of socio-economic structure whose mass and material composition can be reliably assessed, e.g. the mass of past, current and future power plants and distribution grids, mobility infrastructure networks, or buildings (Kalt et al., 2021, 2022; Wiedenhofer, Baumgart, et al., 2024; Wiedenhofer et al., 2015). Progress has recently been made to quantify the mass of important structures such as residential buildings globally (Marinova et al., 2020; Pauliuk et al., 2021), and efforts are ongoing to couple such data with integrated assessment models (Deetman et al., 2020; Ünlü et al., 2024). Various local to regional stock-driven studies, as well as coarse mappings of building stocks in the European context have been published recently, e.g. (Gontia et al., 2019; Heeren & Hellweg, 2019; Lederer et al., 2021; Miatto et al., 2019; Peled & Fishman, 2021); for a comprehensive review see (Lanau et al., 2019). However, consistent and comprehensive European-wide stock-driven accounts of material stocks across multiple end-use product groups are missing so far.

3.3.4. Comparison of methods

The advantage of inflow-driven models is that these models rely strongly on data from material flow accounts and industrial production statistics, e.g. those of Eurostat. They can therefore be used to construct material stock accounts that are fully consistent with such statistics and could in the future be implemented as extensions of such statistical services. However, they also have some disadvantages: The accuracy of such models critically hinges on assumptions of lifetimes, which vary between products and regions. Many inflow-driven models only quantify the mass of materials (e.g., concrete, steel, glass) but do not differentiate product groups or sectors, such as buildings, roads, railroads, factories, furniture, vehicles, etc. Only recent methodological progress (Streeck, Pauliuk, et al., 2023; Streeck, Wieland, et al., 2023) enabled differentiating 13 end-use product groups across 21 materials in an inflow-driven modelling approach (Wiedenhofer, Streeck, et al., 2024).

Still, results from inflow-driven material stock modelling have limited detail in terms of their ability to distinguish different types of structures, and quantify material stocks only as national totals, without any spatial structure. By contrast, stock-driven models can be used to map material stocks over larger regions with high spatial resolution, even down to national coverage in 10x10m grid cells (Frantz et al., 2023; Haberl, Wiedenhofer, et al., 2021; Milojevic-Dupont et al., 2023). Similar approaches were used to map transport infrastructure globally, with high spatial resolution (Wiedenhofer, Baumgart, et al., 2024). However, flows estimated from such stock-driven models are not automatically consistent with data from ew-MFA, because these models do not cover the entire life cycle of materials yet. Stocks estimated with the two approaches currently diverge substantially, with medium to high divergences between studies estimating the same material stocks. For stock end-uses (e.g. buildings), which comprise multiple materials, most global-level estimates show divergences within 140%. At the national-level, estimates for the USA diverge by less than 210%, while those for China by less than 550%. At the urban scale, most estimates for Beijing fall within 90%, and for Vienna, within 70%. For individual materials, differences are often substantially higher. The discrepancies are particularly large for low-income countries and non-residential building stocks. (Streeck et al., 2024). Although highly important, reconciling these differences would require major primary research beyond the scope of the present project. In the Annex A. Methods and data on material stock modelling, § 10.1.2, we provide a comparison of existing stock-driven studies to inflow-driven results and give an overview of major deviations and knowledge gaps across European countries, and qualitatively discuss such deviations.

In comparison, a purely flow-based account of net-additions to stocks (NAS = material inputs – outputs) that does not consistently integrate material stocks entails two major shortcomings (for details see next section). Firstly, domestic material consumption as compiled under MFA conventions (Eurostat 2018) are not consistent with domestic processed outputs as reported in waste statistics and emission inventories. Secondly, long lifetimes of material stocks imply that end-of-life materials from stocks in a specific year comprise different materials than the material inputs in the same year.

Consequently, comprehensive data based on direct accounts of material stocks and the related material flows are necessary, also greatly improving data quality and robustness of ew-MFA estimates of material flows for domestic material consumption, GAS, NAS, EoL, recycling and domestic processed outputs. In recent years, data and methods to estimate material stocks using direct modelling approaches have become available in the research community. Those can help statistical offices and environmental agencies to properly include material stocks and the related flows in their monitoring and reporting (Lanau et al., 2019).

3.3.5. Stock considerations in EU / Eurostat approaches

In economy-wide material flow accounting, the socio-economic system is simplified as a "black box", with a focus on flows into and out of the system, but neglecting processes within the system (Krausmann, Schandl, et al., 2017). An estimation of societal stocks requires opening up the black box, tracing material flows through industrial processing to stock accumulation. Outflows from stocks occur annually but represent stock additions of several years or decades back, depending on the lifetime of in-use stocks. A thorough consideration of stock inflows and outflows over longer time periods allows for a consistent mass-balance of economy-wide material inputs and outputs. Early stock estimations (e.g., H. S. Matthews, 2007) used a highly simplified method where stocks are estimated as a net -balance between inputs and outputs, suggesting full systems closure but actually absorbing any inconsistencies and uncertainties.

There are two challenges that make theoretical consistency impossible in practical implementation. Firstly, material inputs (domestic extraction and imports) as compiled under MFA conventions (Eurostat 2018) are not consistent with domestic processed outputs as reported in waste statistics and emission inventories; highly aggregate mass-balancing procedures need to be applied to mediate between these two spheres. All remaining errors are accumulating in NAS estimates (Mayer et al., 2018). The main inconsistencies between ew-MFA inputs and waste statistics are, e.g., emissions from respiration, emission from calcination of limestone, under-reporting of excavated soils or construction and demolition waste, differences in moisture contents, etc. Furthermore, an exact allocation of waste flows to raw material groups as reported in ew-MFA is not possible, due to the former reporting mixed waste streams by origin, while the other reports raw materials by their main property (e.g. non-metallic minerals, ores and metals, etc.). A link between these two spheres without an understanding of intermediate material uses along commodities/products is nearly impossible.

While economy-wide material inputs are relatively well documented and underlying methods internationally harmonized (Eurostat, 2018; UN, 2017), the outputs exhibit a fragmentary nature such as of international waste statistics which lack consistency with ew-MFA system boundaries (Moriguchi & Hashimoto, 2016; Tisserant et al., 2017). Indicators and accounting methods for output flows are still to a large extent based on waste statistics without consistency checks with ew-MFA inputs or material stock information (Eurostat, 2001; Fischer-Kowalski et al., 2011; Kovanda, 2017; Kovanda et al., 2007). Subtracting annual outputs from inputs to calculate annual stock changes therefore builds any mismatches into the estimates of in-use stocks. In addition, such a flow-centered approach does not provide direct insights into the composition and dynamics of in-use stocks themselves, which constitutes an important knowledge gap itself (Krausmann, Schandl, et al., 2017; Pauliuk & Müller, 2014; Weisz et al., 2015).

The second major shortcoming pertains to the issue of relatively long lifetimes of material stocks, particular for durable stocks such as buildings, infrastructure or machinery. Those imply that end-of-life materials from stocks in a specific year comprise different materials than the domestic material consumption in the same year. Therefore, a simple flow-centric balance account (indirect approach) to estimate NAS/yr is prone to large errors and it is not suitable for calculating the size of stocks by different material groups and the outflows from discarded stocks.

A comparison and discussion of empirical results of the inflow-driven stock modelling (MISO2) and the Eurostat account is presented in 4.4 “A Sankey Diagram for the EU27 in the year 2016” and the related Annex A. Methods and data on material stock modelling, §10.1.3.

3.4. Summary of conceptual perspective on material stocks

Socio-economic material stocks refer to long-lived physical assets such as buildings, infrastructure, machinery, and vehicles that form the biophysical foundation of societies. These stocks provide essential services, including housing, mobility, nutrition, water and energy supply, hygiene, and healthcare. It is estimated that two-thirds of all Sustainable Development Goals (SDGs) directly or indirectly depend on infrastructure, which constitutes the majority of material stocks. However, statistical analyses showed that patterns of built structures (settlements and infrastructures) co-determine levels of per-capita final energy demand and CO2 emissions as well as DMC and the material footprint almost as strongly as per-capita GDP.

The accumulation and maintenance of material stocks require significant material and energy inputs. Net Additions to Stocks (NAS/yr) is a key indicator of stock growth, where an increasing NAS/yr signals accelerating stock expansion, while a decline still indicates growth but at a slower pace. Stock stabilization or ‘saturation’ occurs when NAS/yr reaches zero. Over the past century, the expansion of material stocks has driven global resource use, rising from 20% in 1900 to nearly 60% today. While stock accumulation is predominant in early industrialization phases, maintenance and replacement become the primary resource demands in mature economies such as the USA and Europe.

A comprehensive assessment of circular economy progress requires tracking material flows across all stages—from extraction and production to final use and eventual repurposing, reuse, or recycling. Accurate accounting of changes in material stocks and the time-lags between material input and end-of-life output is essential for an effective CE assessment and sustainable resource management.

4. Status of EU material stocks 2016

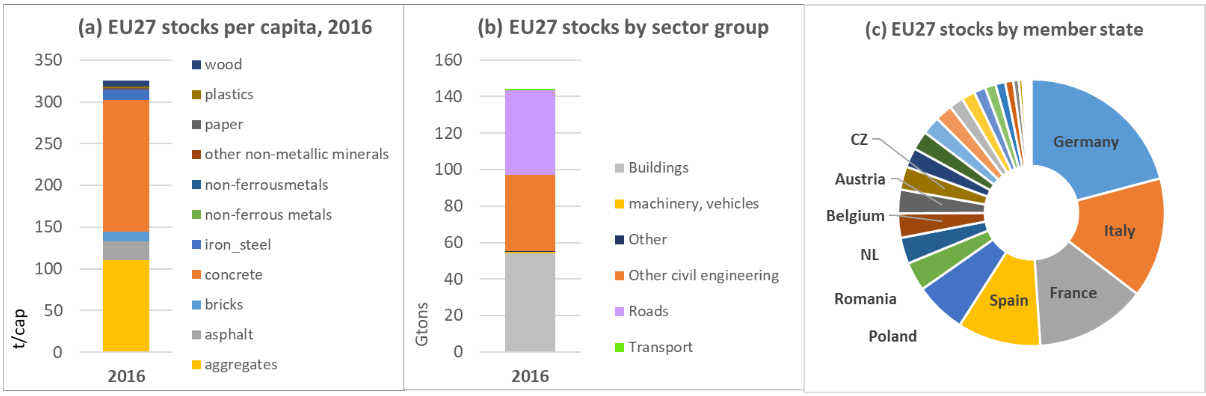
4.1. Material stocks in the EU27 in 2016 per material and end-uses

The data discussed in this chapter covers the currently available information on material stocks from the three databases introduced in section 3.1.2 (MISO2 for economy-wide stock estimates, Haberl et al. 2024 for a buildings mapping, and Wiedenhofer et al. 2024 for a mobility infrastructure mapping). Together with the stock data, related input flows ('gross additions to stock', GAS/year) and output flows ('end-of-life outflows' EoL/year) as well as 'net additions to stocks' (calculated as GAS-EoL) will be presented. Stock-relevant flow data are derived from MISO2 model (Wiedenhofer, Streeck, et al., 2024) as well.

Material stocks in the EU27 region have been estimated to amount to 144 Gt or 325 t/cap in 2016 (see Figure 4-1a). Three materials make up for 89% of per capita stocks, these are concrete (49%), aggregates (i.e. sand, gravel; 34%) and asphalt (7%). Another three materials cover another 10%, these include bricks and iron/steel (4% each) and wood (2%). The remaining 1% include all other materials such as glass, plastics, all other metals, and other materials. The largest part of the stock-building materials are used as built structures, including buildings (54 Gt), roads (46 Gt), and other infrastructure (42 Gt) like dams, canalisation, bridges, tunnels, etc. termed "other civil engineering" in Figure 4-1b; only a small amount of materials are used in stationary machinery (0.6 Gt), vehicles (0.4 Gt) and other material goods (1.1 Gt).

In terms of geographical distribution, four EU Member States make up for 60% of EU27 stocks: Germany (30 Gt, 21%), Italy (21 Gt, 15%), France (19 Gt, 14%), and Spain (15 Gt, 10%) (see Figure 4-1c). Further 20% are accumulated in Poland (9 Gt, 6%), Romania (5 Gt, 4%), the Netherlands (5 Gt, 3%), Belgium (4 Gt, 3%), Austria (4 Gt, 3%), and the Czech Republic (4 Gt, 3%).

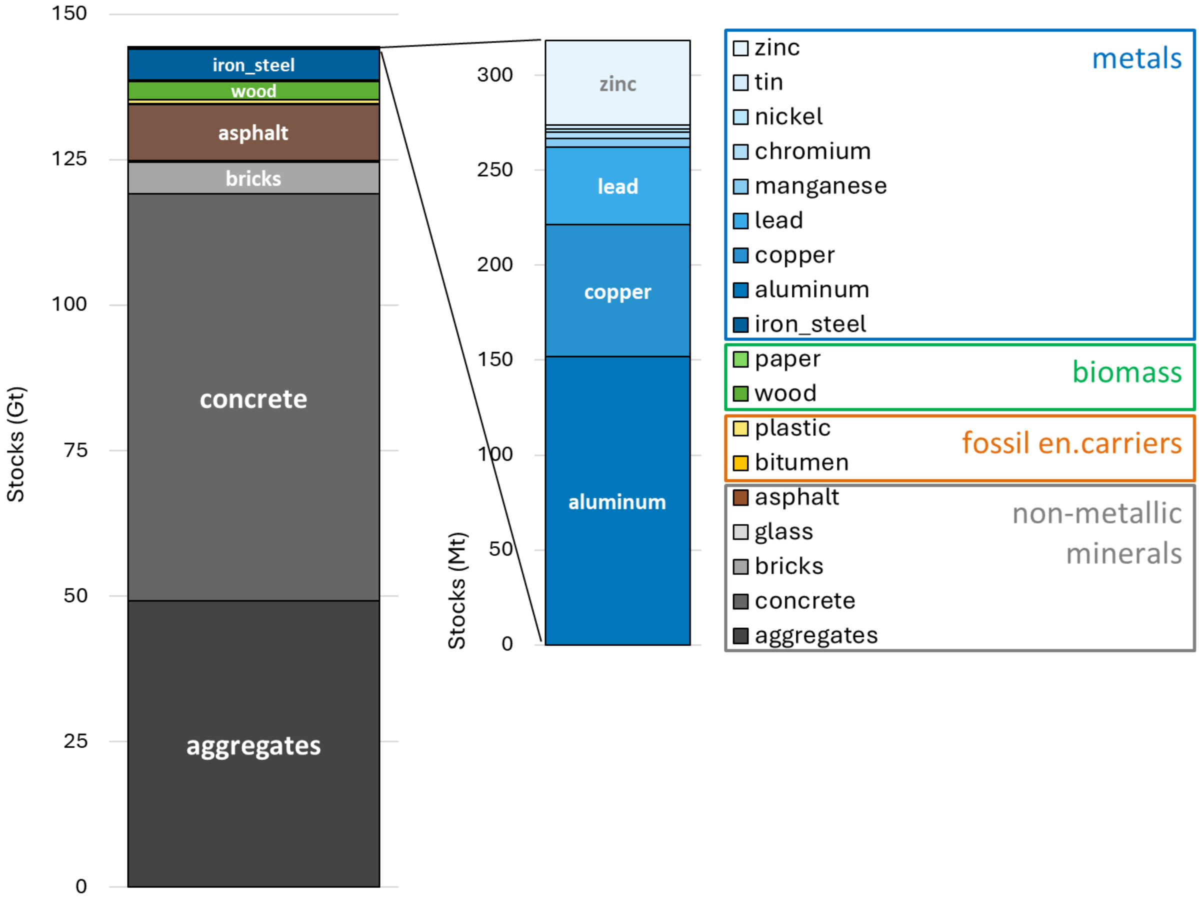
Figure 4-1: EU27 stocks in 2016 grouped by (a) materials in t/cap, (b) sectors in Gt, (c) member state in %



Data: *MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)*

In Figure 4-2 more details on the aggregated material groups of Figure 4-1 is provided. The figure shows how a small group of materials comprising concrete, aggregates, asphalt, bricks, iron/steel, and wood dominate total material stocks. It also zooms into the materials which are used in smaller amounts, which also includes most metals. Among materials used in relatively smaller quantities we find plastics (680 Mt), glass (280 Mt), paper (270 Mt), bitumen (77 Mt) as well as several metals: aluminium (150 Mt), copper (70 Mt), zinc (45 Mt), and lead (40 Mt). Together, the 14 materials shown in make up for 99.99 % of the total weight of material stocks.

Figure 4-2: material stocks in the EU27 in 2016 by detailed materials

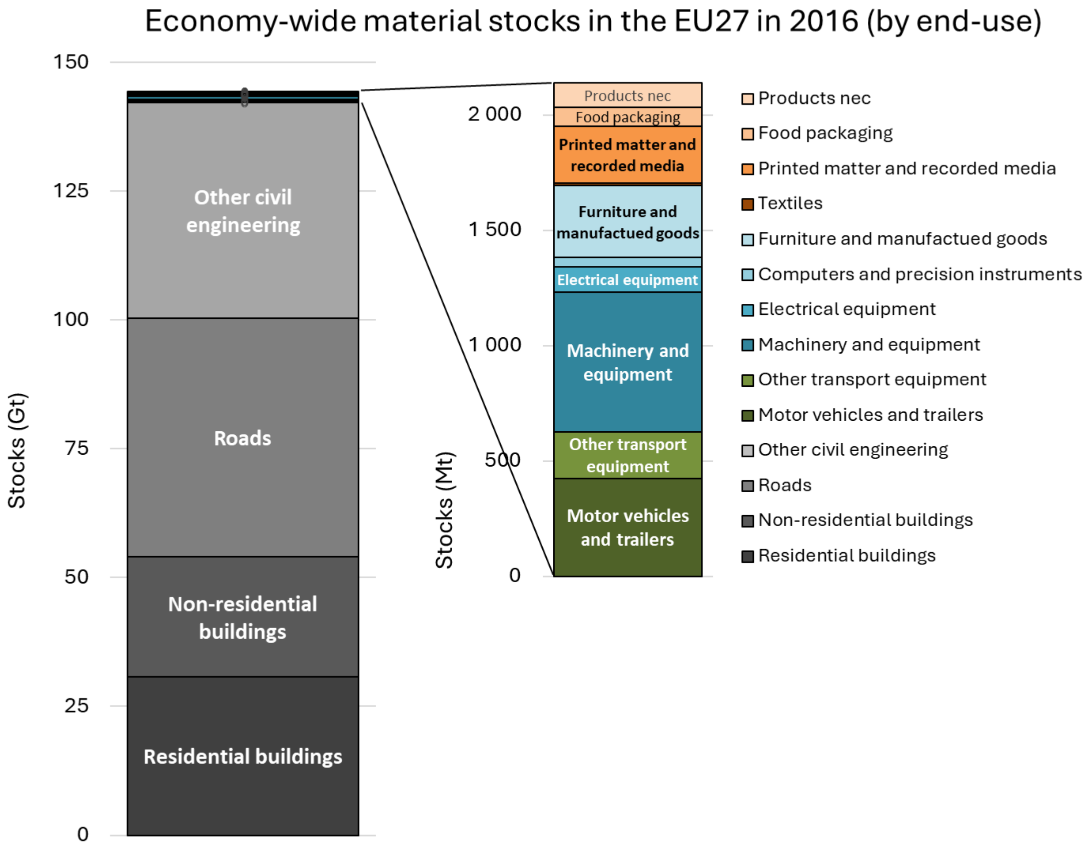


<u>Note:</u> the category "asphalt" is a mixture of bitumen (fossil fuel based) and sand/gravel (non-metallic minerals) with the latter constituting the major fraction. Hence, "asphalt" is allocated to the group of non-metallic minerals.
<u>Data:</u> MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

Among the materials making up for smaller amounts in total stocks (Figure 4-2), we find some of the materials classified and listed as critical (strategic) raw materials (CRM) by the EU (European Commission, 2024): Bauxite (Aluminum), Manganese, Copper, Nickel. The other 30 CRM are used in much smaller quantities, which are not covered in the material stock estimations in the MISO2 model. Unfortunately, no other systematic and economy-wide estimation of CRM in material stocks is currently available that is consistent with the economy-wide material stocks and flow modelling presented here and with ew-MFA conventions. However, in section 1.5 an estimate of CRM stocks is presented for the year 2012 (or 2013 depending on data availability), which was compiled in a study by Bio by Deloitte (funded by the European Commission; European Commission, 2015). The data mostly likely differ with regard to methodological conventions but provide an idea of the difference in total masses.

Figure 4-3 provides more detail on the end-use types of stocks shown in Figure 4-1. Next to the biggest groups, i.e. roads, other civil engineering, residential and non-residential buildings, the figure zooms into the smaller end-uses, which includes different kinds of machinery, vehicles and other durable consumer products. Among these, we find machinery and equipment (600 Mt), motor vehicles and trailers (425 Mt), other transport equipment (200 Mt), furniture and other manufactured goods (310 Mt), printed matter (250 Mt), as well as small amounts of electrical equipment (110 Mt), food packaging (80 Mt), textiles (12 Mt), computers and precision instruments (4 Mt) and products not specified elsewhere (105 Mt).

Figure 4-3: material stocks in the EU27 in 2016 by detailed end-use categories

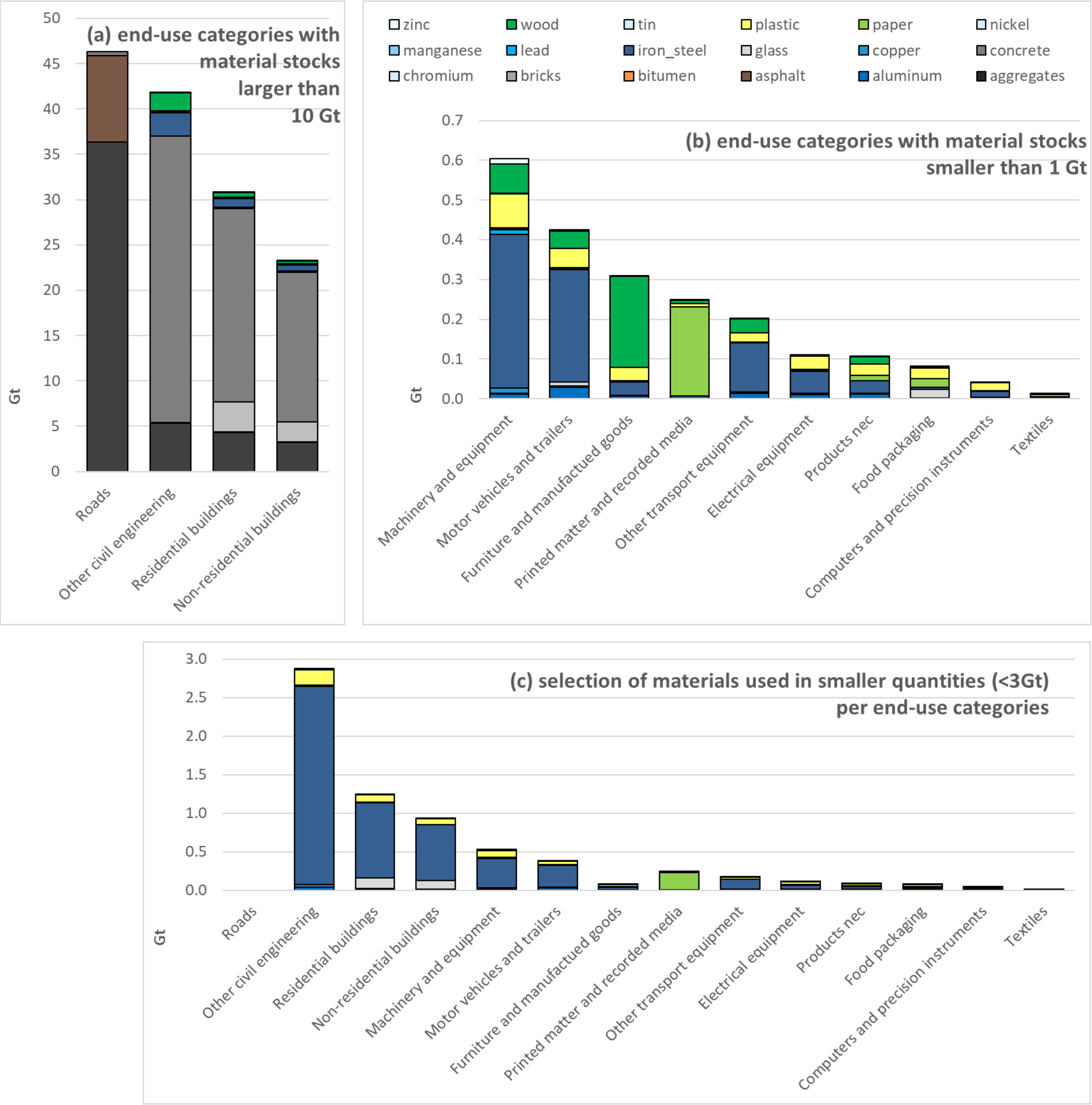


Data: *MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)*

In line with Figure 4-1, the more detailed perspective reveals the importance of construction activities producing buildings, mobility- and other infrastructure. 99% of the material stocks are covering buildings, roads and other civil engineering (railways, bridges, tunnels, water supply pipes, harbours, dams, power plant construction, etc. (see Table 10-3 in Annex A. Methods and data on material stock modelling).

The use of materials is differing between end-uses, with non-metallic minerals mainly used in buildings, roads, and other civil engineering (Figure 4-4a), whereas metals are used across all end-use categories except for roads (see Figure 4-4c).

Figure 4-4: material stocks (Gt) in EU27, 2016, by end uses and material categories

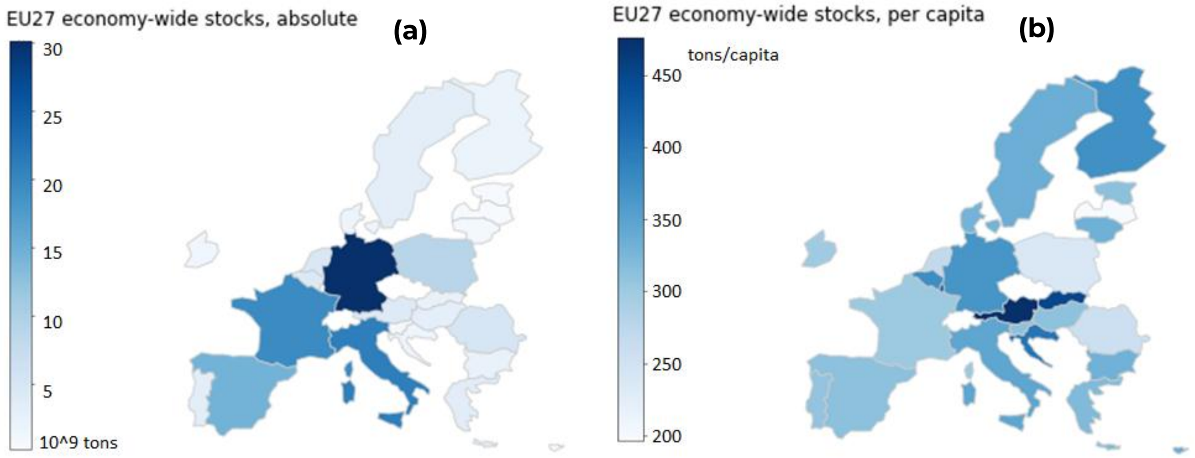


Data: *MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)*

4.2. Spatially-explicit maps of the EU material stock of buildings and mobility infrastructure

A geographical map with the country distribution of stocks (aggregated over all materials; based on MISO2) in 2016 is presented in Figure 4-5. The left panel (a) illustrates the absolute stocks per country, while the right panel (b) shows per capita stocks in 2016, darker colors indicate higher amounts of stocks. While Germany stands out with highest absolute amount of stocks with 30 Gt, followed by Italy and France with 21 and 20 Gt respectively, Austria is the country with highest per capita stock accumulation at 476 t/cap (Figure 4-5b) followed by Slovakia (451 t/cap), Luxembourg (443 t/cap), Croatia (402 t/cap), Finland (372 t/cap) and Germany (366 t/cap).

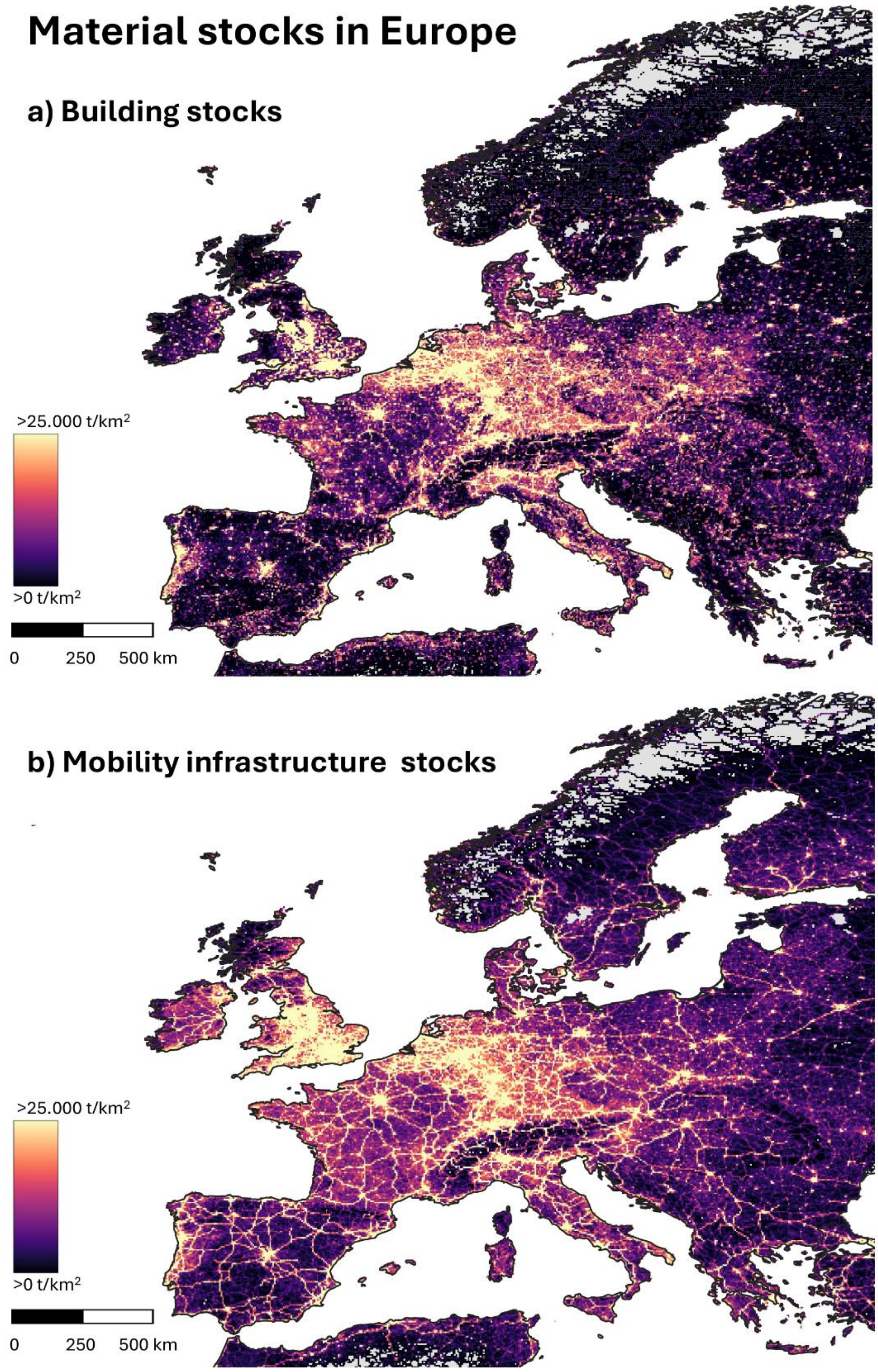
Figure 4-5: EU maps on absolute amounts of economy-wide stocks in Gt (a) and in t/capita (b), aggregated for each of the 27 member states for the year 2016)



Data: *MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)*

Figure 4-6 presents currently available spatially explicit information on material stocks of buildings and mobility infrastructure. Figure 4-6a (upper map) shows the spatial distribution of building stocks for the European region and Figure 4-6b (lower map) shows the distribution of road and rail-based infrastructure in Europe (in both maps lighter colors show higher stock density per unit of area). Building stocks are more concentrated in populated urban and sub-urban regions of Europe, while mobility infrastructure is more dispersed across the continent Stock densities for both buildings and transport infrastructure are highest in the densely populated central European “blue banana” region, in and around major European cities and transport corridors; they are lowest in the sparsely populated Northern regions of Europe and the Iberian Peninsula.

Figure 4-6: spatially explicit maps on material stocks of buildings in 2019 (a) and stocks of roads and rail-based mobility infrastructure in 2024 (b) for Europe



Legend: *Lighter colour indicate more t/km^2*

Source: (a): https://geoservice.dlr.de/data-assets/h80jhtr41x48.html ; (b): (Wiedenhofer, Baumgart, et al., 2024) and https://zenodo.org/records/10158807

4.3. Stock related flows: gross additions to stocks, net additions, maintenance & replacement

Gross additions to stocks represent the total mass flow which is accumulating in stocks in a given year, either for maintenance and replacement of existing stocks, or for building up new stocks. In 2016, total GAS accounts for 2.3 Gt/yr[12]. The material composition of GAS is similar to the one of stocks themselves, but for some categories some differences are visible. Four material categories (concrete, aggregates, asphalt, iron/steel) that enter the stock account for 87% of GAS/yr (Figure 4-7a). In total material stocks, the same four categories make up for 93%. However, concrete represents 48% of material stocks, but in GAS/yr concrete only covers 33%. Asphalt on the other hand accounts for 7% of material stocks, but 22% of GAS/yr.

End-of-life materials illustrate the flow of material outputs occurring during maintenance, replacement and total or partial demolition of buildings, roads or other infrastructure. Since material stocks in the EU are growing, the end-of-life outputs mathematically represent the amount of material used for maintenance or replacement (M&R/yr) of existing stocks (however, with differences in material composition mainly for replacement activities). In 2016, total EoL flows amounted to 1.2 Gt/yr (Figure 4-7b). The largest categories are again asphalt (32%), concrete (29%), aggregates (8%), bricks 87%), and iron/steel (6%). Excluding bricks, the four categories cover 76% of total EoL/yr. In 2016, EoL materials amount to 52% of GAS/yr, the remaining 48% are therefore net additions to stocks (NAS/yr), which means that material stocks are growing.

The material composition of EoL materials is again slightly different for the four main categories. The biggest fraction is asphalt (32%) followed by concrete (29%). Aggregates only make up for 8% of EoL. At the example of asphalt, we see that the difference in GAS/yr, stocks and EoL/yr points towards a higher demand for M&R activities for asphalt uses, which are roads.

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[12] *Total GAS in the MISO2 data differs from the Eurostat estimate, which is driven by a difference in non-metallic mineral flows while biomass, fossil energy carriers and metal are more or less consistent with Eurostat accounts. The MISO2 results is lower as compared to the ew-MFA accounts of Eurostat due to differences in the material coverage of the Eurostat and MISO estimate as well as potential inconsistencies in the coverage of secondary flows. For more details on the difference see Annex § 10.1.3. on "Methods applied to compile the Sankey diagram presented in chapter 4.4".*

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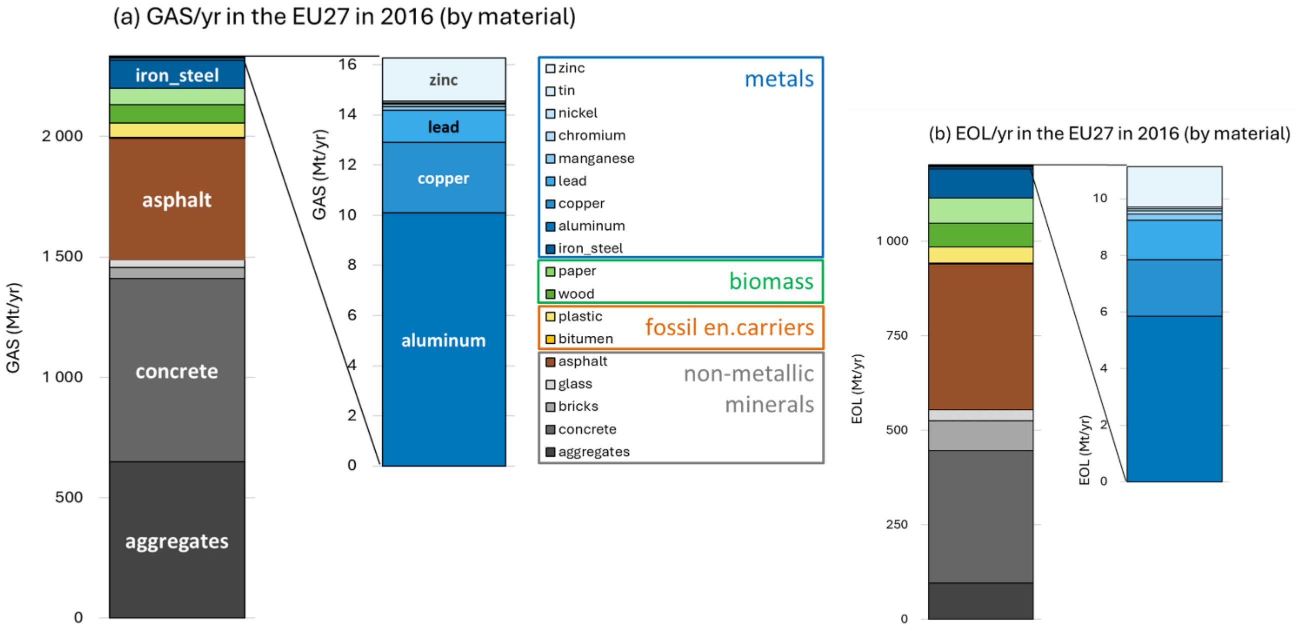
Figure 4-7: economy-wide GAS/yr and EoL/yr in the EU27 in 2016 by detailed material categories



(a) GAS/yr in the EU27 in 2016 (by material)

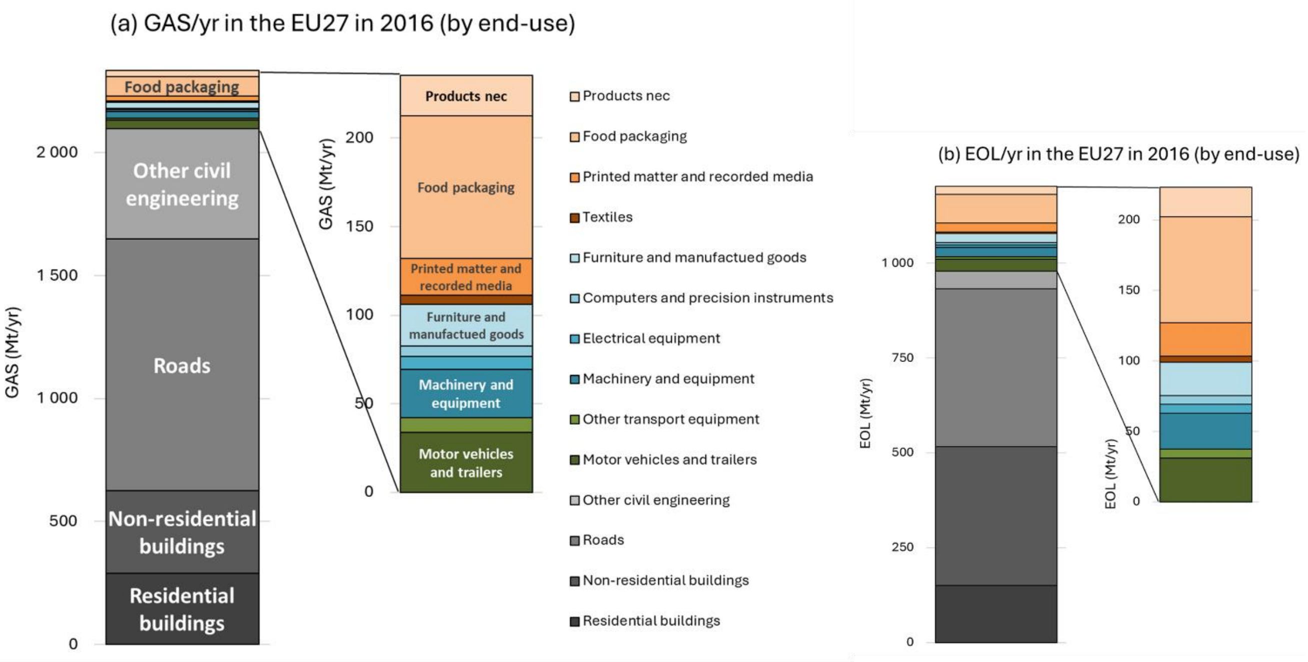
(b) EOL/yr in the EU27 in 2016 (by material)

Data: MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

A disaggregation of stock-related flows according to the type of end-use the materials are used in, is illustrated in Figure 4-8a, with total GAS being again 2.3 Gt/yr. Just as in material stocks, the largest GAS/yr are used for buildings (27%), roads (44%), and other civil engineering (19%). Following the four construction-based end-uses, food packaging is the fifth largest end use category (3.4%) in GAS/yr, followed by motor vehicles, machinery and equipment, furniture and manufactured goods, printed matter and recorded media.

The largest end-use type causing EoL/yr (Figure 4-8b) are buildings, as the sum of residential (13%) and non-residential buildings (30%), followed by roads (35%). Hence, the share of non-residential buildings increases significantly compared to GAS/yr. The high GAS/yr and EoL/yr (mathematically equalling M&R/yr) associated with roads is remarkable and emphasizes the findings presented above, where asphalt was an important category in GAS/yr but even more so in M&R/yr.

Figure 4-8: economy-wide GAS/yr and EoL/yr in the EU27 in 2016 by detailed end-uses



<u>Data:</u> MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

4.4. A Sankey Diagram for the EU27 in the year 2016

Sankey diagrams are a valuable tool that is widely used to visualize the magnitude of flows as arrows of respective width, making it easy to identify major and minor flows within the system. Sankey's help to communicate complex and multi-facetted results to stakeholders, aiding in decision-making and comparative analysis. In addition, a consistent Sankey diagram requires consistent mass balancing because each material input is traced from inputs, through the system, down to outputs.

The Sankey diagram of material flows through the EU27 economy in 2016 is created by integrating MISO2 data (i.e., gross additions to stocks, outputs from material stocks (EoL) and secondary material flows) at the detailed level of specific end-use types (e.g., buildings or machinery) with material flow data from the ew-MFA accounts of Eurostat (DE, IM, EX). In addition to the stock-building materials presented so far, the Sankey diagram includes material used for energy provision as well as material throughput (for details on methods see Annex A. Methods and data on material stock modelling, § 10.1.3). Energy use in the Sankey stands for the technical energy use of materials (fossil energy carriers, fuel wood) as well as food for humans and feed for livestock. Throughput stands for all material flows that are not added to material stocks, meaning their lifetime is shorter than 1 year (e.g., fertilizers, solvents, agrochemicals, packaging materials, or wastes from material processing that are not destined for use within the socioeconomic metabolism and are subsequently discarded to the natural environment).

The Sankey diagram for the EU27 in 2016 is presented in Figure 4-9. In 2016, the physical imports and exports amounted to 1574 and 608 Mt/yr respectively, thereby designating the EU27 as a net-importer of materials (939 Mt/yr). Of the total processed materials (PM; 6070 Mt/yr), approximately 62% (3775 Mt/yr) are derived from domestic extraction, 25% (1547 Mt/yr) from imports, and 12% (748 Mt/yr) from secondary materials[13]. 45% (2755 Mt/yr) of processed materials (PM) are used for energy purposes, comprising biomass materials for food and animal feed as well as technical energy from fossil fuels and biomass. Besides energy use, 37% (2253 Mt/yr) of PM are added to stocks (GAS/yr), 10% (608 Mt/yr) are exported, and 7% (454 Mt/yr) constitute material throughput resulting from short-lived goods, dissipative uses and losses. Of the total economy-wide stock-building materials (2253 Mt/yr), gross additions to stocks (GAS/yr) of the built environment (e.g., buildings, roads, bridges, dams and so forth) account for 93%, with all other end-uses, i.e. non-technical products (e.g. furniture, textiles), transport vehicles, technical equipment (e.g. machinery, computers) accounting for ca. 145 Mt/yr, or approximately 7% of total GAS/yr. Total end-of-life flows (EoL/yr) sum up to 1127 Mt/yr. Of this, 86% (979 Mt/yr) originate from the built environment. The total GAS with 2253 Mt/yr is approximately twice the size of the EoL flows (1127 Mt/yr). The Sankey diagram further illustrates that of all the materials that enter waste treatment (1581 Mt/yr), approximately 47% (748 Mt/yr) are recycled or downcycled as secondary materials. Furthermore, we find that the wastes deposited in landfills plus the total domestic processed outputs (DPO/yr) of the EU27 in 2016 is comparable to the size of the total domestic extraction (DE/yr).

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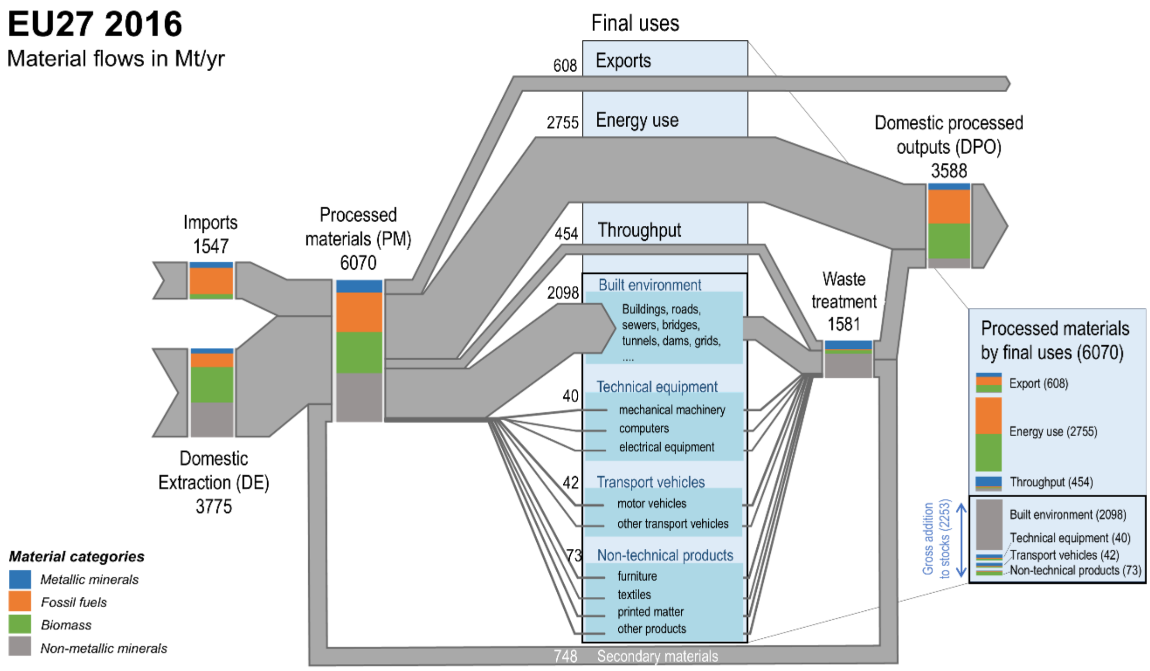
[13] *Imported goods may very well and for some products most likely comprise secondary materials. However, trade data do not provide information on the share of secondary materials, but only on traded wastes or scrap destined for recycling. Consequently, to date, secondary materials in traded goods cannot be fully considered. In this Sankey diagram, secondary materials represent the material from recycling activities in the country or region as well as traded wastes or scrap destined for recycling.*

Figure 4-9: Sankey diagram for the EU27 in 2016



Note: Flows of biomass, fossil energy carriers and metal are consistent with Eurostat accounts for DE, IM and EX. However, it is important to note that the non-metallic mineral flows in the Sankey diagram differ from the ew-MFA accounts of Eurostat (see Annex A. Methods and data on material stock modelling § 10.1.3 for details)

Source: based on Wiedenhofer et al. (2024); Wiedenhofer, Grammer, et al. (2025)

The MISO-based Sankey diagram differs from the Eurostat Sankey diagram[14] in several aspects. The most significant differences arise from larger flows of non-metallic minerals in the Eurostat data as previously described. Additionally, the diagrams differ in terms of flow structure; for instance, the Eurostat Sankey does not distinguish between material throughput and additions to stocks and does not indicate emissions from energy uses. Furthermore, differences exist in the definition of nodes, such as material use, material accumulation, gross additions and net-additions to stocks. These represent only the most apparent discrepancies. A more comprehensive analysis of these and other, potentially hidden, differences would be highly valuable but require further research.

From a **circular economy perspective**, the Sankey diagram reveals that 45% of all processed materials are used for energy provisioning, that is a dissipative use with mainly CO_2 emissions as outputs. This material is therefore 'lost' from a CE perspective. 10% of PM is exported. 19% of PM is accumulated in stocks (NAS/yr), which is material not available for loop closing in that year. Finally, 26% of PM is entering waste management, nearly half of this material (47%) is recycled. The **Circular Material Use Rate** (CMUR; Eurostat, 2024), which

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[14] https://ec.europa.eu/eurostat/cache/sankey/circular_economy/sankey.html?geos=EU27_2020&unit=THS_T&materials=TOTAL&material=TOTAL&highlight=&nodeDisagg=0101100100&flowDisagg=true&language=EN#

is calculated as the share of secondary materials in PM/yr is 12%. An EEA scenario exploration (EEA, 2023) showed that an increase of recycling to 70% would increase the CMUR only to 22%. This underlies the urgent need for taking a broader perspective on CE, expanding CE measures beyond recycling rates towards slowing and narrowing activities and including energy savings in addition.

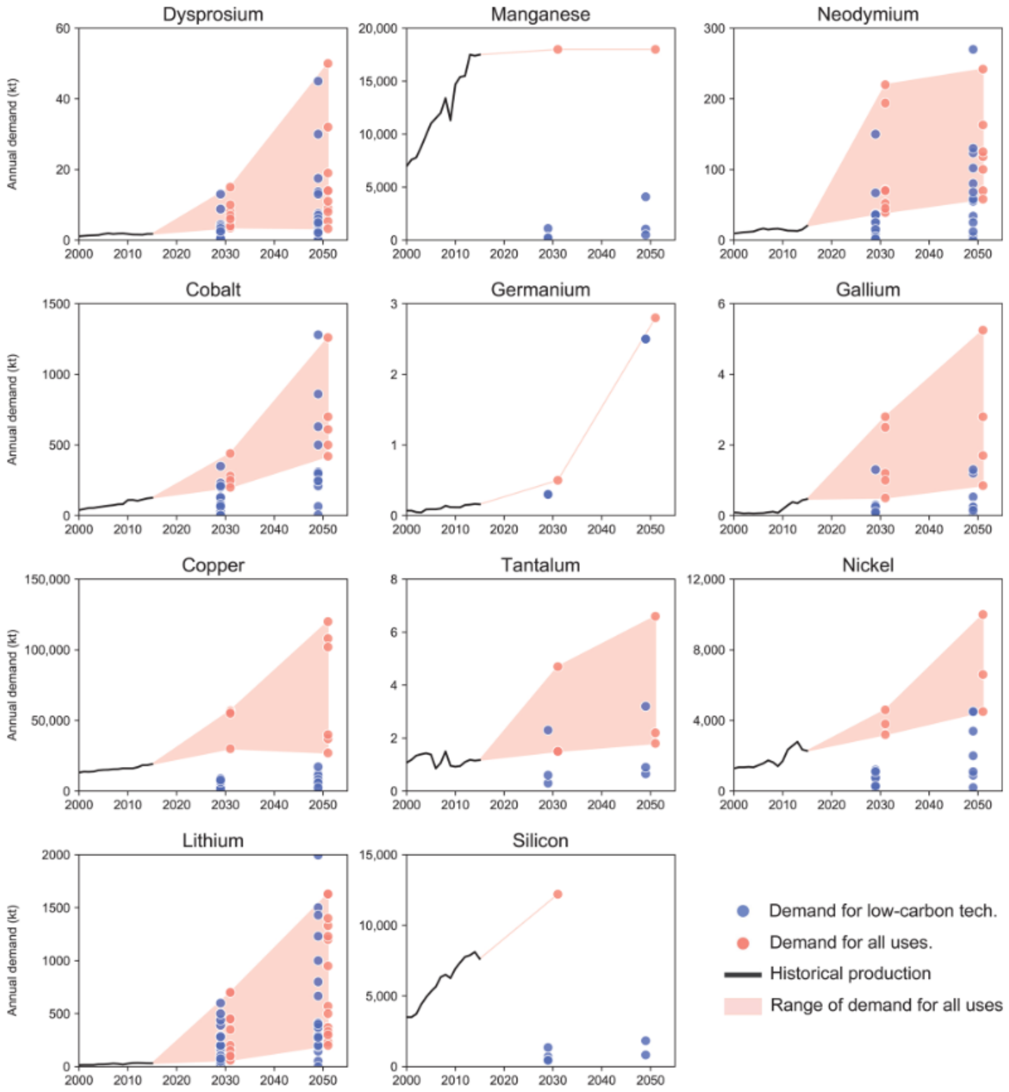
4.5. Stocks and flows of critical raw materials

In economy-wide material flow accounting (Eurostat, 2018; Krausmann et al., 2017), the empirical data is measured in metric tons. Consequently, EW-MFA is focussing more on the quantitatively large material flows such as construction materials or biomass. However, smaller flows, such as the group of critical raw materials (European Commission, 2024), which are in the focus of EU policies due to their strategic and economic importance, are part of the MFA category metals, which contribute to DMC with only 7%. But despite their little mass, the use of metals is closely linked to economic development (Graedel & Cao, 2010; UN IRP, 2013) and is therefore of strategic importance for urgent environmental challenges such as the energy transition. Unfortunately, the strategic importance of metals and CRM comes with a series of negative environmental impacts (e.g., climate heating, health impacts, biodiversity loss) occurring during metal extraction and processing as well as use in strategic technologies (UNEP, 2024).

While numerous empirical studies provide insights into specific aspects of critical raw materials, no comprehensive analysis is available that applies an economy-wide approach comparable to MFA with consistent calculation methods across different materials. Consequently, the following overview serves as an illustrative first overview rather than an exhaustive compilation and analysis.

Due to the coming energy transition in industrialized countries and in parallel the industrialization and the expansion of buildings, roads and infrastructure in emerging economies and countries of the Global South, a sharp increase in demand for critical and strategic raw materials is forecast (European Commission. Joint Research Centre., 2023; Watari et al., 2021) (see Figure 4-10).

Figure 4-10: projections of increasing global demand for metals and CRM



Source: *Watari et al. (2021)*

Resource use is increasingly influenced and confronted with geopolitical crises, threatening of global supply chains. In response to that, the EU has introduced a classification of raw materials according to their criticality (European Commission: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2017; European Commission, 2024, 2023a). A material is classified as to be critical if two facts are given: firstly, the material has strategic relevance for specific industrial processes, especially those used in future technologies, such as batteries or magnets in wind turbines and electric cars. Secondly, criticality also takes into account the risk of supply, which increases with concentration of production in a few countries, the political stability of the countries and trade relations. In 2023, the EU published an updated list of 34 critical and strategic raw materials (European Commission, 2024) (see Table 4-1) and adopted the Critical Raw

Materials Act in 2024 (European Commission, 2024), which addresses these risks in the supply of critical raw materials. Figure 4-11 illustrates the large number of technologies and socio-economic end-uses, Critical Materials are used for.

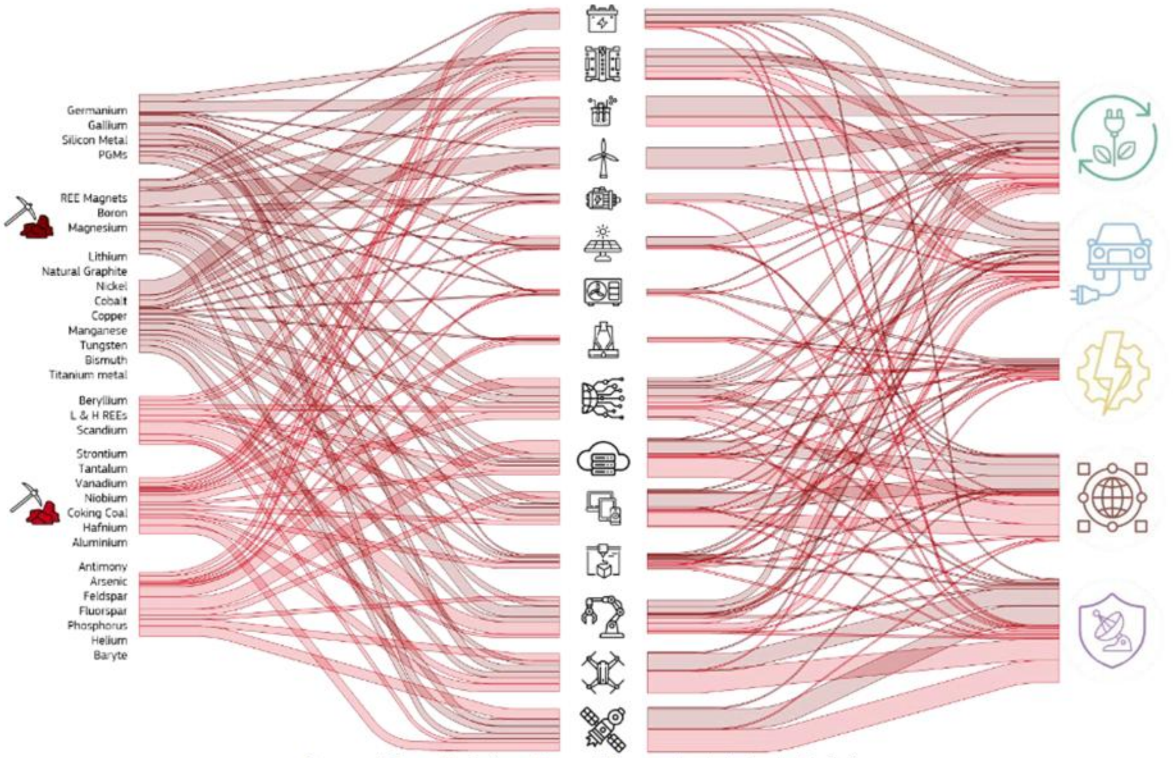
Table 4-1: list of critical raw materials (CRM) in 2024

Bauxite	Boron	Germanium	Magnesium	Copper	Titanium
Antimony	Cobalt	Hafnium	Manganese	Phosphorus	Tungsten
Arsenic	Coking coal	Helium	Natural Graphite	Scandium	Vanadium
Baryte	Feldspar	Heavy REE	Niobium	Silicon metal	Nickel
Beryllium	Fluorspar	Lithium	Platinum GM	Strontium	
Bismuth	Gallium	Light REE	Phosphate Rock	Tantalum	

Note: REE = rare earth elements

Source: European Commission (2024)

Figure 4-11: flow chart illustrating the use of material for specific technologies and socio-economic end-uses

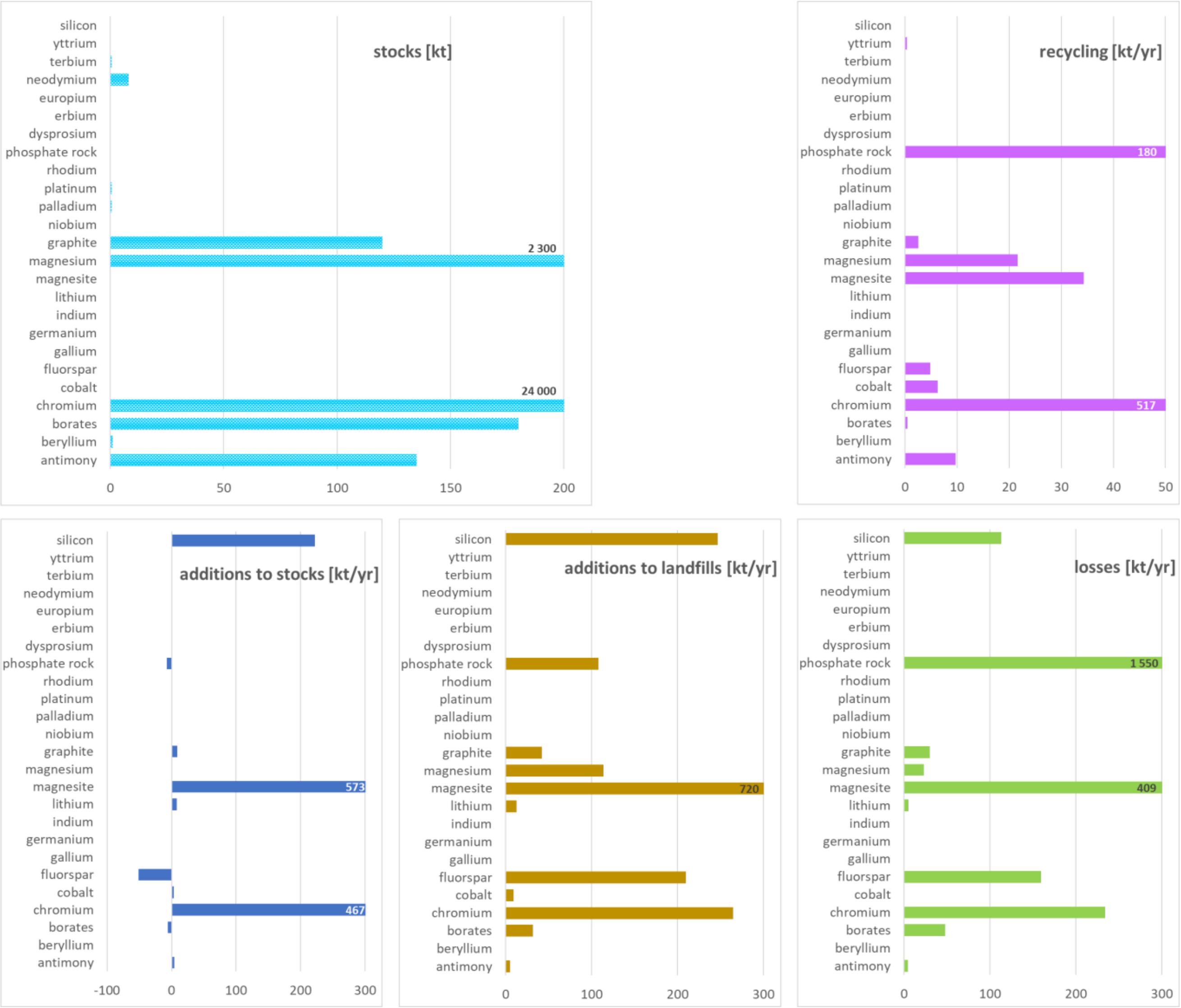


Source: JRC analysis (see Annex 3 for methodological details).

Source: European Commission. Joint Research Centre (2023)

As already mentioned, data on stocks and flows of CRM is limited from an economy-wide perspective. In the following, data from a study by Bio by Deloitte (funded by the European Commission; European Commission, 2015) is summarized for the EU28 in the year 2012 (or 2013 for some CRM) and compiled in Figure 4-12. Largest stocks and flows are observed for chromium (24 Mt), magnesium (2.3 Mt), borates (180 kt), antimony (135 kt), graphite (120 kt) (Figure 4-12). Total stocks for CRM account for 26.7 Mt. In comparison to the total stocks resulting from the MISO2 model, CRM make up for 0.02% of total stocks (144 Gt). Interestingly, the study also revealed that large amounts accumulate in landfills. While NAS amount to 3.2 Mt/yr, additions to landfills account for 2.1 Mt/yr, which underlies the relevance of landfills as urban mines and the importance of Circular Economy measures, whose overall aim is recovering these materials *before* they are landfilled.

Figure 4-12: CRM stocks and flows for the EU28 in 2012 (2013)



<u>Source:</u> own compilation based on European Commission (2015)

4.6. Environmental impacts of material use and material stocks

Environmental problems arise from both the quantity of resources used and the quality of their specific environmental impact. The quantitative dimension of resource is measured with environmental accounts (EU, 2011; UN, 2017) such as material flow accounts, which quantify the total mass of materials consumed, waste produced and emissions released into the environment. But the specific environmental impacts of one ton of material can differ greatly, imagine the impact of one ton of lithium in comparison to one ton of sand. Measures for quantifying the environmental impacts are for example life-cycle assessments, which calculate the environmental impact of products along the entire production chain or even including disposal). However, the environmental impact of a material, for example, depends on various factors, such as: the final product, the material is used in, the selection of impact categories (i.e., climate heating, land use, ozone depletion, human toxicity, particulate matter, ionising radiation, photochemical ozone formation, acidification, eutrophication, ecotoxicity, land use, water use, resource use), the allocation of multifunctional processes such as used infrastructure, means of transport, etc to the products, etc. Consequently, an LCA assessment is a complex matter, in particular if different countries and different points in time are analysed and compared. Due to the complex data requirements, an impact assessment is best done for companies or specific products, but very difficult on the national level requiring a series of weighty assumptions. For this reason, MFA indicators are used as a proxy for the related environmental impact on the national level.

Only few examples are available where an LCA impacts assessment is linked to MFA results. Most prominently, the UN International Resource Panel published an impact assessment in the 2024 report Global Resources Outlook (UNEP, 2024) covering the following environmental impacts: climate impacts, PM health impacts, water stress, biodiversity loss (land), biodiversity loss (freshwater eutrophication), amended by socioeconomic impacts on value added, workforce (see Figure 4-13). Among the provisioning systems, one category addresses the built environment (red category in Figure 4-13) and hence closely links to material stocks. From the IRP analysis, the built environment has the highest impact on climate heating, PM health impacts, and to a lesser extent on biodiversity losses. A similar evaluation could be performed for the EU27 in a follow-up research activity to this study. A recent volume in scientific journal is following similar lines, focussing on the issue of sand and its underestimated sustainability relevance (e.g. Pereira et al., 2025; Watari et al., 2025). An EEA study (EEA, 2023) on the other hand, identified the environmental footprint of ready-to use non-metallic minerals as minor in comparison to the other material categories.

Figure 4-13: global environmental impacts resulting from provisioning systems, 2022

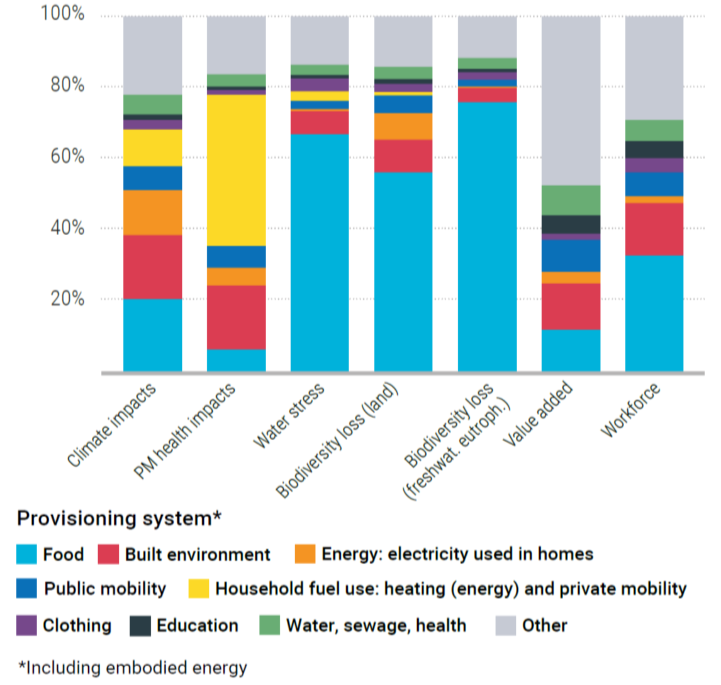


Figure 3.6: Relative contribution of provisioning systems to global environmental and socioeconomic impacts for 2022. For each provisioning system, impacts cover the whole life cycle including extraction, production, transport, use and end-of life. The provisioning systems energy and mobility are represented in the graph by public mobility (dark blue), energy (orange, including electricity, hot water supply and the production of fuels) and household fuel use (yellow, including direct emissions from private mobility and heating). Energy and mobility used by the other provisioning systems (such as for food) are allocated to these provisioning systems.

Source: *UNEP (2024)*

4.7. Conclusions on the size, composition and uses of material stocks

In 2016, **material stocks in the EU27 amounted to 144 Gt, averaging 325 t/cap. Concrete (49%), aggregates (34%), and asphalt (7%) are dominating the stocks**, with buildings (54 Gt), roads (46 Gt), and other infrastructure (42 Gt) as primary end-uses concentrated in urban areas and transport corridors. Together with bricks and iron/steel (4% each) and wood (2%), these materials cover 99% of total stocks. The remaining 1% include all other materials such as glass, plastics, the large variety of metals, and all minerals listed among the critical raw materials.

In 2016, gross additions to stocks (GAS) amounted to 2.3 Gt/year, with 87% consisting of concrete, aggregates, asphalt, and iron/steel. End-of-life outflows (EoL) of stocks make up for 1.2 Gt/year, representing all discarded products and demolished buildings or infrastructure. In a situation of growing material stocks, the discarded material needs to be replaced on the input-side and thus represents maintenance and replacement of existing structures. Consequently, **in the EU27, 52% of material inputs to stocks (GAS) are used for maintenance and replacement (M&R).** The example of asphalt shows a higher relative share in EOL as compared to the other materials, highlighting its high replacement rate in roads. The net additions to stocks (NAS) amount to 48% of GAS, confirming overall stock growth.

A Sankey diagram of material flows showed that nearly half of processed materials were used for energy purposes, the other half is material use mainly accumulated in stocks. A minor share of material use (18%) is used and reaches end-of-life stage within a year. Of the 1.6 Gt/yr entering waste management only half is recycled. **The Circular Material Use Rate (CMUR) stood at 12%, underscoring the need for broader circular economy measures.**

While bulk materials, e.g. construction materials, dominate in volume, materials used in smaller amounts such as critical raw materials have high strategic importance and are characterized by higher direct environmental impacts. The current energy transition **boosts the demand for CRMs, which are at the same time facing geopolitical risks in supply as well as challenges in recycling. Hence, the need for circular economy strategies along the full spectrum of 10Rs is evident.** We have to rethink and reduce the size and growth of material stocks, enhanced all activities slowing resource use (reuse, maintain, repair, refurbish, remanufacture, repurpose) before we finally exploit full potential of recycling and recover as the least option.

5. Trends in material accumulation

Chapter 5.1 presents the long-term development of material stocks and related material flows (inflows: GAS/yr and NAS/yr; outflows: EoL/yr) in the EU27 from 1970 to 2016. Chapter 5.2 investigates the relation of stock development with economic development as well as energy use and CO_2 emissions for the period 1990 to 2016 and compares stock flow trends across EU27 member states and in international comparison (Japan, USA and China).

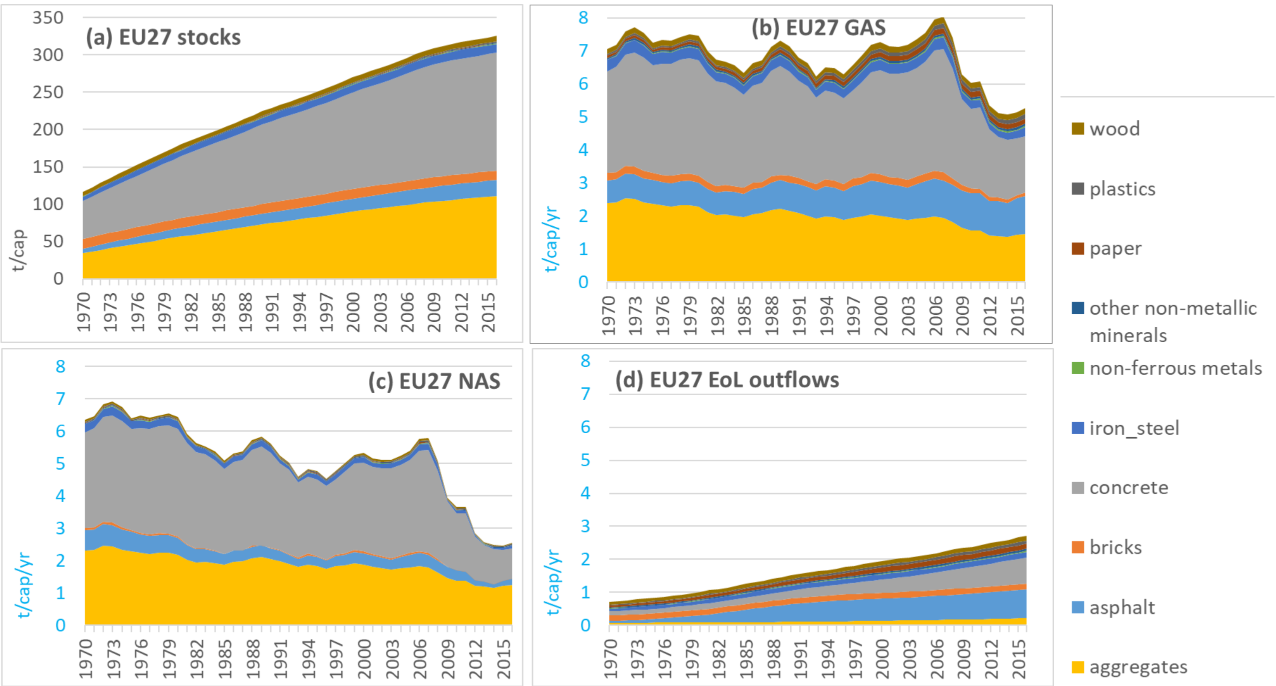
5.1. Trends in EU material stock accumulation

Material stocks grew continuously in the EU27 (Figure 5-1a) from 117 t/cap in 1970, to 325 t/cap in 2016, resulting in a growth by a factor of 2.8 over 45 years. Annual growth rates were 5% at the beginning of the 1970s, then steadily declined to 2.5% in the mid 80s, 1.5% in the early 2000s and since 2011 dropped below 1%. Material stock growth seems to be close to stagnation until the end of the observed period with an annual growth of 0.6% in 2016. Ongoing updates of these time series will show if European material stocks indeed stabilize, or if stock growth accelerated again.

Material composition did not change significantly during the 45 years considered. Concrete constitutes the largest fraction (44% in 1970 and 48% in 2016) followed by sand and gravel, summarised as “aggregates” (29% in 1970 and 34% in 2016). Bricks still made up 11% of material stocks in 1970 but declined in relevance and in 2016 only accounted for 4%.

In contrast to the steady growth of material stocks, additions to stocks followed a slightly different path, showing how stock-flow dynamics behave differently. Gross additions to stocks (GAS/yr, representing the total amount of material accumulated in stocks each year) were more or less constant between 1970 and 1990, although with fluctuations between a maximum of 7.7 t/cap/yr in 1973 and a minimum of 6.3 t/cap/yr in 1985. Since 1990, the trend changed, with GAS/yr declining by 26% from 7.1 t/cap/yr to 5.3 t/cap/yr in 2016 (Figure 5-1b). The decline was observed for all bulk construction materials, but most pronounced for bricks and concrete (-49% and -46% respectively). Net additions to stocks (NAS/yr) followed a very similar trend (Figure 5-1c) as observed for GAS/yr, with a decline from 7 t/cap/yr in 1973, to 5.6 t/cap/yr in 1990 (-19%), and then dropping again by -55% to 2.6 t/cap/yr in 2016. Outflows from stocks, i.e., end of life wastes (EoL/yr, Figure 5-1d) in the form of demolition and discards were constantly increasing, from 0.7 t/cap/yr to 2.7 t/cap/yr, by a factor of 3.8. The steady increase of EoL/yr is a characteristic time-lagged pattern that goes along with increasing and ageing stocks.

Figure 5-1: Development of stocks and stock-related flows in the EU27 between 1970 and 2016, along material groups; (a) total accumulated stocks in t/cap, (b) gross additions to stocks (GAS) in t/cap/yr, (c) net additions to stocks (NAS) in t/cap/yr, end of life outflows (EoL) in t/cap/yr.

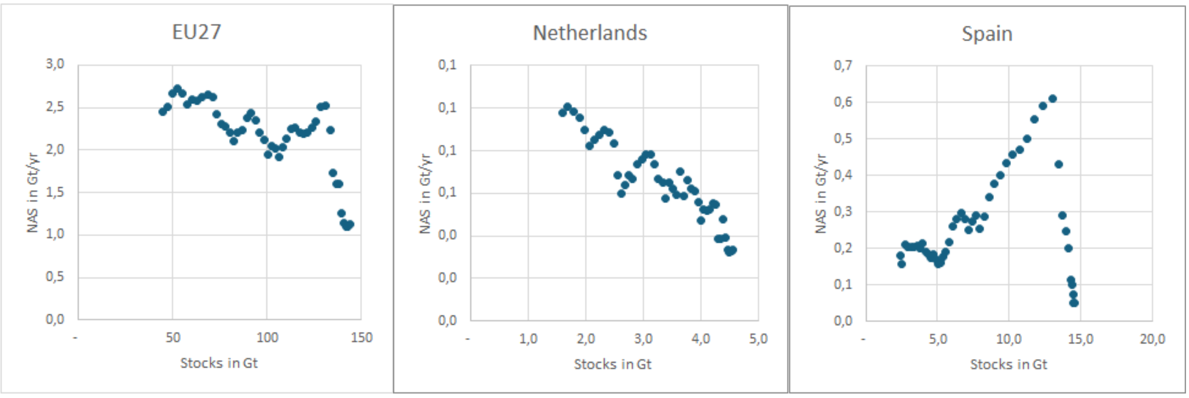


Data: MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

The contribution of member states to the EU aggregate did not change in relative terms. Germany, France and Italy were the top three countries with largest total amounts of stocks both in 1970, as well as 2016. However, different patterns of stock development can be observed within the EU member states.

Figure 5-2 shows trajectories of stock growth in the EU27 and two countries (The Netherlands and Spain) which are characterised by different types of trajectories. To show the evolution and speed of stock growth, data on the net additions to stock per year (i.e. the annual net flow of stock-building materials into stocks) is plotted against the size of total stock for the period 1970 to 2016. In the EU27 (Figure 5-2a) NAS/yr shows an overall declining trend, interrupted by shorter periods of increasing NAS/yr. The slowly declining trend in the 1970s and 1980s means that while stocks kept growing, stock growth slowed down. After the financial crisis in 2008, NAS/yr saw a strong decline from 2.5 Gt/yr to only 1 Gt/yr in 2016. If this trend is to continue, stocks will eventually stabilize in the EU27. Looking at trends in NAS across member states, we find different types of stock trajectories: We can identify a group of countries with continuously declining NAS/yr, i.e. in these countries stock growth gradually slows down. If this trend continues, these countries are on a path towards stock saturation. Among the countries with such a trend are the Netherlands (Figure 5-2b), Germany, France or Finland. Another group of countries is characterized by a strong increase in NAS/yr (i.e. exponential stock growth) which peaks around 2008, followed by a strong decline in NAS. Among these are countries, which first catch up economically and are then hit hard by the 2008 economic crisis., are e.g. Spain (Figure 5-2c), Portugal, Ireland or Cyprus. The Eastern European countries typically show strong fluctuations in NAS/yr, often beginning with a strong decline in NAS/yr after 1990, followed by a strong increase which peaks around 2008, followed by another decline.

Figure 5-2 Speed of stock growth 1970-2016: Net additions to stock (y-axis) plotted against stocks (x-axis) in the EU27 (a), The Netherlands (b) and Spain (c)

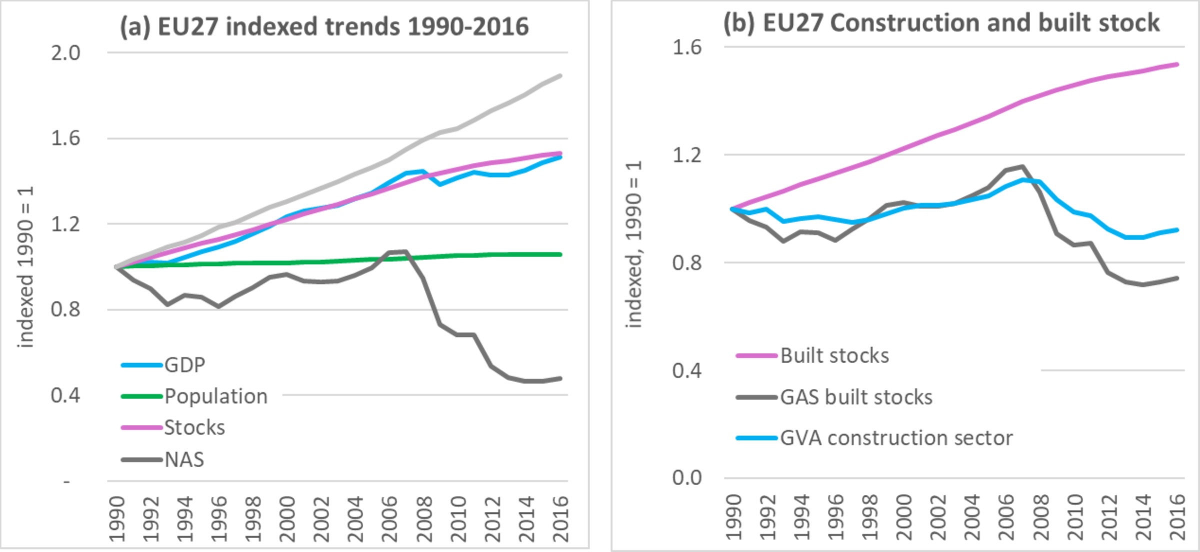


Data: *MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)*

5.2. Links between material stocks and other biophysical and socio-economic data

Since 1990 material stocks in the EU27 have grown by a factor 1.5 (Figure 5-3a), i.e. much faster than population, indicating that the size of per capita stocks has been increasing in the EU27 (see Figure 5-3a) also shows that overall stocks have grown at a similar pace as GDP and followed largely the same trajectory as GDP until 2008, the year of the global financial crisis, when stock growth slowed down compared to GDP, with a slight slowdown of stock growth compared to GDP since 2008. Material flows associated with the build-up of new stocks (net additions to stock; NAS/yr) and the maintenance of stocks & the replacement of end-of-life stocks (M&R/yr) follow a different trajectory: As a result of strong stock growth in the past decades, a growing share of the stock is reaching its end-of-life and thus a growing amount of material is used to maintain or replace the already existing stock (M&R/yr). As a consequence, M&R flows have been growing steadily by factor 1.9 since 1990, reaching 1.2 Gt/yr in 2016. In contrast, net additions to stock (NAS/yr) have declined over time from 2.4 Gt/yr in 1990, to 1.1 Gt/yr in 2016, experiencing a particularly strong decline since 2008 (-55% from 2008-2016). The reduction of NAS/yr at the EU27 level is strongly related to a decline in construction activity (as indicated in terms of a decline in Gross Value Added (GVA) of the construction sector) following the 2008 financial crisis: Figure 5-3b shows the development of the built stock (comprising stocks of buildings, roads and other civil infrastructure) in relation to the development of GAS/yr related to built stocks and the GVA in the construction sector. The masses of materials entering stocks (GAS/yr) closely follows the trajectory of GVA in the construction sector with a strong decline since 2008, while built stocks continue to grow, albeit at a somewhat slower pace.

Figure 5-3: Development of EU27 material stocks and material flows (net additions to stock (NAS/yr), maintenance & replacement (M&R/yr)[15], gross additions to stocks (GAS/yr), GDP/yr and population from 1990 to 2016. (a) Total stocks and flows and (b) Built stocks and construction. Indexed with values in 1990 = 1



<u>Data:</u> MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

Stocks have been growing faster than population in the EU27, resulting in increasing stocks per capita. On average, the mass of buildings, infrastructures and durable goods available per capita in the EU27 has increased by 45% between 1990 and 2016, when it reached 324 t/cap (Figure 5-4a). This is a higher level than in Japan (282 t/cap), but considerably less than in the USA (439 t/cap). Meanwhile, average per capita stocks in China have grown rapidly from a very low level in 1990 (35 t/cap), to 224 t/cap in 2016. Across EU27 countries, per capita stocks ranged between 196 t/cap in Latvia and 477 t/cap in Austria in 2016.

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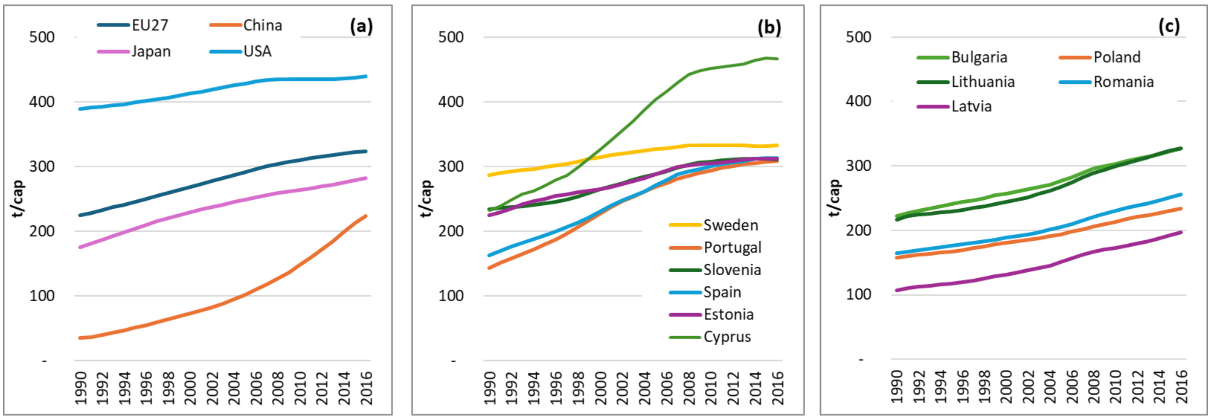
[15] *Note that the near linear increase of M&R is an artefact of the applied modelling approach, which cannot capture year to year fluctuations due to e.g. economic fluctuations. The overall increasing trend and the magnitude of growth of M&R is, however, robust.*

Figure 5-4: development of material stocks per capita of population from 1990 and 2016 for (a) EU27, USA, Japan and China, (b) selected countries with stabilizing per capita stocks, and (c) selected countries with growing per capita stocks.

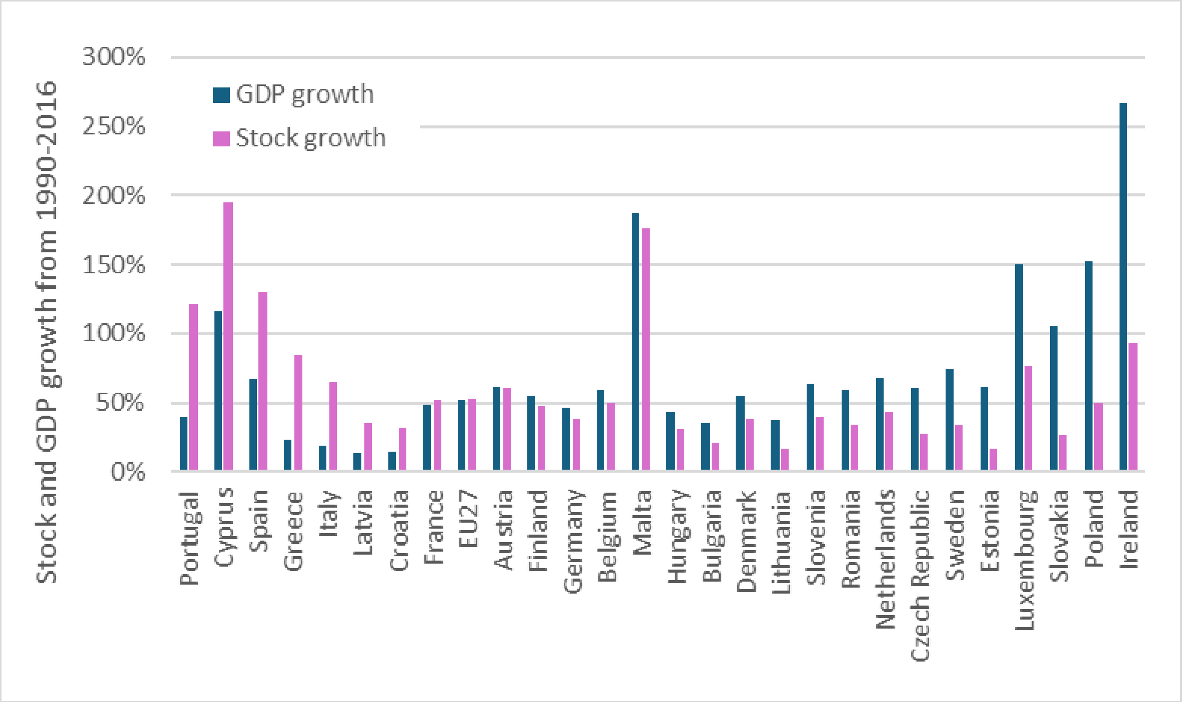


Data: *MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)*

Trends of per capita stock development also differ strongly across EU27 countries. In most countries growth of per capita stocks has slowed down over time and seems to approach saturation at high levels. In some countries, among them Sweden, Slovenia, Portugal, Spain and Estonia, per capita stocks seem to have stabilised, often since around 2008 (Figure 5-4b). But there are also countries where stocks continue to grow and a stabilisation of per capita stocks is not yet visible (Figure 5-4c). Many of the countries with continuously high growth rates of per capita stocks are Eastern European countries, which started at lower stock levels available per person. Further analysis is required to scrutinize country-specific patterns and trends to understand the drivers behind these different trajectories.

While aggregate stocks in the EU27 have grown largely with the economy between 1990 and 2016 (Figure 5-3a), across EU27 member states stock and GDP growth show considerable divergence. Figure 5-5 compares the growth of stocks and GDP in the period 1990-2016. It shows that in only 7 countries (Austria, Finland, Germany, Belgium, Malta, Hungary and Bulgaria) stocks and GDP grew at a similar pace (less than 15% points difference) in the observed period; in 11 countries (on right side of Figure 5-5) stocks grew at a significantly slower pace than GDP (e.g. in most Central and Eastern European countries but also in Ireland – all countries with comparatively high economic growth), but there are also 7 countries in which stocks grew much faster (e.g. Spain, Portugal, Italy or Greece).

Figure 5-5: Growth of stocks and GDP in EU27 member states from 1990-2016. The order of countries is according to the difference between stock growth and GDP growth. Countries with a much larger stock than GDP growth are shown on the left side and countries with a much faster GDP growth on the right side

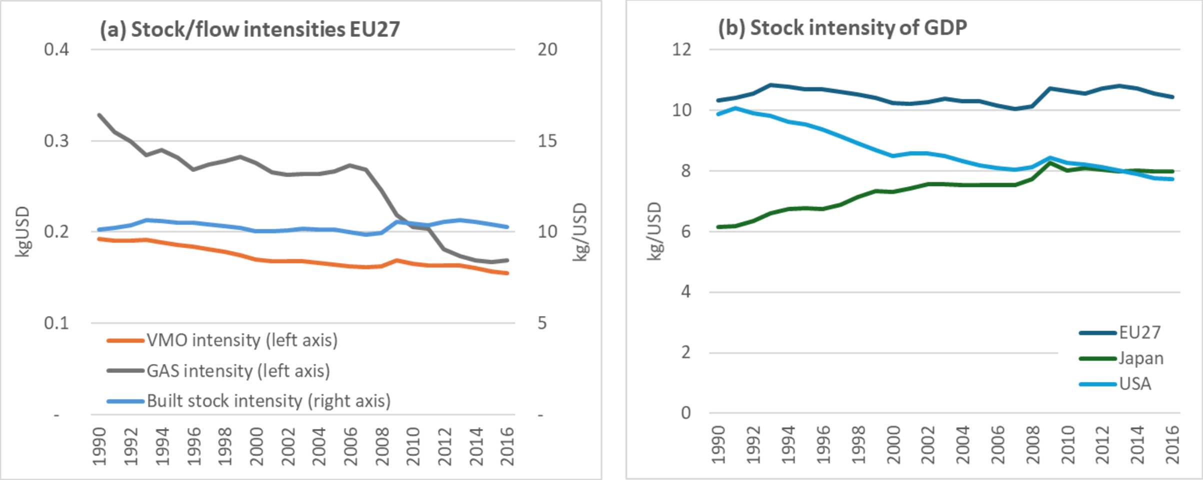


Data: *MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)*

Resource intensity, i.e. the flows of materials and energy used per unit of GDP (often also the inverse is used, which is termed resource efficiency) is an important aggregate indicator for the resource dependency of an economy. Also, material stocks and the related material flows are intimately related to production and consumption processes. The indicators GAS per unit of GDP (stock-building intensity of GDP) and stock per unit of GDP (material stock intensity) relate the inflow of stock building material and the accumulated material stocks to economic activity and provide a highly aggregate perspective on the resource efficiency of an economy. For a decoupling of stocks and flows from GDP, improvements in stock and flow intensity need to be achieved. Figure 5-6a shows these relations in terms of the development of stock and flow intensities of GDP in the EU27. It shows that in 2016 in the EU27 ca. 0.15 kg of stock of stationary machinery, vehicles and other durable goods (MVD stock) and 10 kg of built stocks were in use per US$ of GDP; in terms of flows around 0.17 kg of materials were used to maintain and expand stocks (GAS) per US$ of GDP. Over time, stock intensity of GDP did not change much for both MVD and built stocks for the EU27 total, indicating that no considerable decoupling between stocks and GDP occurred. With respect to gross additions to stocks (GAS/year), however, intensity improved considerably, with an acceleration after 2008; this mirrors the general trend of a decoupling of GDP and material use (DMC/yr) in the EU27 after 2008 (Eurostat 2024). Across EU27 countries, stock and flow intensities vary by a factor of 11 for built stocks, a factor 6 for

MVD stock and factor 7 for material inflows. In 2016 the lowest stock and flow intensities were recorded for Ireland, Netherlands, Denmark and Luxembourg; among the countries with the highest stock flow intensities were Bulgaria, Croatia, Romania and Slovakia. Figure 5-6b shows that in the EU27 more stocks are used per unit of GDP than in Japan and the USA: Total stock intensity of GDP in the EU27 was more than 30% higher than in Japan and the USA in 2016. While stock intensity in the EU27 did not show a significant improvement over time, it declined considerably in the USA and increased and later stabilised in Japan.

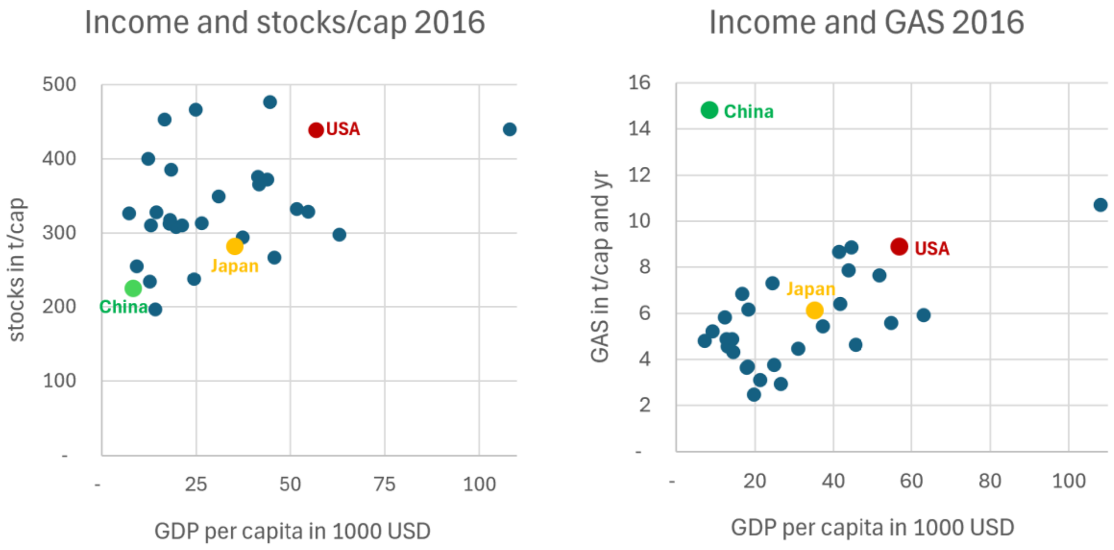
Figure 5-6: Development of stock and flow intensities from 1990 to 2016 for a) built stocks and stationary machinery, vehicles and other durable goods (MVD stock) and gross additions to stock (GAS) for the EU27, b) Total stock intensity for EU27, Japan and USA. GDP in US Dollars at constant 2015 prices (United Nations 2024).



Source: Data: MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

Globally across all countries, a clear relation between the level of income (GDP/cap) and the level of per capita stocks and related flows can be observed. On average, high-income countries have factor 10 higher per capita stocks of buildings, infrastructure, vehicles, machinery and goods and also higher per capita stock related material flows (e.g., GAS) than countries with low income (Plank et al. 2022; Wiedenhofer et al. 2024). Within the EU27 countries no clear relation between income and total per capita stocks can be found, as all those countries are already classified as high income countries. In Figure 5-7 a total material stocks per capita and in panel b gross additions to stocks (GAS) per capita are plotted against income. It shows that within the high income country group, there is no clear pattern that countries with higher income are likely to also have higher levels of stocks or related material flows. Countries like Ireland or the Netherlands have comparatively low per capita stocks (below 300 t/cap) and per capita GAS (5-6 t/cap/yr) despite very high income levels; vice versa, Cyprus or Slovakia are at the lower end of the EU27 income range, but have very high per capita stocks (above 450 t/cap).

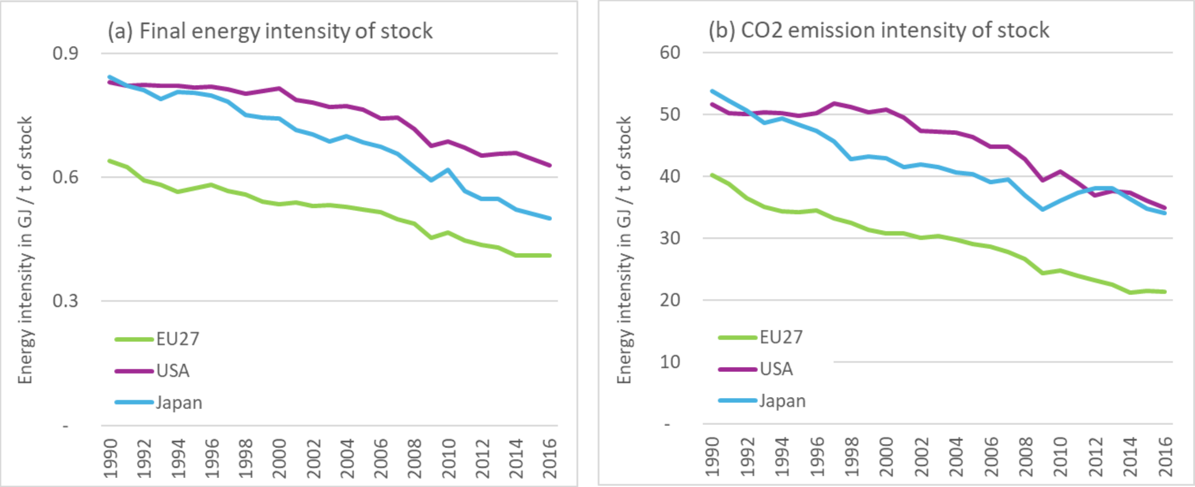
Figure 5-7: (a) Material stocks per capita and (b) material flows (GAS) per capita vs. income (GDP/cap/yr) in 2016 in EU27 member states and in the USA (red dot), Japan (yellow dot) and China (green dot). GDP in US Dollars at constant 2015 prices (United Nations 2024)



<u>Data:</u> MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

Previous research has shown a strong relation between energy consumption and material stocks, because most of the final energy used in a country is either used to produce stocks (i.e., more or less all industrial final energy use) or to provide services from stocks (e.g., energy use for transport, residential energy use, operating machinery and electronic devices) (Krausmann et al. 2020). Figure 5-8 investigates the development of the relation between material stocks and final energy consumption and CO_2 emissions for the EU27 from 1990 to 2016 in comparison with the USA and Japan. Figure 5-8a shows the amount of final energy (most of which is used to operate stocks and provide services from them) in a country. The trajectory over time is a result of changes in the stock mix (e.g. built structures, vehicles, machinery – which have very different level of energy requirement per ton of stock) and improvements in the energy efficiency of each stock type (i.e. of operating a car or heating a building). Overall energy intensity of stocks has continuously improved over time in the EU27 and is much lower than in the USA and in Japan. In 2016 aggregate final energy intensity of stocks was only 0.4 GJ/ton of stock and year in the EU27 compared to around 0.6 GJ/ton and year in the USA and 0.5 GJ/ton in Japan. Across EU member states final energy intensity of stocks varied by more than a factor of 3 from 0.2 GJ/ton in Croatia to 0.69 GJ/t in Finland. Also, in terms of CO_2 emission intensity of stock (Figure 5-8b), which also factors the CO_2 intensity of the energy system in, the EU27 performs better than the USA and Japan. Emission intensity in the EU27 has improved by -47% compared to -32 and -37% in the USA and Japan, respectively and is 37 to 39% lower than in these countries. The decline in emission intensity is a result of reductions in final energy intensity of stock and improvements in the decarbonisation of the energy system in the EU27.

Figure 5-8: Trajectories of final energy intensity (a) and CO_2 emission intensity (b) of stocks in the EU27 in comparison to USA and Japan



Sources: Based on data sourced from the International Energy Agency, 2024 (Final Energy Consumption) and World Bank, 2024 (Carbon dioxide (CO2) emissions (total) excluding LULUCF (Mt CO2e))

Data: MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

5.3. Conclusions on stock trends

Stock growth and saturation: Stock growth is a major driver of material and energy use, because building up, maintaining and operating stocks requires continuous flows of materials and energy. Growing stocks also hamper the closing of material loops in a circular economy, because of the simple physical principle of mass-balance – larger material flows are required to grow material stocks, than secondary end-of-life materials are occurring as outputs of the use phase of material stocks. To minimise the demand for primary materials, energy and the outflow of emissions, it is therefore necessary that stock growth comes to a halt and that stock production and operation becomes more material and energy efficient.

The empirical evidence presented here indicates that the EU27 is not yet on track. While stock growth has slowed down in particular since 2008, EU27 stocks continue to grow, although they are already at a rather high level per capita of population. In some member states, however, there are signs of saturation of per capita stocks. It is, however, unclear, if the stabilisation of per capita stocks, which in many countries coincided with the 2008 financial crisis is a lasting phenomenon or only temporary.

Stocks and economic development: Stocks are key for production and consumption processes and to provide services like mobility, shelter or communication to society. On a global scale, stocks have roughly been growing in unison with GDP (Krausmann et al. 2017). In the EU27 stocks grow at a slower pace as GDP, which means that there is a relative decoupling of stock growth and economic development. In contrast, material inflows to build up and maintain stocks have declined since 2008, i.e. we observe an absolute decoupling of stock related material flows (GAS/yr) from GDP. While there is a coupling of GDP and stock development in EU27 countries over time, income (GDP/cap) seems not a good predictor for the level of (per capita) stocks across EU27 member states and we find countries with very high income with lower per capita stock levels than countries with lower income. Obviously other factors have a strong influence on the stock level. The role of e.g. urbanisation, population density or climate conditions for the level of per capita stocks requires further investigation. Over time we observe considerable improvements in the aggregate energy and CO_2 intensity of stocks, which reflects improvements in the energy efficiency of industrial processes and stock operation and of the decarbonisation of the energy system; however, improvements have slowed down – and in some countries intensities are still high.

6. Links between Circular Economy and material stocks – cross-sectoral perspective

Chapter 6 provides a cross-sectoral overview of the interlinkages between the Circular Economy and material stocks and consists of the following sub-chapters:

- A reminder of the policy context of the Circular Economy in the European Union (§ 6.1);
- A high-level justification of the relevance of considering material stocks for the implementation of Circular Economy (§ 6.2);
- A qualitative description of the impacts that Circular Economy measures are intended to have on the stock of fixed assets and of durable consumer goods (§ 6.3);
- A quantification of the reciprocal impacts that the existence of material stocks has on the implementation of Circular Economy measures (§ 6.4 and 6.5);
- A concluding summary table of these interlinkages between material stocks and Circular Economy (§ 1.4).

6.1. The policy context of the Circular Economy

The Circular Economy (CE) concept is currently the most prominent approach towards sustainable use of **material resources** (European Commission 2023, 2020). More sustainable resource use is necessary in a finite world. By reducing the need for the production of new primary basic metals, materials and chemicals (BMMCs) that are the major industrial sources of Greenhouse Gases (GHG) emissions[16], the CE also has the potential to play a major role in the **mitigation of climate change**. It thereby complements the other climate policies oriented towards the decarbonisation of production processes and the sustainable use of energy (European Commission 2019).

CE activities (see detail in § 6.3 below) aim to cover the **whole lifecycle** of materials and products, through measures aiming to (a) narrow material cycles (refusing product use,

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[16] *The sectors:*

- *Manufacture of paper and paper products (NACE rev. 2 code 17);*
- *Manufacture of coke and refined petroleum products (NACE rev. 2 code 19);*
- *Manufacture of chemicals and chemical products (NACE rev. 2 code 20);*
- *Manufacture of other non-metallic mineral products (NACE rev. 2 code 23);*
- *Manufacture of basic metals (NACE rev. 2 code 24);*

represent between 89% and 90% of all GHG emissions of non-food manufacturing (NACErev.2 code C, without codes C10 to C12) over the years 2008 to 2023. Source: Eurostat (2024) Air emissions accounts by NACE Rev. 2 activity [env_ac_ainah_r2] https://ec.europa.eu/eurostat/databrowser/view/env_ac_ainah_r2__custom_14791756/default/table?lang=en rethinking products and new product design, reducing the number and size of products used), (b) slowing material cycles by extending product lifetimes (reuse, repair, refurbish, remanufacture, repurpose), and only as the final step (c) closing material cycles (recycling, recover) (see the 10R scheme by Morseletto, 2020; based on Potting et al., 2017). The three groups that structure the 10Rs entail a hierarchy with the highest priority given to narrowing strategies, which focus on reducing the amount of material entering socio-economic processing. Then, second priority is given to slowing strategies that address the use phase of products and assets and aims at prolonging this to the largest possible extent. Only the third and last step is at the point of products reaching their end-of-life stage and entering waste management. At that point, materials should be recycled and only if a further material use is no longer possible or feasible, then thermal recovery is the final R-option. The CE hence goes beyond a waste and end-of-pipe oriented perspective, and addresses the whole economy, economy-wide resource use and societal stock accumulation.

In the EU, the policies supporting the move towards a more circular economy have borne on:

- The **ecodesign** of **products** (towards longevity, maintainability, repairability, recyclability, the reduction of energy or water use, the avoidance of hazardous substances), via the Ecodesign for Sustainable Products Regulation (ESPR)[17];
- The **material efficiency** of **industrial processes**, via the revision of the Industrial Emissions Directive (IED 2.0)[18];
- **Product/sector-specific** measures on:
    - Construction (see details in § 7.2.1 below);
    - Batteries (see details in § 7.3.1 below).

CE policies are developed in the EU, but also in other jurisdictions (Haas et al. 2015, 2020, 2023; Jacobi et al. 2018; de Wit et al. 2019; Miatto et al. 2024; Wang et al. 2020; Škrinjarić 2020; Bianchi and Cordella 2023; Wiebe et al. 2019; Aguilar-Hernandez et al. 2021; Röck et al. 2021).

The progress towards a CE is **monitored** economy-wide (European Commission 2014, 2015), using tools based on the methods developed by the Institute of Social Ecology at BOKU in Vienna – Austria (Haas et al. 2015; Mayer et al. 2019).

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[17] *Regulation (EU) 2024/1781 establishing a framework for the setting of ecodesign requirements for sustainable products, available at: http://data.europa.eu/eli/reg/2024/1781/oj*

[18] *Directive 2010/75/EU on industrial and livestock rearing emissions (integrated pollution prevention and control), as emended by the Directive (EU) 2024/1785, consolidated text available at: http://data.europa.eu/eli/dir/2010/75/2024-08-04*

6.2. Relevance of considering material stocks for the implementation of Circular Economy

Current Circular Economy measures and indicators focus on resource **flows** and largely ignore the key role of material **stocks in shaping flows**. This role of material stocks appears in the following fields:

1. At a global level, 55% of all material inflows were used for the set-up and maintenance of material stocks in 2010 with the trend growing (this value was only 50% between 1970 and 1990, 30% in 1945 and 25% in 1900).[19,20] In the EU27 in 2016, the share of processed materials dedicated to the build-up and maintenance of stocks was 41%, as illustrated in the Sankey diagram of the European Union (Figure 4-9). Consequently, acting on the **size** and dynamics of material stocks is likely to have a major impact on the global as well as European resource use and on the sustainability of its economic and social model;
2. The existence of stocks strongly contributes to the quality of life and to the productivity of our economies (as shown above in section 5.2 and hence is a strong determinant of the metabolism of our societies (Vélez-Henao and Pauliuk 2023; Krausmann et al. 2020; Tanikawa et al. 2021);
3. The continuous expansion of in-use stock has been identified as a major barrier for loop closing; as long as stocks continue to grow, even very high recycling rates will not be sufficient to close material loops. Consequently, the **growth rate** of material stocks is of relevance;
4. The largest part of all waste flows – and hence of all potential secondary materials – is end- of-life waste from discarded stocks that date back several decades. Recent research has shown that large amounts of potential secondary material will become available in the coming years (Streeck et al. 2021); hence, knowledge of, and (in the longer term, action upon) the **age**, **location**, **material composition** and **quality** of material stocks is essential for effective planning of measures aiming to slow material cycles (refurbish, repair, remanufacture), as well as measures aiming to close material cycles (recycling, downcycling, energy recovery).

As will be developed in § 6.3 below, stocks and their use are considered major leverage points for a sustainable CE (Leipold et al., 2023). Stock-related CE measures include:

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[19] *F. Krausmann, D. Wiedenhofer, C. Lauk, W. Haas, H. Tanikawa, T. Fishman, A. Miatto, H. Schandl, H. Haberl (2017) Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use, Proc. Natl. Acad. Sci. U.S.A. 114 (8) 1880-1885, https://doi.org/10.1073/pnas.1613773114(2017 (Figure A) .*

Krausmann, F., Lauk, C., Haas, W., Wiedenhofer, W., (2018) From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015, Global Environmental Change, Volume 52, Pages 131-140, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2018.07.003 (Figuer 2B)

[20] *In 2015, of the remaining 45%, 16.9% is used for technical energy from mainly fossil fuels, 12.5% for feed, 4.9% for direct human food, 5% in extractive wastes in mining and metal processing, and the remainder (6.9%) is used for “other dissipative uses” i.e. products that are consumed and turned into wastes and emissions within one year such as detergents, hygiene products, pharmaceuticals, single-use batteries, lubricants, fertilizers, pesticides, single-use packaging material, etc.*

1. the reduction of the weight of new anthropogenic material stocks (narrowing);
2. the increase of stock lifetimes (slowing), and
3. the use of secondary materials in stock-building (closing).

The interrelations between **anthropogenic material stocks** and **Circular Economy** will hence be considered along the two opposing causal relationships:

1. How Circular Economy measures alter material stocks and flows (developed in § 6.3 below) and reciprocally;
2. How the existing material stocks, and their dynamics, affect the implementation of Circular Economy measures
    a. negatively as barriers (in §6.4) or
    b. positively as opportunities (in §6.5).

6.3. The impacts of Circular Economy measures on the stocks and flows of matter

Circular Economy measures can reduce the environmental impacts of contemporary societies in the following way. The satisfaction of societal needs rely on:

- A **flow** of resources (food, water, energy, consumable goods); and
- A material **stock** (of durable goods and fixed assets: production and transport equipment, infrastructure and buildings) that makes the usage of this flow of resources more efficient to satisfy these needs.

The resources used by this material stock can be modelled at a high level as follows[21]:

1. a given **need in society**, at a given **service level**, is satisfied by the availability of a given **stock** of **durable goods or fixed assets**, these durable goods or fixed assets being present in a given number of units in the stock, and each unit being characterised by a given service level provided per unit;
2. the **maintenance** and the **growth** of this stock depends on a **yearly flow** of incoming new units – which runs in parallel with a flow of outgoing discarded units;
3. the **resource used** by the material stock is the sum of:
    (i) the resource needed to generate that **yearly flow of new units**, computed as: (number of new units / year) x (mass of material / unit) x (resource used / kg of material);
    (ii) the resources needed to **maintain** and **operate** the existing stock, computed as: (number of units in stock) x (resources needed to maintain and operate one unit over one year).

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[21] *Trinomics, VITO, TNO (2022) Impacts of Circular Economy on EU climate policies, currently being further developed for the JRC (upcoming)*

Circular Economy measures act on each element of this model:

1. **Narrowing** measures reduce the size or number of new items entering the stock, and hence ultimately the size of this stock (in terms of number of items and / or of size of these items);
2. **Slowing** measures reduce the rate at which items in the stock are being replaced, and hence the flow of units needed per year to maintain the stock;
3. **Closing** measures reduce primary resource used per kg of material, because they save the resource-intensive stage in which the basic metal, material or chemical is manufactured from a virgin raw material[22].

Table 10-5 in §10.2.1 in the Annex B. Supplementary materials and methods supporting section "Links between Circular Economy and material stocks – cross-sectoral perspective" provides examples of Circular Economy measures in each of these high-level categories and explains how they are susceptible to act on the stocks or flows of durable goods, production equipment or fixed assets. The **quantification** of the effects of these CE measures on the material flows is limited[23], so that the consolidated effects on stocks remains largely unknown.

6.4. Barriers placed by material stocks to Circular Economy

The existing stock of durable goods and fixed assets in the economy and society – and the materials that they contain – strongly determine consumption and production patterns, and hence impact the implementation of Circular Economy measures, which are part of these consumption and production patterns.

The dimensions along which the existing stock of durable goods are likely to **hinder** the implementation of, and hence constitute **barriers** to, Circular Economy measures are the following:

- The **geographic location** of the fixed assets, itself related to the **residence** of the **population** and of the **production activities** (§6.4.1):
    - The current geography of housing is very much **dispersed** in low-density sub-urban areas caused by the generalised availability of individual motorised transport in the latest decades, whose material and energy efficiency is lower than that of higher density residential patterns;

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[22] *This production stage is resource-intensive because:*

- *It uses non-renewable mineral resources extracted from a finite pool of deposits of sufficient concentration for their exploitation to be economically and environmentally sound;*
- *It relies on energy-intensive chemical reactions (in general: reduction reactions, e.g. from metal oxide to metal).*

[23] *Material Economics, Sitra (2018) The Circular Economy: a Powerful Force for Climate Mitigation, available at: https://www.sitra.fi/en/publications/circular-economy-powerful-force-climate-mitigation/*

Trinomics, VITO, TNO (2022) Impacts of Circular Economy on EU climate policies

European Commission – Joint Research Centre, Trinomics, VITO, Fraunhofer Institute (upcoming) Socio-economic impacts of the Circular Economy

  - The **human geography** of the EU evolves, as the result of demographic evolutions (births and deaths) and of migrations within regions, between regions in the same Member State, between EU Member States and between the rest of the world and the EU. As a consequence, new housing (and the corresponding infrastructure of public services, transport, energy, water, sewage and telecommunications networks) needs to be built where the population rises, whereas these same assets become redundant where the population declines – with no cancelling out of needs in one location by surplus in another location, because of the fixed nature of these assets;
  - The **geography** of **productive fixed assets** is also dependent on that of production activities, with the same consequences when this activity moves;
- The Circular Economy is likely to reduce the need for primary Basic Metals (steel, aluminium, copper, other non-ferrous), non-metallic Materials (cement, glass, ceramics, pulp & paper) and Chemicals (monomers, strong acids and alkali) – BMMCs. This induces the risk that the industrial assets that exist to satisfy the current demand become redundant if that demand declines before they are fully amortised in the manufacturers' accounts, generating thereby important financial losses in the form of **stranded assets** – in addition to the **social consequences** of these facility closures if not well anticipated (§ 6.4.2);
- The existing stock of assets constitutes also a **social norm** of ownership, which is notoriously slow to change (§ 6.4.3);
- Finally, the very existence of a material stock consumes materials and energy for its **maintenance** and **operations** (§).

The magnitude of these effects is quantified in the following paragraphs.

6.4.1. Geography of fixed material assets

A significant part of the stock of durable goods, and, unsurprisingly, those that embody the largest share in the mass of materials of that stock, tend to be **fixed**, or to move only very slowly and at high economic and energy cost. These fixed durable goods include housing, commercial and industrial buildings, transport, energy and networks (water, sewage, electricity, gas, district heating & cooling, telecommunications) infrastructure (Lanau 2019). Similarly, but in less absolute terms, production machinery tends to move only at high costs and is moved only in exceptional circumstances.

This (semi-)fixed nature of the largest share (in mass) of the stock of durable goods frames the **geography** of human consumption and production patterns, and their environmental sustainability.

Urban sprawl: low-density suburban instead of high-density urban housing and infrastructure

The most obvious illustration thereof is the lost opportunity constituted by the build-up of suburban housing since the 1950s to host the population that had migrated from the countryside, instead of urban housing. Suburban housing was designed and built in synergy with motorised individual transport. It is hence dispersed and often over-sized. It provides limited pooling (and hence generates extensive usage) of resources for the construction and operation of networks or other infrastructure. This phenomenon is often referred to as "urban sprawl". This constitutes a lost opportunity, because important resources in the construction of infrastructure networks (and in valuable agricultural soil) could have been saved if this population had been housed in more densely populated cities instead.

The three degrees of urbanisation (cities; towns and suburbs; rural areas) were defined jointly by six organisations — the European Commission, the Food and Agriculture Organization of the United Nations (FAO), the United Nations Human Settlements Programme (UN-Habitat), the International Labour Organization (ILO), the Organisation for Economic Co-operation and Development (OECD) and The World Bank[24]. A short description of the degrees of urbanisation is provided in § 10.2.2 of the Annex B. Supplementary materials and methods supporting section "Links between Circular Economy and material stocks – cross-sectoral perspective".

Over the period 2012-2023, the population of the loosely-populated "rural areas" in the EU27 decreased by 19.9 million, and the total population increased by 8.2 million inhabitants. Of this population flow, only 2.8 million persons settled in densely-populated "cities" (i.e. 9.8% of the flow), whereas the rest (25.8 million, i.e. 90.2%) settled in less-densely populated "towns and suburbs". This is shown in Table 6-1.

This geography strongly frames – and limits – the gains that could be expected from:

- a pooling and intensification of the usage of existing durable goods or from
- systemic changes in the delivery of services to society, such as substituting motorised individual transport by collective transport.

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[24] *European Union/FAO/UN-Habitat/OECD/The World Bank, 2021, Applying the Degree of Urbanisation. A methodological manual to define cities, towns and rural areas for international comparisons. Downloadable at: https://ec.europa.eu/eurostat/en/web/products-manuals-and-guidelines/-/ks-02-20-499 with an updated digital version available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Applying_the_degree_of_urbanisation_manual_-_Methodology_for_applying_level_1_of_the_degree_of_urbanisation_classification*

Table 6-1. Population in the EU 27 per degree of urbanisation, 2010-2023, millions.

Degree of urbanisation	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Change 2012-2023
Cities	173.1	174.3	173.4	167.9	170.9	173.0	174.6	168.2	172.5	174.3	173.4	175.9	+2.8
Towns and suburbs	130.4	134.6	136.7	142.2	138.5	140.1	140.7	151.2	151.1	156.1	156.9	156.2	+25.8
Rural areas	136.6	132.4	131.8	132.9	134.5	131.2	130.0	126.3	123.4	115.0	115.5	116.7	-19.9
Total	440.6	441.3	442.3	442.9	444.0	444.7	445.3	446.1	447.0	445.9	445.8	448.8	+8.2

Source: own calculations which are further explained in §10.2.3 of the Annex B. Supplementary materials and methods supporting section “Links between Circular Economy and material stocks – cross-sectoral perspective”, and based on:

- Eurostat, 2024. Distribution of population by degree of urbanisation, dwelling type and income group, https://ec.europa.eu/eurostat/databrowser/view/ilc_lvho01__custom_12978358/default/table?lang=en
- Eurostat 2024. Population on 1 January by age and sex. Online data code demo_pjan https://ec.europa.eu/eurostat/databrowser/view/demo_pjan__custom_13620221/default/table?lang=en

Migrations at all scales and demographic change

Changes in residence showcase that the geography of the existing stock of dwellings generates losses in the usage of resources.

Another conclusion to be drawn from Table 6-1 above is that, whereas the overall population of the EU27 increased by 8.2 million inhabitants only over the period 2010-2023, homes were built in “Towns and suburbs” and in “cities” for 28.6 million inhabitants, with no possibility to re-use the homes left vacant in “rural areas”. The **geographic location of the built stock** per **degree of urbanisation**, corresponding to small-scale migrations within a given region, led over that period to an **excess in the construction of homes** (and of the attached infrastructure), by **a factor of 3.5**.

Similarly, when considering **inter-regional migrations**, when the population in a region diminishes, some dwellings there remain vacant, whereas those needed in the regions where the population increases need to be built, with no capacity to re-use those left vacant elsewhere.

The Table 10-6 in §10.2.4 of the Annex B. Supplementary materials and methods supporting section “Links between Circular Economy and material stocks – cross-sectoral perspective” considers each year the small-scale NUTS3 regions experiencing a population loss, and those with a population gain, and adds the total losses of all loss-making regions, and the total gains of the gaining regions. As shown in the table, every year, dwellings need to be built for the fraction of the EU population that settles in NUTS3 regions where the population increases, even if other dwellings are left vacant by the population that leaves the NUTS3 regions where the population decreases. Over the 4 years considered here (2018-2022), dwellings needed to be built for a total of 9,759,066 persons having settled in NUTS3 regions where the population increased, whereas the total EU27 population increased by 749,523 persons only over the same period. This implies that the **geographic location of the built stock** led to an **excess in the construction of homes** (and of all the infrastructure attached to homes: networks of all kinds, public services) corresponding to more than **9 M people**, i.e. **2% of the EU27 population**, in just **4 years**.

Another way of considering this result is that the geographic location of the built stock resulted in a **multiplication of the construction of new homes** by a **factor of 13**, compared to what would have been possible if people settled in the geographic region where housing is available.

Vacancy of buildings

One of the consequences of this mis-match between the nature and geographic location of the existing built stock and the one that is needed at a given moment in time is that the **stock of vacant buildings** in the EU27 is important. As can be seen in Table 6-2 below, more than **3.7 bio m^2 of useful floor area** is left **vacant** in the EU27, representing **12% of the total available floor area**, with an additional **1.7 bio m^2**, i.e. **5.6% of the total**, used as **secondary homes**, which implies a form of under-utilisation (i.e. part of the time only).

Table 6-2 Useful floor area (Mm^2) of buildings in the EU27 per building occupancy based on 2020 'Building Stock Observatory' data

Building occupancy			
Primary residence	**Secondary residence**	**Vacant**	**Total**
25,499 Mm^2	1,730 Mm^2	3,717Mm^2	**30,946 Mm^2**
82.4%	5.6%	12.0%	**100.0%**

Source: European Commission. EU Building Stock Observatory. Building Stock: Useful floor area per building occupancy. https://building-stock-observatory.energy.ec.europa.eu/database/

Location of economic activities

Economic activities migrate in the same way as the population does, with the same consequences. The geographic location of productive assets is fixed (fully for buildings, very much so for machinery and equipment), so that the gains in productive assets in some geographic locations – and the resulting consumption of resources – are not compensated by the loss of productive assets elsewhere.

The magnitude of this phenomenon is illustrated by Table 10-7 to Table 10-13 in § 10.2.5 in the Annex B. Supplementary materials and methods supporting section "Links between Circular Economy and material stocks – cross-sectoral perspective", which provide the evolution of gross assets of seven productive sectors identified at a coarse (1-digit NACE code) level of aggregation (agriculture; mining & quarrying; manufacturing; electricity, gas, steam and air conditioning supply; water supply, sewerage, waste management and remediation; transportation & storage; information & communication) over the period 2000-2021. Gross assets are representative of the magnitude of the materials contained in these assets, because they do not include the depreciation of these assets over time (which reduces their economic value, but not their mass).

The inadequate geographic location of the stock of productive assets led to the construction of EUR 55.1 bio. in the **agriculture** sector and EUR 42.7 bio. in the **mining & quarrying** sectors of "Other buildings and structures" that could have been entirely spared had the location of these new assets matched that of where they were needed. As for the **manufacturing** sector, EUR 242 795 bio. could have been spared had the location of these new assets matched that of where they already were present, leaving EUR 52 237 bio. net to be built anew. A more extensive description can be found in § 10.2.5 of the Annex B.

In the four sectors related to **infrastructure**, namely (1) electricity, gas, steam and air conditioning supply, (2) water supply; sewerage, waste management and remediation activities, (3) transportation and storage and (4) information and communication, the build-up of fixed assets has been considerable across most Member States, with diminutions of gross assets in some Member States remaining quantitatively far below the build-up of new assets. In the cases of these four sectors, the geographic location of the stock of assets does not seem to have played any meaningful role in the usage of resources needed to build up the infrastructure: even if all the infrastructure made redundant in some Member States had been available for re-use in the other Member States with a net increase in their assets, the reduction in the resource use would have remained very limited.

6.4.2. Productive assets at risk of being stranded by a transition to a Circular Economy – financial and social consequences

Similarly, in an effect that is economic and social, but not physical, the existence of production facilities dedicated to the manufacturing of virgin materials constitute an **asset** that is likely to be **stranded** or at least in need of a transformation in case of a reduction of the overall demand for these materials (because of successful CE policies aiming at narrowing or slowing flows) or of a conversion to secondary end-of-life materials or to sustainable biobased materials (in case of successful CE policies aiming at closing flows). Indeed, the very purpose of Circular Economy policies is to reduce, via these three pathways, the demand for primary raw materials such as Basic Metals, Materials and Chemicals (BMMCs). The owners of these economic assets, and the workers employed by them, constitute a factor of **political and social resistance** against the implementation of such Circular Economy measures and therefore require measures for a just transition.

The sectors where some production capacity is likely to be affected by a transition to a Circular Economy are those that manufacture primary BMMCs, also referred to as Energy-Intensive Industries (EIIs) namely:

- Manufacture of coke and refined petroleum products (NACE rev2 C.19);
- Manufacturing of chemicals and chemical products (NACE rev2 C.20);
- Manufacture of other non-metallic mineral products (NACE rev2 C.23);
- Manufacture of basic metals (NACE rev2 C.24).

For all these sectors, Circular Economy measures are likely to:

- Reduce the overall demand for the BMMC; and
- Within that reduced overall demand, to reduce even further the demand for *primary* BMMC.

Some facilities in these industries are dedicated to the manufacture of primary BMMCs, and cannot easily (if at all) be reconverted to the manufacture of secondary materials. These facilities solely dedicated to the manufacture of primary BMMCs and hence at a higher risk of becoming redundant include:

- Steam crackers manufacturing monomers (e.g. ethylene and propylene) from petroleum naphtha;
- Polymerisation units manufacturing virgin polymers (e.g. polyethylene and polypropylene) from the corresponding monomers;
- Cement kilns manufacturing clinker from limestone and clay;
- Brick kilns manufacturing bricks from clay;
- Blast furnaces manufacturing pig iron by a chemical reduction of iron oxide with coke;
- Aluminium smelters manufacturing aluminium metal by an electrolytic reduction of aluminium oxide (aka. alumina).

The exact fraction of the current production capacity for primary BMMC that is likely to be made redundant by the implementation of Circular Economy measures still is the purpose of ongoing research and studies.[25] However, the total amount of the productive assets and of the employment in these industries provides the order of magnitude of what is at stake when a reduction in the demand of BMMCs is anticipated because of the implementation of Circular Economy measures.

For each of these sectors, the Table 6-3 below provides, at the scale of the EU27:

- The total net assets;
- The total employment.

The method is further explained in §0 in the Annex B. Supplementary materials and methods supporting section "Links between Circular Economy and material stocks – cross-sectoral perspective".

Table 6-3 Net fixed assets and people employed by sectors manufacturing Basic Metals, Materials and Chemicals, and whose production is hence susceptible to be reduced by a shift to a Circular Economy

Sector	NACE rev.2 code	Total (net) fixed assets in 2019[26] (in million euro)	Employment in 2021[27]
Manufacture of coke and refined petroleum products	C.19	168 331	160 150
Manufacturing of chemicals and chemical products	C.20	308 007	1 220 464
Manufacture of other non-metallic mineral products	C.23	157 001	1 197 413
Manufacture of basic metals	C.24	169 574	890 000
TOTAL		802 913	3 468 027

Source: own estimations, based on method and data provided in Annex B

As can be seen in Table 6-3, the total net fixed assets of the sectors manufacturing primary Basic Metals, Materials and Chemicals (BMMCs) can be estimated at **ca. EUR 800 bio** in 2019, i.e. 5.7% of the EU27 GDP of that same year[28], and **36% of the annual value added of the manufacturing sector** (NACE rev2 code C). Similarly, the employment in these sectors represents **11% of the total employment of manufacturing**[29].

As reminded above, the exact share of these productive assets and of this employment that would disappear or need a deep transformation because of the reduction in demand (reduction in total demand and reduction in the demand for primary BMMCs) due to the shift to a Circular Economy still needs to be determined by further studies. However, these

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[25] *E.g. Trinomics, Fraunhofer ISI, VITO (2025 – upcoming) "Socio-economic impacts of Circular Economy" study for the Joint Research Centre (JRC) of the European Commission.*

[26] *estimated from Eurostat (2024) Cross-classification of fixed assets by industry and by asset (stocks) . https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_12980834/default/table?lang=en .See the details of the computation in the Annex 1: Methodology*

[27] *Eurostat, 2024. Enterprise statistics by size class and NACE Rev.2 activity (from 2021 onwards) https://ec.europa.eu/eurostat/databrowser/view/sbs_sc_ovw__custom_13119001/default/table?lang=en*

[28] *Source Eurostat GDP and main components (output, expenditure and income) Online data code: nama_10_gdp https://doi.org/10.2908/NAMA_10_GDP*

[29] *Eurostat, 2024. Enterprise statistics by size class and NACE Rev.2 activity (from 2021 onwards) https://ec.europa.eu/eurostat/databrowser/view/sbs_sc_ovw__custom_13449689/default/table?lang=en*

figures provide the order of magnitude of the maximum possible social and financial impacts. The actual impacts will be lower, but how much lower remains unknown.

6.4.3. Social norms of ownership

Finally, the level of service provided by a given stock of material goods tends to constitute the **social norm** for the population that benefits from it. Evolutions in the service level provided by the stock of material (e.g. in the surface per person in housing) follow a non-revertible, ratchet-like course. Whereas the evolution towards consumption of larger and more numerous products is easy, a subsequent move in the opposite direction meets with a great deal of resistance because of the aversion to loss common to many humans.

It should be noted that consumers are not the only ones bearing the responsibility for this increase in the number and size of products in the stock: the whole socio-economic system, including advertising, pushes in that direction.

These social norms can be illustrated in the examples of:

- The housing surface per person;
- The number of cars per household;
- The mass of cars.

Housing surface per person

Table 10-18 in §10.2.7 of the Annex B. Supplementary materials and methods supporting section "Links between Circular Economy and material stocks – cross-sectoral perspective" computes the useful floor area per person available in primary residential buildings (i.e. the surface in secondary homes and in vacant buildings is not included), in 2008 and 2020. The average useful floor area per person in the EU was **35.9 m2/person** in **2008**, and had increased to **38.44 m2/person** in **2020**, i.e. a rise by more than 7% in 12 years.

This can be compared to the surface per person that recent research in sustainable housing[30] considers as being "sufficient", namely **20 m2/person**. Based on this research, the current stock of housing surface per person in the EU27 is ca. 1.9 times what would be needed.

Number of cars per household

Table 10-19 in §10.2.7 of the Annex B shows the average number of cars per household in the EU27 between the years 2016 and 2022.

The average number of cars per household **increased** from **1.21** to **1.27 cars/household** between 2016 and 2020, and stabilised over the following 2 years. This evolution shows that the tendency leans towards an increase in the individual ownership of cars, in a direction opposite to the transition to a Circular Economy.

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[30] *Cohen, Maurie J.. (2020). New Conceptions of Sufficient Home Size in High-Income Countries: Are We Approaching a Sustainable Consumption Transition?. Housing, Theory and Society, (), 1–31. doi:10.1080/14036096.2020.1722218)*

Mass of cars

Not only has the average number of cars per household increased, but the **vehicle mass** of each of these passenger cars has also steadily been **increasing** throughout the past two decades. According to the International Council of Clean Transportation's (ICCT) 2022/23 report[31], over the years 2001 to 2023, the mass of passenger cars in the EU27 has had an almost permanent increasing trend from approximately **1 280 kg in 2001** to 1 480 kg in 2021 (see Figure 10-5 in the Annex B below). In addition, the European Environment Agency (EEA) published a press release on car mass providing data beyond the data of this figure, and whereby the average mass of new passenger cars was **1 545 kg in 2023** representing a 1.3% increase from 2022[32] and a **20.7% increase** compared to the 2001 figure.

6.5. Circular Economy measures enabled / made easier by the existence of material stocks

In the opposite direction to the previous paragraph, material stocks can also **support**, and hence constitute **opportunities** for, the implementation of Circular Economy measures along the following dimensions:

- **Material- and energy-efficient manufacturing processes**, embodied in the corresponding machinery and infrastructure, have the potential to ensure the delivery of reliably and consistently high-quality goods with low environmental impacts;
- Material stocks, if their composition is known and if their processing at end of life is appropriate, can constitute sources of **secondary materials**.

6.5.1. Material- and energy-efficiency of manufacturing processes

As mentioned above in section 5.2, the **economic** efficiency of the material stock (total and of machinery, vehicles and other durable goods – MVD) has increased, at the scale of the whole economy, over the last decades, in the EU27 and in other comparable economies (USA, Japan).

In addition, some elements enable to assess the evolution of the **material** efficiency of the material stock, translating the technological progress of the equipment therein. In order to assess the manufacturing efficiency brought by the operation of the existing stock of machinery, it is possible to look at the evolution of pre-consumer waste in some selected sectors.

In the **steel** sector, a study by Dworak and Fellner (2021)[33] considers the two stages where pre-consumer scrap is generated:

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[31] *ICCT (2022). European Vehicle Market Statistics. Pocketbook 2022/23. https://theicct.org/wp-content/uploads/2023/01/Pocketbook_2022_23_Web_corrections-v1_VS.pdf*

[32] *EEA, 2024. New data: CO2 emissions from new cars and vans further decrease as electric vehicle sales grow in Europe. https://www.eea.europa.eu/en/newsroom/news/new-data-co2-emissions-of-new-cars-and-vans*

[33] *Dworak, S. & Fellner, J. (2021). Steel scrap generation in the EU-28 since 1946 – Sources and composition, Resource, Conservation and Recycling, 173. https://doi.org/10.1016/j.resconrec.2021.105692*

- During the production and forming of the steel – leading to Production and Forming Scrap (PFS);
- During the usage of the steel in the subsequent manufacturing stages of the final product – leading to Fabrication Scrap (FS).

In the 1950s, nearly 25% of crude steel production became PFS, but in the 2010s this has improved to about 8.7%, demonstrating significant advancements in material efficiency within the industry. The introduction of continuous casting steel production in the 1970s brought about major efficiency improvements. Between 1970 and 1997, the proportion of PFS relative to crude steel production decreased from 22% to 11%.

The generation of Fabrication Scrap however experienced an evolution in the opposite direction. The ratio of FS to crude steel production has risen to 17% in 2017, up from about 10% in the 1950s, largely due to the increased production of flat products and their subsequent processing into finished goods. Flat products account for a substantial share of fabrication scrap (77%) due to their lower material efficiency during the manufacturing process compared to long products. Indeed, the cutting out of the desired shape from the steel sheet leaves more unused surface than the cutting of the desired length from a steel bar[34].

Regarding pre-consumer **textile** waste, in most EEA member countries pre-consumer waste only generates on average 1% of textile waste, while post-consumer textile waste makes up a large portion of all textile waste (82%). Unfortunately, there are significant gaps in the data available for pre-consumer waste. However, Slovenia reported that pre-consumer waste was 1% (2021), Lithuania reported that pre-consumer waste was around 4% (2021), and Italy reported that pre-consumer waste was 6% (2020)[35].

Pre-consumer **plastic** waste is generated during the production and conversion of plastics, such as from defective products, sprues, edge trims of plastic sheets, and leftover materials from production. However, it does not include materials like regrind or scrap that are reprocessed and reused within the same manufacturing process. There is limited data on pre-consumer plastic waste, however it is estimated that 3.6 million tonnes of pre-consumer recycled plastics are now incorporated into new products in the EU27+3[36].

From this limited evidence, it appears that the **nature** of the stock of machinery, and its **technological level**, have an influence on the material efficiency of industrial production in the steel sector, but less so in the sectors of textiles and plastics.

In order to assess whether the existence of a given stock of machinery is or not an obstacle to enhanced circularity, some careful study is needed. Indeed, this is a particular case of the general sustainability dilemma of improving technology, where a trade-off needs to be made on a case-by-case basis between the future efficiency gains of using newer

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[34] *ibid*

[35] *Deckers, J., Duhoux, T., & Due, S., (2024). ETC CE Report 2024/25: Textile waste management in Europe's circular economy.*

[36] *Plastics Europe (2022). The circular economy for plastics. A European Overview. https://plasticseurope.org/knowledge-hub/the-circular-economy-for-plastics-a-european-overview-2/*

technology vs. the environmental costs of discarding an equipment that still is operational and contains embodied environmental impacts.

6.5.2. Usage of secondary materials

At the end of its useful service lifetime, the existing stock of materials turns into a flow of secondary materials that can supply the economy.

The degree by which secondary materials contribute to satisfying the demand for materials to manufacture new goods is measured with three indicators:

- On the output side, the **recycling rate** is the share of discarded materials that are recycled or prepared for re-use[37];
- On the input side, the **Circular Material Use Rate (CMUR)** is defined as the ratio of the circular use of materials to the overall material use[38];
- Similarly, on the input side, the **end-of-life recycling input rate (EOL-RIR)** measures for a given raw material, how much of its input into the production system comes from the recycling of "old scrap" (or “end-of-life scrap”) i.e. scrap and waste derived from the treatment of products at their end-of-life (EOL)[39].

When the stock of materials grows, even a high recycling rate does not enable a high value for the CMUR or the EOL-RIR, simply because the needs for new products are quantitatively superior to the flow of end-of-life products.

As can be seen from Table 10-20 in §10.2.8 of the Annex B. Supplementary materials and methods supporting section “Links between Circular Economy and material stocks – cross-sectoral perspective” and from Table 6-4 below on the contribution of recycled materials to raw material demand below, the contribution of recycled materials to the EU economy remains limited, and shows only a very slow positive evolution, if any.

For the most part, the total circular materials use rate (CMUR) seems to be slowly improving, but this improvement is uneven among classes of materials. While some materials (biomass, metal ores, fossil energy materials/carriers) have an increasing CMUR, it is decreasing for others (non-metallic minerals).

The table below shows the evolution of contribution of recycled materials (end-of-life recycling input rates) to raw materials demand in percentages. **Lead**, **Copper**, **Zinc**, and **Iron** consistently show high recycling rates, with **Lead** having the highest at 83% in 2022[40].

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[37] *As per Art.11(2) of the Directive 2008/98/EC on waste, consolidated version available at: http://data.europa.eu/eli/dir/2008/98/2024-02-18*

[38] *The overall material use is measured by summing up the aggregate domestic material consumption (DMC) and the circular use of materials. DMC is defined in economy-wide material flow accounts. The circular use of materials is approximated by the amount of waste recycled in domestic recovery plants minus imported waste destined for recovery plus exported waste destined for recovery abroad. See: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Circular_economy_-_material_flows#Circularity_rate*

[39] *https://ec.europa.eu/eurostat/cache/metadata/fr/cei_srm010_esmsip2.htm*

[40] *Eurostat, n.d., Contribution of recycled materials to raw materials demand - end-of-life recycling input rates (EOL-RIR) (cei_srm010) ESMS Indicator Profile (ESMS-IP) https://ec.europa.eu/eurostat/cache/metadata/en/cei_srm010_esmsip2.htm*

However, the figures for some materials are highly unstable and vary considerably from one sample year to the following one (3 years later), with no clear trend appearing.

Table 6-4. Contribution of recycled materials to raw materials demand (in percentages) in four different time periods in the EU.

Material / Year	2013	2016	2019	2022
Aluminium	35.0%	12.4%	12.3%	32%
Copper	20.0%	55.0%	16.9%	55%
Iron	22.0%	24.0%	31.5%	31%
Lead	:	75.0%	75.0%	83%
Nickel	32.0%	33.9%	17.0%	16%
Zinc	8.0%	30.8%	31.0%	34%

Note: (:) – Not available

Source: Eurostat, 2023. Contribution of recycled materials to raw materials demand - end-of-life recycling input rates (EOL-RIR).
https://ec.europa.eu/eurostat/databrowser/view/cei_srm010/default/table?lang=en&category=cei.cei_srm

Deterioration of quality due to loss of purity

A study on the economic value of secondary materials in the EU economy[41] explains the main reasons why some recycled materials are of lower quality than primary raw materials:

- mixing of different natures of materials (e.g. concrete mixed with the reinforcing steel recovered from demolition waste, copper from electric cables mixed with steel recovered from end-of-life cars);
- mixing of different types of plastic polymers (e.g. polyethylene mixed with polypropylene, or different densities of polyethylene mixed together) or of alloys (for steel or for aluminium);
- alloying of metals, i.e. the mixing of categories of steel made of different ferro-alloys; and
- contamination (in particular by hazardous substances that forbid the further use of the recycled material for some applications, such as food contact).

All these phenomena boil down to a **loss of purity** of the material when it is processed after recovery.

This idea can especially be applied to plastics and it remains the reason for such low recycling rates (10.5%), compared to 81% for steel and 69% for aluminium. For steel, 66% of value is preserved after one use cycle, however quality does become worse, especially due to alloying and contamination. Regarding aluminium, 52% of the value is preserved after one use cycle, and also experiences downgrading in quality due to alloying. Contamination, mixed colours and polymer grades, as well as the recycling process all affect the quality and volume of plastic. Quality of recycled materials determine the applications the recycled

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[41] *Material Economics (2020). Preserving value in EU industrial materials - A value perspective on the use of steel, plastics, and aluminium. https://www.climate-kic.org/wp-content/uploads/2020/11/MATERIAL-ECONOMICS-PRESERVING-VALUE-IN-EU-INDUSTRIAL-MATERIALS-2020-compressed.pdf*

material can be used for and to what extent it can replace demand for primary raw materials. In many cases, lower quality causes a lower market price, therefore, making it not very economically worthwhile to recycle the material. Unfortunately, this means that, in the present state of material recovery and processing, secondary materials have a quality and value that are too low to fully replace primary materials.

Conditions for secondary materials to retain the purity (and hence quality)

The existence of large quantities of materials embodied in the stocks of durable goods could constitute a source of valuable materials for **secondary use**, so that they constitute a larger share of material input, including for demanding applications requiring high-performance materials with a high purity and control on their composition (Potential positive impact on CE measures of Category 6.2 Increase share of secondary materials).

For this to happen however, a significant number of **conditions** need to be met, such as the implementation of the following measures:

1. Limit the size of the stock, so that the outgoing flow of discarded materials matches quantitatively that of incoming materials;
2. Ecodesign: use reversible assembly processes between pieces made of different qualities of a given material (e.g. between different alloys of the same metal) and between pieces made of different materials at the manufacturing stage to enable lossless and high-purity disassembly at end of life;
3. Digital Product Passport containing the exact nature of the material used in each homogeneous component, to facilitate high-purity, circular recycling;
4. Limit the number of different materials (e.g. metal alloys, additives to polymers) used for a given application, enabling the management of separate high-purity waste streams for circular recycling;
5. Increase efficiency of separate waste collection (including avoidance of leakage) and of sorting;
6. Implement industrial-scale dis-assembly of end-of-life durable goods instead of their shredding;
7. Execute demolition and transport of end-of-life building components with care, to facilitate separate sorting and high-purity recycling.

6.6. Summary of the interlinkages between material stocks and the Circular Economy

As can be deduced from the discussion above, the interlinkages between material stocks, and Circular Economy measures, are profound and fundamental. Including material stocks in the scope of reflection and knowledge is hence a considerable contribution to the effectiveness and comprehensiveness of policies aiming at developing the Circular Economy in Europe

The main conclusions to be drawn of this chapter can be summarised as follows:

- The fixed nature of housing, infrastructure and a significant part of machinery results in geographical mismatches of supply and demand, whereby the material assets discarded in one geographic location cannot be re-used in the other geographic location where the demand (population, economic activity) has moved to;

- The persistent dispersion in the stock of housing leads to reduced efficiency in the usage of the materials providing the transport, energy, water and data networks supplying these settlements;
- Circular Economy measures have the potential to reduce the demand for Basic Metals, Materials and Chemicals (BMMCs), in particular of *primary* BMMCs. The facilities manufacturing these primary BMMCs are likely to be discarded before they are fully amortised, potentially leading to premature write-offs, a phenomenon known as "stranded assets". Similarly, the employment of persons in these facilities is likely to be affected as well, if no just transition measures are implemented. Whereas the exact share of the production facilities susceptible to become thus "stranded" remains unknown, the total net assets and employment of the relevant sectors provide a first orders of magnitude approximation of the maximum foreseeable impacts;
- The development in the EU27 of the social norms of ownership investigated (surface of housing per person, number of cars per household, mass per car) all have moved in the direction opposite to that of material efficiency over the last decades.
- The material efficiency of the stock of productive assets has increased in the case of steel (but not visibly for textiles or plastics), as the result of technological progress embodied in the stock of machinery;
- The usage of secondary materials in the EU27 has been stagnating over the last decade. Structured action relying on ecodesign facilitating dis-assembly and a Digital Product Passport conveying appropriate information for the easy recovery of materially homogeneous parts could be a pathway to improve the situation. Further measures include the scale up of recycling and waste management systems, the adaptation of waste regulations to ease handling of secondary materials, as well as a socio-ecological tax reform shifting the burden of taxation towards the usage of primary resources.

7. Material stocks: Barriers and opportunities for circularity in the construction and batteries sectors

7.1. Rationale for the case studies

The chapter consists of two case studies. It takes a closer look at the barriers and opportunities for circularity in the material stocks of two contrasted categories of products: buildings and batteries. These two categories of products can briefly be characterised by the following contrasted sets of features:

- **Buildings** are large items (with a cross-section of several tens of metres), made of low-value, chemically inert materials, most of which being non-metallic minerals. They are fixed and designed to last for long periods of time, typically several decades;
- **Batteries** are small items (a few centimetres across), made of high-value, chemically active materials, a large fraction of which being metals and / or Critical Raw Materials (CRMs)[42]. They are mobile and designed to last for shorter periods of time, often a few years, rarely above ten.

Investigating these case studies in greater detail enables a deeper look at two extremes of the stock of anthropogenic materials.

Other product categories in the anthropogenic stock of materials are likely to lie somewhere in between in terms of size, composition and lifetime. The characteristics of their material stocks can hence be anticipated also to lie between those described hereafter for the construction and the batteries sector.

7.2. Barriers to and opportunities for Circular Economy – construction sector

While the construction sector uses hundreds of components in complex and interwoven combinations, material stocks as well as related flows are dominated by a limited number of materials used in large masses, i.e., aggregates, concrete, asphalt, and bricks (see Figure 7-1 as well as the analysis in chapters 4 and 5 on status and trends in EU27 stocks). The largest fraction of construction materials is used in buildings and road infrastructure (70% of GAS), followed by other civil engineering infrastructure including railway lines, bridges, tunnels, and dams. Scale and composition of construction materials is illustrated in Figure 7-1.

To reduce the total mass of materials used, the consideration of the construction sector and the material stocks of the built environment are highly relevant. While the construction sector involves a large mass flow of bulk materials, it also has to be noted that the

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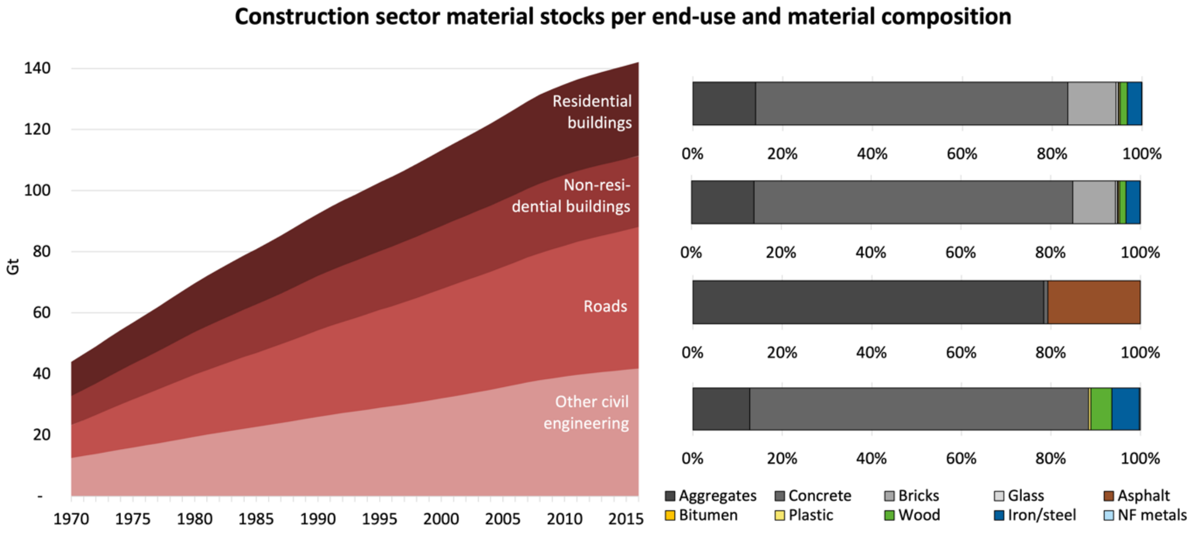
[42] *As defined in the Annex II, section 1 of the Regulation (EU) 2024/1252 establishing a framework for ensuring a secure and sustainable supply of critical raw materials, available at:* *http://data.europa.eu/eli/reg/2024/1252/2024-05-03*

environmental impact of material use not only results from the sheer quantity of used resources — such as the total mass of materials and energy used, waste generated, and emissions released — but also from the specific nature of these materials. The environmental impact of resource use varies significantly depending on the type of material involved. For instance, the extraction and processing of one ton of lithium impose far greater environmental burdens than extraction and processing of an equivalent mass of sand. E.g., certain metals or fossil fuel-based products can react chemically with the physical environment when disposed of, thereby increasing environmental impacts in the waste management phase, whereas construction minerals such as bricks tend to be rather inert. A comprehensive assessment of the environmental impact of material use therefore has to consider both, the absolute quantity (measured in metric tons) but also qualitative aspects, including the material's properties, the derived processed good as well as its intended application (see also chapter 4.5 “Stocks and flows of critical raw materials”). While critical and strategic materials and their potential for circularity are extensively researched, a comprehensive understanding of bulk materials and their relevance for a circular economy is less well understood. Hence, this chapter focusses on the construction sector and buildings in particular, and the use of bulk materials therein.

For a reduction of overall material inputs and waste outputs as well as in regards to overall CE indicators, the reduction of bulk materials and thus of material stocks is inevitable. Next to the direct material use reduction, a reduction of built-up stocks and related flows will, in addition, induce further, indirect effects that positively contribute to dematerialization, decarbonization as well as other environmental challenges. Among those are: a reduction of land sealing contributing to combatting biodiversity loss and land fragmentation; a reduction of GHG emissions through reduced production and transportation of construction materials for building up new stocks as well as a decline of resource requirements for maintenance of stocks; less energy consumption and consequently GHG emissions for heating, cooling, lighting smaller and fewer houses. Finally, every building newly constructed requires infrastructure in order to function (e.g., connection to infrastructure grids such as energy infrastructure, water grid and canalization, road infrastructure as well as parking space, etc.) as well as furniture and equipment, which often include critical raw materials. Hence, a reduction of the built environment will reduce the amount of material and energy use for furniture and equipment installed in buildings as well as a reduction of energy use and consequently of GHG for producing and using these.

In chapter 4 material stocks, their material composition and end uses were presented and discussed. Figure 7-1 focuses on the material stocks and flows of the construction sector including buildings. Total construction stocks in the EU27 more than tripled from 44 to 142 Gt from 1970 to 2016. Buildings (both residential and non-residential) accounted for 47% of total construction material stocks in 1970, while roads and other civil engineering infrastructure (e.g., railway lines pipelines, dams, bridges, tunnels) accounted for the other 53%. Until 2016, the share of buildings decreased to 38%. While the dominant material in road stocks are asphalt and aggregates used in subbase layers, concrete holds the highest share in buildings and other civil engineering (70-76% of the total stock). In addition, bricks and timber are materials with significant shares in buildings and other civil engineering, respectively.

Figure 7-1: Construction sector material stocks per end-use from 1970 to 2016 with material composition of stocks in 2016 on the right

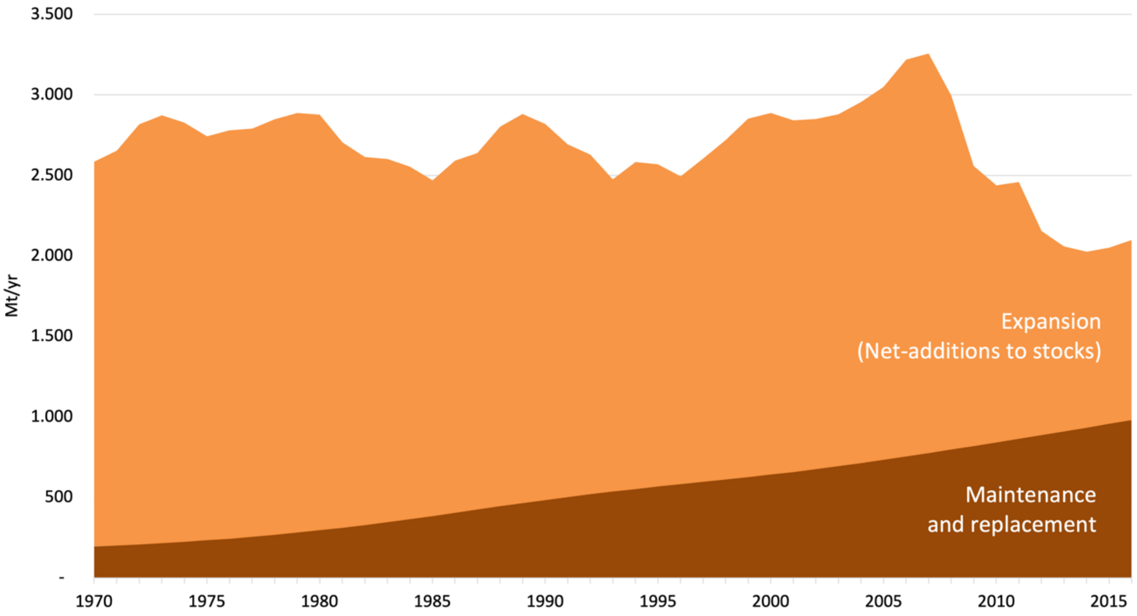


Legend: *NF metals = Non-ferrous metals including aluminium and copper.*

Data: *MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)*

The ratio of annual material inflows for stock expansion (NAS) and for maintenance and replacement activities (M&R) changes over time, as can be seen in Figure 7-2. While material consumption used for stock expansion accounted for 92% in 1970, this share decreased to 53% by 2016, representing the increasing need for maintenance and replacement of a growing material stock body. The continued and growing material input required for maintaining stocks illustrates the substantial legacy built stocks represent. Expansion flows (net-additions to stocks) decreased from 2,391 to 1,119 Mt/yr from 1970 to 2016, while maintenance and replacement increased from 194 to 970 Mt/yr.

Figure 7-2: Construction sector material inflows from stock expansion (net-additions to stocks) and from maintenance and replacement activities



<u>Data:</u> MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

Beyond their immediate impact on resource use and land consumption, material stocks of buildings, roads and other infrastructure pose a challenge to sustainable resource use because of their longevity. Residential buildings, for example, often are in use for more than a century. During their long lifetimes, they are operated and need to be maintained, requiring continuous material and energy inputs. Likewise, road pavements commonly are in place for several decades before they are completely replaced after multiple pothole fillings and other maintenance activities. Demolition (or replacement) of these material stocks is likewise energy intensive. In addition, demolition can be too costly wherefore stocks are often neglected and kept in so-called hibernation, as is often the case with railway lines for example. Newly constructed buildings, both residential and non-residential, require road and railway infrastructure for the transportation of people and goods, thereby reinforcing stock expansion. Because of their long lifetimes, it takes long to structurally change these stocks, meaning that whatever we construct now will exist for a long time before alternative options can be implemented. The consequence is a so-called lock-in effect, or path dependency.

To increase circularity in the construction sector, the European Union has adopted several legislative measures as well as guidelines. Establishing uniform products requirements in regards to safety, functionality, and environmental impact, the revised 'Construction Products Regulation' (CPR) outlines that construction works and their components must be designed, constructed, used, maintained, and deconstructed in a way that ensures the sustainable use of resources throughout their lifecycle. This includes increased use of secondary materials (through increased recyclability and ease of deconstruction), reduction of energy consumption during production, and minimization of waste generation (European Parliament, 2024b). Similarly, the EU Construction and Demolition

Waste Protocol and Guidelines (European Commission, 2018) aims to improve circularity in construction by providing a non-binding framework to enhance the management and recycling of construction and demolition waste. Further, the EU document 'Circular Economy – Principles for Building Design' (European Commission, 2020) promotes recycling and reuse of materials through focusing on durability, adaptability, and reducing waste and facilitating high quality waste management. More information on EU regulations and guidelines can be found in the Annex C. Supplementary materials and methods supporting section "Material stocks: Barriers to and opportunities for circularity in the construction and batteries sectors", § 10.3.1, below. These documents mostly have a supply-side perspective, focusing predominantly on recycling and waste management. However, beyond technological solutions to achieve circularity in construction, sufficiency-based demand-side measures have significant potentials, as outlined below.

7.2.1. Potential Circular Economy measures in the construction sector

Growing material stocks of buildings, roads, and other infrastructure induce large masses of material inputs for new construction as well as maintenance and replacement of existing stocks. Consequently, strategies aimed at reducing demand in construction materials, or at increasing their circularity, have a significant impact on total material stocks as well as on economy-wide circular economy indicators. Strategies focussing on the increasing material efficiency and circularity of buildings along the life cycle of a building are well researched (Benachio et al., 2020; Rahla et al., 2021; Sáez-de-Guinoa et al., 2022; Akhimien et al., 2021). From a systemic perspective, buildings do not exist in isolation from the surrounding infrastructure. Instead, they are integrated into a broader built environment that connects them to essential networks, including electricity, water, and sewage systems. Additionally, buildings are linked to transportation networks that facilitate movement between residential areas and locations for work, commerce, and leisure activities. Hence, circularity in relation to buildings is not sufficiently addressed when focussing on buildings. Instead, buildings need to be perceived as embedded in the larger built-up infrastructure that are organised by urban and rural planning. Finally and most importantly, buildings aim at serving particular function for or need of society (Haberl et al., 2021; Plank et al., 2021) that is not reflected in the mass or material composition of a building. The broader perspective on buildings and their circularity requires an interdisciplinary and transformative approach and new and innovative ideas on social organisation and wellbeing that goes beyond known strategies on efficiencies and recycling and thus are less frequently studied but of utmost importance.

Wiedenhofer et al. (2025) have mapped CE measures along the three groups: narrowing, slowing, and loop-closing that are used to structure the 10R-strategy (Potting et al., 2017) see chapter 6.1. Measures relevant for material stocks in buildings and civil engineering infrastructure are selected and discussed below.

Narrowing flows

Reduce demand

A reduction of socio-economic demand for material stocks can contribute to reducing material flows related to the built environment. In the building sector, demand for floor space increases as a result of higher demand for spacious living, weekend homes, tourism increases, lowered use rates and population growth and consequently further construction activities. To reduce demand, various approaches exist that either tackle the existing building stock, or newly constructed buildings. One example is the more efficient use of the building stock, also known as housing sufficiency (Lehner et al., 2024), e.g., by living in smaller apartments or houses or by increasing the number of people sharing one household. Average per capita residential floor area varies significantly across EU countries (Enerdata, 2013). While a general decent living standard for housing was defined at a much lower level (Rao & Min, 2018), there is no EU target regarding how much floor area can be reduced to provide the same level of service (shelter, comfort). Nevertheless, any reduction from current average EU levels would improve circularity indicators as less extraction of non-metallic minerals would be required.

While progress has been made in reducing overcrowded households, the share of people living in under-occupied homes is around 33% with a rising trend in recent years (Eurostat, 2023). Consequently, downsizing or sharing (Lehner et al., 2024) are options that could potentially reduce current per capita floor size, leading to a more equal distribution of existing material stocks, and reduce demand in newly constructed buildings.

Demand reduction is also highly relevant in the context of other material stocks such as mobility infrastructure. Haas et al. (2025) consider the current extent of the road network as sufficient in providing an adequate level of transportation services. A stabilization of road construction together with demand-side measures (shifts from one material-intensive modal type to another) can save significant amounts of construction materials. However, at the same time, demand in other materials, e.g., demand in metals in the case of railway line expansion, can increase significantly.

Finally, a reduction of material stocks of buildings, roads and other infrastructure will reduce the amount of energy required to operate and provide services from stocks. This allows for reduced energy infrastructure and related material inputs.

Rethink design

Strategies on "Rethink" often start at the point of "rethinking a product" but should already be thought of earlier, i.e., rethinking the required socioeconomic service provided by a building to best fulfil the needs of residents which is then implemented by innovative designs (e.g., multifunctional uses of buildings and space, more intensive uses by shared space, etc.) that minimize the material inputs required while maximizing the service for society and people (not buildings). Only in a second step, as soon as the required product is defined, product design aspects follow.

The service provided by residential buildings for example is living space. While theoretically, absolute floor space required is driven by the size of the population and sufficiency in per capita floor space requirements, other aspects most likely have a higher impact in practice; these are for example: migration within and beyond country borders, vacancies and buildings not in use, secondary homes, vacant or low intensive uses in offices in combination with home office, living space as investment and sparsely used, AirBNB and other touristic uses, financial support for construction of single-houses, shift from more-person homes to single-homes, with single-homes having more floor space per capita.

Rethinking settlement development as well as support for flexible living concepts for different life phases has to be considered key for sustainable housing in the future. Where a house can be built and in what way is largely regulated by regional and urban planning as well as building regulations that lie outside the decision-making options of construction companies or individuals. Hence, before the planning of a house begins, political planning of settlement (accompanied by regulations, incentives, taxes etc. that favour environmentally favoured options) can have a significant impact on what stocks are built in what way. Examples for new and innovative planning are:

- Mixed high-density areas with high quality green space for recreation and short distances for daily trips;
- Spatially well-designed settlement areas can reduce the number of roads and other infrastructure significantly;
- Communal and easy to access facilities for childcare, specialised household chores and sportive as well as social activities;
- Smaller but appropriate per capita floor space with more intensive use rates made possible by more high-quality communal facilities;
- Financial and administrative support as well as brokerage platforms for flexible living concepts for different life phases.

Concepts like superblocks (López et al., 2020; Brenner et al., 2024) and 15-minute cities (Pozoukidou & Angelidou, 2022) are concepts to combat urban sprawl2 and minimize the need for roads while shifting mobility towards public transport. Reducing demand for future building and road network expansions can be achieved through urban planning (Creutzig et al., 2016). However, since people need roads and railway lines to travel from their homes to work, places of daily needs, and places of interest, mobility infrastructure is closely interlinked with the spatial configuration of both residential and commercial buildings.

On product design, options and measures are much more common (Norouzi et al., 2021). One strategy is the substitution of materials by less environmentally burdening ones. The main source of emissions in the construction sector is the production of construction materials such as concrete and steel (UNEP, 2023). A shift towards different and potentially local (e.g. Costa et al., 2019) construction materials such as adobe/earth, or timber construction has the potential to save large amounts of non-metallic mineral material inputs.

An already more widely applied substitute material is timber. Past studies have shown that timber construction can be used in a variety of building use types, ranging from single-family houses to high-rise buildings (Tupenaite et al., 2021, 2023). Particularly efficient is the use of off-site manufacturing of wood panels compared to more intensive on-site assembly (Švajlenka & Kozlovská, 2020). Recent pilot projects have achieved single-family houses where concrete has been completely substituted by timber (Isopp, 2022). Emission-wise, timber construction in the EU was shown to have the potential to save 46 million tonnes of CO2-eqv. per year by 2030, however, changes in policy related to carbon emissions treading and incentives for voluntary use of wood as a construction material are needed (Hildebrandt et al., 2017). But it has to be noted that the increase in timber use for construction is expected to have a negative impact on forest ecosystems and their carbon sink capacities (Hart & Pomponi, 2020). Hence, timber construction might play a beneficial role in sustainable construction but most likely only in a society with stabilized stocks where timber is carefully utilized for the replacement of demolished.

Slowing flows

Repair over new construction

Construction of new buildings is the main driver of bulk material demand in the housing sector. Consequently, reducing the overall need for constructing new buildings has great implications on resource use. Comparisons of the environmental impact of renovation of an existing building vs. its demolition followed by construction of a new building showed that the former is considerably more environmentally friendly, but requires that the original building stock is in a physical state that allows for renovation to be conducted (Hasik et al., 2019; Itard & Klunder, 2007; Lederer et al., 2021). However, even with severely damaged buildings, repair and retrofit work can have a lower economic and environmental impact than total building replacement (Alba-Rodríguez et al., 2017).

Renovation of buildings effectively extends their lifetime, requiring fewer resources. However, because older buildings usually have worse thermal properties compared to newer buildings, it is important to consider sufficient insulation when renovating existing building stock to reduce operational energy use and emissions (Lederer & Blasenbauer, 2024).

Repair instead of new construction are also highly resource-saving in mobility infrastructure, where maintenance repairs in certain intervals are usually the case already. Due to constant use, often by heavy vehicles such as trucks and buses, in most cases a complete replacement of the road surface is required at some point. However, when the point is reached, where not only pothole fillings suffice, but the whole road has to be demolished and reconstructed, can be pushed into the future.

Repurposing buildings

Similar to repairing and retrofitting the existing building stock, changing its use can allow for an effective lifetime extension (Gursel et al., 2023). Especially in areas, where a shift from commercial to residential use of buildings, or vice versa, occurs, repurposing an existing building for a use different to that before can avoid destruction or buildings falling in disuse and entering so-called hibernation (Bullen, 2007). Repurposing historic buildings, particularly in town centres, can revitalize them and mitigate urban sprawl (Aigwi et al., 2018; Foster, 2020).

Loop-closing

Increased material recycling and recovery

While the above outlined narrowing and slowing strategies reduce material demand overall and thereby contribute to the circular economy, keeping materials within material cycles reduces wastes and demand for primary materials, as they are substituted by recycled, or secondary, materials. Secondary materials can be sourced from wastes occurring during construction activities, or from demolished buildings and infrastructure. Both sources are collectively called construction and demolition wastes (C&D). With two thirds of all wastes, the construction sector represents the largest waste flow in the EU (Interreg Europe, 2025). In a study on Vienna, Lederer and colleagues found that recycling construction minerals (e.g., concrete, brick, gravel) can substitute 3 million tons of raw materials annually (Lederer et al., 2020).

Reuse of products and components

Because recycling involves energy-intensive processes such as disassembly, material sorting, treatment, reprocessing, and remanufacturing and assembly of end-use products (Turner et al., 2015), the reuse of entire products or product components is preferable. Particularly in the context of buildings, environmental benefits of reusing of modular elements significantly surpasses those of recycling (Minunno et al., 2020). However, reuse of building components, or modules, perquisites considerations and foresight during the design phase. The potential of deconstructing buildings and reusing building components is dependent on various factors. This includes a low building complexity including a minimization of components and types, the use of reusable and eco-compatible, non-hazardous materials, transparency in building construction plans, and a definition of building deconstruction methodologies (Arora et al., 2020). It was shown that deconstructing a building that has reached its end-of-life can have lower net costs than demolition. Further, a systematic building disassembly allows for over 80% of embodied materials to be reused and recycled (Tatiya et al., 2018).

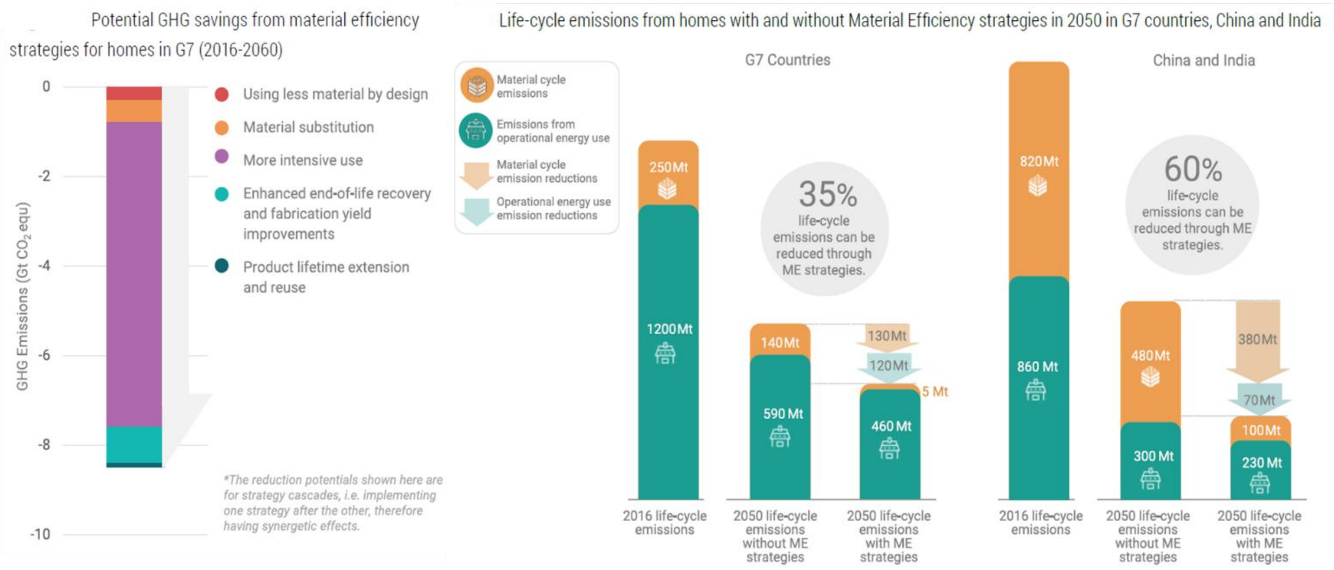
7.2.2. Scientific assessment of circularity potentials in the construction sector

In recent years, scientific research increasingly broadened the narrow perspective on material efficiency strategies for buildings towards a comprehensive analysis of circular economy measures along the 10R strategies and under consideration of cross-cutting synergies with, most prominently, decarbonization (Akhimien et al., 2021; Munaro et al., 2020; Munaro & Tavares, 2023; Norouzi et al., 2021; Santos et al., 2024). In the following, three studies will be summarized that explore circularity potentials in the construction sector from a systemic, economy-wide perspective.

Pauliuk et al. (2024; UN IRP, 2020) developed a dynamic stock model for the global residential and non-residential building sector and assessed the potential of circularity measures, in particular also material efficiency measures, to reduce GHG emissions for cement, bricks, wood, plastics, steel, and other metals. The study includes several strategies for the building sector, including narrowing (e.g., more intensive use of floor area, building designs considering lower quantities in material), slowing (e.g., lifetime extension, fabrication yield improvement and scrap diversion), and loop-closing strategies (e.g., increased recovery rates, material and component reuse), as well as material substitution such as a shift towards timber construction. Results show that the narrowing strategies (see left bar in Figure 7-3), particularly reduced floor space and lightweight buildings, contribute the most to the reduction of material consumption and GHG emissions. Although the study focusses on the reduction of GHG emissions, the measures applied are

CE measures that – next to the GHG savings – also positively contribute to a reduction of material use.

Figure 7-3: Life-cycle emissions from homes with and without material efficiency strategies in 2050 in G7 countries, China and India

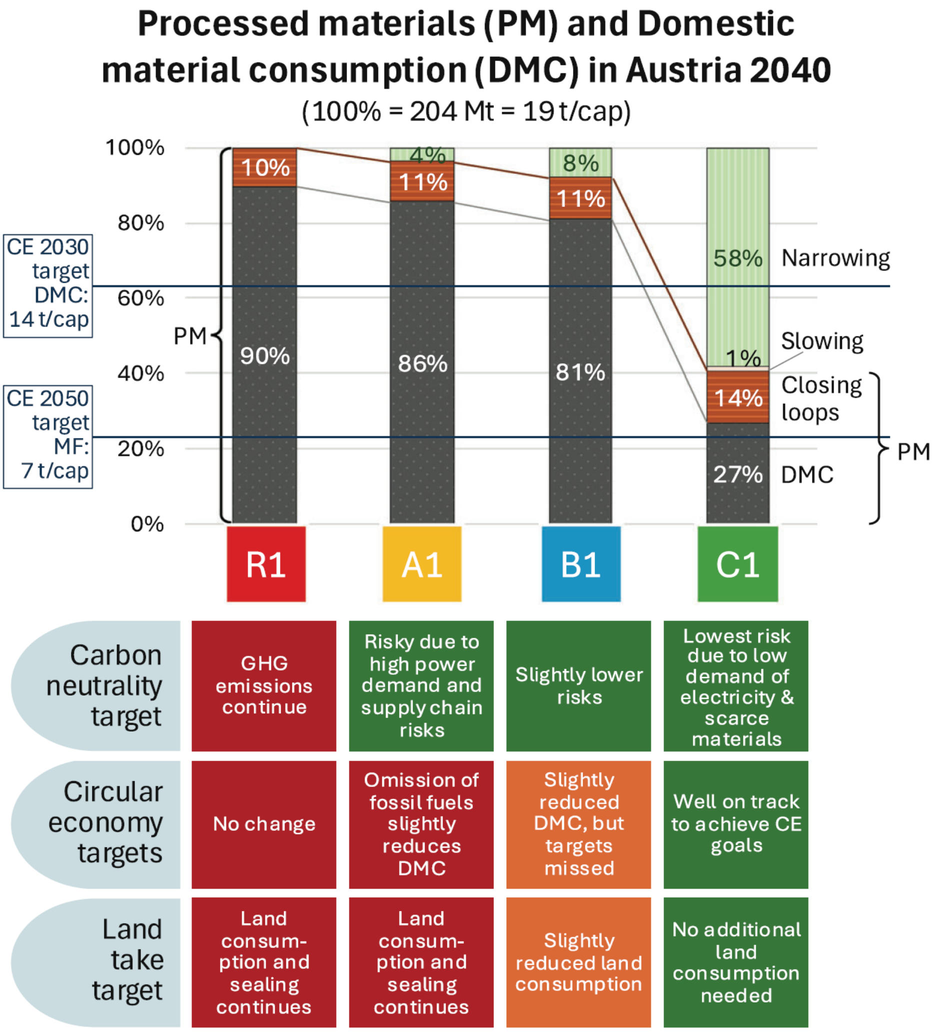


<u>Source:</u> UN International Resource Panel (2020)

In three studies Lederer and colleagues (Lederer et al., 2019, 2020, 2021) investigated the buildings stock in Vienna, Austria, and the effect of different CE measures on overall material inputs to buildings. The findings point towards significant reduction potentials in these material inputs. Renovation and building preservation (i.e., lifetime extension) is identified as the most effective CE measures for reducing material demand (-47% in 2050 as compared to 2015). The reduction clearly outweighs demolition and replacement of old buildings by new ones, which only reduces material use by 37% (Lederer et al., 2021). The increase of recycling of construction and demolition wastes is mentioned as the second most important measure, which can reduce material demand by 56% (Lederer & Blasenbauer, 2024). In addition, the authors highlight the importance of further CE measures such as material substitution and reduction of floor space per capita. These measures can push material savings even further.

A recent study for Austria (Haas et al., 2025) points to a very similar direction. The study assesses the potential of circularity measures to reduce resource use in the context of decarbonization (Haas et al., 2025). Material and energy use of the building, mobility, and electricity sectors were quantified and scenarios developed from 2018 to 2040. Results show that circular economy measures can ease decarbonization as reducing material flows and increasing circularity through narrowing, slowing, and loop-closing can substantially reduce the energy demand. Sufficiency-based measures (narrowing in Figure 7-4) were shown to have the largest effect on material demand overall. An example is that a stepwise stop of building construction on unbuilt land can lower final energy demand by over 10% und reduce material consumption by more than 40% by 2040. The involved reduction of per capita floor space is relatively low and can be compensated by better use rates of buildings. with a 25% reduction in per capita floor space in new building construction reducing economy-wide material consumption by 4% in 2040. A halt in road network expansion and a focus on merely maintaining the existing road network would reduce material consumption by more than 20%. The reductions in building and mobility infrastructure stocks are accompanied by reductions in goods furnishing buildings or vehicles required for the use of roads. With construction sector stocks causing the majority of annual material flows, transitioning from an expansion to a stabilization or even reduction of building and mobility infrastructure stocks appears most effective.

Figure 7-4: Contributions of narrowing, slowing, and recycling to the reduction of Austrian processedmaterials (PM) and consequently of domesticmaterial consumption (DMC) in 2040 along four scenarios in the buildings, transport, electricity sector



	R1	A1	B1	C1
Carbon neutrality target	GHG emissions continue	Risky due to high power demand and supply chain risks	Slightly lower risks	Lowest risk due to low demand of electricity & scarce materials
Circular economy targets	No change	Omission of fossil fuels slightly reduces DMC	Slightly reduced DMC, but targets missed	Well on track to achieve CE goals
Land take target	Land consum-ption and sealing continues	Land consum-ption and sealing continues	Slightly reduced land consumption	No additional land consumption needed

Legend: 100%refers to economy-wide reference scenario PM in 2018; the blue lines represent the 2030 and 2050 CE strategy targets when proportionally applied to the three sectors based on their 2018 DMC and for 2050, assuming a typical Austrian ratio between DMC and material footprint (MF); the boxes below the graph discuss the results of the scenarios in terms of specific policy targets: red boxes indicate that no change toward the target can be detected, orange boxes indicate a change in the desired direction but not strong enough to achieve the target, and green boxes indicate that the targets in these scenarios are within reach.

Source: Haas et al. 2025

7.2.3. Barriers and opportunities placed by material stocks to the implementation of Circular Economy measures in the construction sector

The characteristics of material stocks present both barriers to realizing the full potential of circular economy measures and opportunities to reduce the demand for materials. Some of these barriers and opportunities are described in this section.

Longevity of material stocks and effects on material use

Material stocks in the construction sector have particularly long service lives. While some stock types such as vehicles and technical equipment have service lives of up to around 20 years, buildings often remain in use for 80 to 100 years, or longer (Bahramian & Yetilmezsoy, 2020). Likewise, while the upper layers of roads have to be replaced at certain intervals (Hoxha et al., 2021), the main structure of the road remain in place for long times and even after decommissioning, roads often remain in situ as hibernating stock. The longevity of the built environment makes changing patterns and composition of construction sector material stocks a very slow process just circular economy measures implemented. Consequently, long lifetimes require that these stocks are planned carefully. That includes:

- Construction, operation, demolition, and reconstruction (replacement) of built stocks is material- and energy-intensive. A reduction of size and number of stocks as well as their material intensity per service unit (e.g. floor area) is the overarching aim.
- Our built-up environment was planned in a car-based system enabling inefficient structures like urban sprawl and single-houses. Shifting to a less emission-intensive, public transportation-focused system requires infrastructure investment and urban planning that is often hindered by prior car-focused decisions.

Conflict of goals between reductions in material use and the energy transition

While CE and decarbonization measures can co-benefit from each other (Material Economics, 2018), achieving energy demand reductions or shifting to renewable energy in many cases boosts material demand. On example is the thermal renovation of buildings which reduces heating and cooling demand significantly. However, insulation requires new material to be added with its production being emission-intensive, depending on the choice of insulation material (Füchsl et al., 2022). Another example is the shift from fossil fuels to renewable energy sources which requires a transformation of energy infrastructures and stocks. The expansion of existing green electricity capacities to supply electricity for electricity-based heating systems (e.g., electric heating, heat pumps) and for electric vehicles is material intensive (Kalt et al., 2022) because new wind parks, hydropower plants, photovoltaic systems need to be built, and the electricity grid, storage capacities or e-charging infrastructure needs to be expanded. The most effective measure to address this goal conflict is to reduce the socio-economic energy use and by that reduce the amount of energy infrastructure that needs to be newly built.

Complexity in and lack of information on building design and material composition

To exploit the full potential of all 10R strategies in the building sector full information on design of buildings and its material composition is required (Munaro & Tavares, 2023).

Though buildings in the EU primarily consist of concrete, bricks, iron/steel and timber, they also contain considerable amounts of other materials such as aluminum, copper, plastics or glass and the material specifics vary significantly across buildings, as does the design of components. Hence, by 2026, EU members states are directed to introduce building renovation passports (European Parliament, 2024). Likewise, the ISO 19650-1:2018[43] has been developed to organize and digitalize information on buildings and civil engineering works. Currently, the end-of-life phase is largely neglected in the planning of new buildings (Rahla et al., 2021). Together with limited technological capacities for separating materials or sourcing whole components from buildings (e.g., windows, walls), this limits the quality of secondary materials sourced from construction and demolition waste (CDW). Consequently, CDW is often downcycled to aggregates for reuse in foundations in buildings or in subbase layers in roads and therefore not substituting material inputs from primary sources.

Economic and political barriers

CE processes involved in deconstructing buildings, sorting materials and components and recycling are energy and cost-intensive. At the same time, recycled materials compete with virgin raw materials of usually low price that are abundantly available (Munaro & Tavares, 2023). A lack of market investments and marketing strategies for the reuse of secondary materials are likewise identified as economic barriers (Munaro & Tavares, 2023). A recent study on deconstruction cost prediction, however, has found that deconstruction can have lower net costs compared to conventional demolition (Tatiya et al., 2018). When considering that quality loss of end-of-life materials can be kept low and more material becomes available for reuse, deconstruction can become more attractive economically to contractors and architects.

Political barriers include a lack of regulatory instruments including reward and penalty schemes for construction and demolition waste management. Further, current building code regulations are often not flexible (Paiho et al., 2020), hindering innovation and a sustainable reuse of generated construction waste. Lastly, current regulation prioritizes resource use efficiency over demand reduction (Hossain et al., 2020; Munaro & Tavares, 2023), leading to significant circularity potentials being neglected. Hart et al. (2019) further mention lack in a consistent regulatory framework (within and across national boundaries) as well as incentives for CE.

In addition, Hart et al. (2019) identify cultural barriers being a lack of interest, knowledge/skills and engagement in producers and consumers as well as a lack of collaboration between businesses (sometimes due to competitive thoughts and silo thinking within and between businesses).

Public perception of narrowing strategies

Voluntary, sufficiency-based demand reductions require behavior changes. This in turn requires that public opinion regarding, for example, reductions in per capita floor space is positive. Haas et al. (2025) have shown that implementing a 25% reduction in per capita

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[43] https://www.iso.org/standard/68078.html

floor area in newly constructed buildings in Austria, average per capita floor space would decrease by only 7% by 2040. Nevertheless, in a study on acceptance, motivation and side-effects of voluntary living space reduction in the European Union found that across five different countries, there is an overall negative sentiment towards smaller living (Lehner et al., 2024). However, the study also reports willingness among respondents to relinquish excessive square meters, although the share of respondents willing ranges from 15% in Hungary to 42% in Spain. Acceptance levels for shared housing was generally lower across countries, ranging from 11% in Hungary to 33% in Spain. Although overall opinion is negative, a significant portion of the population was willing to reduce space, which would enabling a reduction in future floor space and consequently in material demand. A study for Germany (Kitzmann, 2024) showed that 29% of the home-owning elderly population (60 years and older) is open to reduce floor space per capita. Further, 11 % of elderly tenants are overburdened and assess their housing conditions as too spacious.

Specific barriers in the construction sector

An interesting article by Hart et al. (2019) particularly focus on barriers and drivers for the case of the built environment, where buildings and infrastructure feature numerous and different stakeholders with different interests and incentives in different phases of long lifespans and hundreds of components. Among the sectoral barriers they name:

- complexity and confused incentives,
- long product life cycles that detach decision-makers from the consequences of their choices, lead to fragmented supply-chains and multiple stakeholders/owners along the way,
- technical challenges regarding material recovery, challenges in recovery/reuse/recycling in particular for composite products/parts, lacking standardization as well as insufficient use or development of CE-focused design and collaboration tools, information and metrics
- As more fundamental barriers discussed in the article, are a lack of bandwidth which they see as not explicitly addressed in literature. They point at competing and overlapping priorities and an uncertainty by stakeholders to what extent the CE framework has an overarching quality or is subdue to other frameworks, such as sustainable development.
- As another sector-specific cultural barrier they discuss the sector itself. They state "*that the sector is its own enemy in terms of CE. By nature it is wary of innovation, and takes an adversarial, risk-averse approach to contractual terms on liability that can restrain innovation further.*" (Hart et al., 2019, p. 622)

7.3. Barriers to and opportunities for Circular Economy – batteries sector

7.3.1. Brief overview of the markets for batteries

What are batteries and what are they used for?

Batteries are devices that store energy in a chemical form and give it back as a usable electric energy, as direct current and a rather low voltage (a few volts). Some batteries are built in a way that they can only be used once (primary batteries), while others are rechargeable and can be used several times (secondary batteries).

Batteries are classified per **chemistry**, each chemistry corresponding to a specific set of **active materials** (e.g. Lithium, Cadmium, Cobalt, graphite) in its cells and to corresponding features in terms of energy density, longevity and price.

Batteries are used for the following **applications**:

- To supply energy to portable electronic devices, such as:
    - Mobile phones;
    - Tablets;
    - Cameras and game consoles;
    - Portable computers;
    - Portable power tools;
- To start and ignite the engine, and to feed the lighting and the on-board electronic devices of an internal combustion engine vehicle (Start – Lighting – Ignition or SLI);
- To ensure a reliable and stable electric power supply in fixed applications:
    - Uninterrupted Power Supplies (UPS) for critical installations (networks, industrial process control, medical & healthcare, transport equipment);
    - Compensation for the intermittent electric energy production of renewable sources;
- To feed the electric motor of vehicles that are partially or entirely propelled by an electric motor:
    - Electrically-assisted bicycles;
    - (Plug-in) Hybrid motor vehicles;
    - Full electric motor vehicles.

The market for and stock of batteries can hence be considered along the three dimensions of (1) chemistries, (2) active materials and (3) applications. These dimensions are not independent from each other (one application tends to be served by one chemistry and hence one set of materials), but do not overlap fully either (one application can be served by several chemistries, one material can be used in several chemistries and one chemistry uses several materials). In what follows, we will present data along these three dimensions.

What are the main components of the batteries market?

A simple way of considering the current market for batteries is to subdivide it into the following components:

- Two homogeneous categories of traditional batteries that still represent the largest share in mass of the stocks and flows of batteries:
    - Lead-acid (Pb-acid) batteries for the Start, Lighting and Ignition of internal combustion vehicles (SLI);
    - Zinc (Zn)-based primary batteries, often referred to as “alkaline” batteries;
- One heterogeneous category of batteries for recent and developing applications (mobile electronic devices, complement to intermittent renewable energy sources, electric mobility), which represent a very rapidly growing minority of the mass in the stock and flows of batteries:
    - Nickel-Cadmium (NiCd) and Nickel-Metal Hydride (NiMH) batteries, found only in fixed industrial applications;
    - The considerable diversity of Lithium-ion batteries, used in all other applications.

What are the main recent and forecast evolutions of the market for batteries?

The major changes observed on the market for batteries are the following:

- Shift from Internal Combustion Engines to electric traction in the automotive sector;
- Increased use of renewable electric energy production and of corresponding electric energy storage.

These trends align with the decarbonation of the mobility and electric energy production sectors and are hence anticipated to continue over the next decades.

What is the legislation applicable to batteries?

The main legislation applicable to batteries are:

- The Batteries Regulation[44] and the
- Regulation on the rules on calculating recycling efficiencies of the recycling processes of waste batteries and accumulators.[45]

These Regulations are described in greater detail in Annex C. Supplementary materials and methods supporting section “Material stocks: Barriers to and opportunities for circularity in the construction and batteries sectors”, § 10.3.2.

7.3.2. Main circularity features of the existing stock of batteries

The main source of information on the stock of batteries in the European Union is the **Raw Materials Information System (RMIS)** of the European Commission’s Joint Research Centre – JRC, in its section “Raw Materials in the Battery Value Chain”[46], which provides historic data

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[44] European Commission, 2023. Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/E, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02023R1542-20240718

[45] European Commission, 2012. Commission Regulation (EU) No 493/2012 of 11 June 2012 laying down, pursuant to Directive 2006/66/EC of the European Parliament and of the Council, detailed rules regarding the calculation of recycling efficiencies of the recycling processes of waste batteries and accumulators Text with EEA relevance, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012R0493

[46] *Available at: https://rmis.jrc.ec.europa.eu/bvc#/v/apps*

for the years 2006 to 2018 and forecasts for the years 2019 to 2021, for the EU28 (i.e. including the United Kingdom).

As will be illustrated further in this section, the main messages on the stock of batteries as of 2021 are:

- Traditional, homogeneous applications and chemistries still dominated the stock in 2021;
- The stock of new battery chemistries is very diverse;
- The stock of active materials in batteries is 91.9% made of lead, the rest mainly of Critical Raw Materials (CRMs) in Lithium-ion batteries;
- When taking into account the scarcity of and the energy needed to extract and process the materials present in batteries, the relative weight of materials in the stock changes considerably;
- The recycling of the metal content of batteries is very efficient, even if that of Lithium-ion batteries still is confronted with some technical challenges;
- The stock of batteries is very badly tracked and accounted for.

Traditional, homogeneous applications and chemistries still dominated the stock in 2021

The total mass of whole batteries (i.e. the active cells, but also other materials like electrolytes, packaging, the Battery Management System – BMS) in stock was estimated at 11.061 Mt in 2021.

The Table 7-1 below provides the mass of the whole batteries in stock, per **application**, as provided by the RMIS database. A can be seen, the two applications that dominate the stock are:

- “Start – Lighting – Ignition (SLI)” for internal combustion engines (5.732 Mt in 2021, i.e. 51.8% of the total); and
- Fixed industrial applications (4.096 Mt in 2021, i.e. 37% of the total).

When removing these two dominant applications, we observe that:

- Primary batteries still represent an important share of the stock remaining after the removal of the two major applications (487 kt in 2021, i.e. 39.5% of the remaining 1.233 Mt);
- Electric traction of vehicles (Hybrid Electric Vehicles – HEV, Plug-in Hybrid Electric Vehicles – PHEV and Battery Electric Vehicles – BEV, electric bicycles) still represent a minor share of the stock (3.6% of the total stock, 32.1% of the remaining stock), even if very rapidly growing (multiplied by 188 between 2006 and 2021).

Interestingly, the mass of batteries in stock increases over time, not only for ‘new’ applications such as portable electronic or electric devices, or for electric vehicles, but also for ‘traditional’ ones.

Table 7-1 Mass of batteries in stock in the EU28, 2006-2021, per application

Year	Total mass of batteries 2006 (kt)	Total mass of batteries 2021 (kt)	As share of total mass of batteries 2021 (%)	As share of total mass of batteries 2021 without SLI and fixed industrial (%)	Change of total mass 2021 vs. 2006 (%)
Start – Lighting – Ignition (SLI)	3,721	5,732	51.8%	-	+54%
Fixed industrial	2,166	4,096	37.0%	-	+89%
Primary	456	487	4.4%	39.5%	+6.8%
Electric traction of vehicles[47]	2	396	3.6%	32.1%	X 188
Portable electronic devices[48]	53	185	1.7%	15.0%	X 3.5
Portable tools and other portable devices	81	165	1.5%	13.4%	X 2.0
Total without SLI and fixed industrial	591	1.233	11.1%	100.0%	
Total	6,479	11,061	100.0%		+71%

Source: European Commission, Joint Research Centre (JRC) RMIS – Raw Materials Information System, Raw Materials in the Battery Value Chain, accessible at: https://rmis.jrc.ec.europa.eu/bvc#/

Similarly, the Table 7-2 below provides the mass of the whole batteries in stock, per **chemistry**, as provided by the RMIS database. A can be seen, the chemistry that dominates the stock is Lead-acid (9.669 Mt in 2021, i.e. 87.4% of the total). When removing this dominant chemistry in, we observe that:

- Zinc-based primary batteries represent similarly as above an important share of the stock remaining after the removal of the dominant chemistry (487 kt in 2021, i.e. 35% of the remaining 1.392 Mt);
- The dominant and fastest-growing family of chemistries is the Lithium-ion batteries, which represented a stock of 656 kt in 2021, i.e. 47.1% of the remaining 1.392 Mt.

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[47] *Battery Electric Vehicles, Hybrid Electric Vehicles, e-bicycles*

[48] *PC, tablets, mobile phones, cameras, game consoles*

Table 7-2 Mass of batteries in stock in the EU28, 2006-2021, per chemistry

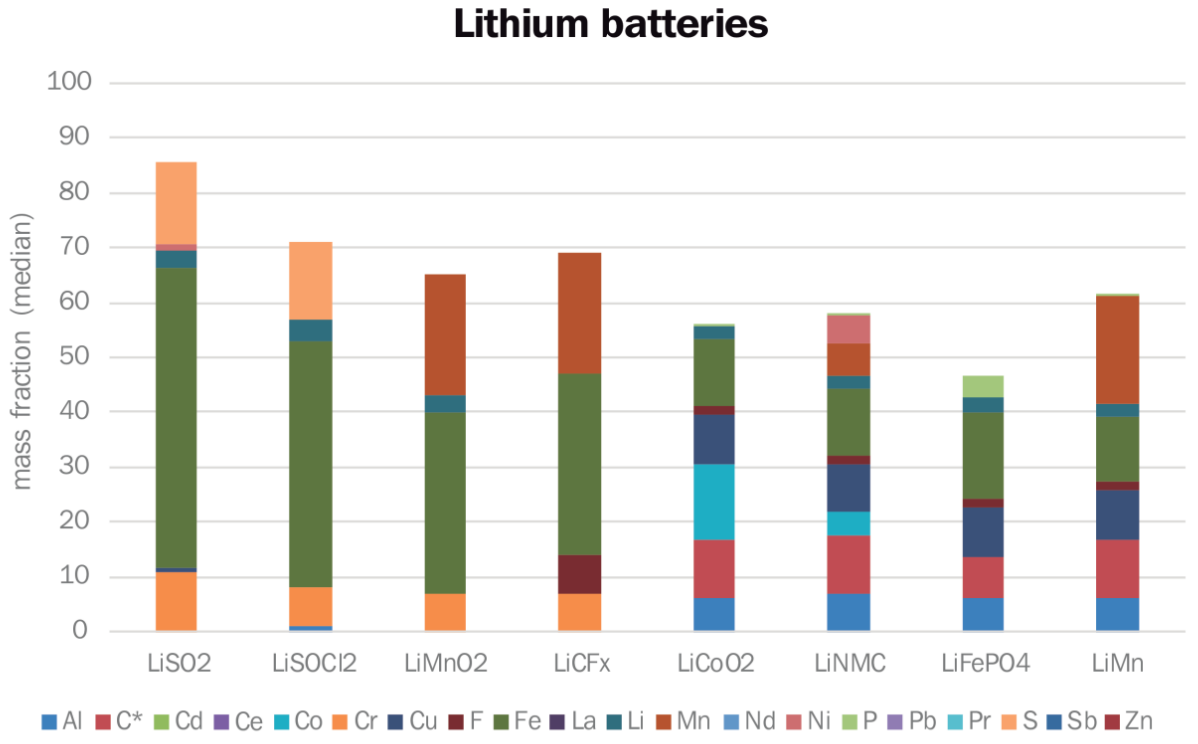
Year	Total mass of batteries 2006 (kt)	Total mass of batteries 2021 (kt)	As share of total mass of batteries 2021 (%)	As share of total mass of batteries 2021 without Pb-acid (%)	Change of total mass 2021 vs. 2006 (%)
Pb-acid	5,853	9,669	87.4%	-	+70.1%
Zn	456	487	4.4%	35.0%	+6.8%
Li-ion	46	656	5.9%	47.1%	X 14.3
NiCd	55	82	0.7%	5.9%	+50.3%
NiMH	39	95	0.9%	6.8%	X 2.5
Other	31	72	0.6%	5.1%	X 2.3
Total excluding Pb-acid	625	1,392	12.6%	100.0%	
Total	6,479	11,061	100.0%		+71%

<u>Source:</u> European Commission, Joint Research Centre (JRC) RMIS – Raw Materials Information System, Raw Materials in the Battery Value Chain, accessible at: <u>https://rmis.jrc.ec.europa.eu/bvc#/</u>

The stock of new battery chemistries is very diverse and evolves fast

The material diversity of Lithium-ion batteries is illustrated by the Figure 7-5 below, which shows the material composition of various families of Lithium-ion batteries.

Figure 7-5 Median material composition of families of Lithium-ion batteries



<u>Source:</u> J. Huisman et al. (2017) Prospecting Secondary Raw Materials in the Urban Mine and mining wastes (ProSUM) - Final Report, available at: <u>https://futuram.eu/library/prosum-project-results/</u> , Figure 14.

Legend : LiSO2: Lithium-Sulphur Oxide; LiSOCl2: Lithium – Sulphur Chloride; LiMnO2: Lithium Manganese Oxide; LiCFx: Lithium Carbon Fluoride; LiCoO2: Lithium Cobalt Oxide; LiNMC: Lithium nickel manganese cobalt; LiFePO4: Lithium Iron phosphate; LiMn: Lithium Manganese

Al = Aluminium; C = Carbon graphite; Cd = Cadmium; Ce = Cerium; Co = Cobalt; Cr = Chromium; Cu = Copper; F = Fluor; Fe = Iron; La = Lanthanum; Li = Lithium; Mn = Manganese; Nd = Neodymium; P = Phosphorus; Pb = Lead; Pr = Praseodymium; S = Sulphur; Sb = Antimony; Zn = Zinc.*

The chemistries for Lithium-ion batteries are not only diverse, depending on the application (portable electronics, portable electric tools, traction of vehicles). They also evolve over time as the result of massive investments in R&I aiming at increasing their power density per kilogramme or per litre, as illustrated in the Table 7-3 below.

Table 7-3 Anticipated evolution of Lithium-ion batteries technologies over time (2018-2030)

Cell generation	Cell chemistry	Typical energy density (Wh / l)
Generation 5 (>?)	· Li-O_2 (lithium air)	1,000 (R&D)
Generation 4 (>2025?)	· All solid state with lithium anode · Conversion materials (primarily lithium sulphur)	700 (R&D)
Generation 3b (~2025)	· Cathode: High energy NMC, High Voltage Spinel · Anode: silicon/carbon	700 (under development)
Generation 3a (~2020)	· Cathode: NMC 622 to NMC 811 · Anode: silicon/carbon	650 (under development
Generation 2b (current)	· Cathode: NMC532 to NMC 622Anode: carbon	500
Generation 2a (current)	· Cathode: NMC111 · Anode: 100% carbon	500
Generation 1 (current)	· Cathode: LFP, NCA · Anode: 100% carbon	350

Source: Huisman, J., Ciuta, T., Mathieux, F., Bobba, S., Georgitzikis, K. and Pennington, D. (2020) RMIS – Raw materials in the battery value chain, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-13854-9, https://doi.org/10.2760/239710 , Figure 10

The stock of active materials in batteries is 91.9% made of lead, the rest mainly of Critical Raw Materials (CRMs) in Lithium-ion batteries, and has grown considerably over the last 15 years

As can be seen in Table 7-4, the active materials contained in batteries amount to a total of 6.9 Mt and consist very predominantly in **lead** (91.9% of the total).

The remaining 559 kt consist in:

- **Critical Raw Materials (CRMs)** found **only in Lithium-ion batteries**: Cobalt – Co (6.8% of the stock without lead), Copper – Cu (10.6%), graphite carbon (12.4%) and Lithium – Li (2.9%);
- **CRMs** found in Lithium-ion batteries but also in other chemistries: Manganese – Mn (26.2%) found mainly in Zinc-based primary batteries; and Nickel – Ni (11.1%) found also in Nickel-based batteries (NiCd and NiMH);
- Cd – Cadmium, a toxic element, found only in the declining stock of Nickel-Cadmium – NiCd batteries (1.9% of the stock without lead);

- Sb – Antimony, a Critical Raw Material found in traditional Lead – acid batteries (14.9% of the stock without lead);
- Zn – Zinc, found very predominantly in primary batteries (13.2% of the stock without lead).

The stock of materials contained in batteries has **increased considerably** over the last years, for all materials except Zinc:

- It was multiplied by 14 for Graphite, Li – Lithium and Cu – Copper, all Critical Raw Materials (CRMs);
- It was multiplied by 5 for Co – Cobalt and by 2.5 for Ni – Nickel, also CRMs;
- It grew between 50% and 80% for all other materials, including Pb – Lead.

Table 7-4 Stock of active materials in batteries in 2006 and in 2021

Chemical element	Stock in batteries in 2006 (tonnes)	Stock in batteries in 2021 (tonnes)	Change in stock 2006 – 2021 (%)	Share of total in 2021	Share of total without Pb – Lead in 2021
C - Graphite	4,916	69,487	x 14	1.0%	12.4%
Cd - Cadmium	6,427	10,408	+ 61.9%	0.2%	1.9%
Co - Cobalt	7,487	38,214	x 5.1	0.6%	6.8%
Cu - Copper	,4,132	59,040	x 14.3	0.9%	10.6%
Li - Lithium	1,148	16,400	x 14.3	0.2%	2.9%
Mn - Manganese	96,672	146,470	+51.5%	2.1%	26.2%
Ni - Nickel	24,817	61,919	x 2.5	0.9%	11.1%
Pb - Lead	3,847,077	6,362,819	+65.4%	91.9%	-
Sb - Antimony	46,088	83,605	+81.4%	1.2%	14.9%
Zn - Zinc	68,858	73,997	+7.4%	1.1%	13.2%
Total	4,109,622	6,922,359	+68.5%	100%	-
Total without Pb - Lead	262,545	559,540	+113.1%	8.1%	100.0%

Source: *European Commission, Joint Research Centre (JRC) RMIS – Raw Materials Information System, Raw Materials in the Battery Value Chain, accessible at: https://rmis.jrc.ec.europa.eu/bvc#/*

When taking into account the scarcity of and the energy needed to extract and process the materials present in batteries, the relative weight of materials in the stock changes considerably

The materials present in batteries differ very strongly in their rarity in the Earth's crust and in the energy that was needed to extract and process them to a usable state.

One approach to quantify these differences has been proposed by Science Europe[49], by computing:

- The energy that was needed to extract and process the chemical element of interest, which quantifies the **embodied environmental footprint** of the material;
- The energy that humans inherited from nature that concentrated for free this chemical element in the terrestrial crust from a reference state where all minerals would be evenly distributed and dispersed in it, which quantifies the **rarity** of the material and hence its potential strategic value.

In physical terms, the nature of the energy being used is referred to as "exergy". The computations made according to this method[50] provide a complete table of these values for a large number of metals.

Table 7-5 below provides a computation of the exergy embedded in the stock of materials present in the EU28.

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[49] *Science Europe (2015) 'A Common Scale for Our Common Future: Exergy, a Thermodynamic Metric for Energy. Recommendations from the Science Europe Physical, Chemical and Mathematical Sciences Committee': D/2015/13.324/, available at: https://doi.org/10.5281/zenodo.7022853*

[50] *Valero, A., & Valero, A. (2018). Accounting for Mineral Depletion Under the UN-SEEA Framework. InTech. doi: 10.5772/intechopen.77290, available at: http://dx.doi.org/10.5772/intechopen.77290*

Table 7-5 Energy needed for the replacement and for the extraction and processing of the materials present in the stock of batteries in the EU28

Chemical element	Stock in batteries in 2021 (tonnes)	Exergy replacement costs (GJ / tonne)	Mining and metallurgical costs (GJ / tonne)	Total exergy for replacement costs, expressing rarity, in stock (millions of GJ)	Share of total	Total exergy for mining and metallurgical costs, expressing environmental footprint, in stock (millions of GJ)	Share of total
C - Graphite	69,487	20	1	1.39	0.1%	0.07	0.1%
Cd - Cadmium	10,408	5,898	542	61.39	6.5%	5.64	8.3%
Co - Cobalt	38,214	10,872	138	415.46	**43.8%**	5.27	7.8%
Cu - Copper	59,040	292	57	17.24	1.8%	3.37	5.0%
Li - Lithium	16,400	546	433	8.95	0.9%	7.10	**10.5%**
Mn - Manganese	146,470	16	58	2.34	0.2%	8.50	**12.5%**
Ni – Nickel (sulphides)	61,919	761	115	47.12	5.0%	7.12	**10.5%**
Pb - Lead	6,362,819	37	4	235.42	**24.8%**	25.45	**37.6%**
Sb - Antimony	83,605	474	13	39.63	4.2%	1.09	1.6%
Zn - Zinc	73,997	1,627	56	120.39	12.7%	4.14	6.1%
Total	6,922,359			949.34	100.0%	67.75	100.0%

Source: Own elaboration, based on European Commission, Joint Research Centre (JRC) RMIS – Raw Materials Information System, Raw Materials in the Battery Value Chain, accessible at: https://rmis.jrc.ec.europa.eu/bvc#/ and on Valero, A., & Valero, A. (2018). Accounting for Mineral Depletion Under the UN-SEEA Framework. InTech. doi: 10.5772/intechopen.77290, available at: http://dx.doi.org/10.5772/intechopen.77290

The respective weights of the materials contained in the stock of batteries is much more balanced when considering the rarity or the environmental impact of the materials than when considering their mass:

- **Cobalt** (43.8%) and **Lead** (24.8%) concentrate the bulk of the replacement costs of these materials, representing their **rarity**;
- **Lead** (37.6%), **Lithium**, **Nickel** and **Manganese** (ca. 10% each) dominate the mining and metallurgical costs of these materials, representing their **environmental footprint**.

The recycling of the metal content of batteries is very efficient, even if that of Lithium-ion batteries still is confronted with some technical challenges

Following the requirements of the Batteries Directive[51] that preceded the Batteries Regulation, and methodologies defined in further Delegated Acts[52], Eurostat monitors the efficiency of the recycling of batteries and of their metal content for lead and for cadmium.

The Table 7-6 below provides, for the years 2014, 2018 and 2021, the total mass of **lead** being recovered from recycled batteries and the total mass of the lead contained in these batteries in the reporting Member States of the EU27[53], and deduces the average yield of this recycling.

Table 7-6 Recycling yield of lead contained in batteries in the EU27 in 2014, 2018 and 2021

Year	**2014**	**2018**	**2021**
TOTAL recycled lead (tonnes)	580,108	836,737	869,935
TOTAL input lead (tonnes)	604,610	873,801	893,785
Recycling yield (%)	95.9%	95.8%	97.3%

Source: Eurostat (2025) Recycling of batteries and accumulators. Online data code: env_wasbat, available at: https://ec.europa.eu/eurostat/databrowser/view/env_wasbat__custom_15240495/default/table?lang=en

As can be seen, the average yield of the recycling of lead in the EU27 has been consistently very good over the last decade, above 95%, but remains stagnant at that high level.

The recycling of **cadmium** is less well monitored and applies to very small amounts of metal: between 400 and 500 tonnes / year since 2017, in the 21 EU Member States that report values[54]. The yield values computed from these reports display limited consistence over time, leading to concerns on the validity of the data.

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[51] *Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators, available at: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32006L0066*

[52] *Commission Decision 2008/763/EC establishing a common methodology for the calculation of annual sales of portable batteries and accumulators to end-users*

Commission Regulation (EU) No 493/2012 laying down detailed rules regarding the calculation of recycling efficiencies of the recycling processes of waste batteries and accumulators

[53] *All Member States except Denmark, Hungary, Ireland, Malta/*

[54] *Eurostat (2025) Recycling of batteries and accumulators. Online data code: env_wasbat, available at: https://ec.europa.eu/eurostat/databrowser/view/env_wasbat__custom_15240495/default/table?lang=en*

The achievable technical performance for the recycling of the metals contained in **Lithium-ion batteries** has been the purpose of a recent study[55], briefly summarised below.

The main stages in the recycling of batteries are:

1. Discharging the remaining energy in the battery, for safety reasons;
2. Shredding the battery, a cheaper option resulting in small, mixed parts, or disassembling it, a costlier option enabling to obtain purer elements;
3. Applying thermal and physic-mechanical pre-treatment processes;
4. Pyrometallurgy alone or combined with hydrometallurgy.

Pyrometallurgy consists in high-temperature treatments (1,250 to 1,500°C) that melt all the metals contained in the battery and enable a separate collection by leveraging the differences in melting temperatures of each component metal. Hydrometallurgy consists in leaching valuable metals from cathodic active materials in acidic environments.

The average yields reported in the literature for the recovery of the main metals contained in Lithium-ion batteries are summarised in the Table 7-7 below.

Table 7-7 Recovery yields of metals in the recycling processes of Lithium-ion batteries

Metal	Average yield pyrometallurgy processes	Average yield hydrometallurgy processes
Aluminium – Al	99.34%	71.0% ± 34%
Cobalt – Co	86.35% ± 15%	91.7% ± 12%
Copper – Cu	96.25%	-
Iron – Fe	-	91.5% ± 13%
Lithium – Li	-	96.2% ± 5%
Manganese – Mn	88.40% ± 4%	88.4% ± 19%
Nickel – Ni	98.37% ± 1%	90.1% ± 15%

Source: Martina Bruno, Silvia Fiore (2024) Review of lithium-ion batteries' supply-chain in Europe: Material flow analysis and environmental assessment, Journal of Environmental Management, Volume 358, 2024, 120758, https://doi.org/10.1016/j.jenvman.2024.120758 , Tables 1 and 2.

As can be seen above, the recovery yields achieved are already very good, even if several challenges remain[56]:

- The difficulty in determining the exact chemistry of the battery, and hence the correct treatment to apply to it;
- The cost and safety risks of dis-assembly;
- The low energy efficiency of the thermal pre-treatment phase;
- The incapacity of pyrometallurgy to recover Lithium;

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[55] *Martina Bruno, Silvia Fiore (2024) Review of lithium-ion batteries' supply-chain in Europe: Material flow analysis and environmental assessment, Journal of Environmental Management, Volume 358, 2024, 120758, https://doi.org/10.1016/j.jenvman.2024.120758 .*

[56] *Martina Bruno, Silvia Fiore (2024) Review of lithium-ion batteries' supply-chain in Europe: Material flow analysis and environmental assessment, Journal of Environmental Management, Volume 358, 2024, 120758, https://doi.org/10.1016/j.jenvman.2024.120758 . §3.3.6.*

- The environmental consequences of hydrometallurgy.

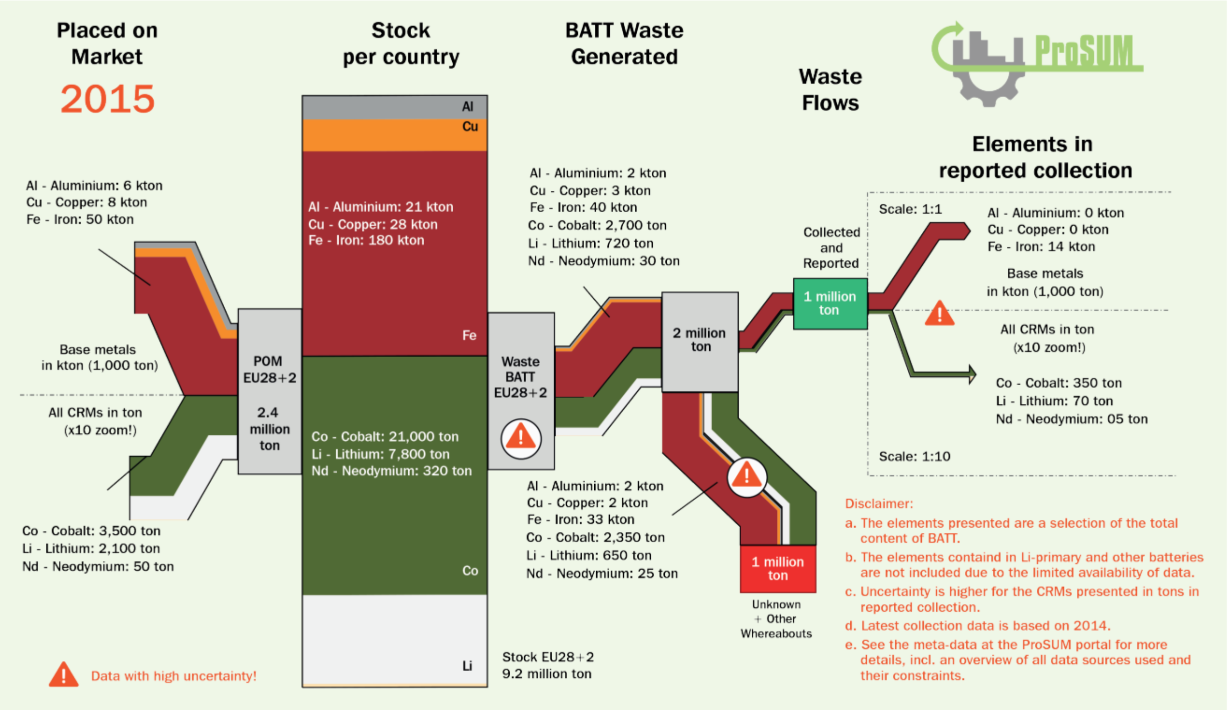
The main area in which the circularity of the stock of Lithium-ion batteries can be improved lies in their **ecodesign**: more accurate labelling of the chemistry, better ability to be dis-assembled, less hazardous electrolytes.

The stock of batteries is very badly tracked and accounted for

As can be seen in Figure 7-6 below, a very important share of the stock of several materials used in Lithium-ion batteries is not accounted for: it is assumed to have reached its end of life, but has not been registered as selectively collected waste in the Extended Producer Responsibility (EPR) schemes in Member States. It is either ‘hibernated’, i.e. kept as a dormant stock in homes and businesses, or illegally dumped in the flow of mixed municipal waste.

N.B.: The figure does not account for lead and zinc, which are the two dominant materials in the stock of batteries.

Figure 7-6 Sankey diagramme of selected materials in batteries (lead and zinc are not represented)



<u>Source:</u> J. Huisman et al. (2017) Prospecting Secondary Raw Materials in the Urban Mine and mining wastes (ProSUM) - Final Report, available at: <u>https://futuram.eu/library/prosum-project-results/</u> , Figure 19

7.3.3. The anticipated evolution of the demand for batteries (2020-2030)

As shown in Figure 7-7, European Lithium-ion battery market is poised for significant growth over the next decade, driven primarily by the implementation and adoption of electric vehicles (EVs), with demand in the for light-duty vehicles (<3.5 tonnes) EU forecast to rise from ca. 50 GWh in 2020[57] and 238 GWh in 2024 to 630 GWh (pessimistic scenario), 885 GWh (realistic scenario) and up to 1,050 GWh (optimistic scenario) in 2030 and an

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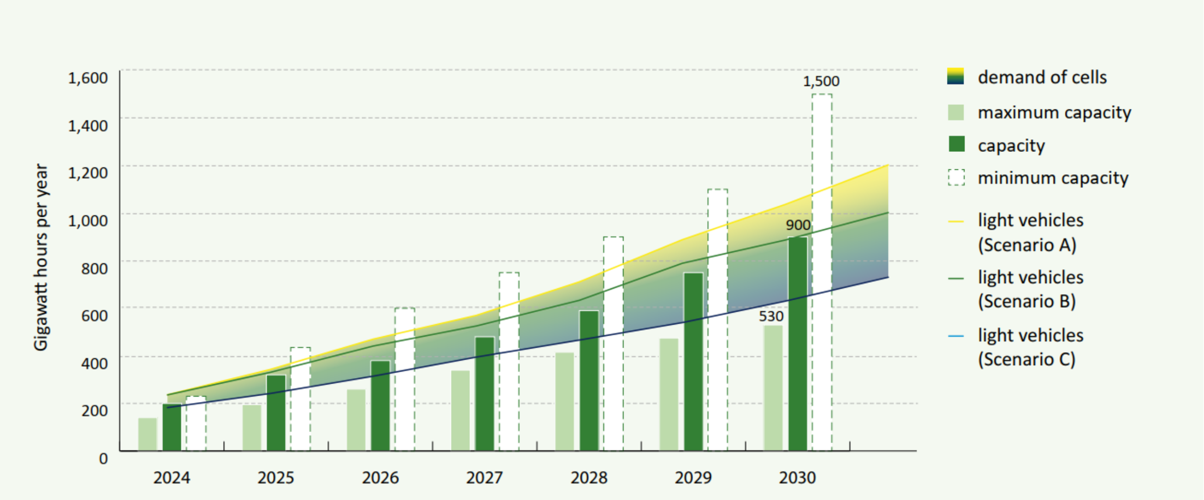
[57] *Avicenne Energy (2021). EU battery demand and supply (2019-2030) in a global context, available at: <u>https://www.eurobat.org/wp-content/uploads/2021/05/Avicenne_EU_Market_-_summary_110321.pdf</u>*

upper bound of 1,260 GWh to 1,500 GWh when electric vehicles reach 100% market penetration (presumably in 2035)[58]. Furthermore, European production capacity for Li-ion batteries is projected to expand to meet this burgeoning demand, signalling the region's readiness to support the transition to e-mobility.[59]

Figure 7-7: Demand and supply for Li-ion batteries for light-duty vehicles in Europe, 2024-2030



Legend: Scenario A (optimistic): 21.1 M vehicles in 2030, 70% electrification; Scenario B (realistic): 18 M vehicles in 2030, 70% electrification; Scenario C (pessimistic): 18 M vehicles in 2030, 50% electrification.

Source: IPCEI Batteries – Market update Q2 2024, available at: https://www.ipcei-batteries.eu/fileadmin/Images/accompanying-research/publications/2024-05-BZF_Kurzinfo_Marktanalyse_Q2_engl.pdf

Alongside the significant increase in electric mobility, global battery demand for energy storage will also rise, as will demand for consumer electronics, though to a lesser extent. For energy storage, key growth drivers include increasing shares of intermittent renewables (requiring battery capacity for wind and solar expansion), supporting decentralized power systems, stabilizing grid frequency, and enabling commercial and industrial solar-plus-storage solutions.[60]

Besides Li-ion batteries, lead-based batteries will remain a dominant market segment, with a slight increase expected in the coming years, from 65 GWh in 2020 to 68 GWh in 2030.[61]

7.3.4. The impact of stock-related CE measures on narrowing, slowing, closing on overall CE indicators for batteries

The Circular Economy measures that can be implemented on batteries take place at the following points of the product's life cycle:

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[58] *IPCEI Batteries – Market update Q2 2024, available at: https://www.ipcei-batteries.eu/fileadmin/Images/accompanying-research/publications/2024-05-BZF_Kurzinfo_Marktanalyse_Q2_engl.pdf*

[59] *Avicenne Energy (2021). EU battery demand and supply (2019-2030) in a global context, available at: https://www.eurobat.org/wp-content/uploads/2021/05/Avicenne_EU_Market_-_summary_110321.pdf.*

[60] *WEF (2019). A Vision for a Sustainable Battery Value Chain in 2030. Available at: https://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf*

[61] *Avicenne Energy (2021). EU battery demand and supply (2019-2030) in a global context, available at https://www.eurobat.org/wp-content/uploads/2021/05/Avicenne_EU_Market_-_summary_110321.pdf.*

- design phase, to increase the battery's longevity, capacity to be re-used and to be recycled;
- use phase: user advice and management system to increase longevity – even if repair or maintenance operations are in general impossible because the device is sealed for safety reasons;
- end of life phase: downgraded re-use or recycling.

The Batteries Regulation will progressively improve some circularity features of the stock of batteries

The Batteries Regulation progressively implements CE measures belonging to each of the categories above, as described in Table 7-8 below.

Table 7-8 Circular Economy measures implemented and enabled by the Batteries Regulation

Circular Economy measure implemented by the Batteries Regulation	Article in Batteries Regulation	Categories of Circular Economy measure	Stage(s) in the product lifecycle when the measure is applied	Example closest to the implemented CE measure
Minimum average duration of non-rechargeable batteries	Art.9	2. Slowing 2. Increase lifetime	Before use – Rethink	**2.b** Design for longevity/ durability
Minimum delayed discharge performance of non-rechargeable batteries	Art.9	2. Slowing 2. Increase lifetime	Before use – Rethink	**2.b** Design for longevity/ durability
Minimum endurance in cycles of rechargeable batteries	Art.9 Art.10	2. Slowing 2. Increase lifetime	Before use – Rethink	**2.b** Design for longevity/ durability
Minimum charge retention Maximum capacity fade	Art.9 Art.10	2. Slowing 2. Increase lifetime	Before use – Rethink	**2.b** Design for longevity/ durability
Removability and replaceability	Art.11	2. Slowing 2. Increase lifetime	Before use – Rethink	**2.b** Design for re-use
Enhanced Producer Responsibility	Art.56	3. Closing 3.3 Increase share of secondary materials	Before use – Rethink (*)	**3.3.a** Ecodesign: reversible assembly processes to enable lossless disassembly at end of life **3.3.c** Limit the number of different materials to facilitate separate high-purity waste streams
Minimum efficiency of waste recycling	Art. 59 to 61 Art.71	3. Closing 3.3 Increase share of secondary materials	After use – Recycle	**3.3.d** Increase efficiency of separate waste collection
Minimum recycled content	Art.8	3. Closing 3.3 Increase share of secondary materials	After use – Recycle	**3.3.f** Minimum recycled content in new products

<u>Legend:</u> (*) The effect of the Extended Producer Responsibility on the ecodesign is indirect. It is anticipated that, if manufacturers bear the responsibility for the costs of recycling and for reaching demanding targets on the efficiency of materials recovery as required in the other Articles of the Regulation, they are likely to change the design of their products to facilitate their high-performance and high-purity recycling. The Regulation hence acts there as an enabler of ecodesign measures by manufacturers.

<u>Source:</u> Own elaboration

As the eco-design features in the Table 7-8 are progressively implemented, at the start of the product life-cycle, on the new batteries integrating the stock, that stock progressively acquires features making it compatible with the implementation of the end-of-life Circular measures on recycling efficiency and recycled content.

Durability requirements

The durability requirements foreseen by the Batteries Regulation in Art.9 are not yet in place. The studies aiming at the definition of these requirements[62], published in February 2024, only are at their initial phase, namely that of taking stock of the literature regarding:

- the indicators of battery durability (calendar aging, cycle aging) and
- the factors leading to a degradation of battery performance over time.

The positive impacts of the Batteries Regulation on the durability of the batteries in stock will only happen after the corresponding implementing legislation is in place, which itself requires the underlying technical studies to be finalised. The date at which this will happen is not known at the date of publication of the present study (March 2025).

Removability and replaceability requirements

Similarly, the removability and replaceability requirements foreseen by the Batteries Regulation in Art.11 are not yet in place. The studies aiming at the definition of these requirements[63], published in January 2024, only are at their initial phase, namely that of a review of:

- normative references on the tools, the availability of spare parts and batteries, disassembly information and disassembly depth;
- the concepts of 'independent professional' and 'end-user';
- the partial or total exemptions from the requirements for some product groups.

For the same reasons as above, the positive impacts of the Batteries Regulation on the durability of the batteries in stock will start materialising at a date that is not known at the date of publication of the present study (March 2025).

7.3.5. Barriers placed by material stocks to the implementation of Circular Economy measures in the batteries sector

Based on the information summarised in the sections 7.3.2 to 7.3.4 above, the main **barriers** placed by the existing stock to the implementation of Circular Economy in the batteries sector can be summarised as follows:

- **The large fraction of the stocks of batteries dispersed in unknown and unreported locations**. The share of battery materials whose location is unknown, sometimes to the owner of the battery him/herself (as is the case of "hibernated" devices), lies in the range of 50% for the main materials used in Lithium-ion batteries. This constitutes a barrier for the re-use or the recycling of these batteries;

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[62] *European Commission, Joint Research Centre, Szczuka, C., Sletbjerg, P. and Bruchhausen, M., Performance and Durability Requirements in the Batteries Regulation - Part 1: General assessment and data basis, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/289331 , JRC136381*

[63] *European Commission: Joint Research Centre, Spiliotopoulos, C. and Magrini, C., Technical input for the guidelines on removability and replaceability of portable and light means of transport batteries, Publications Office of the European Union, Based2024, https://data.europa.eu/doi/10.2760/564746*

- **The heterogeneity and fast evolution of battery chemistries, specifically for Li-ion batteries.** Several generations of Lithium-ion batteries co-exist in the stock, and more are expected to be introduced as the technology makes progress, and are hence mixed, and will further be mixed, in the waste flows. This creates difficulties for the recycling of batteries. It requires a specific process for each chemistry, each of which processing a small yearly flow and with a fast obsolescence of the equipment. The small scale of the operations, which can only be compensated by a concentration of flows using costly logistics, combined with the short duration of operations of the facility, reduce its profitability.

7.3.6. Circular Economy measures enabled / made easier by the existing stock of batteries

Based on the information summarised in the sections 7.3.2 to 7.3.4 above, the main **enablers** created by the existing stock to the implementation of Circular Economy in the batteries sector can be summarised as follows:

- Lead-acid batteries constitute a very large (87.4% of the total mass of batteries in stock in 2021) and homogeneous stock of batteries. Similarly, Lead constitutes 91.9% of the mass of the stock of active materials in batteries in 2021. These dominant shares in the respective stock of batteries and of active materials is likely to continue over the next years. Indeed, the growth in fixed industrial power storage related to the introduction in the power mix of intermittent renewable electricity sources, is likely to compensate, at least partially, the decrease in Starting – Lighting – Ignition (SLI) batteries associated with internal combustion engines. This large and homogeneous stock of Lead-acid batteries already constitutes an important source of secondary lead. It is well addressed by proven and efficient collection and recycling processes, and explain the very high Circular Material Use Rate of lead;
- Contrary to the current stock of more advanced batteries (in particular, Li-ion batteries), which is insufficiently compatible with the implementation of Circular Economy measures, the batteries anticipated to be placed on the market following the entry into force of the ecodesign requirements of the Batteries Regulation, will constitute a growing share of the future stock of batteries in the EU27. This future stock of Li-ion batteries will by design be more compatible with Circular Economy measures: longer lifetime, better re-usability, increased recyclability, better collection processes;
- Because of the considerable growth in the demand for batteries in the automotive sector over the next decade, the share of the demand for active materials that is likely to be served by the recycling of the end-of-life batteries is expected to remain limited, even under the hypothesis of near-perfect recovery and recycling. Considering an average lifetime of automotive Li-ion batteries equal to 15 to 20 years[64], the batteries put on the market in 2020 (i.e. 50 GWh capacity) will only become available for recycling in 2035 at the earliest, when the demand is expected to reach 1,260 to 1,500 GWh. Thereby, even under near-perfect recovery and recycling of these end-of-life batteries, and assuming that the materials in these

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[64] *Carbone 4: Misconceptions about electric vehicles, https://www.carbone4.com/en/analysis-faq-electric-vehicles, accessed 17 March 2025*

batteries are compatible with the chemistries being manufactured at that date (an optimistic assumption considering the fast evolution of these technologies, as seen above), **only 3.3 to 4% of the material demand for the manufacture of Li-ion batteries will be susceptible to be supplied by the recycling of batteries in 2035**. This does not take into account the possible re-use of Li-ion batteries for fixed applications such as grid stabilisation, which is likely to increase the active lifetime of these batteries even further, and to delay accordingly their availability for recycling[65]. This situation will only slowly evolve, as the current vehicles with internal combustion engines (ICE) in stock are replaced by electric ones, i.e. when the number of batteries leaving the stock at end of life increases compared to that of the new batteries entering the stock. Complete balance (i.e. 100% replacement potential) will happen only after all the ICE-powered vehicles of 2035 (date at which, in theory, only electric vehicles are allowed to be placed on the EU market) have reached their end of life, i.e. between 2053 and 2063, considering the average lifespan (18.1 years in Western Europe, 28.4 years in Eastern Europe) of vehicles in the EU[66].

7.4. Main conclusions of the case studies bearing on barriers and opportunities for circularity created by the existing stock in the construction and the batteries sectors

7.4.1. Construction sector

The construction sector heavily relies on materials like concrete, asphalt, and bricks, with EU27 material stocks (buildings, roads, other infrastructure) tripling from 44 to 142 Gt between 1970 and 2016. While initially focused on stock expansion (92% in 1970), the activity increasingly shifted towards maintenance and replacement of stocks now dominating material demand (47% in 2016 as compared to 53% of stock expansion). This underlies the continued and **growing material input required for maintaining stocks and the substantial legacy built stocks represent. This creates a lock-in effect, where current construction decisions persist for decades.** Hence, it takes long to structurally change these stocks, meaning that whatever we construct now will exist for a long time before alternative options can be implemented.

EU policies prioritize recycling and waste management, but sufficiency-based demand-side measures hold untapped potential. Narrowing strategies advocate reducing material use through efficient spatial planning, multifunctional buildings, and sustainable urban designs. Slowing strategies focus on renovation over demolition, extending building lifetimes and reducing resource depletion. Loop-closing strategies promote material recycling and reuse, with modular component recovery proving more effective than recycling. Scientific research highlights sufficiency measures like halting new construction on unbuilt land and reducing per capita floor space as key to cutting material demand and

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[65] *European Commission: Joint Research Centre, Mathieux, F., Di Persio, F., Tecchio, P., Pfrang, A. et al., Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB) – JRC exploratory research (2016-2017) – Final technical report, August 2018, Publications Office, 2018, https://data.europa.eu/doi/10.2760/53624*

Campoverde-Pillco, J.; Ochoa-Correa, D.; Villa-Ávila, E. y Astudillo-Salinas, P. "Reuse of Electrical Vehicle Batteries for Second Life Applications in Power Systems with a High Penetration of Renewable Energy: A Systematic Literature Review," Ingenius, Revista de Ciencia y Tecnología, N.◦ 31, pp. 95-105, 2024, doi: https://doi.org/10.17163/ings.n31.2024.08

[66] *Held, M., Rosat, N., Georges, G. et al. Lifespans of passenger cars in Europe: empirical modelling of fleet turnover dynamics. Eur. Transp. Res. Rev. 13, 9 (2021). https://doi.org/10.1186/s12544-020-00464-0*

emissions. Renovation and building preservation are particularly impactful. These **strategies can reduce material inputs to construction by 50-60%.**

However, barriers persist. Long building lifespans slow change, while decarbonization efforts often increase material use through energy-efficient retrofits and renewable energy infrastructure expansion. Challenges include a lack of data on buildings design and material composition, leading to inefficient reuse/refurbish/remanufacture. EU regulations now require building renovation passports and digital records to improve traceability. Economic barriers include high deconstruction costs and competition with low-cost virgin raw materials, while political obstacles involve rigid regulations and weak incentives. Cultural resistance to smaller living spaces and risk aversion within the industry further hinder CE implementation.

7.4.2. Batteries sector

The overall stock of batteries in the EU is estimated at 11 Mt in 2021.

In that stock; the traditional, homogeneous lead-acid batteries represent by far the largest share (9.7 Mt, i.e. 87.4% of the total) and are used for the Start – Lighting- Ignition (SLI) of Internal Combustion Engines and for fixed industrial applications. This stock is still growing, even if slowly (at a Compound Annual Growth Rate – CAGR of 3.6% over 2006-2021). It is recovered and recycled with an excellent yield, above 95%. This enables the End-of-life Recycling Input Rate (EOL-RIR) in the EU for lead to be among the highest for metals, at 83% in 2022. The consumption of lead-acid batteries is anticipated to remain stable in the EU27 until 2030, with a decrease in SLI being compensated by a growth in fixed industrial applications.

Lithium-ion batteries still represented a small share of the stock of batteries in 2021 (656 kt, i.e. 5.9%), but this stock is growing extremely fast (a more than 14-fold increase between 2006 and 2021, i.e. a CAGR of 19%). This family of chemistries is diverse and evolves fast, as the technology improves to increase energy density. This makes its recycling more challenging, even if very high yields are reported in research (between 70 and more than 99%, dependent on material and recycling technology used).

The demand for batteries for the traction of electric vehicles is anticipated to grow very fast, from 238 GWh in 2024 to between 630 GWh and 1,050 GWh in 2030 and a plateau between 1,260 and 1,500GWh in 2035 (i.e. when new cars are anticipated to all be electric). This implies a CAGR between 17.6% and 28.1% until 2030, and then 7.4% between 2030 and 2035. Correspondingly, the stock of batteries will include an increasing, and ultimately dominant, share of Li-ion batteries.

When considering the active materials present in the stock of batteries (6.9 Mt in 2021), lead represents 6.3 Mt, i.e. 91% of the total. The remaining stock of materials is composed of some Critical Raw Materials (CRMs): Cobalt – Co (6.8% of the stock without lead), Copper – Cu (10.6%), graphite carbon (12.4%) and Lithium – Li (2.9%), all found in Li-ion batteries, but also Manganese – Mn (26.2%), Nickel – Ni (11.1%) and Sb – Antimony (14.9%) present in other chemistries. Other active materials present in the stock include Cd – Cadmium (1.9%) and Zn – Zinc (13.2%).

When considering the rarity and the environmental footprint required by the manufacturing of these active materials:

- Cobalt (43.8%) and Lead (24.8%) concentrate the bulk of the metric representing the rarity of the active materials present in the stock of EU batteries in 2021;
- Lead (37.6%), Lithium, Nickel and Manganese (ca. 10% each) dominate the metric representing their environmental footprint of the active materials present in the stock of EU batteries in 2021.

The Batteries Regulation acts on the design of batteries and of products using batteries to increase their durability and recyclability, and in parallel increases the market for recycled content in batteries. This coherent framework will increase the compatibility of the future stock of batteries with Circular Economy measures. This is of particular relevance considering the very strong growth being anticipated in the consumption of batteries for electric vehicles.

Considering the fast demand growth for Li-ion batteries and their lifetime, the share of new batteries that is likely to be manufactured from end-of-life batteries is likely to remain small. In 2035, this share is anticipated to lie between 3.3% and 4%, even under optimistic assumptions. A balance between the flow of end-of-life batteries and that of new batteries is anticipated to take place after 2050 only, when the last ICE vehicles reach their end of life.

A further hurdle on the path towards circularity of batteries is the current high share (above 50%) of ‘hibernated’ batteries, whose location is unknown.

8. Monitoring material stocks – Contribution to the definition of metrics

8.1. Purpose of any proposed indicator

The first step in suggesting and selecting potential indicators is to define what the purpose of the indicator is, i.e. what issue(s) is it intended to illustrate. The preceding sections of this report have highlighted a wide range of important links between material stocks and a more circular economy. It is therefore important to consider the indicators that the EEA already use, as many of these links can already be covered by these existing indicators. This section begins with a consideration of the indicators that the EEA already use in comparison to the link between stocks and CE. Section 6.2 states that (Potting et al, 2017, Morseletto 2020) stock related CE measures can be considered under the following three headings

1. "smarter product use and manufacture", which targets every new product (smarter manufacture), as well as use intensification of existing stocks (narrowing);
2. the increase of stock lifetimes (slowing), and
3. the use of secondary materials in stock-building (closing).

Looking at the indicators presented on the EEA's Circularity Metrics Lab[67], some of the key matches between existing indicators and these three headings are as follows:

Narrowing – smarter product use and manufacture

Europe's material footprint, Material stock growth, Production and consumption of chemicals, Consumption volumes in the EU between 2000 and 2022, Total plastics consumption by end-users in the EU.

Slowing – the increase of stock lifetimes

Resource productivity, Car sharing, Turnover in the repair sector, CE requirements in ecodesign product regulation, Products evaluated against the French repairability index, Bike sharing systems in European cities, Age of the EU passenger cars, Durability of mobile phones, Washing machines intensity of use, Jobs in the B2C repair sector, Evolution of the average lifespans of household appliances..

Closing – the use of secondary materials in stock-building

Circular material use rate, Price of PE scrap, Use of recycled plastics, EU's mechanical recycling capacity, Average price of plastic scrap, Waste recycling - % of overall waste in the EU recycled, Batteries collection rate, WEEE collection rate. Disposal of waste in landfill, Residual waste generation.

This analysis indicates that the EEA already has multiple indicators of relevance. However, the preceding sections have illustrated some interesting issues, which appear to be less well covered by the existing indicators. The key issues that offer potential for better / different coverage are:

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[67] https://www.eea.europa.eu/en/circularity

8.1.1. A. The size, evolution and intensity (stocks / service the stock provides) of material stocks.

Size of stocks with the aim of curbing stocks; sufficiency (1-2): The issues of interest here are to illuminate the total size of the stock, with an indication of why the stocks are being added (i.e. the end use)

Growth of stock (3-4): The issues here are to illustrate that the stocks are growing, with an indication of how much is being added (gross additions to stock / year) and how much is leaving the stock (End of life materials / year)

Stock related flows (5-9): The issues here are to show the nature and the rate of change, with individual indicators focussing on certain aspects of stock addition and end of life.

Stock intensity (10-17): The issue here are to illustrate the links between stock levels and other factors that are either drivers of stock demand (e.g. increases in economic activity, on the assumption that the link between demand and stock use ideally needs to change for resource efficiency / circularity to improve) and/or other indicators of resource use / demand for the services that the material stock enables (again, here the assumption is that less resource intensive provision illustrates an improvement in circularity).

8.1.2. B. The fact that the (increasing and/or large size of the stocks) leads to resource consumption to maintain and operate that stock;

This issue here relates to the materials required to retain the functionality of the services that are being provided by the material stocks. This is interesting because it illustrates how larger stocks require more flows of materials and energy to maintain them and extend their overall lifetime. Another aspect of this that is of interest is the stocks required to maintain services that may be of less relevance in a more circular economy – i.e. the issue of potentially / partially stranded assets.

8.1.3. C. The nature of the material stock, e.g. that depending on the environmental pressures and impacts of interest, different materials are of relevance.

The issue here is to consider the relationship between the volumes of stock and their potential environmental impacts. Important aspects here include the fact that while the larger volumes of materials used do not have major impacts per ton of material, their overall large volume of use still results in pressures and impacts on the Earth System. Other materials used in smaller volumes might have large potential environmental impacts per ton, and relate to other aspects of policy interest, e.g. criticality of raw materials. Finally, material stocks also occupy land, therefore issues of soil sealing and subsequent impacts on water cycles as well as loss of bio-productive land and impacts on biodiversity are to be considered.

8.1.4. D. Examples of the inflow and outflow of certain key materials.

The issue here is to show the balance between inflows and outflows of certain key materials. This should illustrate the growth of stocks of these materials, as well as providing insight into how long these materials stay in stock, and the speed at which they leave stocks (and either become waste, or available for reuse / recovery). These indicators are also statistically interesting as they illustrate the difference between data on material inputs and on waste arisings (and recovery rates) – with differences (and misalignments) in categories and degree of detail.

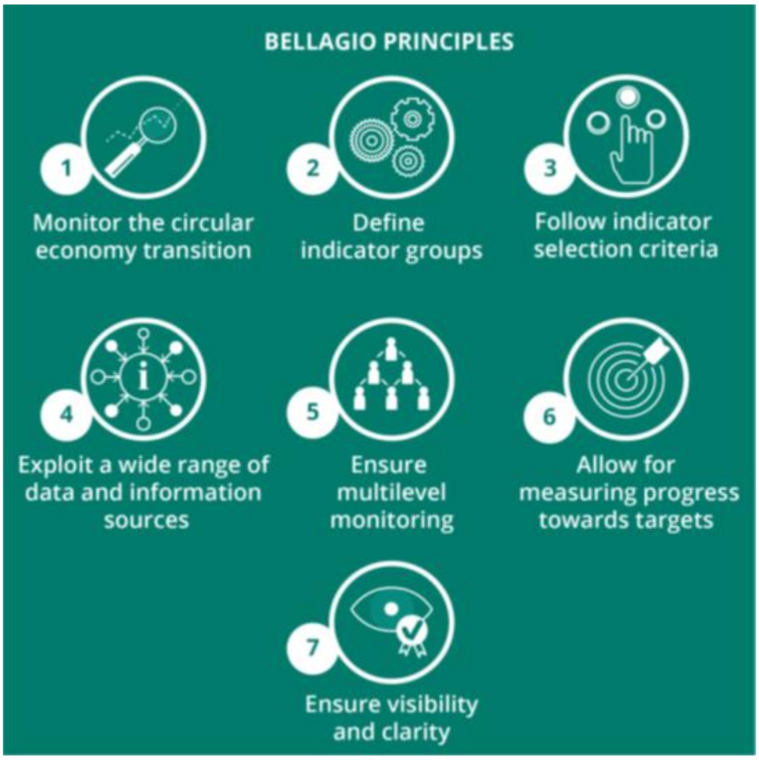
8.1.5. E. Policy measures / activities designed to (inter-alia) reduce material use, increase longevity of stocks and increase material recovery and reuse

This group of indicators concerns the policy responses that are of interest / relevance in trying to address the 'narrowing', 'slowing' and 'closing' of material stocks mentioned at the start of this section. There are a very large amount of policies of some relevance to these objectives. It is not possible to cover every issue of interest, so we have focussed on the examples given in the rest of this report.

8.2. Indicator assessment method

"The "Bellagio Declaration" is a set of principles on how to ensure that a monitoring of the transition to a circular economy captures all relevant aspects and involve all relevant parties. It serves to guide national and European authorities in the development of monitoring frameworks and indicators" [68]. The Bellagio principles are summarised in the figure below.

Figure 8-1 Principles included in the Bellagio Declaration



Source: EEA

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[68] https://www.eea.europa.eu/themes/waste/measuring-europes-circular-economy/BellagioDeclaration.pdf

These principles have been (and are being) used in the selection and presentation of the indicators set presented on the EEA's Circular Metrics lab[69] that was discussed at the start of this section. The principles mainly relate to the selection of an indicator set, rather than the testing of specific indicators. As such, though of relevance to this project as a whole, they appear of less relevance to this specific section, other than the analysis of indicators at the start of the section shows a good coverage of the issues capture in material flow analysis by the existing indicators set of the Circular Metrics Laboratory.

The EEA's RACER criteria offer a better checklist for potential individual indicators. The RACER criteria are:

- **Relevant**, i.e. closely linked to the objectives to be reached. They should not be overambitious and should measure the right thing (e.g. a target indicator for material use needs to cover a material that has a large use and environmental impact).
- **Accepted** (e.g. by staff, stakeholders). The role and responsibilities for the indicator need to be well defined (e.g. if the indicator is the recycling rate of a particular material it needs to be a well-known and high-volume material, with accepted processes and definitions).
- **Credible** for non-experts, unambiguous and easy to interpret. Indicators should be simple and robust as possible. If necessary, composite indicators might need to be used instead – such as country ratings, well-being indicators, but also ratings of financial institutions and instruments. These often consist of aggregated data using predetermined fixed weight values. As they may be difficult to interpret, they should be used to assess broad context only.
- **Easy** to monitor (e.g. data collection should be possible at low cost).
- **Robust** against manipulation (e.g. administrative burden: If the target is to reduce administrative burdens to businesses, the burdens might not be reduced, but just shifted from businesses to public administration).[70]

8.3. Potential metrics – RACER analysis – Long List

This section looks at each of the key issues in turn, suggests potential indictors based on the analysis in the previous sections of this report also stock indicators from literature.

Each potential indicator is then scored against each of the RACER criteria out of 5. This scoring was all done by one senior individual in the contractor team with a good knowledge of CE and indicators. Using one person to do the scoring ensures consistency, though as with any scoring it's a personal preference. Therefore, this scoring was discussed and moderated with the EEA and the project team during a project meeting.

The results of this scoring are provided below in Table 8-1 to Table 8-5.

The highest scoring indicators are highlighted in each group, to form the final short list.

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[69] *https://www.eea.europa.eu/en/circularity*

[70] *European Commission (n.d.) Tool #41. Monitoring arrangements and indicators*

Table 8-1 Long list of potential indicators monitoring the material stocks in Europe, with their RACER evaluation. Purpose category A “The size, evolution and intensity of material stocks”

A. The size, growth, flows and intensity of material stocks	R	A	C	E	R	TOTAL	Comment
1. Total stocks in Gt	5	5	5	4	4	**23**	Strong - relatively simple, could not reuse the Eurostat data source – doesn’t have total stock, only flows. Slow rate of change.
2. Material stock by end use	4	4	3	3	3	**17**	Weakened by the influence of many external factors, that are not CE driven
3. Stocks growth in % (i.e., delta stock)	4	4	3	3	2	**16**	Many external influence, and rate of growth is a more complex issue to understand
4. Growth of stocks (GAS) vs. EOL by end use	4	3	3	2	2	**14**	Weakened by trying to combine growth and end of life in one indicator - link between resource use and waste produced is complex - may be too complex to try and put into one indicator
5. Delta stocks / capita	4	3	3	3	2	**15**	Weakened by combining population size with resource use, if population drops, will resource use? Regardless of CE progress?
6. Delta stock / primary production	3	3	3	3	2	**14**	Weakened by complexity of relationship between primary production and stock - many other influences on primary production, that are not CE relevant.
7. Stock-related flow - GAS	4	4	3	4	3	**18**	Relatively simple, but hides complexities on what’s included, so lower on robustness – could combine with NAS. Eurostat has growth of stocks data. Talking about growth of stocks.
8. Stock-related flow - NAS	4	3	3	3	2	**15**	Appear simple, but the assumptions on what leaves stocks are reliant on multiple strands of waste data
9. Stock-related flow - EOL	3	4	3	4	3	**17**	Interesting, but could be considered to be more about waste and recycling.
10. Index over time of GDP, population, stocks, NAS, M+R inflows	3	4	4	3	3	**17**	Lots of indexes in the same indicator, GDP and population are very well known, but the others would require explaining each time. Having so many things showing means that there are a very large amount of possible influences
11. Final energy consumption and/or CO2e emissions / stock over time	3	3	3	4	2	**15**	Main drivers of energy use are not stock related. Likely to show similar trends to GDP/stocks.
12. Resource intensity over time – Stock/GDP, GAS/GDP,	3	3	3	4	3	**16**	GDP and stocks do have a relationship over time, but the time horizon required to show this seems to be quite long, 20-30 years, this is interesting, but is arguably more about economic development than CE.
13. Stock of productive assets (= machinery & equipment, freight vehicles) / GDP	4	3	3	3	4	**17**	This might give some insight into stranded assets (which is interesting), but the choice of productive assets is key, and the trend in these assets is influenced by many factors
16. Service provisioning by stocks: floor space / stocks	4	3	3	3	3	**16**	This gives a link to housing and buildings area, but the weakness is the source of data on the floor space and the number of influences on this that are not related to CE/stocks.
17. Service provisioning by stocks – mobility/stocks, e.g. person kilometer	4	3	3	3	3	**16**	This gives a link to stocks used for mobility, but the weakness is the number of influences on mobility that are not related to CE/stocks.
18. Service provisioning by stocks – hibernating stocks / total stocks or stocks in-use / total stocks	5	4	3	3	1	**14**	Good relevance as it picks up the stocks not in use question. Credibility no robustness hinge on the level of confidence in the stocks not in use / stocks hibernating number. No data. Complex definition.

Source: *Own elaboration*

Table 8-2 Long list of potential indicators monitoring the material stocks in Europe, with their RACER evaluation. Purpose B. "The fact that the (increasing and/or large size of the stocks) leads to resource consumption to maintain and operate that stock"

B. The fact that the (increasing and/or large size of the stocks) leads to resource consumption to maintain and operate that stock;	R	A	C	E	R	TOTAL	Comment
1. Maintenance and replacement in flows of stock.	5	4	4	3	5	**21**	Picks up the key point of stock additions being needed to maintain stocks. Key weakness is the need to use the MISO or some other model) to get the data. Eurostat MFA does not measure this. GAS – EOL. Repeat of group A – but different issue being considered.
2. M+R inflows for construction / infrastructure	4	4	3	3	4	**18**	Picks up the issue of maintenance stocks in the sector with the largest material use (construction/infrastructure). Weakness is the source and split of the stock inputs used for maintenance as opposed to growth - the credibility hinges on this definition and split.
3. Stock retention time: material stock / primary material inflow (see Tanikawa et al. 2021)	5	3	3	3	4	**18**	The issue of how long stock stays in use is highly relevant. Potential weakness in the complexity of how this is measured - does this indicator really pick it up?
4. Secondary materials / GAS	3	4	4	4	3	**18**	Possible weakness in the relevance as it could be argued that this is more about success of resource recovery - which is of relevance in general, but maybe less so for this particular issue. Coverage of secondary materials? All of MISO model. Are all secondary material used for stock? (are some used for e.g. packaging.)
5. Hibernating stocks / total stocks	5	4	3	3	2	**17**	Also included in A. and could be included in D - this relevance to more than one issue strengthens the case for this indicator – but the lack of a credible data source means its score falls.

Source: *Own elaboration*

Table 8-3 Long list of potential indicators monitoring the material stocks in Europe, with their RACER evaluation. Purpose C. "The nature of the material stock e.g. that fact that a large part of it is inert material"

C. The nature of the material stock e.g. that fact that a large part of it is inert material	R	A	C	E	R	TOTAL	Comment
1. Composition of stocks - by material category: biomass, fossil fuels, metals, non-metallic minerals	5	5	5	5	3	**23**	Shows the breakdown of stocks (and with a time series how this changes over time) - so good score on relevance. Good data sources. Potential weakness in that there are a very large number of influences on the stocks of everything being shown, though this could be covered in other indicators – Already included in A.
2. Composition of stocks by end uses: by buildings (residential, non-residential), mobility infrastructure, other infrastructure (see report), machinery, vehicles, other transport equipment, nes	5	5	5	5	3	**23**	Same strengths and weaknesses as above. Presenting by end use may slightly improve the credibility, in that users will more easily see what the materials are being used for. – Included but moved to group E
3. Construction additional, stocks, recycling and losses	4	4	4	3	3	**18**	Focusses on the largest material use. Likely to require matching up of material use and waste / recycling data, also implies a link between material going in and material going out - when they are arguably driven by different issues - hence lower scores for robustness and ease.

C. The nature of the material stock e.g. that fact that a large part of it is inert material	**R**	**A**	**C**	**E**	**R**	**TOTAL**	**Comment**
4. Stock inputs vs, environmental footprints (EEA figure – https://www.eea.europa.eu/publications/how-far-is-europe-from)	5	4	3	3	4	**19**	Picks up the issue that volume of stock is not the same as its environmental impact (that some of the smaller stocks have big impacts). Possible weaknesses linked to the complexity of how the env impact is modelled - multiple issues and assumptions involved that reduce the credibility and ease scores. Carbon footprint of stocks – could combine 1 and 4 (EEA have update)
5. Impacts by stocks: CO2 em / stocks	4	4	4	3	3	**18**	Assumed to pick up life cycle CO_2 equivalents, so good for relevance, as this considers more than just energy use. Relationship between stocks and CO_2 is driven by multiple factors, and may not be easy to explain simply, so ease and robustness score lower.
6. Impacts by stocks: energy use / stocks	4	3	3	3	3	**16**	Would pick up the issue of the energy use associated with stocks, but this is mainly driven by factors that are not entirely CE relevant – e.g. energy in buildings, transport demand, economic activity - not that easy to link these issues directly to (and simply) to material stocks.
7. Impacts by stocks: built-up land / stocks (i.e. addressing sealing of land)	3	4	3	4	3	**17**	Picks up the issue of the link between development and resource use/ However the built up land numbers do not provide information on things like density of housing, and this risks implying that all development is negative - which may be the case in terms of lost habitat, but that is not the issue of interest here.
8. Battery stock by active material (Li, Co, Ni, graphite, Pb, etc)	3	4	3	4	3	**17**	Shows the presence of potentially harmful, and some scare materials in the stock for well-known use, where there is active policy intervention, but risks being focused on a relatively small part of the stocks. The battery stock data is also not entirely reliable (see the difference between stock into market and batteries at end of life).

Source: Own elaboration

Table 8-4 Long list of potential indicators monitoring the material stocks in Europe, with their RACER evaluation. Purpose D. “Examples of the inflow and outflow of certain key materials”

D. Examples of the inflow and outflow of certain key materials.	**R**	**A**	**C**	**E**	**R**	**TOTAL**	**Comment**
1. Inflow and outflow of iron/steel, copper, aluminum	5	4	4	3	4	**20**	Picks up high profile / well known materials where there is some possibility of match between material use and waste arising data. However the data matching is not easy (from open sources). Copper is interesting, but no specific waste data. The iron / steel data is the best match from DMC and waste arisings.
2. Batteries - % of recovered material used (partially available from Batteries regulation)	3	4	4	3	3	**17**	The soon to come into force batteries regulation will track this number, on the assumption that it will improve - so no historical data, but there will be data in the future. Although batteries are interesting there is a risk that this is being picked mainly because of data availability.
3. Environmental footprint of battery stock. using exergy values of the active materials such as Li, Co, graphite, Ni, Pb (as in the report)	4	3	3	2	3	**15**	As above, batteries are an interesting example, but there is a risk of being led by data availability. Ease of indicator is low due to the need for external sources to quantify the environmental impact of the materials.

D. Examples of the inflow and outflow of certain key materials.	R	A	C	E	R	TOTAL	Comment
4. Batteries EPR scheme – goods onto the market, collection rates and recycling efficiencies (as available from the batteries regulation)	4	4	3	3	3	**17**	Very similar to 2, but with a longer availability of data, albeit with some differences in method between MSs.

Source: *Own elaboration*

Table 8-5 Long list of potential indicators monitoring the material stocks in Europe, with their RACER evaluation. Purpose E. “Policy measures / activities designed to (inter-alia) reduce material use, increase longevity of stocks and increase material recovery and re-use”

E. Policy measures / activities designed to (inter-alia) reduce material use, increase longevity of stocks and increase material recovery and reuse	R	A	C	E	R	TOTAL	Comment
1. Housing density	4	4	4	3	3	**18**	Housing density is important in material use. Weaknesses include the difficulty of measuring this, the slow change in density if total figures are used, the wide range of other factors that affect this - land price, consumer preference, etc.
2. Degree of urbanisation	3	4	3	4	3	**17**	Urbanisation implies more building and resource use. However, the drivers of this are multiple and many are not strongly influenced by CE policies. Will not differentiate urbanisation that is less resource intensive - e.g. by reusing material, so robustness is not that strong.
3. Vacant buildings (and second homes)	4	4	4	3	3	**18**	High rates of building vacancy and second homes imply under use of built resources (and the materials in them) - so ok for relevance. Problems come in the ease of monitoring - do all MS track and classify this data consistently? Also likely that the indicator is driven by many other issues - property prices vs, income, cost of building refurbishment / repurposing, spatial planning approach. etc.
4. Housing surface per person	5	5	4	4	4	**22**	A simple indicator that shows the material used (for provision of housing) per person. Weaknesses re that the rate of change is likely to be slow, and the patterns are likely to vary by MS for cultural / historic reasons, the factors that modify this also include many factors not related to material use, and there is no information on the resource intensity of the buildings that provide this housing.
5. No. cars per person	5	5	4	4	3	**21**	Clear indicator of the resource intensity used to provide personal mobility, with a (compared to housing) more rapid change likely to be visible. Does not pick up the resource intensity per vehicle, Arguably more driven by transport policy than resources., Combine housing, surface, and cars and batteries in and index, appears promising.
6. Mass of cars	4	4	4	4	3	**19**	A good addition to the above indicator, as it should show that the average weight of vehicles (implying less resource use) is not going down - would need to be an average mass of cars to pick up vehicle size issues, as total mass might be more small cars.
7. Use of secondary materials (lead, copper, zinc, iron)	3	4	4	4	3	**18**	Good indicator for the resource recovery aspect, with data available on these potentially environmentally harmful, resource intensive and (some rare). Does not cover overall use of these resources. – score down more – recycling focus.

E. Policy measures / activities designed to (inter-alia) reduce material use, increase longevity of stocks and increase material recovery and reuse	**R**	**A**	**C**	**E**	**R**	**TOTAL**	**Comment**
8. Price / value of recovered materials (plastic, metal, paper etc)	4	4	4	3	3	**18**	Key to the profitability (and therefore likelihood) of reusing these materials, and the target of many incentive measures. Prices are not easy to track, and the prices can be volatile (often driven by external factors - energy prices, economic cycle etc.) - score down
9. Use of timber in construction (unsure of data availability and significance?)	4	3	3	3	3	**16**	Could show the use of less resource intensive timber (as opposed to concrete). Weaknesses include sourcing of data, It's possible that concrete use could stay high as well as more wood use. Does not consider the source of the wood.
10. Use of offsite construction (if data is available on this activity?)	5	3	3	3	3	**17**	Would highlight the use of more efficient construction technique. Weaknesses - lack of data. Definitions not straightforward - does it include building components?
11. Construction & Demolition Waste (CDW) recovery	5	4	4	3	4	**20**	Would show how much of the highest volume material stock is being recovered. Problems in the quality of the data available - level of reuse is not easy to track - low grade uses appear the same as higher grade. Is there data? Doesn't change over time. Rate looks high. (backfilling issue)
12. Level of building refurbishment / repurposing vs. demolition (source: observatory of housing in Europe led by DG ENER which we used in the report to obtain data on the surface of housing that also has data on the level of renovation works in Europe)	5	4	4	4	4	**21**	Would show the success of efforts to prolong the life (and high level use) of the highest volume material stocks. Weaknesses on complexity of definition - how much of the material is retained to qualify as refurb vs. demolitions.
13. Road building	4	4	4	4	3	**19**	Would show the level of development - picks up infrastructure as opposed to housing. Growth is linked to multiple factors - transport policy, economic growth etc. where resource efficiency policies are not that influential. Does not show the material already in existing roads, and the efforts needed to keep these roads in use.
14. Modal shift (passenger and freight)	4	5	4	4	3	**20**	Illustrates the use of more (material and energy) efficient methods of delivering transport services. Main weakness is that the policy drivers are transport and energy rather than material use (although these do generally align).

Source: Own elaboration

8.4. Proposed indicators

8.4.1. Short list of indicators and introduction to the indicator fiches in the Annex D

Extracting the highest scoring indicators per area of interest results in the following 9 indicators for retention and potential addition to the CML website,

A. The size, growth, flows and intensity of material stocks

- Total stocks in Gt (from MISO model)
- Stock-related flow - GAS and NAS

B. The fact that the (increasing and/or large size of the stocks) leads to resource consumption to maintain and operate that stock;

- Maintenance and replacement in flows of stock (same as A2, but from a different angle)

C. The components and environmental impacts of consumption.

- Stock inputs vs. environmental footprints.

D. Examples of the inflow and outflow of certain key materials.

- Inflow and outflow of iron/steel and copper – there are two potential approaches to sourcing the data for this – this is discussed on the following sub-section)

E. Policy measures / activities designed to (inter-alia) reduce material use, increase longevity of stocks and increase material recovery and reuse

- Index of housing surface per person, No. cars per person (already have age of cars in CML). Battery demand
- CDM recovery
- Level of building refurbishment / repurposing (prepared, but with concerns over the data availability)
- Modal share (passenger and freight)
- Composition of stocks - by end uses: (buildings (residential, non-residential), mobility infrastructure, other infrastructure, machinery, vehicles, other transport equipment and nes.)

Fiches for each of these indicators have been prepared, and are provided in Annex D. Fiches for the indicators proposed to monitor the state of material stocks, for potential addition to the CML. The format of these fiches is as follows:

Metric – chart/graph. With Title, headline sentence, Coverage: Source:

Assessment – 1-3 paragraphs on what the data shows – trends and clear influences.

Background – 1-3 paragraph on why the indicator is of relevance.

Supporting information – bullet points, covering: Definition (components). Methodology (source and any data manipulation done) and Metadata (Data source -weblink), units, temporal coverage (years x-y), Geographic coverage (e.g. EU 27):

8.4.2. Indicator D.1 Inflow and outflow of iron/steel and copper – data issues

The most complex of the shortlisted indicators is the one that attempts to match inflows and outflows of a particular material. This section discusses the potential data sources for this and the issues involved.

The idea of this indicator is to track the flow of a particular material into, through, out of (with some back into) the material stock. The materials suggested are those where there is believed to be good (i.e. material specific) data. In addition

- **Iron / steel**, which has the benefit of being used in a wide variety of sectors across the whole economy, such as buildings & infrastructure, machinery, vehicles and packaging;
- **Copper**, which give a stronger focus on electronics and electrical engineering and is a Critical Raw Material, as per the Annex II of the Regulation[71] that lists them;
- **Aluminium**, which may be somewhat redundant with steel and less cross-cutting.

It would also be interesting to consider other materials, where there are ongoing policy efforts to reduce use and increase recovery / reuse rates. For example, paper & cardboard or plastic, or a material that dominates the stocks level (e.g. concrete or aggregates). The main issue with using such materials for this indicator, is the lack of material specific data on their volumes within the waste stream, and on their reuse / recovery. Another issue for certain materials (e.g. those uses extensively in packaging like paper and plastics) is that their lifespan is often too short for them to appear in different years in terms of input and output from the stock.

An attempt has been made to identify and extract the data required to construct this indicator from data available on Eurostat.

Information on material used

The most comprehensive source of data on material production, imports and exports is the Eurostat ‘Sold production, exports and imports’ [72]dataset. This data set contains Prodcom data on volumes of Own production, Export and Import. The units volumes are (kg, m2, number of items, etc) that is appropriate for the product. There are approximately 4000 headings representing manufactured products and some industrial services, in the NACE Rev.2 sectors.

It is possible to extract data on the volumes of all products containing iron. However this list contains iron as a raw material (e.g. [24101100] Pig iron and spiegeleisen in pigs, blocks or other primary forms) and the products that are made from iron (e.g. [25112100] Iron or steel bridges and bridge-sections). This makes it difficult to identify the volume of iron that is produced in a single year, as there is a risk of double counting raw material that is turned into products. The unit volumes are also not routinely reported on the Eurostat data so there is a risk of combining number of products with tonnes of product. Eurostat also warn against the concept of calculating apparent consumption by assuming that it equals own

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[71] *Regulation (EU) 2024/1252 establishing a framework for ensuring a secure and sustainable supply of critical raw materials, available at: https://eur-lex.europa.eu/eli/reg/2024/1252/oj/eng*

[72] *https://ec.europa.eu/eurostat/databrowser/view/ds-056120/legacyMultiFreq/table?lang=en&category=prom*

production + imports – exports[73]. Therefore, even if the problems of the material unit and the double counting of products and raw materials could be overcome this source does not appear suitable for the proposed indicator.

An alternative source of material input is the Eurostat data set on Material flow accounts[74]. This is source used for the Circular Material Use rate[75] indicator. This source has data available for Domestic consumption (I.e. own production – exports + imports) for 76 materials, including iron, copper and aluminium. However, the domestic consumption for the EU 27 for Iron and steel and aluminium is marked as confidential, but this only because of a confidential mark on one MS (Bulgaria). The indicator has been constructed with the exclusion of the Bulgarian data.

Waste arisings and recovery

Looking at the available data on waste arisings and recovery by material, the source of this information in the Circular Material Use rate indicator is the Eurostat data on Treatment of waste by waste category, hazardousness and waste management operations[76]. This provides data for 46 waste categories, which includes Metal wastes, ferrous, Metal wastes, non-ferrous and Metal wastes, mixed ferrous and non-ferrous. Metal wastes, ferrous, appear a reasonable match for Iron/steel but there is no copper or aluminium specific waste category.

Matching Material used and waste arisings data

Comparing the categories in the Material flow accounts with the categories in the Treatment of waste by waste category data set illustrates the problem of trying to create a material specific CMU indicator.

Table 8-6: Comparison of Material Flow and Waste Treatment categories

Material flows (2022 Domestic material consumption (kt)) (C) = confidential	**Wastes** (2022 Waste for treatment, Recycling (kt))
Some similarity	
Iron (C)	Metal wastes, ferrous (63,740, 63,540)
Non-ferrous metal (C)	Metal wastes, non-ferrous (8,330, 8320)
Products mainly from fossil energy products (17,284)	Plastic wastes (12,460, 9,370)
Fibres (1,202) Other products from animals (animal fibres, skins, furs, leather, etc.) (561)	Paper and cardboard wastes (30,650, 30,300) Textile wastes (1,380, 1,020)
Wood (297,781) Timber (industrial roundwood) (218,063) Wood fuel and other extraction (79,718)	Wood wastes (41,400, 19,820)
Products mainly from metals (4,302)	Discarded vehicles (2,160, 2,160) Batteries and accumulators wastes (1,490, 1,450)
Copper (117,420) Nickel (21,782) Lead (3,410)	Metal wastes, mixed ferrous and non-ferrous (4,120, 4,120) Metallic wastes (W061+W062+W063)

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[73] See section 4.2.7.1. SOME REMARKS CONCERNING THE CALCULATION OF APPARENT CONSUMPTION in European business statistics user's manual for PRODCOM 2023 edition

[74] Online data code: env_ac_mfa

[75] Online data code:cei_srm030

[76] Online data code: env_wastrt

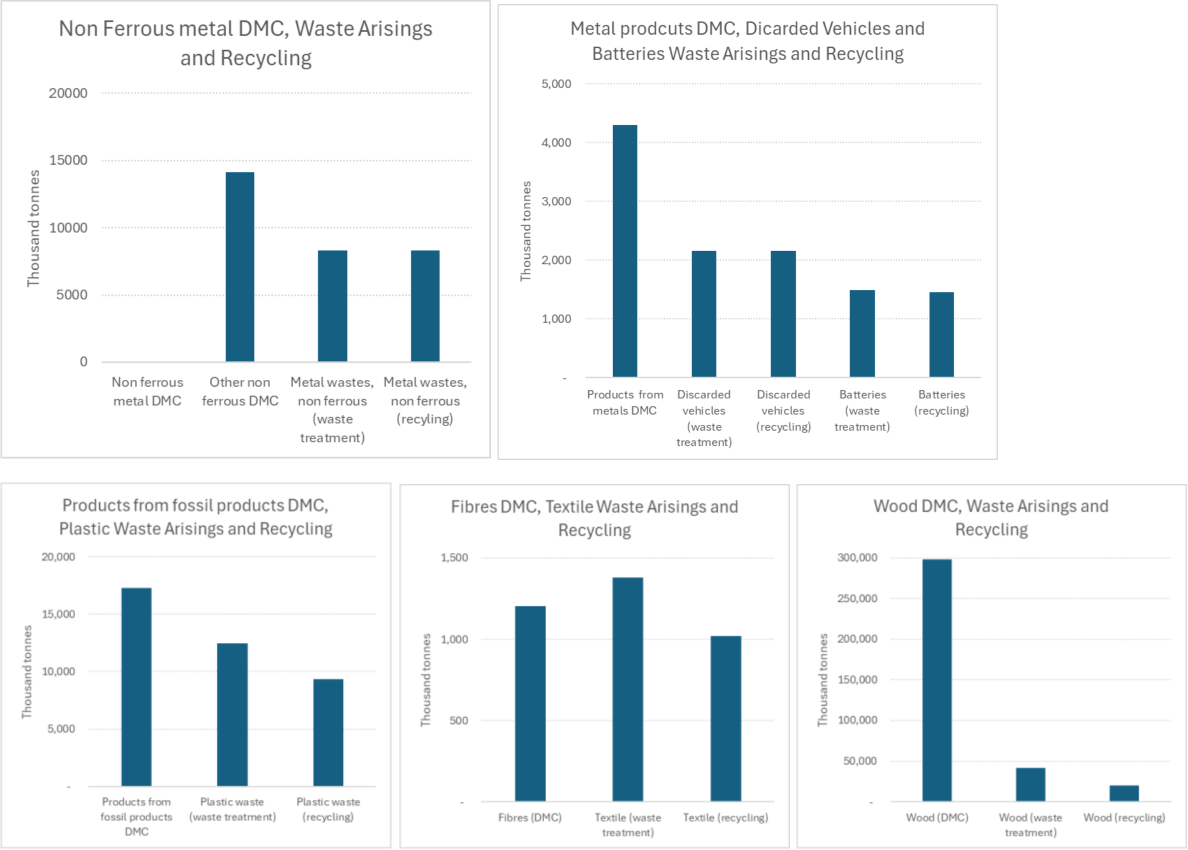
Material flows (2022 Domestic material consumption (kt)) (C) = confidential	**Wastes** (2022 Waste for treatment, Recycling (kt))
Zinc (19,568) Tin (1,300) Gold, silver, platinum and other precious metals (C) Bauxite and other aluminium (C) Uranium and thorium (25) Other non-ferrous metals (14,114)	
Very little or no similarity	
Biomass Crops (excluding fodder crops) Cereals Roots, tubers Sugar crops Pulses Nuts Oil-bearing crops Vegetables Fruits	Animal and vegetal wastes Animal and mixed food waste Vegetal wastes Animal faeces, urine and manure
Meat and meat preparations Dairy products, birds' eggs, and honey Other crops (excluding fodder crops) n.e.c. Crop residues (used), fodder crops and grazed biomass Crop residues (used) Straw Other crop residues (sugar and fodder beet leaves, etc.) Fodder crops and grazed biomass Fodder crops (including biomass harvest from grassland) Grazed biomass	Animal and mixed food waste; vegetal wastes (W091+W092)
Wild fish catch, aquatic plants and animals, hunting and gathering Wild fish catch All other aquatic animals and plants Hunting and gathering Live animals and animal products (excluding wild fish, aquatic plants and animals, hunted and gathered animals) Live animals (excluding wild fish, aquatic plants and animals, hunted and gathered animals) Products mainly from biomass	
Metal ores (gross ores) Non-metallic minerals Marble, granite, sandstone, porphyry, basalt, other ornamental or building stone (excluding slate) Chalk and dolomite Slate Chemical and fertiliser minerals Salt Limestone and gypsum Clays and kaolin Sand and gravel Other non-metallic minerals n.e.c. Products mainly from non metallic minerals	Chemical and medical wastes Spent solvents Acid, alkaline or saline wastes Mineral waste (except non-hazardous dredging spoils, valid up to 2008) Common sludges and dredging spoils (W11+W127, valid up to 2008) Common sludges Mineral waste from construction and demolition Other mineral wastes Mineral wastes from waste treatment and stabilised wastes Soils Dredging spoils Chemical wastes Glass wastes Waste containing PCB Discarded equipment (except discarded vehicles and batteries and accumulators waste) Rubber wastes
Fossil energy materials/carriers Coal and other solid energy materials/carriers Lignite (brown coal)	Combustion wastes Used oils

Material flows (2022 Domestic material consumption (kt)) (C) = confidential	**Wastes** (2022 Waste for treatment, Recycling (kt))
Hard coal Oil shale and tar sands Peat Liquid and gaseous energy materials/carriers Crude oil, condensate and natural gas liquids (NGL) Natural gas Fuels bunkered (imports: by resident units abroad); (exports: by non-resident units domestically) Fuel for land transport Fuel for water transport Fuel for air transport	
Other products Waste for final treatment and disposal Stage of manufacturing - finished products Stage of manufacturing - semi-finished products Stage of manufacturing - raw products	Household and similar wastes Mixed and undifferentiated materials Sorting residues Industrial effluent sludges Sludges and liquid wastes from waste treatment Health care and biological wastes

Source: Own elaboration

If the most promising matches between DMC and waste treatment and arisings are plotted next to each other the following charts (Figure 8-2) can be produced.

Figure 8-2: Material for waste treatment, and material recycled

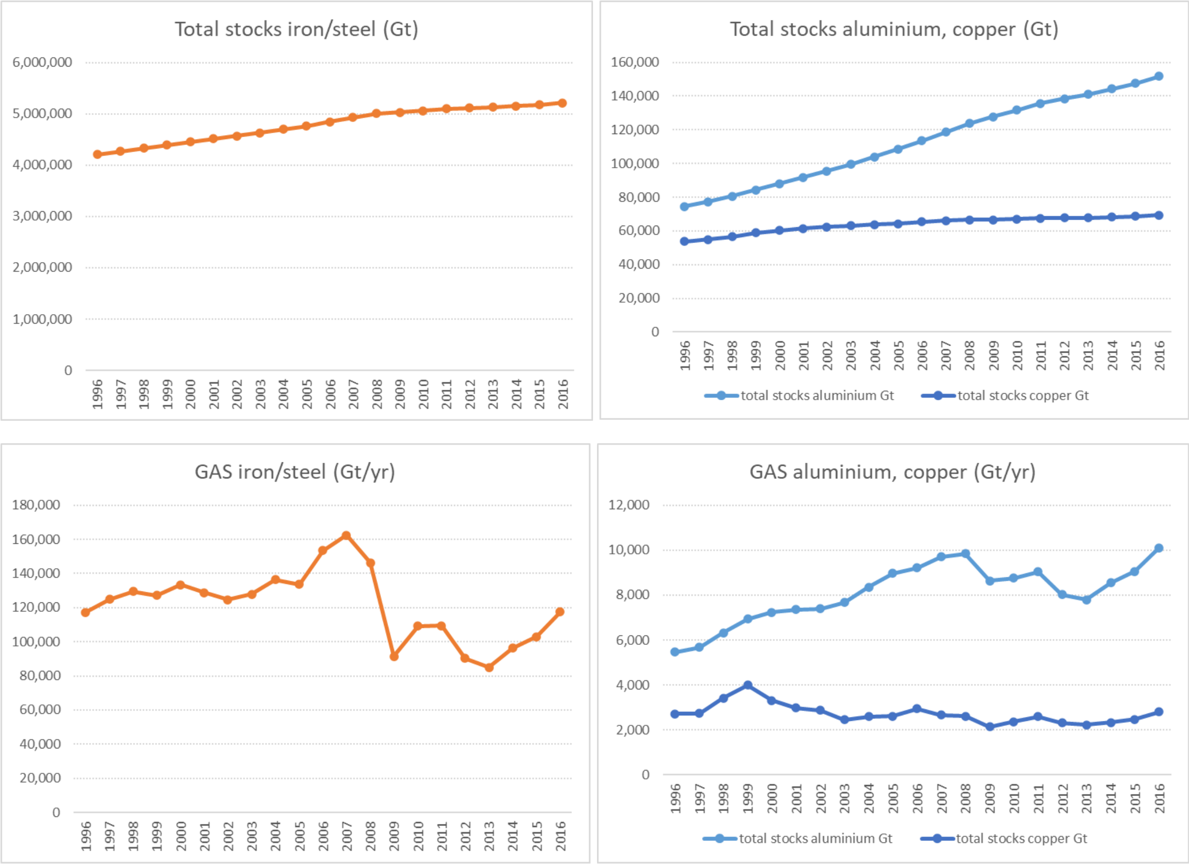


Source: Eurostat: Domestic material consumption env_ac_mfa. Waste treatment env_wastrt

From these figures, the products from fossil products DMC vs, the plastic waste, the Fibres DMC vs textiles waste and the wood DMC vs wood waste appear a similar order of magnitude, which suggests that these indicators could be possible. However, the similarities could be a coincidence.

The MISO model produces outputs concerning specific materials. As an example of this data the figures below present the data on total stocks and additions to stock for iron/steel, copper and aluminium. The model can also provide data on the removals from stock by material.

Figure 8-3: Total stocks and gross additions to stock for iron/steel, copper and aluminium



Source: *MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)*

Using the MISO model would avoid the difficulties of trying to use raw data from Eurostat that have been discussed earlier in this section, but would bring other downsides – namely less up to date data.

8.5. Summary of proposed indicators

A long list of almost 50 indicators, mostly inspired by the other sections of this report, was produced and this refined down, using the RACER criteria, and discussions with the EEA, to a short list of ten. The Table 8-7 below summarises the indicators that have been suggested. It describes what we want to measure / describe, the indicator used and the data source.

Table 8-7: Summary of suggested indicators

Issue of interest	#	Indicator	Data source(s)
The size, growth, flows and intensity of material stocks	A.1	Total stocks in Gt	MISO2 model
	A.2	Stock flows – Gross and net additions to stock (Gt)	MISO2 model
The fact that the (increasing and/or large size of the stocks) leads to resource consumption to maintain and operate that stock	B.1	Maintenance and replacement flows of stock (same as net additions to stock but from a different angle)	MISO2 model
The components and environmental impacts of consumption	C.1	Domestic material consumption (DMC) by main group and CO_2 equivalent (footprint) of this consumption	Eurostat DMC, with environmental impact multipliers from EEA / EIONET work
Examples of the inflow and outflow of certain key materials	D.1	Inflow and outflow of iron/steel and copper	Eurostat DMC and waste sent for treatment – and / or MISO model
Policy measures / activities designed to (inter-alia) reduce material use, increase longevity of stocks and increase material recovery and reuse	E.1	Index of housing surface per person, No. cars per person. Battery demand	Eurostat
	E.2	CDW recovery	Eurostat
	E.3	Level of building refurbishment / repurposing	DG ENER observatory of housing in Europe
	E.4	Modal share (passenger and freight)	Eurostat
	E.5	Stocks by end use	MISO2 model

Source: Own elaboration

The corresponding fiches are provided in the Annex D. Fiches for the indicators proposed to monitor the state of material stocks below.

9. Policy conclusions and lessons learnt

9.1. Policy conclusions

The main conclusions that can be drawn from this study for **environmental public policy** are the following:

- Material stocks are **relevant** for environmental public policy in the EU because:
  - Their operation, maintenance and replacement generates **more than 50% of the material consumption of the EU**;
  - Their geographic location, even at a very small scale, generates **lock-ins** that are costly (if at all possible) to revert;
  - They can constitute a source of **secondary materials** for the manufacture of new goods;
- The following **policies** related to material stocks are susceptible to **support environmental objectives**:
  - **Limit** or **stop** the growth of material stocks, so as to (1) stabilise the flow of resources used for their operations, maintenance and replacement and (2) enable a closing of the loop by ensuring a mass balance between (a) the materials leaving the stock at their end of life and (b) those entering the stock by potentially recycling or re-using those leaving it;
  - Increase the **lifetime** of items in stocks, e.g. by increasing their ability to be maintained, repaired, re-used, re-purposed or refurbished, so as to substitute the replacement flow by a smaller maintenance flow;
  - Ensure that the items in stock are **suitable for recycling or re-manufacturing**, with **minimal loss in quality and purity**, i.e. that they can be dis-assembled into parts made of homogeneous materials and that these materials are traced in documents that are easy to exploit by recyclers and to consolidate into large-scale statistics;
  - **Plan** the **geographic location of fixed material stocks** (housing, infrastructure) taking into account the long-term evolutions of population and economic activity;
- The **recent trends** show **contrasting patterns** regarding the pursuit of these environmental objectives:
  - The **overall material stocks per inhabitant** in the EU tend to **stabilise**, even if at a high level and with some strong contrasts between Member States;
  - The **economic efficiency** of material stocks in the EU (in terms of EUR/year of GDP per tonne in stock) has **stagnated** over the latest decades;
  - The **energy and climate efficiency** of material stocks in the EU (in terms of KWh or tonnes of CO_{2eq} per year per tonne in stock) has continuously **improved** over the latest decades;
  - The **consumption of stock-building goods** goes in the direction **opposite to a Circular Economy**. The housing surface per person, the number of cars per household and the mass of individual cars all have risen over the last decades;

  - A significant share of housing, infrastructure and production capacity is **abandoned**, left **vacant** or **under-used** because of the movement in the geographic location of population and / or of productive activities;
  - The **Batteries Regulation** is a **positive example** of a forward-looking legally-binding legislation that sets rules on the circularity features of a category of products *before* the stocks of this products start a period of massive growth.

9.2. Lessons learnt

Further research on material stocks would benefit from the following lessons learnt upon the occasion of the present study:

1. The lack of consistency in classification systems, system boundaries and definitions between economy-wide Material Flow Analysis (ew-MFA) data, production statistics and waste statistics makes the set-up and maintenance of mass-balanced models for material stocks very challenging;
2. The modelling of material stocks critically depends on data regarding the lifetime of products in stock and on their material composition. This data is scarce, not collected systematically and evolves over time. This adds to the difficulty of setting up a consistent model;
3. The set-up of a model dedicated to the stock of a given category of products requires very fine-grained knowledge of the technical variants of that product (e.g. of the chemistries of batteries), in order to assess their material composition. This makes such a set-up costly in time (as mentioned above) but also in terms of technical expertise at hand;
4. The environmental impact embodied in material stocks still deserves further investigation, as the granularity of that impact provided by existing established sources such as the International Resource Panel (IRP) of the UNEP[77] is insufficient to account for the variety of small-volume materials, and alternative approaches with a finer granularity[78] are not consensual or cannot consistently be aggregated to national or EU-levels;
5. The modelling of the impact of a Circular Economy measure on the future material stock (in terms of longevity – including re-use and re-purposing, and of material recovery) remains an open research question;
6. The data on the compatibility of the material stock with Circular Economy measures is not available at the date of the drafting of this report (March 2025). This particularly concerns R-strategies of the slowing group, that includes information on the ability of products to be dis-assembled into parts, the material purity of these parts, and hence the capacity of the recovered product parts or materials to be used for applications at the same level of technical requirements (fully circular flows), or at a lesser level (downward spiralling flows or down-cycling). This data would be needed to better assess the capacity of the existing stock of materials to provide secondary materials at the level of quality and of technical requirements that meet the demand for new products.

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[77] *https://www.resourcepanel.org/about-us*

[78] *Such as those relying on exergy, as advocated in: Science Europe (2015) 'A Common Scale for Our Common Future: Exergy, a Thermodynamic Metric for Energy. Recommendations from the Science Europe Physical, Chemical and Mathematical Sciences Committee': D/2015/13.324/6, available at https://scienceeurope.org/media/sn1iyyga/exergy_paper_fin_web.pdf*

10. Annexes

10.1. Annex A. Methods and data on material stock modelling

10.1.1. Methods to quantify material stocks and associated flows

Widely used methods and data sources in material stock accounting/modelling include:

Top-down studies using material flow estimates derived from statistics on production, trade and consumption over several decades to calculate material stocks. Such studies can cover all countries worldwide, long time periods, all major bulk- and several specialty materials, and economy-wide end-uses, all mass-balanced and stock-flow consistent (Cao et al., 2017; Du & Graedel, 2011; Krausmann et al., 2017; Müller et al., 2013; Wiedenhofer, Streeck, et al., 2024). However, these studies rarely provide detail below country-resolution and mostly describe an aggregate stock total for individual materials across all end-uses. In some cases, top-down studies can also distinguish stocks by end-use types, although so far with limited resolution. Some studies assess strategies for mitigating material use and GHG emissions (Watari et al., 2022).

Bottom-up studies using statistical data on functional or product units provide detailed assessments of specific end-uses such as residential and non-residential buildings, passenger vehicles, or electricity infrastructure (Deetman et al., 2020, 2021; Kalt et al., 2021). However, as they rely on scarce statistical data, they usually only model a single historical year and focus on a specific end-use type. Sub-national assessments are common (Wuyts et al., 2022), with an increasing number of studies achieving global coverage, although only distinguishing 20-25 countries/world regions for buildings. Several studies dynamically assess prospective material- and energy efficiency strategies (e.g., Pauliuk et al., 2021; Song et al., 2023; Zhong et al., 2022).

Spatially-resolved bottom-up studies deriving functional or product units from 'big data', which includes remote-sensing (aerial photos, laser scanning, satellite images, nighttime lights) and geographic databases (volunteered geographic information, cadastral / survey data). These studies quantify materials in the built environment with high spatial resolution and coverage, sometimes providing component-level information (Dai et al., 2024), often for a single year (Frantz et al., 2023; Peled & Fishman, 2021; Rousseau et al., 2022). The approach can be applied to historical maps to track the development of built environment stocks over time, and also remote-sensing offers examples of decadal time series data (Li et al., 2023; Schug et al., 2023). Different data sources offer varying spatiotemporal coverage and resolution, and geographic and thematic completeness. Therefore, they are often combined to maximise information content, e.g. using Sentinel satellite data to quantify various building properties and Open Street Map for road networks (Cai et al., 2024; Haberl et al., 2021; van Engelenburg et al., 2024) or directly relating nighttime light intensity to material stocks (Peled & Fishman, 2021). Spatially explicit scenario-modelling which dynamically assesses future material stocks (Heeren & Hellweg, 2019) is rare.

Overview on latest available EU27 national-level stock accounts

For the building sector, both Mastrucci et al. (2021) and Pauliuk et al. (2021) have applied a stock-driven approach to quantify residential buildings. The latter was expanded in scope to include non-residential buildings in Pauliuk et al. (2024). Multiple stock-driven estimates are available which further differentiate building types (e.g., single-family houses, multi-family houses, etc.), however there are large disagreements between stock estimates and non-harmonized system boundaries regarding estimated flows (Wiedenhofer et al., 2015; Peled & Fishman, 2021; Haberl et al., 2024; Lotz et al., 2024). Alternatively, using the recently published in-flow driven MISO2 model, Wiedenhofer et al. (2024) modelled material stocks of residential and non-residential buildings for 177 countries.

For transportation infrastructure, multiple studies with a global scope exist that have presented stock-driven quantifications at the country level. Rousseau et a. (2022) modelled the stocks in paved roads. Wiedenhofer et al. (2024) cover all road- and rail-based infrastructure, from motorways to gravel roads, and from railways, subways to tram lines, as well as associated bridges and tunnels, and airport runways. A recent study (van Engelenburg et al., 2024) refined this assessment by also quantifying material stocks of all roads and rail-based infrastructure including parking infrastructure.

For other end-uses such as motor vehicles, stock estimates are available, as well. Both Pauliuk et al. (2021) and Wiedenhofer et al. (2024) have modelled, among other material stocks in European motor vehicle fleet. Further, Wiedenhofer et al. (2024) provide estimates for stocks in other transport equipment, machinery, furniture, textiles, computers and precision instruments, electrical equipment, and other products. In addition to these large masses, a large number of other products and appliances is accumulated as in-use stocks and stay in socioeconomic use for several years. Data on these products and material composition is scattered, varying in terms of accounting methods applied, and not free of double counting or data inconsistencies if aggregated to the economy-wide level. In the following economy-wide material data, full coverage of all materials entering the EU27 economy is warranted. However, details on little masses of some critical or strategic minerals more or less become invisible. For that reason, data on, e.g., various types of batteries, fluorescent lamps, permanent magnets, etc., mostly consist of certain metals, plastics, or critical materials (Guyonnet et al., 2015; Ciacci et al., 2017; Huisman et al., 2017) will be covered in a separate chapter

The MISO2 model – material coverage and stock types

In the presentation of EU27 stocks, this report focusses on results of the **economy-wide, inflow-driven model MISO2** (material inputs, stocks, and output, Wiedenhofer, Streeck, et al., 2024), as well as evidence from two **spatially-explicit, stock-driven bottom-up studies of buildings and mobility infrastructure (Haberl et al., 2024; Wiedenhofer, Baumgart, et al., 2024).**

For mobility infrastructure, material stocks for the year 2021 where mapped using a spatially-explicit stock-driven bottom-up model that combines crowd-sourced Open Street Maps data with archetypical infrastructure designs and material compositions to map stock estimates for road types ranging from motorways to gravel roads, rail-based infrastructure including railway, subway, and tram lines, and associated infrastructure such as bridges and tunnels for 180 countries at a resolution of 5 arcminutes. In addition, material flows related to the expansion, maintenance and replacement of transport infrastructure as well as embodied emissions are calculated. The mapping of global building stocks also used a spatially-explicit stock-driven bottom-up model primarily built on remote sensing data (Haberl et al., 2024) to distinguish 18 different types of materials embedded in five different building types (single-family houses, multi-family houses, as well as high-rise, commercial, and light-weight buildings). By integrating building volumes derived from

Sentinel-1 and -2 Earth Observation data with a building material intensity database, a global material stock map of buildings at a resolution of 90 m is generated.

The MISO2 models economy-wide material cycles and stock dynamics across multiple materials and end-uses at the national to global level. The modeling differentiates 14 material supply chain processes and stock dynamics, fully consistent with economy-wide material flow accounting (ew-MFA) (Wiedenhofer, Streeck, et al., 2024). The model was empirically applied to 21 raw materials transformed into 20 stock-building materials, 13 end-uses, and 177 countries from 1900 to 2016, including a spin-up period from 1820. Based on systematic model data input uncertainty assessments, one-at-a-time uncertainty testing for groups of model parameters for the resulting stock estimates was conducted. Table 10-1 (first table below) shows the design principles of MISO2. Figure 10-1 shows the detailed system definition of the model. Table 10-2 (second table below) shows the materials currently covered. Table 10-3 (third table below) shows the end-use product groups differentiated.

Table 10-1: Design principles of MISO2 model

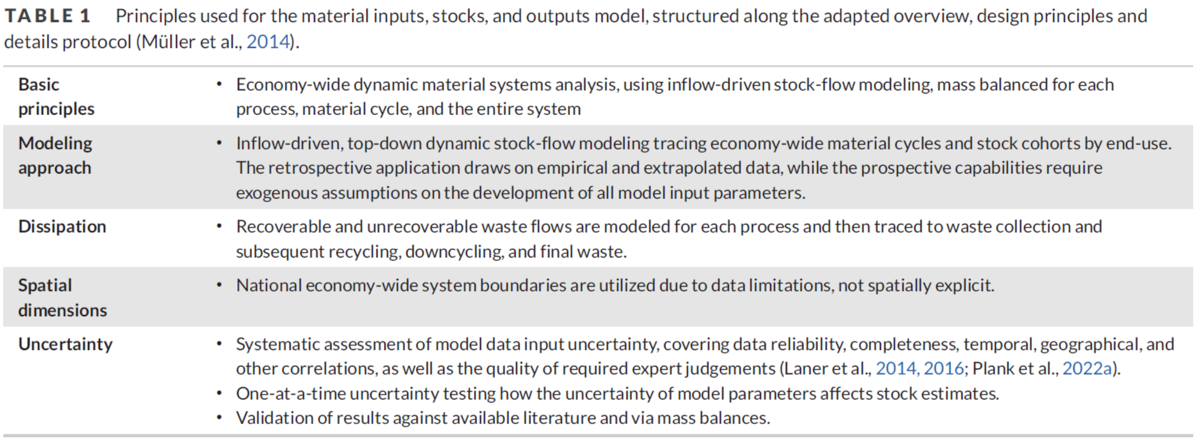


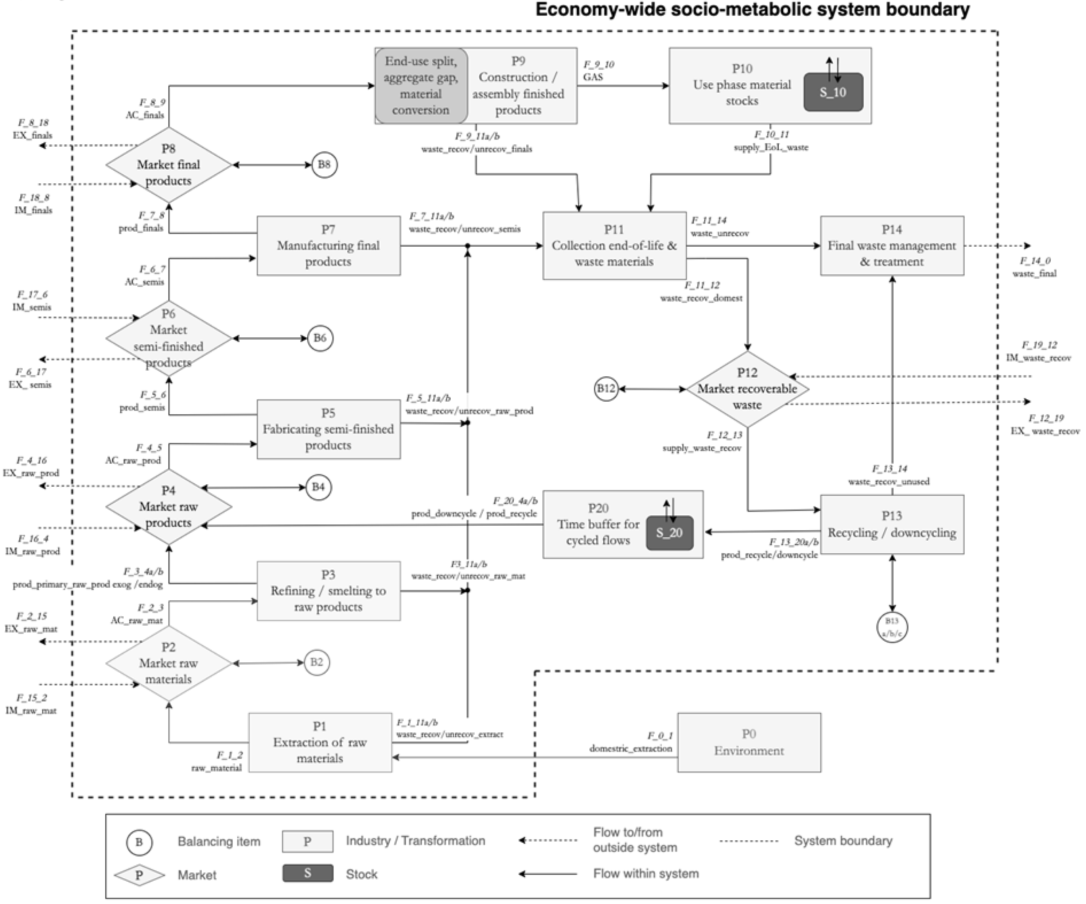
TABLE 1 Principles used for the material inputs, stocks, and outputs model, structured along the adapted overview, design principles and details protocol (Müller et al., 2014).

Basic principles	• Economy-wide dynamic material systems analysis, using inflow-driven stock-flow modeling, mass balanced for each process, material cycle, and the entire system
Modeling approach	• Inflow-driven, top-down dynamic stock-flow modeling tracing economy-wide material cycles and stock cohorts by end-use. The retrospective application draws on empirical and extrapolated data, while the prospective capabilities require exogenous assumptions on the development of all model input parameters.
Dissipation	• Recoverable and unrecoverable waste flows are modeled for each process and then traced to waste collection and subsequent recycling, downcycling, and final waste.
Spatial dimensions	• National economy-wide system boundaries are utilized due to data limitations, not spatially explicit.
Uncertainty	• Systematic assessment of model data input uncertainty, covering data reliability, completeness, temporal, geographical, and other correlations, as well as the quality of required expert judgements (Laner et al., 2014, 2016; Plank et al., 2022a). • One-at-a-time uncertainty testing how the uncertainty of model parameters affects stock estimates. • Validation of results against available literature and via mass balances.

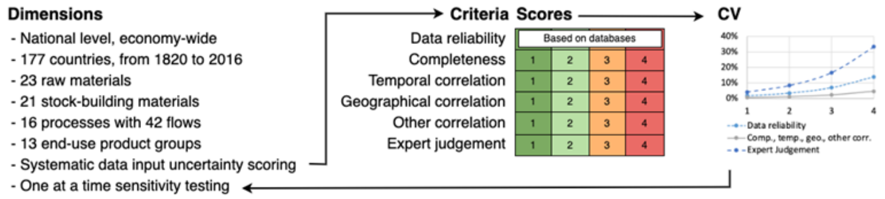
Source: Wiedenhofer, Streeck, et al. (2024)

Figure 10-1 : System definition for the MISO2.0 model (a), and scope of the MAT_STOCKS database version 1.0 (b)

a) System definition



b) Scope



<u>Source:</u> *Wiedenhofer, Streeck, et al. (2024).*

Table 10-2: List of materials covered in MISO2. Relation of (1) raw material extraction as defined and measured in global economy-wide material flow accounting to (2) the material cycles modelled in MISO2.

Raw materials extraction as measured in economy-wide material flow accounting		**MISO2 material cycles and stocks**		
Material categories DE	Description	Processed material	Materials in the stock	Recycling and downcycling of processing- and end-of-life waste
BIOMASS				
A.1.1.1 - 1.1.12.	Crops (different types)	*excluded*		
A.1.2.1-1.2.4.	Crop residues (used), fodder crops, grazed biomass	*excluded*		
A.1.3.1	Timber (Industrial roundwood)	timber; paper	timber; paper	timber; paper
A.1.3.2	Wood fuel and other extraction	*excluded*		
A.1.4.1. - 1.4.5.	Wild harvest (fish catch, hunting, gathering)	*excluded*		
METAL ORES				
A.2.1	Iron ores	iron	steel = iron + tin + zinc	steel
A.2.2	Aluminium ores	aluminum	aluminum	aluminum
A2.2.2.	Nickel ores	nickel	nickel	nickel
A.2.2.3.	Lead ores	*excluded*		
A.2.2.4.	Zinc ores	zinc	zinc	zinc
A.2.2.5.	Tin ores	tin	tin	tin
A.2.2.6.	Gold, silver, platinum and other precarious metals	*excluded*		
A.2.2.8.	Uranium and thorium ores,	*excluded*		
A2.2.9.	Other metal ores	*excluded*		
NON-METALLIC MINERALS				
A.3.1	Ornamental or building stone	*excluded*		
A.3.2.1	Chalk	*excluded*		
A.3.2.2	Dolomite	*excluded*		
A.3.2.3	Limestone	Cement	concrete = cement + aggregates	concrete; C&D waste downcycling*
A.3.4	Chemical and fertilizer minerals	*excluded*		
A.3.5	Salt	*excluded*		
A.3.6	Gypsum	Cement	concrete = cement + aggregates	concrete; C&D waste downcycling*
A.3.7.1	Structural clays	Bricks; cement	bricks; concrete = cement + aggregates	bricks; concrete; C&D waste downcycling*

Raw materials extraction as measured in economy-wide material flow accounting		MISO2 material cycles and stocks		
A.3.7.2	Specialty clays	*excluded*		
A.3.8.1	Industrial sand	flat glass; container glass		
A.3.8.2	Sand and gravel for construction	primary 'virgin' sand and gravel aggregates		
A.3.9	Other non-metallic minerals n.e.c.	*excluded*		
FOSSIL FUELS				
A.4.1.1. - 4.1.3.	Coal and peat	*Excluded*		
A.4.2.1	Crude oil	Plastics; bitumen	plastics; bitumen; asphalt = bitumen + aggregates	plastics; bitumen; asphalt; C&D waste downcycling*
A.4.2.2; 4.2.3; 4.3.	Natural gas; natural gas liquids; Oil shale and tar sands	*excluded*		

<u>Legend:</u> Material classification of domestic extraction (DE) and numbering of material categories derived from classification used in (UNEP, 2023).

(*) Construction and demolition (C&D) waste usually contains a mixture of concrete, bricks, bitumen materials as well as sand and gravel aggregates, which is mainly downcycled into secondary sand and gravel aggregates primarily used as base layers for roads and buildings.

Table 10-3: MISO2 end-use classification and example products contained but not differentiated empirically.

Main end-uses	Detailed end-uses	Example products contained within the modelled end-uses, sourced from the underlying HSCPC classification
Buildings	Residential buildings	One-, two- and multi-dwelling buildings
	Non-residential buildings	Industrial, commercial, and other non-residential buildings
Infra-structure	Roads	Road surfaces of highways, streets, roads, etc., excluding tunnels and bridges
	Civil engineering, except roads	Railways, airfield runways, bridges and elevated highways, tunnels, subways, water supply pipes, harbors, dams, flood control waterworks, power plant construction, outdoor sport and recreation facilities, local and long-distance pipelines, local and long-distance communication and power lines, etc.
Stationary Machinery	Machinery and equipment	Turbines, washing machinery; air conditioning; cranes; shovels, excavators and other construction machine; refrigerators, freezers; tools for pressing, stamping or punching; vacuum pumps, compressors, fans, blowers; rock drilling or earth boring tools; razors; sawing or cutting machines, bridge cranes; bulldozers and angledozers; milling machines; heat exchange units, printing machinery; diesel engines
	Computers and precision instruments	Personal computers; monitors; optical devices, appliances and instruments; wrist watches; TV and radio; loudspeakers; headphones; other sound reproducing apparatus; television cameras; automatic data processing machines & units; photocopying apparatus; video cameras and recorders; instruments and apparatus for physical or chemical analysis; electronic calculators; lasers; etc.
	Electrical equipment	Electric motors, generators and transformers (AC/DC); lighting or visual signaling equipment; ovens; cookers; static/electronic converters; domestic vacuum cleaners; electric heaters; electric fences; domestic food grinders and mixers; fruit or vegetable juice extractor; Handheld drills; electrothermic coffee or tea maker; etc.

Main end-uses	Detailed end-uses	Example products contained within the modelled end-uses, sourced from the underlying HSCPC classification
Transport Machinery	Motor vehicles trailers and semi-trailers	Automobiles including parts and accessories thereof; trucks including parts and accessories thereof; buses; tractors; snowmobiles; mobile cranes; fire fighting vehicles; etc.
	Other transport equipment	Cargo containers; cargo vessels; aircraft; tankers; motorcycles; bicycles and other cycles; trailers; rail locomotive; tanks; cruise ships; baby carriage and parts thereof; railway coaches and cars; helicopters; balloons; motorboats; wheelchairs; rowing boats; Fishing vessels and factory ships
Short lived products	Furniture and other manufactured goods nec	Articles of bedding/furnishing; paintings and drawings; original sculptures and statuary; mattresses; instruments and appliances used in medical or veterinary sciences; furniture for domestic use or office; music instruments of all kinds; toys; sport equipment; umbrellas; etc.
	Printed matter and recorded media	Plans, maps & drawings; books, brochures, leaflets and similar printed matter; newspapers, journals and periodicals; advertising material; Pictures, designs and photographs; dictionaries and encyclopedias, and serial instalments thereof; music, printed or in manuscript; etc.
	Food packaging	Packaging materials like cans, pouches and bags, bottles, jars, cardboard boxes, shrink wrap, cartons, pallets, stretch wrap; etc.
	Products nec	Textiles; medicaments; cigarette; beauty and makeup products; sunscreen or suntan products; photo plates and films; printing ink; soap; glues; etc.

Source: *Own elaboration*

10.1.2. Comparison of different datasets and critical discussion of uncertainties

Quantifying stocks is challenging and bears considerable uncertainties. Different estimates of the same material stocks scrutinised for a recent review often differed by around one order of magnitude, illustrating a still weak scientific basis for policy and planning (Streeck, Baumgart, et al., 2024, in preparation). Material stocks at scales such as in a city or a nation cannot be measured directly. Their quantification thus relies on different and diverse data sources (section 2) of varying availability and quality which introduces inherent uncertainty to material stock estimates (Laner et al., 2014).

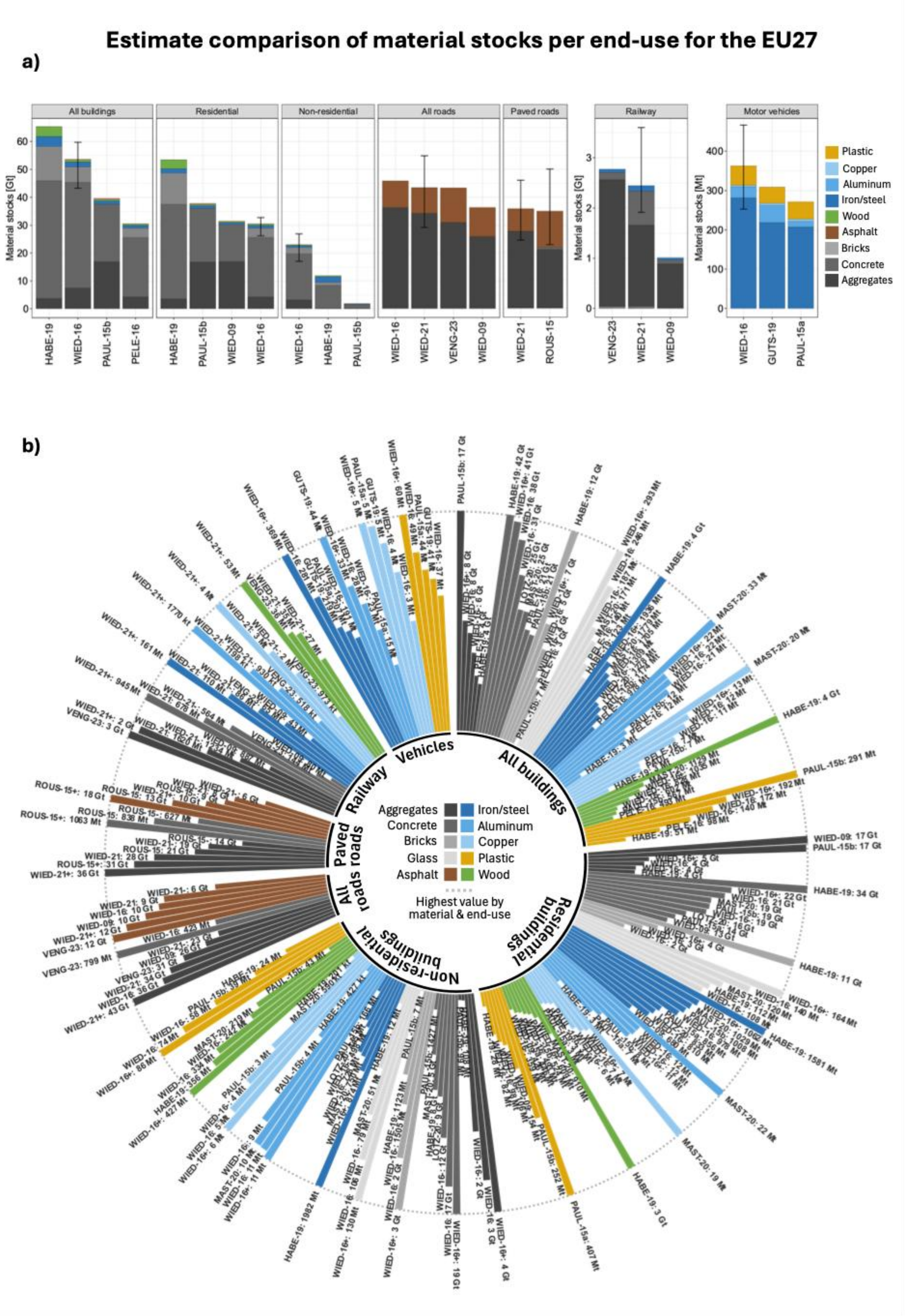
Variations between stock estimates from different studies

For the EU27, we find that stock estimates vary significantly, in some cases by a factor of 2 to 3 (see Figure 10-2.a). For residential buildings, the spatially-explicit bottom-up stock modelling approach produces an estimate significantly larger than that of the statistics-based bottom-up and top-down approaches. For non-residential buildings, however, this is not the case with the spatially-explicit estimate being between available top-down estimates. This highlights the challenges in identifying or allocating materials to building types through different methodological approaches.

For roads (both paved roads and total roads) different methodological approaches seem to yield more similar results in the case of the EU27, while for railways, the spatially-explicit bottom-up approach produces higher estimates than the statistics-based bottom-up approach. For vehicles, estimates are relatively similar across top-down and statistics-based bottom-up approaches.

If we look at individual materials (see Figure 10-2.b), we see that there is significantly more variation in estimates across end-uses. Estimates for bulk materials such as concrete and aggregates tend to be more homogenous, though existing differences can be due to differences in allocation of aggregates to other non-metallic mineral products. In contrast, estimates for other materials such as various metals, plastics, and timber tend to vary more which may be due to differences in scope (e.g., which components of vehicles or building elements are considered).

Figure 10-2 Comparison of material stock estimates for various end-uses, stacked by materials (a) and for various end-uses and materials individually (b).



<u>Note:</u> Only stock estimates are compared which have the same scope end-use- and material-wise. Years in abbreviations correspond to the year of the stock estimate which may differ between studies with '-' and '+' referring to low and high uncertainty estimates, respectively.

<u>Sources:</u> Top-down studies: PAUL-15a (Pauliuk et al., 2021), PAUL-15b (Pauliuk et al., 2024), WIED-16 (Wiedenhofer, Streeck, et al., 2024), MAST-20 (Mastrucci et al., 2021); Statistics-based bottom-up studies: WIED-09 (Wiedenhofer et al., 2015); GUTS-19 (Gutschi, 2022), LOTZ-20 (Lotz et al., 2024); GIS-based bottom-up studies: HABE-19 (Haberl et al., 2024), WIED-21 (Wiedenhofer, Baumgart, et al., 2024), VENG-23 (van Engelenburg et al., 2024), ROUS-15 (Rousseau et al., 2022).

Sources of uncertainty within and between estimates of material stocks

Sources of uncertainty within and between material stock estimates are assessed in detail in (Streeck, Wieland, et al., 2024), which we summarize here. Uncertainty within material stock estimates comes as aleatory and epistemic uncertainty (Huijbregts 1998; Laner et al. 2014; Laner et al. 2016; Brunner and Rechberger 2016). Aleatory uncertainty originates from natural variability in the real world system underlying the scientific problem. An example is the variability of the material intensity of different building construction types. Epistemic uncertainty originates from the uncertainty of choices, models, and parameters. Epistemic choice uncertainty stems from unavoidable modelling choices, which remain to some degree subjective, such as the choice of system boundaries. Epistemic model uncertainty stems from model structure and implied variable relationships, such as stock lifetime functions applied in calculations. Epistemic parameter uncertainty refers to the uncertainty of model input parameters, such as lack of temporally, spatially and technologically representative data, incomplete data, inaccurate measurements and lack of uncertainty information. Parameter fuses with model uncertainty, when data and formal mathematical model are combined via the tailoring of model data to system definition, and when proxies are used for missing values. Last but not least, uncertainty stems from inaccurate communication, for example the using of ambiguous material labels in reporting material intensities.

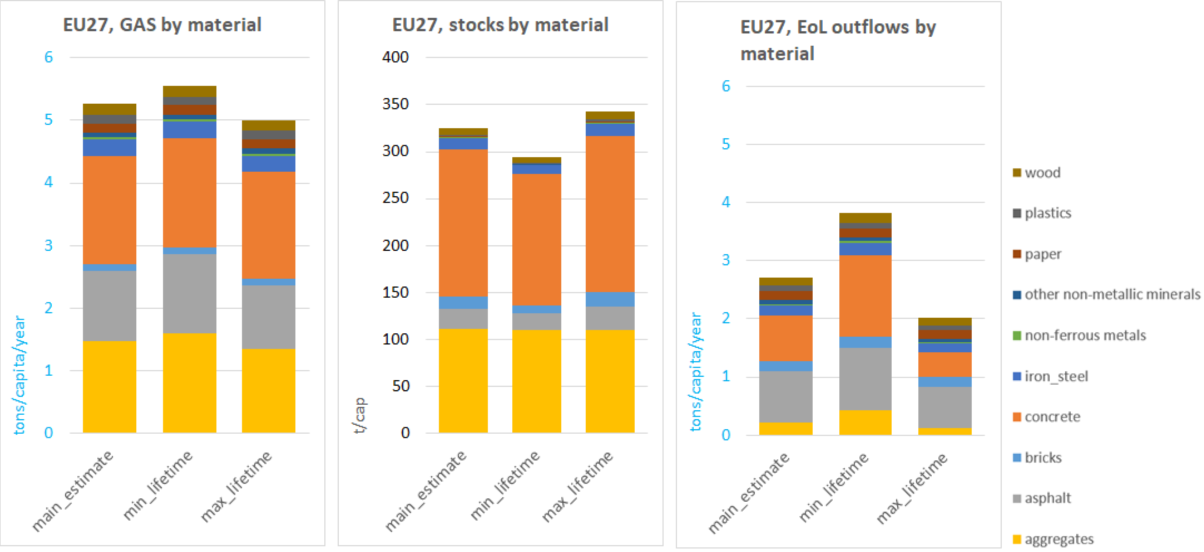
A key source of uncertainty within material stock estimates is scarce and low-quality data which makes it difficult to adequately represent natural variability. High natural variability is, for instance, evident in collections of building material intensity databases (Sprecher et al., 2022; Guven et al., 2022; Yang et al., 2020). However, most such databases do so far not adequately represent natural variability, in part because of the time intensive effort required for their construction (e.g., Gontia et al., 2018; Fishman et al., 2024; Guven et al., 2022). Lacking data then force modelers to make choices, assumptions and/or approximate data which can have strong influence on results. Examples are the extrapolation of sampled data from individual buildings to represent entire countries' buildings material composition; the use of country-level buildings floor space per capita as proxy for entire world regions (e.g., for some regions in Pauliuk et al., 2021); and choices between different average product lifetimes (Wiedenhofer, Streeck, et al., 2024), Relatively better data exists for bulk material flows, functional/product unit stocks and material intensities of residential buildings, roads, and passenger vehicles. Nonetheless, even these available data suffer from limitations such as low coverage of countries and regions (especially in the Global South), limited resolution of construction types, and inadequate representation of geospatial varieties. Less is known about non-residential buildings and other end-uses like industrial machinery, with extremely scarce data on the age-structure and lifetimes of material stocks (Miatto, Schandl, & Tanikawa, 2017; J. Guo et al., 2021), as well as the end-use destinations of material flows (Streeck et al., 2023). Information on the uncertainty associated with model parameters is even harder to come by (Laner et al., 2014), which might be a reason why many studies lack uncertainty analysis.

Uncertainty between material stock estimates originates from differences across steps involved in doing stock-flow assessments. These differences include variations in system boundaries when including distinct parts of a system, and the use of entirely different model structures and data sources. For example, data sources and models may differ substantially in their estimates of functional units (e.g., floor space estimates from remote-sensing by Arehart et al. (2021) being factor 2-3 larger than other sources), their completeness (e.g., differences in indicator definitions, such as reference to useful, net, gross, or total built-up area and in- or excluding unoccupied buildings (Arehart et al., 2021; Schiller et al., 2019)), their level of granularity and use of proxies and inter/extrapolations (e.g., use of average vs. age-cohort-based material intensities; (Ortlepp et al., 2018; Lanau et al., 2019)). More systematic analysis of uncertainty sources between models would be a sensible next step towards more robust assessments in the future.

Robustness of MISO2 stock-flow data

The most relevant parameter in inflow-driven stock modelling like the MISO2 model (Wiedenhofer et al. 2024) are the lifetime distributions of in-use stocks, that is the number of years a product or a built-up structure is in socioeconomic use. Especially with regarding buildings, roads and other infrastructure, lifetimes are a matter of decades, assigning the built environment an extremely important role. To show the implications of changes in lifetime distributions of stocks, we compare three different assumptions for lifetime distributions (Figure 10-3 below). The three assumptions are: the "main_estimate" represents the best guess for stock lifetime distributions according to the available data and expert knowledge; the "max_lifetime" and "min_lifetime" represent variations of +/-30% to assess the sensitivity to stock lifetimes, which is the most influential parameter for this type of (inflow-driven) MFA model. We find a relatively high robustness of the MISO model and the lifetime distributions applied therein. Please note that the differing values of GAS/year in Figure 10-3.a results from a methodological peculiarity: for materials for which only data on primary production data is available, the MISO2 model estimates secondary production based on modelled waste flows from manufacturing processes and stock demolition at their end-of-life. When varying the lifetime of stocks, the amount of material flows from stock demolition varies (as more or less stocks are demolished due to shortened/increased lifetimes, respectively), resulting in varying material availability for recycling which leads to varying amounts of secondary production and thus GAS.

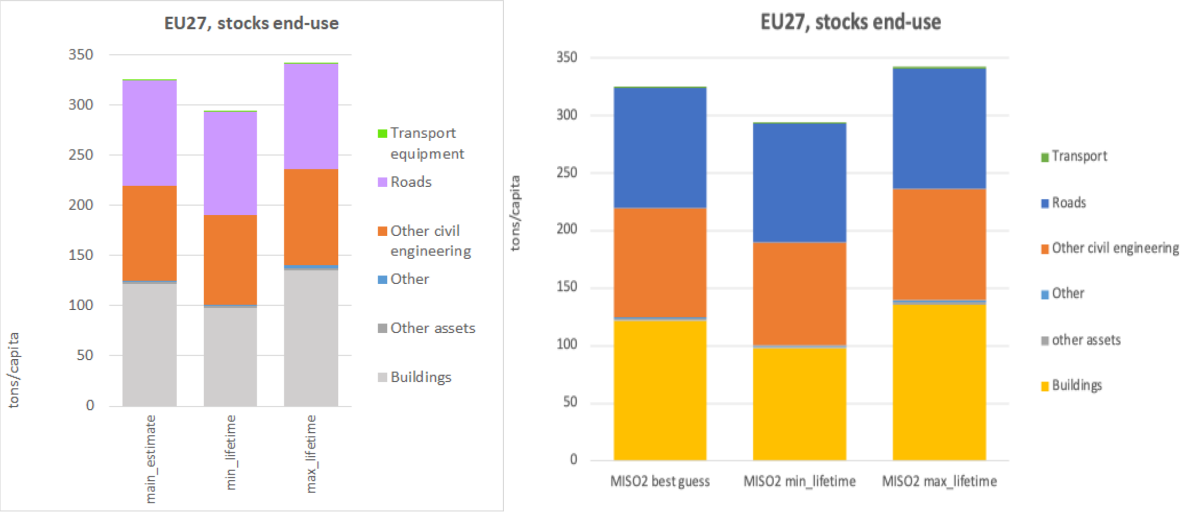
Figure 10-3: Comparison of three estimations of stocks lifetimes and their implication to GAS, stocks, EoL in the year 2016.



Legend: *"main_estimate" represents the best guess for stock lifetimes according to the available data and expert knowledge; the "max_lifetime" and "min_lifetime" represent variations of +/-30% to assess the sensitivity to stock lifetimes. To pont out the important difference between stocks and flows, the y-axis in flow-graphs (tons/capita/year) is coloured in blue, whereas the y-axsis in the stock graph in the middle is given in black colour.*
Data: *MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)*

A similar sensitivity test was undertaken for the modelled end-uses of material stocks as 13 product groups (Figure 10-4), revealing similar coherence among results for stocks and flows.

Figure 10-4: EU27 stocks according to end-uses and uncertainties comparability across model variations, 2016 in tons/capita.



Legend: *MISO2 best-guess represents the best guess for stock lifetime distributions according to the available data and expert knowledge; MISO2 max_lifetime and MISO2 min_lifetime represent variations of +/-30% to assess the sensitivity to changes in average stock lifetimes. The end-use "Other Assets" includes different kinds of electrical and non-electrical machinery; the end-use "Other" includes furniture, textiles, food packaging, printed matter and consumper products not specified elsewhere.*

Data: *MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)*

Stages in the method used to assess material flows in the present study and associated sources of uncertainty

Table 10-4: Mapping of the iterative steps in Material Flow Analysis

Iterative steps of Material Flow Analysis (MFA) & guiding questions to assess uncertainty	Sources of uncertainty	Specification & example for Material Flow Analysis models
1. Problem, system & model definition **+ Do model and system boundaries align with the problem of interest?** **+ Do system boundaries affect decision-making?** **+ How much natural variability can be expected for system components?** **+ Does model structure affect conclusions?**	- natural variability (a)	+ natural variability of products in type, age, size, material, function and local context needs to be considered in modelling, e.g., intensity of different materials in wall and frame of ~740 thousand U.S. single-family houses to vary between 5-27% and 8-91% respectively (Saxe et al., 2020), or the material intensities of roads varying within U.S. regions (Frantz et al., 2023), and even within a small geographic area like Toronto (Kloostra et al., 2022)
	- choice of system boundary (c)	+ choice of which materials, products and processes to include and which unit of measurement to use, e.g., in/exclusion of ancillary facilities such as ventilation systems in material stock assessment of roads explaining 20% of divergences between results of two studies (Z. Guo et al., 2014; Huang et al., 2017; Lanau et al., 2019)
		+ definition of system boundaries is not trivial, e.g., for infrastructure which is an agglomeration of multiple sub-products (Saxe et al., 2020). Currently system definitions are partially implicit and not reported, e.g., for material intensity and material flow data (Heeren & Fishman, 2019; Streeck et al., 2023)
	- model structure (m)	+ formal mathematical implementation, e.g., using Lognormal-, Weibull distributions or Kaplan-Meier functions for estimating buildings' lifetimes, survival and demolition (Bradley & Kohler, 2007; Miatto, Schandl, & Tanikawa, 2017; J. Guo et al., 2021)
2. Input data: inventories, material intensities, transfer coefficients, uncertainty characterization **+ In how far does the study data represent natural variability of parameters?** **+ Can the study prioritize use of local and recent studies for parameters?** **+ Are data sources incomplete or inaccurate?** **+ Is sufficient information for uncertainty characterization available? Semi-quantitative uncertainty evaluation can be an**	- lack of representative data for natural variability (p)	+ temporal: missing data on temporal variability of functional and product units, material intensities (Fishman et al., 2024), age-structure (J. Guo et al., 2021; Milojevic-Dupont et al., 2023), lifetimes (Wiedenhofer, Streeck, et al., 2024), end-use shares (Streeck et al., 2023), demolition and recycling rates (Wiedenhofer, Streeck, et al., 2024), structural-type shares
		+ spatial: missing data on spatial resolution of functional or product units, material intensities (Fishman et al., 2024), material flows (Plank et al., 2022b, 2022a), especially for the Global South and rural areas (Mastrucci et al., 2023)
		+ technological: missing data on distinction of (building) construction types (Fishman et al., 2024), material flow end-use (Streeck et al., 2023)
		+ studies on parameter variance and representativeness are scarce (Fishman et al., 2024)
		+ examples: - current material intensity data for buildings is based on few sources, spread throughout individual literature studies, geographically biased towards Global North, technically based on case-studies of individual or a sample of a few buildings referring to the context of a particular city, on construction manuals, or archetypical buildings (Fishman et al., 2024; Heeren & Fishman, 2019; Röck et al., 2023) - road material intensities derived from construction guidelines/standards may not be representative of actual road construction (Grossegger et al., 2024)

Iterative steps of Material Flow Analysis (MFA) & guiding questions to assess uncertainty	Sources of uncertainty	Specification & example for Material Flow Analysis models
option too (Laner et al., 2016). **+ Would the use of different input data sources affect results?**		- high variance within products even of the same sub type "e.g., high rise residential, or multi-unit low rise" due to heterogeneity in design, material selection and construction both within and between locations (Arceo et al., 2023; Rankin et al., 2024)
	- incomplete data (p)	+ use of indicators not representing the defined product flow or stock of interest leading to over- or underestimation, e.g. using floorspace indicator for conditioned floorspace which excludes attics and stairways to quantify total material stocks of a building (Schiller et al., 2019), as well as including/excluding vacant buildings; U.S. floorspace estimates from statistics and remote-sensing diverge by factor-3 (Arehart et al., 2021)
		+ some temporal parameters are impossible to accurately estimate due to insufficient passage of time, e.g., building lifetime estimates are typically 'right-censored', an issue which is greater for more recently built buildings. If some of a cohort of buildings remain undemolished, it is not possible to estimate the average lifetime or lifetime distribution parameters, because the time of demolition of the remaining buildings is not yet known (Bradley & Kohler, 2007)
		+ functional or product units derived from remote sensing or GIS databases can be incomplete with substantial regional variability in geographic completeness (Barrington-Leigh & Millard-Ball, 2017; Zhou et al., 2022), but also thematic completeness of associated attributes (e.g., pavement types, (Frantz et al., 2023))
	- inaccurate data (p)	+ data not accurately representing measurement of indicator, e.g. through poor quality of statistical reporting of material extraction, production and trade for non-metallic minerals (Miatto, Schandl, Fishman, et al., 2017), measurement error for building height (Cai et al., 2023; Frantz et al., 2021), footprint or building type (Haberl et al., 2021), opaque and ambiguous documentation (e.g., of material intensities (Fishman et al., 2024), and reported road lengths from statistics affected by methods used for estimation (Grossegger et al., 2024)
		+ deviation between records/estimates and what was actually used in construction (e.g., 38% more concrete being used in bridge substructures than shown in drawings (Olanrewaju et al., 2022))
	- uncertain uncertainty (p,c)	+ lack of data on uncertainty resulting in assumptions and arbitrary choices of uncertainty distributions and relations of model parameters (Huijbregts, 1998; Laner et al., 2014)
	- [disagreement] (c)	+ 'There is no consensus among scientists (opposing views), typically because of a lack of data.' (Laner et al., 2014; Morgan et al., 1990) + e.g., disagreement between remote sensing products (Chakraborty et al., 2024)
	- [unpredictability] (p)	+ 'Uncertainty is irreducible in principle as a result of indeterminacy (i.e., practical unpredictability)' (Laner et al., 2014; Morgan et al., 1990), e.g., for parameters in prospective assessments
		+ one off or few off nature of large products means that it is hard to predict in advance the degree of uncertainty (Saxe et al., 2020)
3. Modelling: combine data & quantitative model, uncertainty propagation	- approximation of missing parameter data (p,m,c)	+ e.g., extrapolating lacking data on wood material intensity of a building for years before 1980 by using datapoint from 1980 for all prior years (e.g., for some parameters in Pauliuk et al., 2021)); extrapolating lacking data on nonresidential building material intensity by using those from another country (Lanau & Liu, 2020);

Iterative steps of Material Flow Analysis (MFA) & guiding questions to assess uncertainty	Sources of uncertainty	Specification & example for Material Flow Analysis models
+ If local and recent studies cannot be used to inform parameters, can conversion factors be applied to spatiotemporally misaligned data? **+ How do approximated parameters, assumptions and aggregation affect results?** **+ If uncertainty could be characterized, how does uncertainty propagation affect results?** **+ If uncertainty could not be characterized, sensitivity analysis should be conducted as fallback option.**		use of single values of ceiling-to-ceiling and roof height in calculations of building volume from remote-sensing data (Milojevic-Dupont et al., 2023; Peled & Fishman, 2021) and layer thickness for road surfaces (Grossegger et al., 2024)
		+ e.g., extrapolate from available water infrastructure data in some cities to estimate infrastructure in others (Rankin & Saxe, 2024)
		+ e.g., use data available from specific countries to extrapolate at regional level and make up for data gaps in other countries (Mastrucci et al., 2021)
	- tailor available data to fit system definition (p,m,c)	+ aggregation of real-world granularity underlying system resolution due to lacking representative data, e.g., aggregation of material intensities across construction archetypes (Ortlepp et al., 2018; Lanau et al., 2019) and spatial scales (Kloostra et al., 2022) leading to inaccurate assessment
	- [disagreement]	+ see same category above
4. Interpretation & communication **+ Are workflows and results transparently documented (ideally open-access)?** **+ Do procedures and definitions refer to established frameworks?** **+ Are uncertainty/sensitivity communicated to facilitate decision-making?**	- inaccurate communication (p)	+ e.g., linguistic imprecision by use of ambiguous material labels (Heeren & Fishman, 2019), differently defining 'dissipated stock' term (Lanau et al., 2019)

<u>Source:</u> Adjusted from Brunner & Rechberger (2016) to synthesis of the uncertainty and variability categories in Huijbregts (1998) and data uncertainty categories in Laner et al., 2014, 2016)). Aleatory uncertainty from natural variability (a); epistemic uncertainty from choice uncertainty (c), model uncertainty (m), parametric uncertainty (p). Sources of uncertainty in square brackets [] are not applicable here and are not further discussed.

10.1.3. Methods applied to compile the Sankey diagram presented in chapter 4.4

The Sankey diagram of material flows through the EU27 economy in 2016 is created by integrating MISO2 data (i.e., gross additions to stocks, outputs from stocks (EoL) and secondary material flows) at the detailed level of specific end-use types (e.g., buildings or machinery) with data from the ew-MFA accounts of Eurostat (DE, IM, EX). MISO2 data include only stock-building materials. Additional flows required for a comprehensive

Sankey diagram include non-stock-building material flows (i.e., energy use from biomass and fossil fuels, throughput from non-energy material use, domestic processed outputs) and were derived by triangulating data from MISO2 with Eurostat ew-MFA.

Energy use in the Sankey stands for the technical energy use of materials (fossil energy carriers, fuel wood) as well as food for humans and feed for livestock. Throughput stands for non-energy material use that are not added to material stocks, meaning their lifetime is shorter than 1 year. Throughput includes flows like materials used as fertilizers, solvents, agrochemicals or wastes from material processing that are not destined for use within the socioeconomic metabolism and are subsequently deposited to landfills or discarded to the natural environment.

Eurostat's EU27 data for domestic extraction (DE), physical imports and exports (IM, EX) and processed materials (PM) are taken as constraining values in the estimation of the missing flows of the Sankey (i.e., energy use, throughput, parts of DPO) through mass balancing.

Flows of biomass and fossil energy carriers for energy use are estimated by subtracting the sum of gross additions to stocks + throughputs + exports from PM. All metals and non-metallic minerals are assumed to be used for non-energy purposes. Processing wastes of metals and non-metallic minerals are shown in the Sankey as throughput and are estimated by subtracting the sum of gross additions to stocks + exports from PM. After estimating economy-wide energy use and throughputs, we can calculate the missing inputs and outputs of waste treatment and subsequently DPO. Note that data on secondary flows are sourced from the MISO2 model.

Flows of biomass, fossil energy carriers and metal are consistent with Eurostat accounts for DE, IM and EX. However, it is important to note that the non-metallic mineral flows in the Sankey diagram differ from the ew-MFA accounts of Eurostat due to three reasons.

First, non-metallic minerals in the Sankey only picture those stock-building materials that are modelled in the material processing chains of the MISO2 database, i.e., sand, gravel, clays and kaolin. To be consistent with GAS results in the present report, other stock-building non-metallic minerals (e.g. slate, marble, granite, sandstone and other building stones) where Eurostat does report extraction within the EU27 are not shown in the Sankey.

Second, the extraction of non-metallic minerals that is shown in the Sankey (i.e., sand, gravel, clays and kaolin) differs from Eurostat's extraction accounts due to the presence of secondary material flows (e.g., downcycling of concrete for use in road construction). Because primary statistics on extraction volumes of non-metallics like sand and gravel are usually unavailable or of poor quality, material flow accounting usually relies on multipliers to infer such estimates from data on cement production or concrete consumption (e.g., the amount of sand needed per ton of cement) as well as other proxies for road construction. However, because MISO2 gives us an estimate for these secondary flows, we subtracted the amount of recycled/downcycled non-metallic minerals from the Eurostat's extraction account. In other words, we here assume Eurostat to overestimate the domestic extraction of sand and gravel due to a lack of information on these cycling flows. This approach yields reasonable estimates for all the processes and flows represented in the Sankey, which we interpret as a confirmation of the assumption.

Third, the only non-metallic mineral that is non-stock-building that is shown in the Sankey under throughput is salt. Other non-metallics that could be classified under throughput, such as Eurostat's material item "chemicals and fertilizer minerals", are not reported explicitly in Eurostat's DE account (due to confidentiality reasons) although they form part of the aggregated material group "non-metallic minerals".

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10.2. Annex B. Supplementary materials and methods supporting section "Links between Circular Economy and material stocks – cross-sectoral perspective"

10.2.1. Circular Economy measures in high-level categories and their susceptibility to act on the stocks or flows of durable goods or fixed assets.

Table 10-5: Overview of the relation between Circular Economy measures and their impact on the stock or the flow of durable goods or fixed assets

High-level category of Circular Economy measures	Sub-category of Circular Economy measures	Stage(s) in the product lifecycle when the measure is applied[13]	Examples of possible Circular Economy measures in the category	Impacts on the stock or the flow of durable goods or fixed assets
1. Narrowing	1.1. Reduce service level of units in the stock	Before use - Refuse	1.1.a Quantitative limitation in the housing surface per person 1.1.b Reduce the size and / or power of individual cars	Reduces the size (and hence the mass) of each unit in the stock
1. Narrowing	1.2 Reduce mass of units in the stock (at constant service level)	Before use - Reduce	1.2.a Reduce over-specification in buildings and infrastructure 1.2.b Implement high-strength materials	Reduces the mass of each unit in the stock
1. Narrowing	1.3. Increase usage intensity	During use – Re-use and share	1.3.a Sharing of building spaces (e.g. guest room, party room, laundry room in dwellings, shared office spaces) 1.3.b Car-pooling and ride-sharing in suburban and rural environments 1.3.c Sharing of truck transport capacity 1.3.d Sharing of mechanical and electronic equipment and domestic goods through dedicated platforms	Reduces the number of units in the stock of durable goods to deliver the same service to society
1. Narrowing	1.4 Reduce consumption of end-use goods	Before use – Refuse	1.4.a Quantitative limitation in the total mass of goods purchased per year and per person (acts on the manufacturing machinery and on transport infrastructure) 1.4.b Quantitative limitation in the electric consumption per year and per person (acts on the electricity network) 1.4.c Quantitative limitation in the water consumption per year and per person (acts on the water supply network) 1.4.d Quantitative limitation in the number of kilometres travelled by car, train or plane per year and per person (acts on the transport infrastructure) 1.4.e Quantitative limitation in the data traffic on the Internet per year and per person (acts on the telecommunications network)	Reduces the stock of fixed assets needed to supply the end-use goods

High-level category of Circular Economy measures	Sub-category of Circular Economy measures	Stage(s) in the product lifecycle when the measure is applied[13]	Examples of possible Circular Economy measures in the category	Impacts on the stock or the flow of durable goods or fixed assets
1. Narrowing	1.5 Substitute a technical solution by a more material-efficient one	Before use – (intermediate between Refuse and Re-think)	1.5.a Substitution of office spaces and of commuting by teleworking 1.5.b Modal shift in freight and in personal transport	Substitute a stock of units with high material use by a functionally equivalent stock of units with a significantly lower material use
2. Slowing	2. Increase lifetime	Before use – Rethink During use – Retain During use – Repair During use – Remanufacture	2.a Digital Product Passport, containing the data necessary for disassembly, test, diagnostics, maintenance, repair, and re-assembly 2.b Design for longevity/durability, reversible dis-assembly, maintenance, repair, re-furbishing, re-use and recycling 2.c Modular design 2.d Availability of spare parts over a long period of time 2.e Re-use components or spare parts from discarded technical systems in new systems or for the maintenance or repair of existing systems 2.f Re-use complete technical systems, e.g. via secondary markets 2.f Refurbish and upgrade technical systems	Longer duration of durable goods or fixed assets in the stock, and hence smaller flow of durable goods per year to sustain that stock
3. Closing	3.1. Increase material efficiency in processes along the lifecycle	Before use - Reduce	[Generally highly process-specific, and purpose of continuous, but confidential, improvement by manufacturers. To be developed in the Best Available Techniques (BAT) reference documents (BREFs) elicited by the revision of the Industrial Emissions Directive (IED 2.0)[14]]	Reduces consumption of new materials in the production of new units feeding the stock
3. Closing	3.2 Increase share of sustainably-sourced biobased materials	Before use - Reduce	3.2.a Use of wood in construction 3.2.b Substitution of fossil-based plastics by biobased plastics	Reduce consumption of (material and energy) resources in the production of new units feeding the stock
3. Closing	3.3 Increase share of secondary materials	Before use – Rethink After use – Recycle After use – Return	3.3.a Ecodesign: reversible assembly processes to enable lossless disassembly at end of life 3.3.b Digital Product Passport with exact nature of the material 3.3.c Limit the number of different materials to facilitate separate high-purity waste streams	Reduce consumption of (material and energy) resources in the production of new units feeding the stock

High-level category of Circular Economy measures	Sub-category of Circular Economy measures	Stage(s) in the product lifecycle when the measure is applied[13]	Examples of possible Circular Economy measures in the category	Impacts on the stock or the flow of durable goods or fixed assets
			3.3.d Increase efficiency of separate waste collection 3.3.e Implement industrial-scale dis-assembly of end-of-life durable goods 3.3.f Minimum recycled content in new products	

<u>Source:</u> Own elaboration, based on European Commission: European Innovation Council and SMEs Executive Agency, Zibell, L., Petsinaris, F., Smit, T., Oomkens, J. et al., Impacts of circular economy on EU climate policies – Mitigation and adaptation, Publications Office of the European Union, 2022, <u>https://data.europa.eu/doi/10.2826/892788</u>

<u>N.B.</u> The examples of Circular Economy measures in each category are provided because they have a potential for technical effectiveness, not because of their political or societal acceptability (which in some cases may be low).

10.2.2. Short definition of degrees of urbanisation

Level 1 of the degree of urbanisation classifies small spatial units as (i) cities or densely populated areas, (ii) towns and semi-dense areas or intermediate density areas and (iii) rural areas or thinly populated areas. This is done using 1 km^2 grid cells, classified according to their population density, population size and contiguity (neighbouring cells). Each small spatial unit belongs exclusively to one of these three classes.

Urban areas consist of cities plus towns and semi-dense areas. Because level 1 of the degree of urbanisation classification was developed to capture the urban-rural continuum, it is recommended to report indicators for all three classes instead of only for the urban-rural dichotomy. This is important because towns and semi-dense areas may differ significantly both from cities and from rural areas. Semi-dense areas in low- and middle-income countries are often described as peri-urban areas. In high-income countries, they are usually described as suburbs. In both cases, these areas have a moderate density and are at the transition between a rural area and a city or town.

10.2.3. Method to compute the figures in Table 6-1. Population in the EU 27 per degree of urbanisation, 2010-2023, millions.

The Table 6-1. Population in the EU 27 per degree of urbanisation, 2010-2023, millions. shows the absolute figures relating to the number of dwellings in the EU located in cities, towns and suburbs, and rural areas, as well as the types of residential buildings (apartment buildings and multi-family homes = flats, single-family homes = houses).

To compile this data, percentages were extracted from the Eurostat database on the distribution of population based on urbanisation and dwelling type. Next, data from the Building Stock Observatory was extracted for the year of 2020. Here, we summed up the total number of residential dwellings that were built before 1945 to now which made up the residential building stock in 2020. These absolute figures were then extrapolated from 2020 to other years based on the Eurostat percentages. Therefore, this table aims to portray the number of dwellings per type, based on annual percentages of the share of the population living in cities, towns and suburbs, and rural areas.

10.2.4. Population change in NUTS3 regions

Table 10-6. Total population change in EU27 NUTS3 regions (Total regions present: 1196)

Year		2018	2019	2020	2021	2022
Total population change in NUTS3 regions	Gain	1 624 517	1 695 641	1 128 354	1 558 673	3 751 881
	Loss	-843 757	-781 569	-1 299 093	-1 886 060	-1 061 850
Number of NUTS3 regions experiencing population changes	Gain	621	626	513	586	807
	Loss	548	543	637	577	356
% of total population gains in NUTS3 regions compared to total EU population		0.36%	0.38%	0.25%	0.35%	0.84%
% of total population losses in NUTS3 regions compared to total EU population		-0.19%	-0.18%	-0.29%	-0.42%	-0.24%
Total average EU27 population (million)		446.655 (e)	447.016 (be)	446.993 (be)	446.249 (bep)	447.404 (bep)

(e) – estimated; (be) – break in time series, estimated; (bep) – break in time series, estimated, provisional; (ep) – estimated, provisional.

Source: Eurostat, 2024. Population change – Demographic balance and crude rates at national level. https://ec.europa.eu/eurostat/databrowser/view/DEMO_GIND__custom_13029331/default/table?lang=en

10.2.5. Data on gross fixed assets of economic sectors related to infrastructure per Member State

Table 10-7 The evolution of total gross assets in the **agricultural** sector in EU27 Member States (excluding Sweden)

Category of Assets	Measure	Number of Member States	Total Gross Assets (2000) (million €)	Total Gross Assets (2021) (million €)	Total Change (2000-2021) (million €)	Relative Change (%)
Other buildings & structures[79]	Losses	11	913 409.9	753 151.1	-160 258.8	-17.6%
	Gains	15	156 483.5	211 591.8	55 108.3	35.2%
Machinery, equipment & weapons	Losses	3	119 507.4	109 775.6	-9 731.8	-8.2%
	Gains	23	259 302.0	379 208.7	119 906.7	46.2%

Source: Eurostat, 2024. Cross-classification of fixed assets by industry and by asset (stock) https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_13206330/default/table?lang=en

As shown in Table 10-7, in the **agriculture** sector, EUR 55.1 bio of "Other buildings and structures" were built in 15 Member States between 2000 and 2021, with no possibility to re-use the EUR 160 bio. that were decommissioned in the 11 other Member States over that same period. Consequently, the inadequate geographic location of the stock of productive assets led to the construction of EUR 55.1 bio. of "Other buildings and structures" in the agriculture sector that could have been entirely spared had the location of these new assets matched that of where they were needed.

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[79] *"Other buildings and structures" refers to all building other than residential.*

Table 10-8 The evolution of total gross assets in the **mining and quarrying** sector in EU27 Member States (excluding Sweden)

Category of Assets	Measure	Number of Member States	Total Gross Assets (2000) (million €)	Total Gross Assets (2021) (million €)	Total Change (2000-2021) (million €)	Relative Change (%)
Other buildings & structures	Losses	9	85 612.9	36 317.6	-49 295.3	-57.6%
	Gains	16	103 044.2	145 750.3	42 706.1	41.4%
Machinery, equipment & weapons	Losses	5	49 683.8	24 423.1	-25 260.7	-50.8%
	Gains	20	61 835.9	91 455.6	29 619.7	47.9%

Source: Eurostat, 2024. Cross-classification of fixed assets by industry and by asset (stock) https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_13206330/default/table?lang=en

As shown in Table 10-8, in the **mining & quarrying sector**, the losses in "Other buildings & structures" (gross) over the 2000-2021 period (EUR 49.3 bio) in 9 Member States exceed the construction of new assets in 16 other Member States (EUR 42.7 bio.). Consequently, the inadequate geographic location of the stock of productive assets led to the construction of EUR 42.7 bio. of "Other buildings and structures" in the mining & quarrying sector over the period 2000-2021 that could have been entirely spared had the location of these new assets matched that of where they were needed.

Similarly, of the EUR 29.6 bio. set up of new "Machinery, equipment & weapons" in the mining & quarrying sector in 20 Member States over the period 2000-2021, EUR 25.3 bio. could have been spared had the location of these new assets matched that of where they were needed, leaving only EUR 4.3 bio. net to be built anew. Consequently, the inadequate geographic location of the stock of productive assets led to the multiplication by a factor of 6.9 of the "Machinery, equipment & weapons" built in the mining & quarrying sector compared to a situation where the productive equipment would be at the location where it is needed.

Table 10-9 The evolution of total gross assets in the **manufacturing** sector in EU27 Member States (excluding Sweden)

Category of Assets	Measure	Number of Member States	Total Gross Assets (2000) (million €)	Total Gross Assets (2021) (million €)	Total Change (2000-2021) (million €)	Relative Change (%)
Other buildings & structures	Losses	7	1 119 947.3	877 152.1	-242 795.2	-21.7%
	Gains	19	520 196.2	815 228.0	295 031.8	56.7%
Machinery, equipment & weapons	Losses	6	826 689.1	799 023.0	-27 666.1	-3.3%
	Gains	19	1 404 501.1	1 907 871.3	503 370.2	35.8%

Source: Eurostat, 2024. Cross-classification of fixed assets by industry and by asset (stock) https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_13206330/default/table?lang=en

As shown in Table 10-9, in the **manufacturing** sector, of the EUR 295 032 bio. construction of new "Other buildings & structures" in 19 Member States over the period 2000-2021, EUR 242 795 bio. could have been spared had the location of these new assets matched that of where they were needed, leaving only EUR 52 237 bio. net to be built anew. Consequently, the inadequate geographic location of the stock of productive assets led to the multiplication by a factor of 5.6 of the "Other buildings & structures" built in the manufacturing sector compared to a situation where the productive equipment would be at the location where it is needed.

In the four sectors related to **infrastructure**, namely (1) electricity, gas, steam and air conditioning supply, (2) transportation and storage, (3) transportation and storage and (4) information and communication, the build-up of fixed assets (as shown in the tables below) has been considerable across most Member States, with diminutions of gross assets in some Member States remaining quantitatively far below the build-up of new assets. In the cases of these four sectors, the geographic location of the stock of assets does not seem to have played any meaningful role in the usage of resources needed to build up the infrastructure: even if all the infrastructure made redundant in some Member States had been available for re-use in the other Member States with a net increase in their assets, the reduction in the resource use would have remained very limited.

Table 10-10 The evolution of total gross assets in the **electricity, gas, steam and air conditioning supply** sector in EU27 Member States (excluding Malta and Sweden)

Category of Assets	Measure	Number of Member States	Total Gross Assets (2000) (million €)	Total Gross Assets (2021) (million €)	Total Change (2000-2021) (million €)	Relative Change (%)
Other buildings & structures	Losses	2	70 721.80	67 920.9	-2 800.90	-3.96%
	Gains	23	899 088.80	1 354 737.5	455 648.70	50.7%
Machinery, equipment & weapons	Losses	4	179 463.8	175 080.4	-4 383.4	-2.4%
	Gains	21	253 719.3	479 539.1	225 819.8	89%

Source: Eurostat, 2024. Cross-classification of fixed assets by industry and by asset (stock) https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_13206330/default/table?lang=en

Table 10-11 The evolution of total gross assets in the **water supply; sewerage, waste management and remediation activities** sector in EU27 Member States (excluding Sweden)

Category of Assets	Measure	Number of Member States	Total Gross Assets (2000) (million €)	Total Gross Assets (2021) (million €)	Total Change (2000-2021) (million €)	Relative Change (%)
Other buildings & structures	Losses	2	18 174.8	17 659.8	-515.0	-2.8%
	Gains	24	832 987.5	989 211	156 223.5	18.75%
Machinery, equipment & weapons	Losses	None				
	Gains	26	114,682.10	198,407.30	83,725.20	73.01%

Source: Eurostat, 2024. Cross-classification of fixed assets by industry and by asset (stock) https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_13206330/default/table?lang=en

Table 10-12 The evolution of total gross assets in the **transportation and storage** sector in EU27 Member States (excluding Sweden)

Category of Assets	Measure	Number of Member States	Total Gross Assets (2000) (million €)	Total Gross Assets (2021) (million €)	Total Change (2000-2021) (million €)	Relative Change (%)
Other buildings & structures	Losses	1	29 049	27 254	-1 795	-6.18%
	Gains	25	1 677 864.80	2 398 963.30	721 098.50	42.98%
Machinery, equipment & weapons	Losses	4	82 505.10	71 678.80	-10 826.30	-13.12%
	Gains	22	736 243.70	1 229 125.90	492 882.20	66.9%

Source: Eurostat, 2024. Cross-classification of fixed assets by industry and by asset (stock) https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_13206330/default/table?lang=en

Table 10-13 The evolution of total gross assets in the **information and communication** sector in EU27 Member States (excluding Sweden)

Category of Assets	Measure	Number of Member States	Total Gross Assets (2000) (million €)	Total Gross Assets (2021) (million €)	Total Change (2000-2021) (million €)	Relative Change (%)
Other buildings & structures	Losses	3	182 450.90	136 755.60	-45 695.30	-25%
	Gains	23	319 622.30	465 355.10	145 732.80	45.6%
Machinery, equipment & weapons	Losses	4	36 957.80	32 412.70	-4 545.10	-12.3%
	Gains	22	232 489.60	436 129.10	203 639.50	87.6%

Source: Eurostat, 2024. Cross-classification of fixed assets by industry and by asset (stock) https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_13206330/default/table?lang=en

10.2.6. Method to compute the total net assets of sectors

Eurostat data on the fixed assets of manufacturing sectors is available in a small number of Member States only. In order to estimate this figure for the whole EU27, we extrapolated from the value added of these EU Member States in these sectors, and proceeded as follows:

- We identified the EU27 Member States in which the data was available for both the net fixed assets and the value added for the sector;
- We totalled the net fixed assets and the value added for these Member States;
- We **assumed** that the ratio of the net fixed assets to the annual value added was identical in the sub-set of Member States where the data was available and in the whole EU27;
- We multiplied the value added for the sector at the scale of the EU27 by that ratio as computed for the Member States where the data is available to estimate the net fixed assets at the scale of the whole EU27.

Table 10-14 The total (net) fixed assets and value added at factor cost (both in million euros) per Member State: **Manufacture of coke and refined petroleum products** in 2019 (using available data)

EU27 Member State	Total (net) fixed assets (in million euro)	Value added at factor cost (in million euro)
Austria	1 458.3	1 223.6
Belgium	4 288.3	2 257.4
France	4 255.0	2 346.2
Greece	2 817.6	1 580.9
Italy	29 341.9	1 707.8
Luxembourg	0	0
Netherlands	7 651.5	1 544.2
Sweden	1 917.6	701.3
Total value for Member States where assets and value added are both available	58 394.8	11 361.4
Total for EU27	168 331.6 (e)	32 750.9

Source: Eurostat, 2024, Cross-classification of fixed assets by industry and by asset (stocks). https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_12980834/default/table?lang=en and Eurostat, 2024. Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E) (2005-2020). https://ec.europa.eu/eurostat/databrowser/view/sbs_na_ind_r2__custom_13273764/default/table?lang=en *(e) – Own estimate, as described above*

Table 10-15. The total (net) fixed assets and value added at factor cost (both in million euros) per Member State: **Manufacturing of chemicals and chemical products** in 2019 (using available data).

EU27 Member State	Total (net) fixed assets (in million euros)	Value added at factor cost (in million euros)
Belgium	16 418.4	7 890.4
Czechia	3 920.1	1 744.6
Denmark	4 856.3	3 169.1
Greece	789.5	676.3
France	30 307.4	24 944.1
Italy	30 098.9	12 743.2
Latvia	195.6	71.6
Luxembourg	408.2	85.9
Netherlands	38 929.7	9 484.9
Austria	6 425.8	2 637.6
Slovakia	2848.7	337.5
Finland	4 774.8	2 391.2
Total value for Member States where assets and value added are both available	138 580.1	66 176.4
Total for EU27	308 007.6 (e)	147 083.4

(e) – Own estimate, as described above

<u>Source:</u> Eurostat, 2024, Cross-classification of fixed assets by industry and by asset (stocks) . <u>https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_12980834/default/table?lang=en</u> and Eurostat, 2024. Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E) (2005-2020). <u>https://ec.europa.eu/eurostat/databrowser/view/sbs_na_ind_r2__custom_13273764/default/table?lang=en</u>

Table 10-16. The total (net) fixed assets and value added at factor cost (both in million euros) per Member State: **Manufacture of other non-metallic mineral products** in 2019 (using available data).

EU27 Member State	Total (net) fixed assets (in million euros)	Value added at factor cost (in million euros)
Czechia	4 108.2	2 181.2
Denmark	2 407.3	1 490.3
Greece	983.1	633.0
Latvia	763.4	228.8
Austria	7 104.9	2 895.1
Slovakia	3 144.5	606.9
Finland	1 835.4	1 089.2
Sweden	2 820.2	1 597.5
Total value for Member States where assets and value added are both available	23 167.0	10 722.0
Total for EU27	157 001.3 (e)	72 662.3

(e) – Own estimate, as described above

<u>Source:</u> Eurostat, 2024, Cross-classification of fixed assets by industry and by asset (stocks) . <u>https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_12980834/default/table?lang=en</u> and Eurostat, 2024. Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E) (2005-2020). <u>https://ec.europa.eu/eurostat/databrowser/view/sbs_na_ind_r2__custom_13273764/default/table?lang=en</u>

Table 10-17. The total (net) fixed assets and value added at factor cost (both in million euros) per Member State: **Manufacture of basic metals** in 2019 (using available data)

EU27 Member State	Total (net) fixed assets (in million euros)	Value added at factor cost (in million euros)
Czechia	3 199.5	1 231.9
Denmark	839.0	443.4
Greece	1 405.1	789.8
Latvia	360.3	32.7
Austria	9 485.5	4 851.5
Slovakia	4 352.4	570.6
Finland	4 129.6	1 215.8
Sweden	7 630.3	4 219.7
Total value for Member States where assets and value added are both available	31 401.7	13 355.4
Total for EU27	169 574.9(e)	72 121.6*

(*) 2018 value

(e) – Own estimate, as described above

Source: Eurostat, 2024, Cross-classification of fixed assets by industry and by asset (stocks) . https://ec.europa.eu/eurostat/databrowser/view/nama_10_nfa_st__custom_12980834/default/table?lang=en and Eurostat, 2024. Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E) (2005-2020). https://ec.europa.eu/eurostat/databrowser/view/sbs_na_ind_r2__custom_13273764/default/table?lang=en

10.2.7. Additional figures on social norms of ownership

Table 10-18 The useful floor area of primary residential homes in the EU27 based on 2008 a study by Enerdata and 2020 'Building Stock Observatory' data and useful floor area per person.

Year	2008	2020	Absolute change	Relative change
Primary residential floor area (Mm^2)	15,786	17,183 *(e)*	1,397	8.85%
EU27 population (million)	439.771	446.993	7.221	1.64%
Useful floor area per person (m^2/person)	35.9	38.44	2.55	7.09%

Note: (e) – estimated value based on total surface area of residential buildings in primary use based on 2020 BSO data.

Sources: Residential primary residential floor area 2008: Enerdata. Entranze study https://entranze.enerdata.net/average-floor-area-per-capita.html

Residential primary residential floor area 2020: European Commission. EU Building Stock Observatory. Building Stock: Useful floor area per building occupancy. https://building-stock-observatory.energy.ec.europa.eu/database

EU Population: Source: Eurostat, 2024. Population change – Demographic balance and crude rates at national level. https://ec.europa.eu/eurostat/databrowser/view/DEMO_GIND__custom_13029331/default/table?lang=en

Table 10-19 The average number of cars per household in the EU 27 based on total number of cars and households

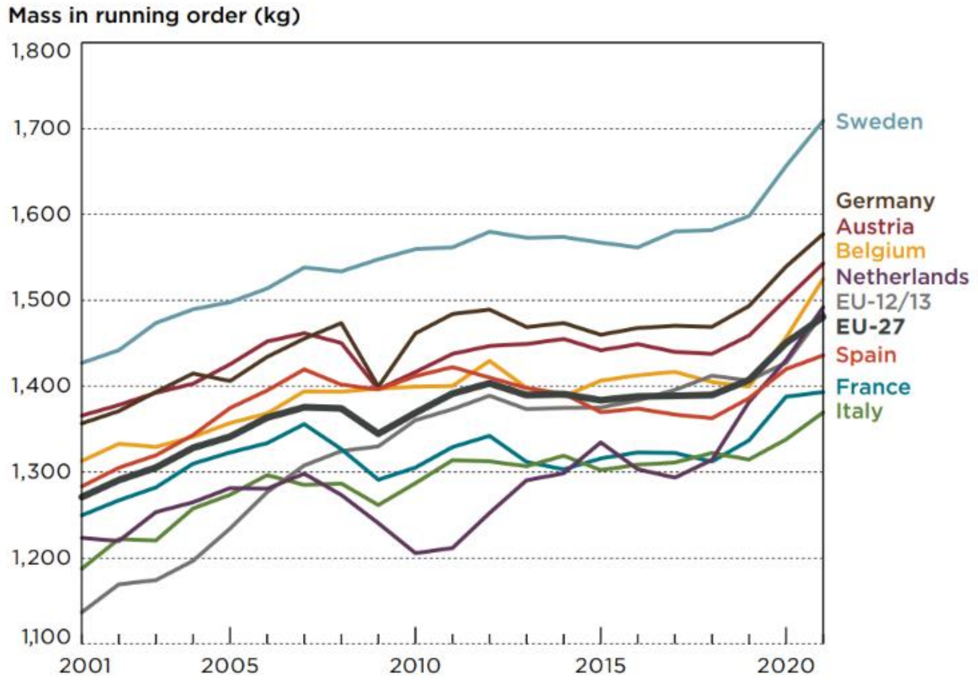
Year	2016	2017	2018	2019	2020	2021	2022
Total number of passenger cars in EU27 (millions)	231.377	236.047	240.409	244.850	247.656	250.246	252.612

Year	2016	2017	2018	2019	2020	2021	2022
Total number of households in EU27 (millions)	191.610	192.843	193.968	195.382	195.728	196.268	198.555
Average number of cars per household	≈1.21	≈1,22	≈1.24	≈1.25	≈1.27	≈1.27	≈1.27

Source: Eurostat, 2024. Passenger cars by age.
https://ec.europa.eu/eurostat/databrowser/view/road_eqs_carage__custom_10409047/default/table?lang=en

Eurostat, 2024 Number of households by household composition, number of children and age of youngest child (1 000).
https://ec.europa.eu/eurostat/databrowser/view/lfst_hhnhtych__custom_13046299/default/table?lang=en

Figure 10-5. Mass of new sold cars per EU Member State, 2001 - 2021



Source: ICCT (2022). European Vehicle Market Statistics. Pocketbook 2022/23. https://theicct.org/wp-content/uploads/2023/01/Pocketbook_2022_23_Web_corrections-v1_VS.pdf

10.2.8. Eurostat data on the usage of secondary materials in the EU27 economy

Table 10-20 Circular Materials Use Rate per material over time in the EU27

Material/Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Biomass	8.8	8.3	9.2	9.3	9.1	9.4	9.2	9.3	9.4	10.0
Metal ores (gross ores)	23.5	25	22.3	21.8	22.8	22.4	22.8	23.3	23.4	23.9
Non-metallic minerals	15.0	14.8	14.6	14.8	15	14.8	14	13.7	13.8	13.7
Fossil energy materials/carriers	2.3	2.5	2.4	2.5	2.5	2.6	2.8	3.2	3.2	3.2
Total	11.2	11.1	11.2	11.4	11.5	11.6	11.3	11.6	11.4	11.5

Source: Eurostat, 2023. Circular Material Use Rate.
https://ec.europa.eu/eurostat/databrowser/view/env_ac_curm__custom_13081545/default/table?lang=en

Table 10-21. Contribution of recycled materials to raw materials demand (in percentages) in four different time periods in the EU

Material / Year	2013	2016	2019	2022
Aluminium	35%	12.4%	12.3%	32%
Copper	20%	55%	16.9%	55%
Iron	22%	24%	31.5%	31%
Lead	:	75%	75%	83%
Nickel	32%	33.9%	17%	16%
Zinc	8%	30.8%	31%	34%

Note: (:) – Not available

Source: Eurostat, 2023. Contribution of recycled materials to raw materials demand - end-of-life recycling input rates (EOL-RIR). https://ec.europa.eu/eurostat/databrowser/view/cei_srm010/default/table?lang=en&category=cei.cei_srm

10.3. Annex C. Supplementary materials and methods supporting section "Material stocks: Barriers to and opportunities for circularity in the construction and batteries sectors"

10.3.1. Established policy measures in the construction sector

The European Union has adopted several legislative as well as non-legislative measures to support the Circular Economy in the construction sector. Three concrete policy measures, which partially overlap in regards to their ambitions, are outlined below.

Construction Products Regulation (CPR)

The revised Construction Products Regulation (CPR) establishes uniform rules for marketing construction products within the EU, establishing uniform product requirements bearing on safety, functionality and environmental impacts, providing a standardized technical language to assess product performance and ensuring reliable information for comparing products across manufacturers and countries. It was signed by the Presidents of the European Parliament and of the Council of the European Union on 27 November 2024, paving the way for its publication in the Official Journal of the EU.

It is a framework legislation that does not regulate products directly, but empowers the Commission, in consultation with Member States, to regulate individual products via Delegated Acts that rely on harmonized technical specifications.

The regulation emphasizes the sustainable use of natural resources in construction works, highlighting key aspects relevant to the circular economy. It outlines that construction works and their components must be designed, constructed, used, maintained, and deconstructed in a way that ensures the sustainable use of resources throughout their lifecycle. This includes: [80]

- Maximization of the resource efficient use of raw and secondary materials
- Minimization of the overall amount of raw materials used

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[80] European Parliament, 2024. European Parliament legislative resolution of 10 April 2024 on the proposal for a regulation of the European Parliament and of the Council laying down harmonized conditions for the marketing of construction products, Annex I(8), p.252. Available at https://www.europarl.europa.eu/doceo/document/TC1-COD-2022-0094_EN.pdf.

- Minimization of the overall amount of embodied energy
- Minimization of the waste generated
- Minimization of the overall use of drinking and service water
- Maximization of the reuse or recyclability of the construction works, in part or in whole, and of their materials after deconstruction or demolition
- Ease of deconstruction

The Regulation sets requirements on the information transmitted to the customer on the product, ensuring that this information is reliable and comparable across the EU, and that the product can be used in a material-efficient way. Furthermore, it requires a performance level in regards to functionality, safety, and the environment.

An important element of the CPR related to the circular economy is the redefined "environmental essential characteristics" listed in its Annex II. Harmonized technical specifications and European assessment documents now need to cover a list of predetermined environmental characteristics related to the life cycle assessment of construction products. This includes climate change effects related to fossil energy carriers, biogenic material, and land use, ozone depletion, acidification potential, eutrophication, photochemical ozone, abiotic depletion (minerals, metals, fossil fuels), water use, particulate matter, ionizing radiation, ecological as well as human toxicity, and land use-related impacts.[81] These specifications also address, where possible, the capacity of products to temporarily bind carbon and other forms of carbon removal, contributing to the broader goal of reducing environmental impact. These characteristics shall be included in the declaration of conformity of the products (Art.15(2) and 15(3)).

The regulation further lists in its Annex III, §3.1, a list of possible product environmental requirements which encompasses the entire lifecycle of a product, including the extraction and processing of raw materials, product manufacturing, transportation of materials and finished products, maintenance during use, its ability to sustain a role within a circular economy for as long as possible, and its end-of-life management. Harmonized technical specifications, established through delegated acts as outlined in Article 7(1), may define requirements for products to be designed, manufactured, and packaged in a manner that addresses one or more of the following inherent environmental aspects across the product's lifecycle. These requirements should be implemented wherever feasible, provided they do not compromise safety, avoid causing greater negative environmental impacts, and are not already regulated by other Union legislation[82]: The requirements are as follows:

- Maximizing durability and reliability of the product or its components
- Minimizing life-cycle greenhouse gas emissions
- Maximizing reused, recycled and by-product content
- Selection of safe, sustainable-by-design, environmentally benign substances
- Resource efficiency

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[81] European Parliament, 2024. European Parliament legislative resolution of 10 April 2024 on the proposal for a regulation of the European Parliament and of the Council laying down harmonized conditions for the marketing of construction products, Annex II, p.254; Available at https://www.europarl.europa.eu/doceo/document/TC1-COD-2022-0094_EN.pdf

[82] European Parliament, 2024. European Parliament legislative resolution of 10 April 2024 on the proposal for a regulation of the European Parliament and of the Council laying down harmonized conditions for the marketing of construction products, Annex III(3), p.261. Available at https://www.europarl.europa.eu/doceo/document/TC1-COD-2022-0094_EN.pdf.

- Modularity and identification of product/component reusability after deinstallation
- Upgradability
- Ease of reparability during the expected life span including compatibility with commonly available spare parts
- Ease of maintenance and refurbishment during the expected life span
- Recyclability and the capability to be remanufactured
- Separability and recoverability during dismantling or recycling procedures
- Sustainable sourcing
- Minimizing packaging and amounts of waste generated, notably hazardous waste

The product environmental requirements in the list are not mandatory: they may (but are not mandated to) be included in the “harmonized technical specification” for a given product, as per the Delegated Act relevant for that product. However, once included in the corresponding Delegated Act bearing on a given product, they become mandatory for that product (and must be explicitly addressed in the product’s declaration of conformity).

The information required by the Regulation to be provided to the customer contains instructions to enhance the circular use of the product, and specifically on maintenance needs with an emphasis on maintaining the performance of the product during its service life span, as described in Annex IV, §2.3. Furthermore, as listed in Annex IV, §2.7, recommendations should be given for a product’s repair, deinstallation, reuse, remanufacturing, recycling, and safe deposit. Where applicable, information on the performance of the product as measured in terms of its climate change effects – total and human toxicity, cancer, as referred to in Annex II should be provided.[83]

EU Construction and Demolition Waste Protocol and Guidelines

The EU Construction and Demolition Waste Protocol and Guidelines provides a non-binding framework to enhance the management and recycling of construction and demolition (C&D) waste across the EU. As the largest waste stream by volume, C&D waste is a key focus of the European Commission's Circular Economy Package, Construction 2020 strategy, and the Resource Efficiency Opportunities in the Building Sector initiative. The protocol promotes better waste identification, separation, logistics, and processing, along with robust quality management and supportive policies. It targets construction professionals, public authorities, certification bodies, and clients of recycled materials, fostering resource efficiency across the EU.

C&D waste streams, as listed by the Commission Decision on the European List of Waste (Commission Decision 2000/532/EC76), include non-metallic mineral waste from concrete, bricks, tiles, ceramics, gypsum-based construction materials, and glass, various metals (iron/steel, aluminum, copper, bronze, brass, lead, zinc, tin, and mixed metals), as well as wood, plastic, bituminous mixtures, insulation materials and asbestos-containing construction materials, and lastly, other construction and demolition wastes containing mercury, printed circuit boards (PCB) and other hazardous substances.[84]

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[83] European Parliament, 2024. European Parliament legislative resolution of 10 April 2024 on the proposal for a regulation of the European Parliament and of the Council laying down harmonized conditions for the marketing of construction products, Annex IV(2.8), p.269. Available at https://www.europarl.europa.eu/doceo/document/TC1-COD-2022-0094_EN.pdf.

[84] European Commission, 2016. EU Construction and Demolition Waste Management Protocol, Annex B, p. 34. Available at https://ec.europa.eu/docsroom/documents/20509/

In §4 a wide range of waste processing and treatment options is described. These are commonly known as preparation for re-use, recycling and material and energy recovery in that order of priority.

Circular Economy - Principles for Building Design

The Circular Economy - Principles for Building Design provides guidance to reduce resource use and to promote the reuse and recycling of materials. The principles focus on three key objectives: durability, adaptability, and reducing waste and facilitating high quality waste management. These guidelines, described below, were developed through collaboration with stakeholders and aim to inform actors across the construction value chain, offering tools to optimize material use, reduce environmental impacts, and support resource efficiency throughout a building's life cycle.

Durability

- Request, update, and share information on products, materials, and designs to ensure relevance throughout the building's life cycle
- Performance-based incentives: promote optimal use and durability through contracts tied to building performance
- Circular business models and guidelines for fittings (e.g., carpets, kitchens) focusing on selection, maintenance, and disposal
- Durable construction techniques and materials that enhance building and material resilience
- Life Cycle Costing (LCC) and environmental assessments to evaluate durability and long-term benefits in investment decisions
- Design and assessment of buildings and products with durability in mind

Adaptability

- Tools to minimize financial costs while supporting maintenance, adaptations, repairs, and monitoring of buildings
- Digital tools (BIM, building passports) to guide maintenance, adaptation, and efficient use of building systems and products
- Provision of detailed guides for building owners and facility managers to support maintenance and adaptations
- As-built documents and logbooks: document changes during the building's use, including reusable materials, to facilitate future adaptations
- Design buildings with flexibility to accommodate changing purposes/requirements
- Resilience and adaptation planning: Incorporate considerations for climate change, functional adaptability, and shorter renovation cycles into designs
- Pre-construction or demolition assessments to evaluate adaptability potential
- Adaptive construction techniques that allow for different levels of reversibility to address maintenance, repair, and transformation needs effectively

Reducing waste and facilitating high quality waste management

- Materials and building passports to document material use, installation, and recovery potential, ensuring traceability throughout the lifecycle
- Regional recycling infrastructure: develop local loops with facilities for sorting and recycling construction waste; incentives like subsidies for recycled materials

- Pre-deconstruction audits to identify resources, assess recovery options, and guide selective deconstruction using tools like BIM and materials passports

10.3.2. Circular Economy legislation applicable to the batteries sector

The Table 10-22 below lists the legislative and non-legislative measures adopted in the EU27 to support the Circular Economy in the batteries sector.

Table 10-22: Overview of circular economy measures applicable to the batteries sector

Measure	Brief description	Update
Batteries Regulation[85]	Comprehensive legal framework to ensure that batteries in Europe are collected, reused, and recycled. It aims to reduce the carbon footprint of batteries, minimize harmful substances, limit dependence on raw materials from non-EU countries, and promote high levels of recycling.	Entered into force as of 17 August 2023.
Regulation on the rules on calculating recycling efficiencies of the recycling processes of waste batteries and accumulators[86]	Regulation establishing rules for recycling waste batteries and accumulators. It specifies methods for calculating the recycling efficiency of processes for waste lead-acid, nickel-cadmium, and other batteries and accumulators.	

Batteries Regulation

The new EU Batteries Regulation ensures batteries are collected, reused, and recycled to reduce environmental impacts and support a circular economy. By limiting harmful substances, reducing reliance on non-EU raw materials, and promoting high recycling rates, it aligns with the European Green Deal and the goal of climate neutrality by 2050. This regulation adopts a full life-cycle approach, addressing sourcing, manufacturing, usage, and recycling. Starting in 2025, it introduces carbon footprint declarations, performance classes, and recycling targets for electric vehicles, light transport (e-bikes, scooters), and industrial batteries. By 2027, portable batteries must be removable and replaceable to extend product lifespans and reduce waste. Key measures include stricter recycling targets for critical materials like cobalt and lithium, QR-code-enabled digital passports for transparency, and due diligence requirements to address environmental and social risks in raw material sourcing.

The regulation responds to the rapid growth in battery demand, driven by transport electrification, and builds on the European Battery Alliance's efforts to establish a sustainable, competitive battery value chain. Implementation across Member States and secondary legislation will follow, replacing the 2006 Batteries Directive with modernized, ambitious standards. It entered into force on 17 August 2023.[87]

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[85] European Commission, 2023. Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/E, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02023R1542-20240718

[86] European Commission, 2012. Commission Regulation (EU) No 493/2012 of 11 June 2012 laying down, pursuant to Directive 2006/66/EC of the European Parliament and of the Council, detailed rules regarding the calculation of recycling efficiencies of the recycling processes of waste batteries and accumulators Text with EEA relevance, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012R0493

[87] *European Commission, 2023. Circular economy: New law on more sustainable, circular and safe batteries enters into force, available at https://environment.ec.europa.eu/news/new-law-more-sustainable-circular-and-safe-batteries-enters-force-2023-08-17_en*

Environmental requirements

Some specific environmental requirements placed on batteries have been listed in **Art. 8** on the **recycled content** in industrial batteries, electric vehicle batteries, Light Means of Transport (LMT) batteries and Starting, Lighting & Ignition (SLI) batteries. From 18 August 2028, industrial batteries (>2 kWh), electric vehicle batteries, and SLI batteries must include documentation specifying the percentage of cobalt, lithium, nickel, and lead recovered from waste for each model and manufacturing plant. This also applies to LMT batteries from 18 August 2033. The minimum percentage share of, respectively, cobalt, lithium or nickel that has been recovered from battery manufacturing waste or post-consumer waste, and the minimum percentage share of lead that is present in the battery and that has been recovered from waste, for each battery model per year and per manufacturing plant is as follows:

- By 18 August 2031: Batteries must include a recycled content of at least 16% for cobalt, 85% for lead, 6% for lithium, and 6% for nickel.
- By 18 August 2036: The minimum recycled content increases to 26% cobalt, 85% lead, 12% lithium, and 15% nickel.

Furthermore, **Art. 9** and **Art. 10** describe **performance and durability requirements**. **Art. 9** specifically focusses on the requirements for portable batteries of general use, namely from 18 August 2028, portable batteries (excluding button cells) must meet minimum electrochemical performance and durability standards as specified in Annex III. The parameters can be found below. Note that the minimum quantitative values for each of the parameters are still under development.

- *Parameters for non-rechargeable batteries*
    - Minimum average duration: minimum average time reached by a sample of batteries on discharge when used under specific conditions, such as temperature and relative humidity.
    - Delayed discharge performance: the relative decrease of the minimum average duration, with the initially measured minimum average duration as the reference point, after a defined period and under specific conditions, such as temperature and relative humidity.
    - Resistance to leakage: resistance to unplanned escape of electrolyte, gas or other material.
- *Parameters for rechargeable batteries*
    - Rated capacity: the capacity value of a battery, under specific conditions, such as temperature and relative humidity, and declared by the manufacturer
    - Charge (capacity) retention: the capacity that a battery can deliver after storage, under specific conditions, such as temperature and relative humidity, for a specific time, without a subsequent recharge and expressed as a percentage of the rated capacity;
    - Charge (capacity) recovery: the capacity that a battery can deliver with a subsequent recharge after storage, under specific conditions, such as temperature and relative humidity, for a specific time and expressed as percentage of the rated capacity.

  - Endurance in cycles the number of charge and discharge cycles a battery can perform under specific conditions, such as temperature and relative humidity, before the capacity drops below a specified fraction of the rated capacity.
  - Resistance to leakage: resistance to unplanned escape of electrolyte, gas or other material.

Art. 10 focuses specifically on the requirements for rechargeable industrial batteries, LMT batteries, and electric vehicle batteries. From 18 August 2024, rechargeable industrial batteries (>2 kWh), LMT batteries, and electric vehicle batteries must include documentation detailing the electrochemical performance and durability values specified in Part A of Annex IV. Starting from 18 August 2027, rechargeable industrial batteries with a capacity greater than 2 kWh, excluding those with external storage, must comply with the established minimum performance and durability values. Similarly, from 18 August 2028, LMT batteries are required to meet comparable minimum standards. The requirements listed in Annex IV are as follows:

- Rated capacity (in Ah) and capacity fade (in %).
- Power (in W) and power fade (in %).
- Internal resistance (in Ω) and internal resistance increase (in %).
- Where applicable, energy round trip efficiency and its fade (in %).
- The expected lifetime of the battery under the reference conditions for which it has been designed, in terms of cycles, except for non-cycle applications, and calendar years.

Art. 11 describes the **removability and replaceability** of portable batteries and LMT batteries. Note that the guidelines foreseen in the regulation are still under development. It stipulates that products incorporating portable batteries must ensure the batteries are easily removable and replaceable by end-users, using commercially available tools, without requiring specialized or proprietary tools. However, there are some exceptions. Products designed for environments exposed to water, such as washable or rinseable appliances, and certain medical devices, may have batteries that are only removable by professionals. Furthermore, the requirement does not apply to products where a permanent connection is necessary for power supply or data integrity reasons.

LMT batteries must also be removable and replaceable by an independent professional during the product's lifetime, and these batteries must be available as spare parts for at least five years after the product is placed on the market, at a reasonable price. Software must not prevent the replacement of batteries with compatible alternatives.

Information requirements

Besides environmental requirements, information requirements have been listed in, among others, **Art. 7**. It states that electric vehicle batteries, rechargeable industrial batteries (>2 kWh), and LMT batteries must include a **carbon footprint** declaration for each battery model per manufacturing plant, which includes administrative details, battery information, geographic location, carbon footprint values, and a public link to the supporting study. These declarations will be required starting from 18 February 2025 for electric vehicle batteries, 18 February 2026 for industrial batteries (excluding those with external storage), and 18 August 2028 for LMT batteries. Annex II outlines the methodology for calculating the carbon footprint of batteries, based on the Commission's Product

Environmental Footprint (PEF) method and life cycle assessment standards. The calculation will consider materials, energy, and auxiliary materials used in manufacturing, with a focus on electronic components and cathode materials.

By 2030, the Commission will assess whether these requirements should be extended to portable batteries and rechargeable industrial batteries (<2 kWh). The regulations do not apply to batteries that have been reused, repurposed, or remanufactured after being placed on the market.

Art. 13 describes the **labelling and marking** of batteries. From 18 August 2026, batteries will require labels with general information including:

- information identifying the manufacturer in accordance with Article 38(7);
- the battery category and information identifying the battery in accordance with Article 38(6);
- the place of manufacture (geographical location of a battery manufacturing plant);
- the date of manufacture (month and year);
- the weight;
- the capacity;
- the chemistry;
- the hazardous substances present in the battery, other than mercury, cadmium or lead;
- usable extinguishing agent;
- critical raw materials present in the battery in a concentration of more than 0,1 % weight by weight.

Rechargeable portable batteries, LMT batteries and SLI batteries will also need to bear a label containing information on their capacity and non-rechargeable batteries will need to indicate their minimum duration and a "non-rechargeable" label. All batteries will bear the "separate collection symbol" from 18 August 2025, with size specifications. From 18 February 2027, a QR code will be required for accessing additional information, including battery passports and conformity declarations. Batteries that have been subject to preparation for re-use, preparation for repurposing, repurposing or remanufacturing shall bear new labels or shall be marked with markings in accordance with **Art. 13**.

Declaration of conformity

The EU Declaration of Conformity as described in **Art. 18** certifies that a battery complies with the requirements outlined in Articles 6 to 10, 12, 13, and 14. If a battery is subject to multiple EU acts requiring a declaration of conformity, a single declaration should be issued to cover all applicable acts, clearly referencing them. By issuing this declaration, the manufacturer assumes full responsibility for ensuring the battery meets the regulatory requirements.

Requirements for the management of waste batteries

Requirements for the management of waste batteries include **extended producer responsibility (EPR)**, as outlined in **Art. 56**. It states that producers are responsible for the EPR of batteries they introduce to the market for the first time within a Member State, in line with the EU Waste Directive. This responsibility also extends to batteries resulting from re-use, repurposing, or remanufacturing operations.

Art. 59 to 61 describes that producers of portable, LMT, SLI, industrial, and electric vehicle batteries, or their designated producer responsibility organizations (PROs), are required to implement comprehensive **waste battery collection** systems that ensure the separate collection of all waste batteries regardless of type, composition, condition, or brand. For portable and LMT batteries, specific targets have been set:

- Waste Portable Batteries
    - 45% collection rate by 31 December 2023.
    - 63% collection rate by 31 December 2027.
    - 73% collection rate by 31 December 2030.
- Waste LMT Batteries
    - 51% collection rate by 31 December 2028.
    - 61% collection rate by 31 December 2031.

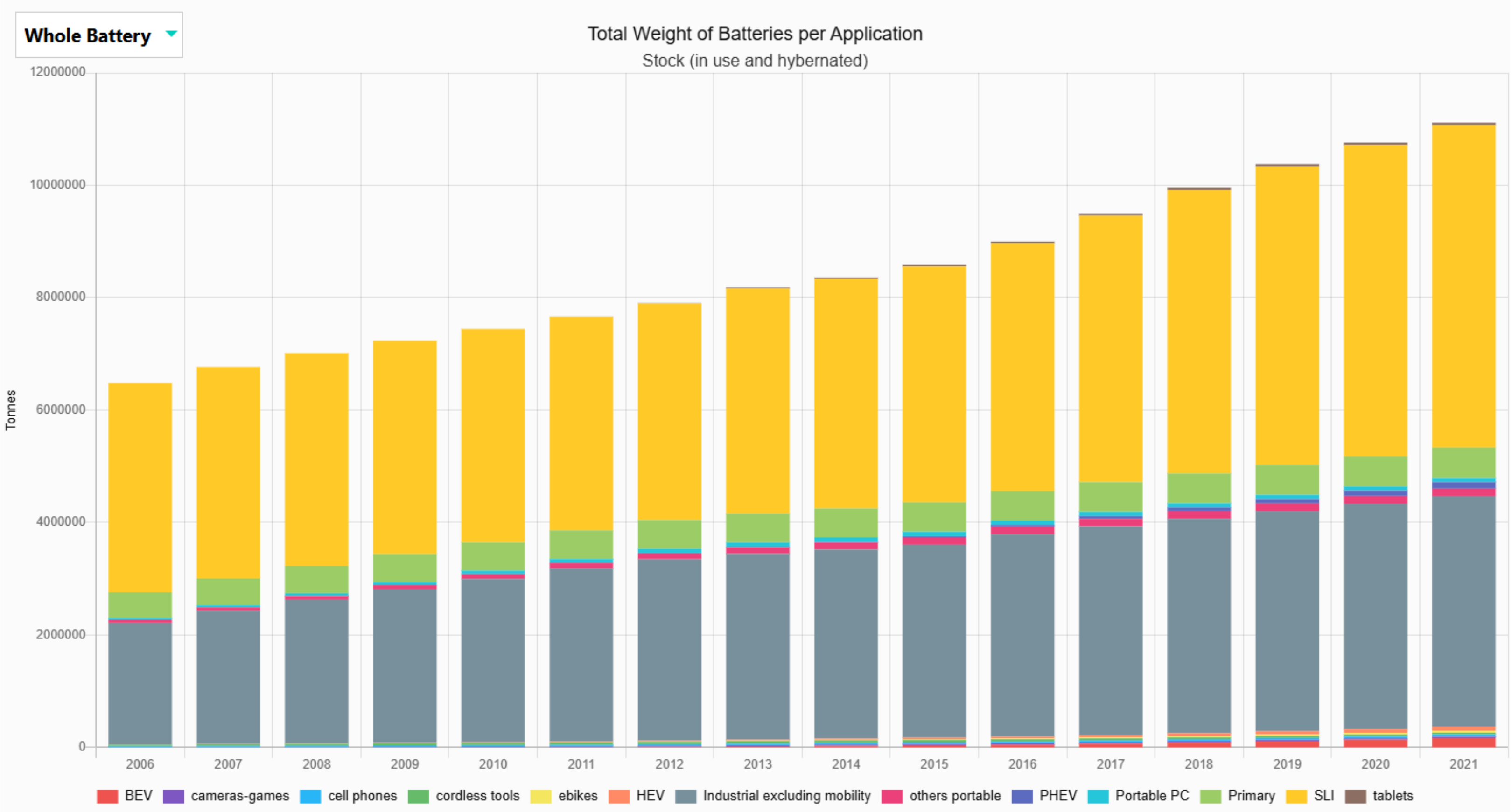
According to **Art. 71**, each permitted facility must ensure that all waste batteries received are accepted and processed for re-use, repurposing, or recycling. Recyclers must meet the **recycling efficiency and material recovery** targets specified in Parts B and C of Annex XII. These targets are as follows:

1. Targets for recycling efficiency (no later than 31 December 2025)
    - recycling of 75 % by average weight of lead-acid batteries;
    - recycling of 65 % by average weight of lithium-based batteries;
    - recycling of 80 % by average weight of nickel-cadmium batteries;
    - recycling of 50 % by average weight of other waste batteries.
2. Targets for recycling efficiency (no later than 31 December 2030)
    - recycling of 80 % by average weight of lead-acid batteries;
    - recycling of 70 % by average weight of lithium-based batteries.

1. Targets for recovery of materials (no later than 31 December 2027)
    - 90 % for cobalt;
    - 90 % for copper;
    - 90 % for lead;
    - 50 % for lithium;
    - 90 % for nickel.
2. Targets for recovery of materials (no later than 31 December 2031)
    - 95 % for cobalt;
    - 95 % for copper;
    - 95 % for lead;
    - 80 % for lithium;
    - 95 % for nickel.

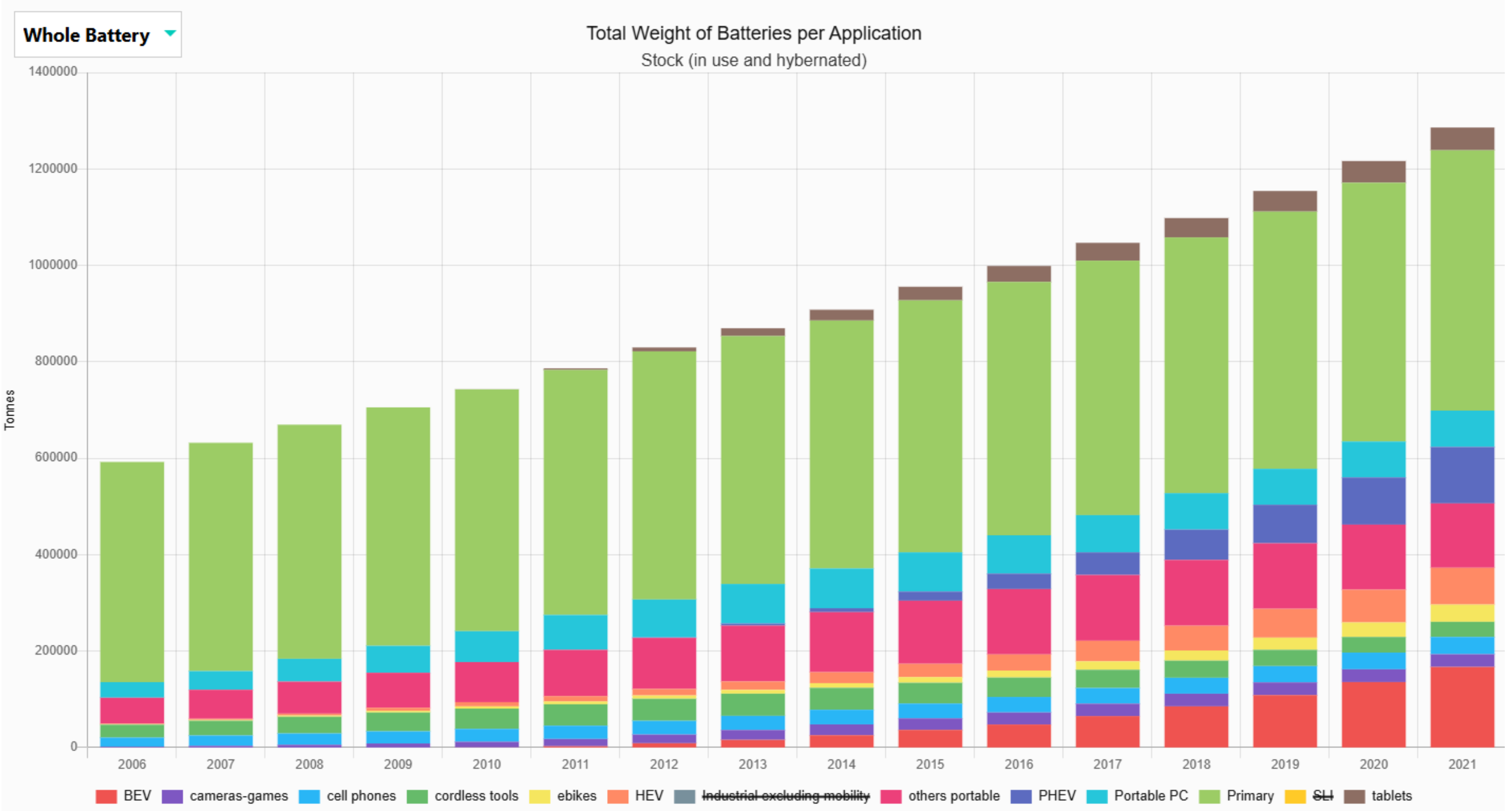
10.3.3. Evolution of the stock of batteries over time 2006-2021 – graphs

Figure 10-6 Total mass of batteries in stock, for all applications



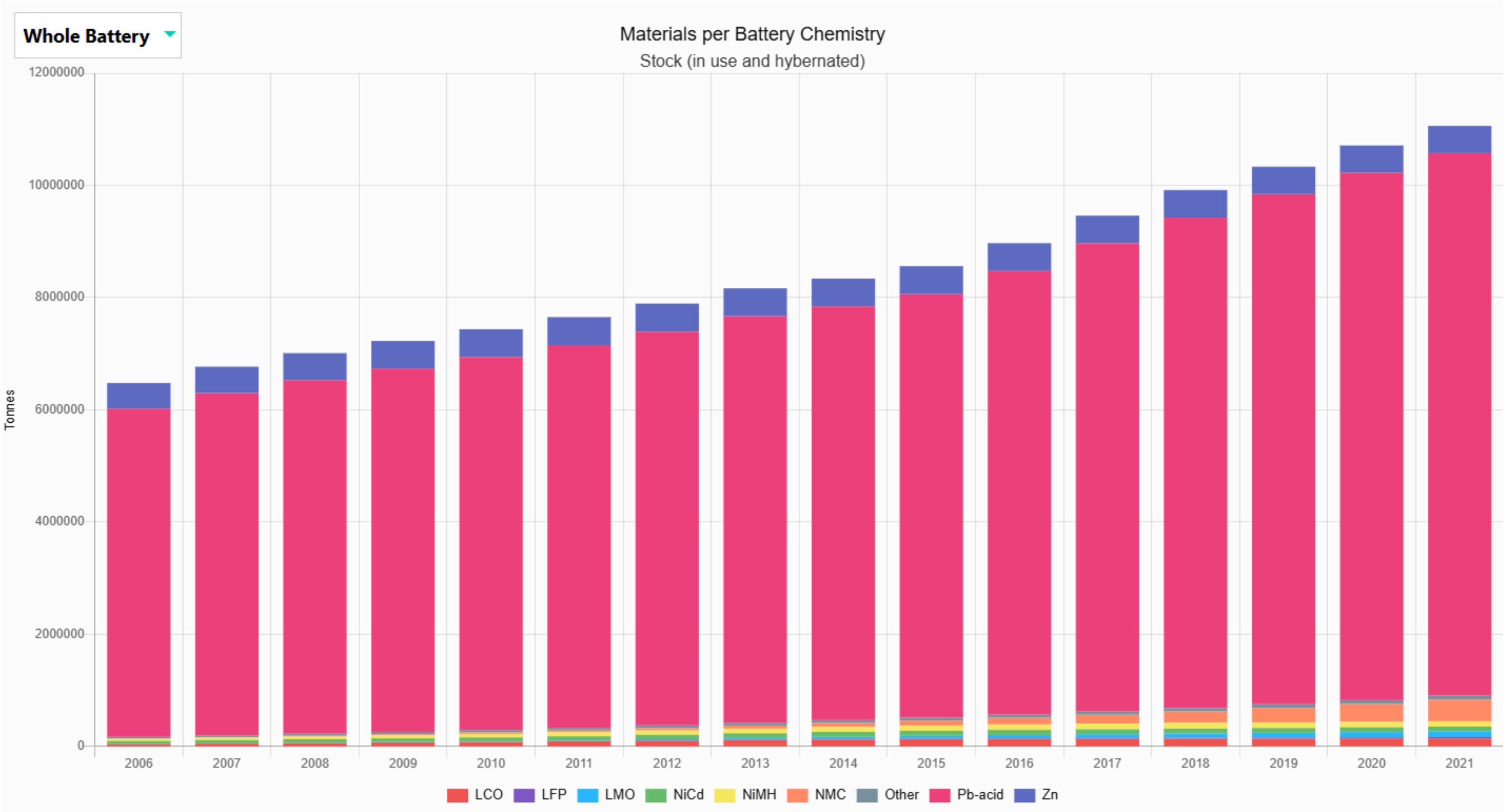
Source: European Commission, Joint Research Centre (JRC) RMIS – Raw Materials Information System, Raw Materials in the Battery Value Chain, accessible at: https://rmis.jrc.ec.europa.eu/bvc#/

Figure 10-7 Total mass of batteries in stock, for all applications except Start - Lighting – Ignition (SLI) and Industrial applications



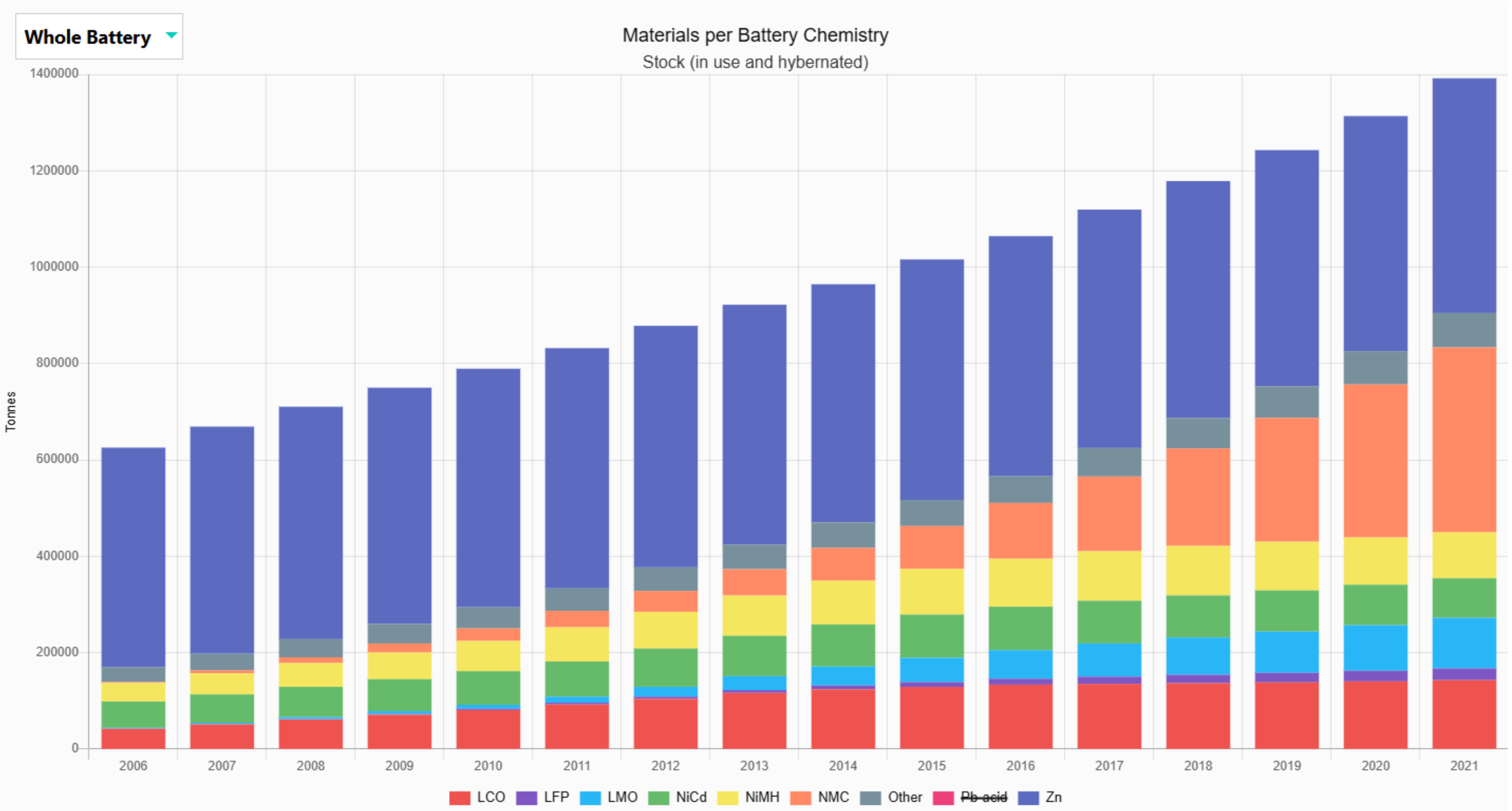
<u>Source:</u> European Commission, Joint Research Centre (JRC) RMIS – Raw Materials Information System, Raw Materials in the Battery Value Chain, accessible at: https://rmis.jrc.ec.europa.eu/bvc#/

Figure 10-8 Total mass of batteries in stock, for all chemistries



Source: European Commission, Joint Research Centre (JRC) RMIS – Raw Materials Information System, Raw Materials in the Battery Value Chain, accessible at: https://rmis.jrc.ec.europa.eu/bvc#/

Figure 10-9 Total mass of batteries in stock, for all chemistries except Lead-acid (Pb-acid)



<u>Source:</u> European Commission, Joint Research Centre (JRC) RMIS – Raw Materials Information System, Raw Materials in the Battery Value Chain, accessible at: <u>https://rmis.jrc.ec.europa.eu/bvc#/</u>

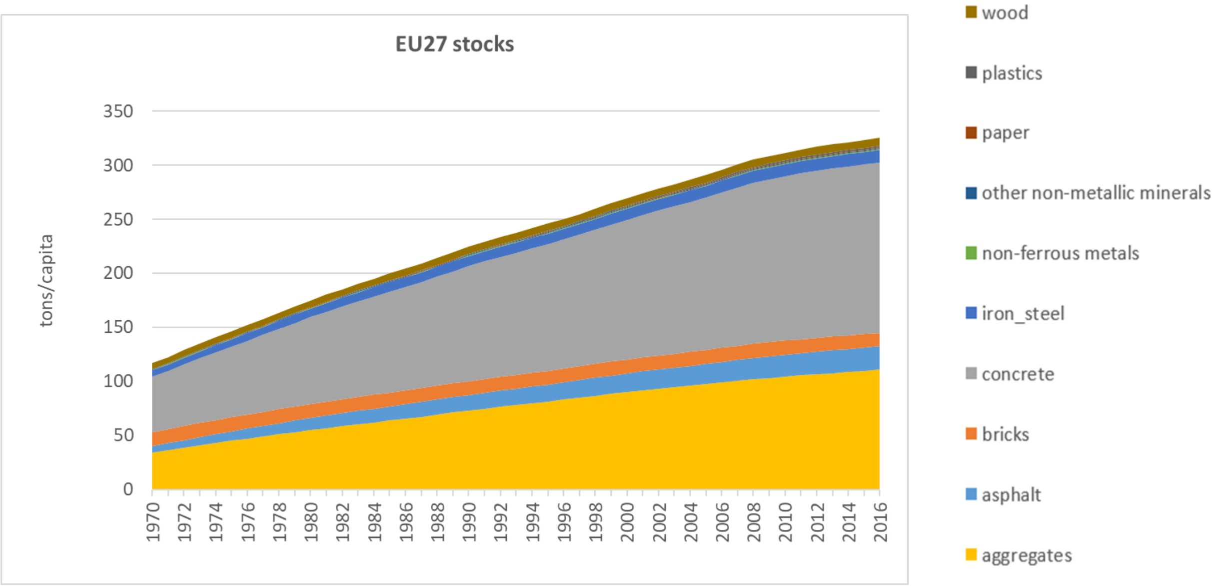
10.4. Annex D. Fiches for the indicators proposed to monitor the state of material stocks

10.4.1. A.1 Total EU Stocks by Material

Metric

Total EU Stocks by Material

Material stocks grew continuously in the EU27 from 117 t/cap in 1970, to 325 t/cap in 2016, resulting in a growth by a factor of 2.8 over 45 years.



*Coverage:*EU27

Source: MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

Assessment

Material stocks grew continuously in the EU27 from 117 t/cap in 1970, to 325 t/cap in 2016, resulting in a growth by a factor of 2.8 over 45 years. Annual growth rates were 5% at the beginning of the 1970s, then steadily declined to 2.5% in the mid-eighties, 1.5% in the early 2000s and since 2011 dropped below 1%. Material stock growth seems to be close to stagnation. Stagnation continued until the end of the observed period with an annual growth of 0.6% in 2016. Ongoing updates of these time series will show if European material stocks indeed stabilise, or if stock growth accelerated again.

Material composition did not change significantly during the 45 years considered. Concrete constitutes the largest fraction (44% in 1970 and 48% in 2016) followed by sand and gravel, summarised as "aggregates" (29% in 1970 and 34% in 2016). Bricks still made up 11% of material stocks in 1970, but declined in relevance and in 2016 only accounted for 4%.

Background

The majority of current Circular Economy measures and indicators focus on resource **flows** and largely ignore the key role of material **stocks in shaping flows**. This role of material stocks is relevant for the following reasons:

1. Most materials globally and in Europe are used to build up, operate and maintain material stocks (Krausman et al 2017). At a global level, 55% of all material inflows were used for these purposes in 2010 with the trend growing (this value was only 50% between 1970 and 1990, 30% in 1945 and 25% in 1900).[88] In 2015, of the remaining 45%, 16.9% is used for technical energy from mainly fossil fuels, 12.5% for feed, 4.9% for direct human food, 5% in extractive wastes in mining and metal processing, and the remainder (6.9%) is used for "other dissipative uses" i.e. products that are consumed and turned into wastes and emissions within one year such as detergents, hygiene products, pharmaceuticals, single-use batteries, lubricants, fertilizers, pesticides, single-use packaging material, etc. In the EU27 in 2016, the share of processed materials dedicated to the build-up and maintenance of stocks was 41% (Wiedenhofer et al. (2024); Wiedenhofer, Grammer, et al. (2025)). Consequently, acting on the **size** and dynamics of material stocks is likely to have a major impact on the overall resource use of global economy, and of the European Union in particular, and on the sustainability of its economic and social model;
2. The existence of stocks strongly contributes to the quality of life, to the energy consumption and to the productivity of our economies and hence is a strong determinant of the metabolism of our societies;
3. The continuous expansion of in-use stock has been identified as a major barrier for loop closing; as long as stocks continue to grow, even very high recycling rates of the materials contained in long and short-lived products, fossil-free energy and very high levels of re-use in agriculture of nutrients from animal and human waste will not be sufficient to close material loops. Consequently, the **growth rate** of material stocks is also of relevance;
4. The largest part of all waste flows – and hence of all potential secondary materials – is end- of-life waste from discarded old stocks. Recent research has shown that large amounts of potential secondary material will become available in the coming years; hence, knowledge of, and (in the longer term, action upon) the **age**, **location**, **material composition** and **quality** of material stocks is essential for effective planning of measures aiming to slow material cycles (refurbish, repair, remanufacture), as well as measures aiming to close material cycles (recycling, downcycling, energy recovery).

Stocks and their use are considered major leverage points for a sustainable CE. Stock related CE measures include:

1. the reduction of the weight of new anthropogenic material stocks (narrowing);
2. the increase of stock lifetimes (slowing); and
3. the use of secondary materials in stock-building (closing).

Supporting information

- Definition (components): https://boku.ac.at/miso/project
- Methodology: https://boku.ac.at/miso/project

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[88] *F. Krausmann, D. Wiedenhofer, C. Lauk, W. Haas, H. Tanikawa, T. Fishman, A. Miatto, H. Schandl, H. Haberl (2017) Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use, Proc. Natl. Acad. Sci. U.S.A. 114 (8) 1880-1885, https://doi.org/10.1073/pnas.1613773114(2017 (Figure A) .*

Krausmann, F., Lauk, C., Haas, W., Wiedenhofer, W., (2018) From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015, Global Environmental Change, Volume 52, Pages 131-140, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2018.07.003 (Figuer 2B)

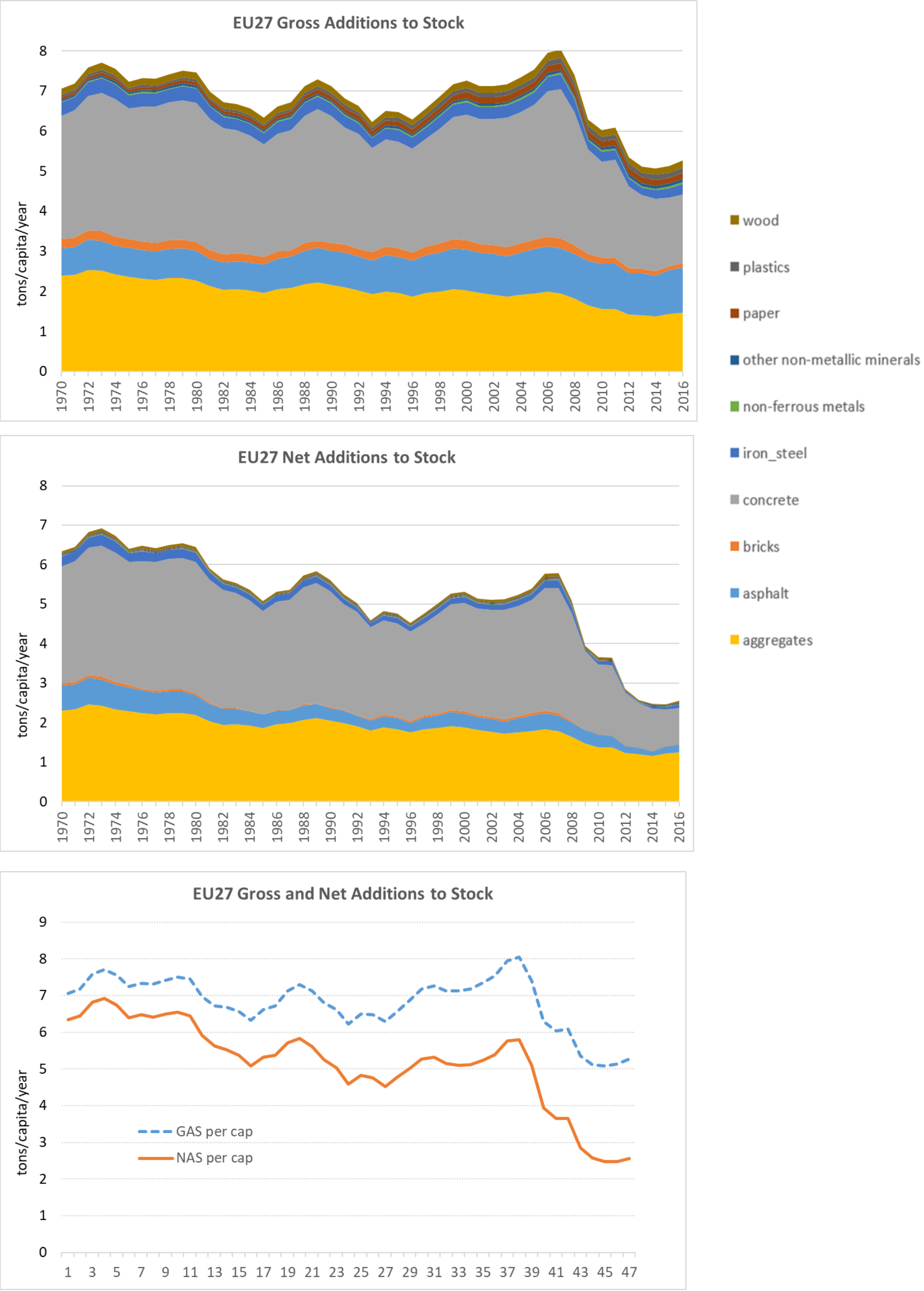
- Metadata: (Wiedenhofer, D., Grammer, B., & Streeck, J. (2025). MAT_STOCKS Database extract for EU27 (1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15090142
- (Krausmann et al, 2017). F. Krausmann, D. Wiedenhofer, C. Lauk, W. Haas, H. Tanikawa, T. Fishman, A. Miatto, H. Schandl, H. Haberl, Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use, Proc. Natl. Acad. Sci. U.S.A. 114 (8) 1880-1885. https://www.pnas.org/doi/10.1073/pnas.1613773114
- Units: tons/capita
- Temporal coverage: 1970 - 2016
- Geographic coverage: EU 27

10.4.2. A.2 Gross and Net additions to stock

Metric

chart/graph. With Title: Coverage: Source:

Gross and Net Additions to Stock



*Coverage:*EU27

Source: MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

Assessment

In contrast to the steady growth of material stocks, additions to stocks followed a slightly different path, showing how stock-flow dynamics behave differently. Gross additions to stocks (GAS/yr, representing the total amount of material accumulated in stocks each year) were more or less constant between 1970 and 1990, although with fluctuations between a maximum of 7.7 t/cap/yr in 1973 and a minimum of 6.3 t/cap/yr in 1985. Since 1990, the trend changed, with GAS/yr declining by 26% from 7.1 t/cap/yr, to 5.3 t/cap/yr in 2016. The decline was observed for all bulk construction materials, but most pronounced for bricks and concrete (-49% and -46% respectively). Net additions to stocks (NAS/yr) followed a very similar trend as observed for GAS/yr, with a decline from 7 t/cap/yr in 1973, to 5.6 t/cap/yr in 1990 (-19%), and then dropping again by -55% to 2.6 t/cap/yr in 2016.

Background

The majority of current Circular Economy measures and indicators focus on resource **flows** and largely ignore the key role of material **stocks in shaping flows**. This role of gross and material stock additions is relevant for the following reasons:

1. Most materials globally and in Europe are used to build up, operate and maintain material stocks (Krausman et al 2017). At a global level, 55% of all material inflows were used for these purposes in 2010 with the trend growing (this value was only 50% between 1970 and 1990, 30% in 1945 and 25% in 1900).[89] In 2015, of the remaining 45%, 16.9% is used for technical energy from mainly fossil fuels, 12.5% for feed, 4.9% for direct human food, 5% in extractive wastes in mining and metal processing, and the remainder (6.9%) is used for "other dissipative uses" i.e. products that are consumed and turned into wastes and emissions within one year such as detergents, hygiene products, pharmaceuticals, single-use batteries, lubricants, fertilizers, pesticides, single-use packaging material, etc. In the EU27 in 2016, the share of processed materials dedicated to the build-up and maintenance of stocks was 41% (Wiedenhofer et al. (2024); Wiedenhofer, Grammer, et al. (2025)). Consequently, acting on the **size** and dynamics of material stocks is likely to have a major impact on the overall resource use of global economy, and of the European Union in particular, and on the sustainability of its economic and social model.
2. The continuous expansion of in-use stock has been identified as a major barrier for loop closing; as long as stocks continue to grow, even very high recycling rates of the materials contained in long and short-lived products, fossil-free energy and very high levels of re-use in agriculture of nutrients from animal and human waste will not be sufficient to close material loops. Consequently, the **growth rate** of material stocks is also of relevance.
3. The largest part of all waste flows – and hence of all potential secondary materials – is end- of-life waste from discarded old stocks. Recent research has shown that large amounts of potential secondary material will become available in the coming years (Streeck et al. 2021); hence, knowledge of, and (in the longer term, action upon) the

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[89] *F. Krausmann, D. Wiedenhofer, C. Lauk, W. Haas, H. Tanikawa, T. Fishman, A. Miatto, H. Schandl, H. Haberl (2017) Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use, Proc. Natl. Acad. Sci. U.S.A. 114 (8) 1880-1885, https://doi.org/10.1073/pnas.1613773114(2017 (Figure A) .*

Krausmann, F., Lauk, C., Haas, W., Wiedenhofer, W., (2018) From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015, Global Environmental Change, Volume 52, Pages 131-140, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2018.07.003 (Figuer 2B)

age, **location**, **material composition** and **quality** of material stocks is essential for effective planning of measures aiming to slow material cycles (refurbish, repair, remanufacture), as well as measures aiming to close material cycles (recycling, downcycling, energy recovery).

Supporting information

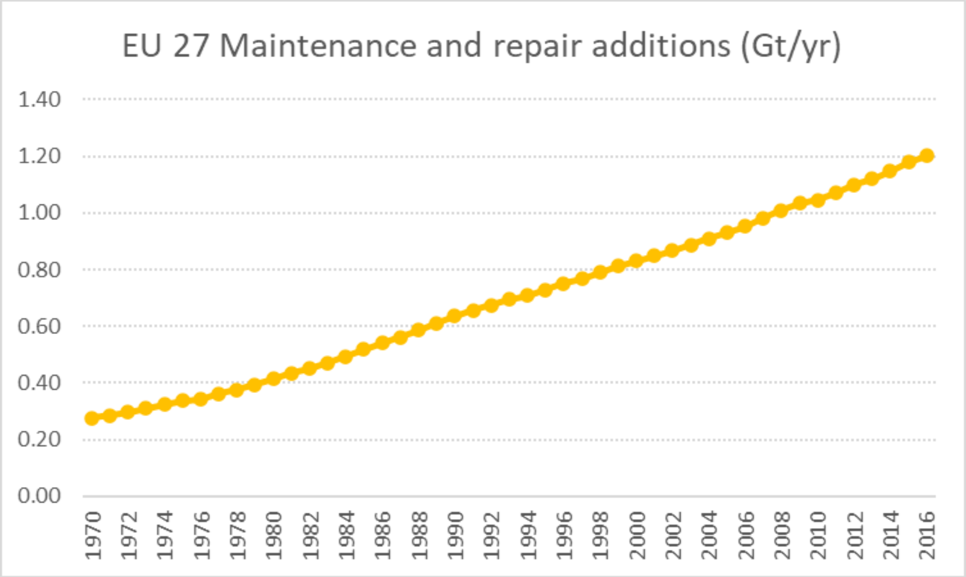
- Definition (components): https://boku.ac.at/miso/project
- Methodology: https://boku.ac.at/miso/project
- Metadata:
    - (Wiedenhofer, D., Grammer, B., & Streeck, J. (2025). MAT_STOCKS Database extract for EU27 (1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15090142
    - Krausmann et al (2017): Krausmann, F.; Wiedenhofer, D.; Lauk, C.; Haas, W.; Tanikawa, H.; Fishman, T.; Miatto, A.; Schandl, H.; Haberl, H. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc. Natl. Acad. Sci. USA 2017, 114, 1880–1885n available at: https://www.pnas.org/doi/full/10.1073/pnas.1613773114, figure 1.A.
- Units: Gt / capita /year
- Temporal coverage: 1970 - 2016
- Geographic coverage: EU 27

10.4.3. B.1 Maintenance and Replacement Flows of Stock

Metric

Maintenance and replacement flows of stock

In 2016, 48% of gross addtions to stock relate to the maintenance and replacement of existing stocks.



*Coverage:*EU27

Source: MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

Assessment

In 2016, total end of life (EoL) flows amounted to 1.2 Gt/a. The largest categories are asphalt (32%), concrete (29%), aggregates (8%), bricks 87%), and iron/steel (6%). Excluding bricks, the four categories cover 76% of total EoL/a. In 2016, EoL materials amount to 52% of Gross additions to stock per year (GAS/year), the remaining 48% are therefore net additions to stocks (NAS/year), which means that material stocks are growing.

The material composition of EoL materials is slightly different for the four main categories. The biggest fraction is asphalt (32%) followed by concrete (29%). Aggregates only account for 8% of EoL. For the example of asphalt, we see that the difference in GAS/year, stocks and EoL/year points towards a higher demand for M&R activities for asphalt uses, namely roads.

A material stock generates, by its very existence, a consumption of resources (energy, consumable and durable materials) for its operations and maintenance, which negatively impacts environmental sustainability in general. This phenomenon has been documented (Krausmann et al 2017) for the period between 1900 and 2010. At a global scale, the share of the global extraction of resources dedicated to stock-building materials has risen from 25% in 1900 to 52% in 2010, meaning that stocks have become the major source of consumption of our societies. The consumption of energy per unit of material in stock has decreased by 53% since the 1970s (i.e. the energy efficiency of that stock has increased), but this has not been sufficient to compensate for the increase in volume of that stock, which has multiplied by a factor of more than seven during the same period (Krausmann et al 2017).

Background

End-of-life materials illustrate the flow of material outputs occurring during maintenance, replacement and total or partial demolition of buildings, roads or other infrastructure. Since material stocks in the EU are growing, the end-of-life outputs mathematically represent the amount of material used for maintenance or replacement (M&R/year) of existing stocks.

Supporting information

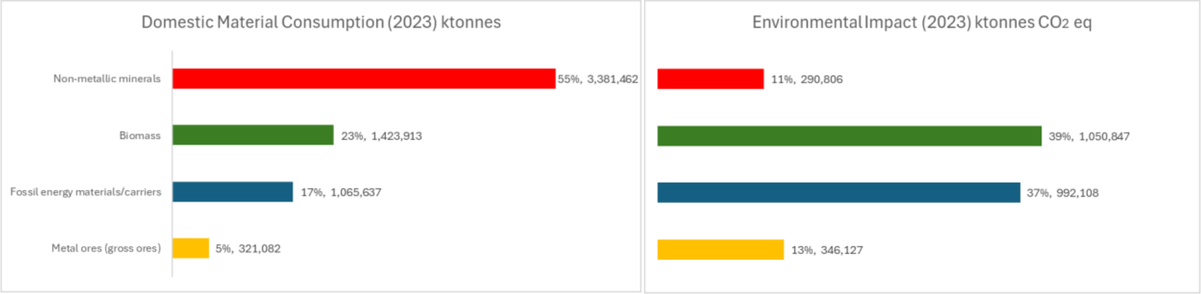
- Definition (components): https://boku.ac.at/miso/project
- Methodology: https://boku.ac.at/miso/project
- Metadata:
    - (Wiedenhofer, D., Grammer, B., & Streeck, J. (2025). MAT_STOCKS Database extract for EU27 (1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15090142
    - Krausmann, F.; Wiedenhofer, D.; Lauk, C.; Haas, W.; Tanikawa, H.; Fishman, T.; Miatto, A.; Schandl, H.; Haberl, H. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc. Natl. Acad. Sci. USA 2017, 114, 1880–1885n available at: https://www.pnas.org/doi/full/10.1073/pnas.1613773114, figure 1.A.
    - Krausmann, F.; Wiedenhofer, D.; Lauk, C.; Haas, W.; Tanikawa, H.; Fishman, T.; Miatto, A.; Schandl, H.; Haberl, H. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc. Natl. Acad. Sci. USA 2017, 114, 1880–1885n available at: https://www.pnas.org/doi/full/10.1073/pnas.1613773114 , figure 2.B and 1.B.
- Units: Gt / year
- Temporal coverage: 1970 - 2016
- Geographic coverage: EU 27

10.4.4. C.1 The Components and Environmental Impacts of Consumption

Metric

The components and environmental impacts of consumption

The materials with the largest consumption do not have the largest environmental impact.



Coverage: EU 27

Source: DMC : Eurostat ENV_AC_MFA(1.0). Environmental impact : ETC CE, 2025

Assessment

From a domestic material consumption perspective, non-metallic minerals account for around 55% of all materials used in the economy, followed by biomass, fossil fuels and metal ores. From an environmental impacts perspective, the picture is considerably different. Fossil fuels account for 37% of the environmental footprint of ready-to-use materials, biomass accounts for 39%, metals for 13% and non-metallic minerals for only 11%. The environmental impacts of biomass are mainly generated during the production phase (ETC CE, 2025).

The environmental footprint of materials refers to the environmental impacts of the extraction and processing of materials that are ready to use in industry (e.g. steel or meat). Such ready-to-use materials account for 76% of the total environmental footprint of EU consumption, while the rest of the economy and household activities account for the remainder (EEA, 2022).

These results highlight that, from an environmental perspective, more focus needs to be put on fossil fuels and biomass products. It is remarkable that these materials, responsible for the highest environmental impacts associated with the production of materials consumed in the EU, are those with the lowest CMURs simply because they are used mainly for energy purposes or as food.

While the environmental footprint of ready-to-use materials can be reduced by decreasing their consumption and increasing their circular use, it can also be reduced by decreasing the environmental impacts per tonne of material during extraction/cultivation e.g. through improving management practices and in processing.

Background

The Circular Material Use Rate (CMUR) is a macro-level, mass-flow indicator that is very useful for understanding the circularity of the EU's economy. However, it is based on all materials and does not reflect the fact that different types of materials have different environmental impacts. Combining knowledge about the circularity and the environmental impacts of different materials can therefore support policymaking that enables the more sustainable use of materials and achieves a net reduction in impacts.

Supporting information

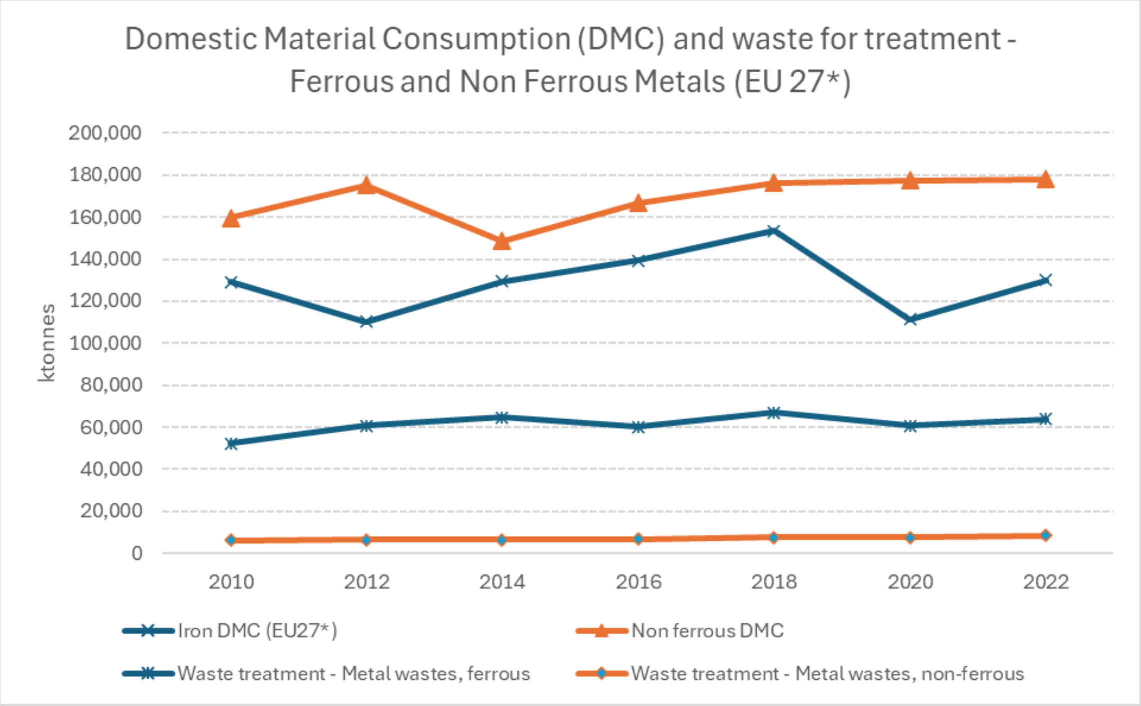
- Definition (components): DMC and kg CO_2-eq/kg
- Methodology (source and any data manipulation done): The DMCs for the four material groups are taken from the Eurostat DMC data, and the environmental impacts are calculated in the ETC report.
- Metadata (Data source -weblink):
    - Domestic material consumption (DMC) https://ec.europa.eu/eurostat/databrowser/view/env_ac_mfa/default/table?lang=en
    - ETC CE Report 2025/3 Measuring environmental benefits of Circular Economy https://www.eionet.europa.eu/etcs/etc-ce/products/etc-ce-report-2025-3-measuring-environmental-benefits-of-circular-economy
    - EEA, 2022, 'The EU Consumption Footprint (top-down approach)', European Environment Agency (Europe's consumption footprint (europa.eu)) accessed 26 January 2023.
- Units: DMC Ktonnes. Environmental impact Ktonnes CO_2-eq
- Temporal coverage: 2023
- Geographic coverage: EU 27

10.4.5. D.1 Inflow and outflow of particular materials

Metric

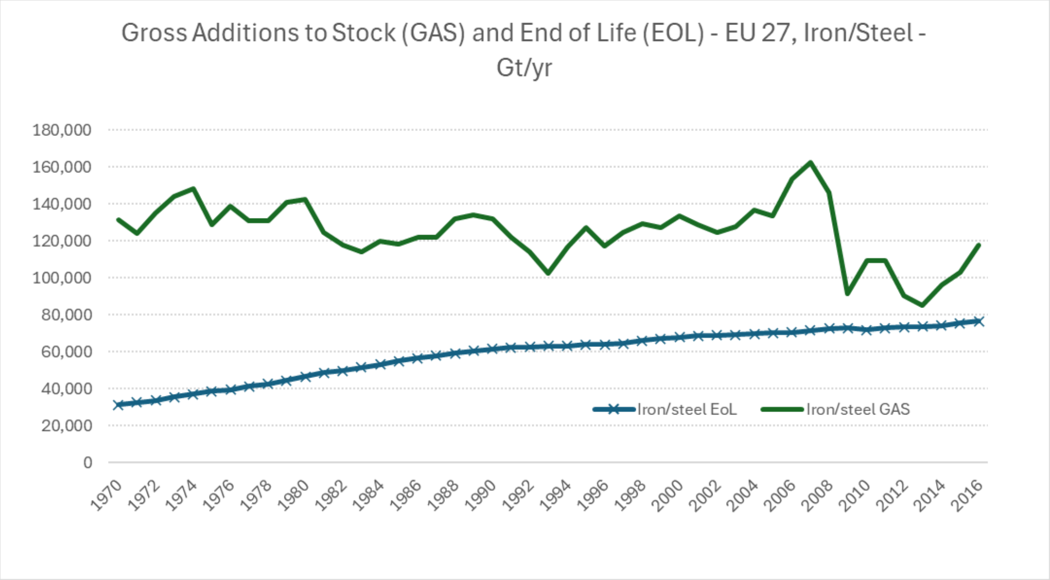
Inflow and outflow of particular materials

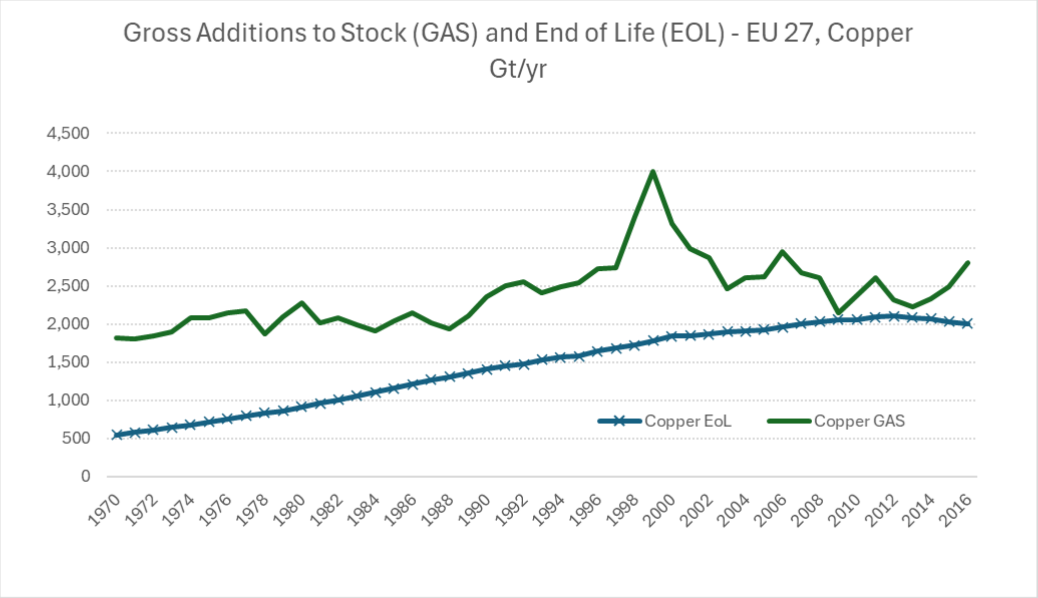
Total stock is increasing as gross additions to stock per year are larger than the amount of material going out of stock (for waste or recycling). The gap between the lines is getting smaller so although stocks are growing the rate of growth is slowing and the EU is getting closer to being (potentially) self-sufficient by recycling its own materials.



*Coverage: EU 27 (*DMC excludes Bulgaria for 2014-2020, because of confidential data.)*

Source: Eurostat. DMC: Material flow accounts [env_ac_mfa). Waste Treatment: [env_wastrt]





Coverage: EU 27

Source: MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

Assessment

Total stock is increasing as gross additions to stock per year are larger than the amount of material going out of stock (for waste or recycling). The gap between the lines is getting smaller so although stocks are growing the rate of growth is slowing and the EU is getting closer to being (potentially) self-sufficient by recycling its own materials. However some applications require virgin material.

Additions to stock are more volatile than end of life stocks, as they are more affected by economic cycles. The growth in the amount of material reaching end of life each year is partly a reflection of the continued growth in total stocks, as a higher volume of stocks implies a higher repair and replacement demand.

Virtually all (99%) of the ferrous and non ferrous metal waste arising for treatment is recycled. But even with these high rates the EU would still requires additional resources to be imported. Some of these imported resources are likely to be material including recycled materials from elsewhere in the world, and some of the material that becomes end of life in the EU is exported out of the EU for recycling.

Looking at the DMC vs. waste arisings the figures for ferrous metal show that the stock is growing (as the DMC is higher than the waste arisings). The DMC figure shows volatility related to economic cycles with an increase in line with economic activity. The waste arising figure is relatively flat by show a slight growth over the observed period, in line with ever increasing total stocks. The DMC for non-ferrous metals follows a similar pattern to DMC for ferrous metals. i.e. increasing and decreasing in line with economic growth and contraction. The non-ferrous metals waste arising figures are very low in comparison to the DMC, this would indicate a very rapid growth in stocks of these materials. While there may be some growth the waste figure for non-ferrous metal is thought to be low because of a combination of factors, that include the amount of waste material that is classified as products, primarily WEEE, vehicles and within CDW is not being classified in this waste category.

Data (Eurostat, 2023) on the contribution of recycled materials to raw materials demand in Europe shows that in 2022, 55% of copper, 83% of lead, 32% of aluminium, 16% of nickel, 34% of zinc, and 31% of iron came from recycled materials. These relatively high percentages suggest that the material being imported into Europe contains material that has been end of life somewhere at some point. This further indicates a weakness in the data on waste treatment volumes for non-ferrous metals in Europe. The figure also indicates that some of the end-of-life Iron/steel coming from Europe is probably being recycled for use elsewhere in the world – because the annual end of life figure for the EU27 is more than 31% of the DMC and GAS.

Background

This indicator is intended to highlight the dynamics of the stock flows and growth for two specific materials. Iron/steel is selected because of it use in both construction and many consumer products. Copper is selected because of its

The indicator also shows the complexity of trying to match material use statistics with waste statistics, as the way that data is classified and collected for these is very different.

The indicator also highlights the complexities involved when new products and the material for them, is imported into Europe, and some end-of-life material is exported out of Europe, potentially for recycling.

Supporting information

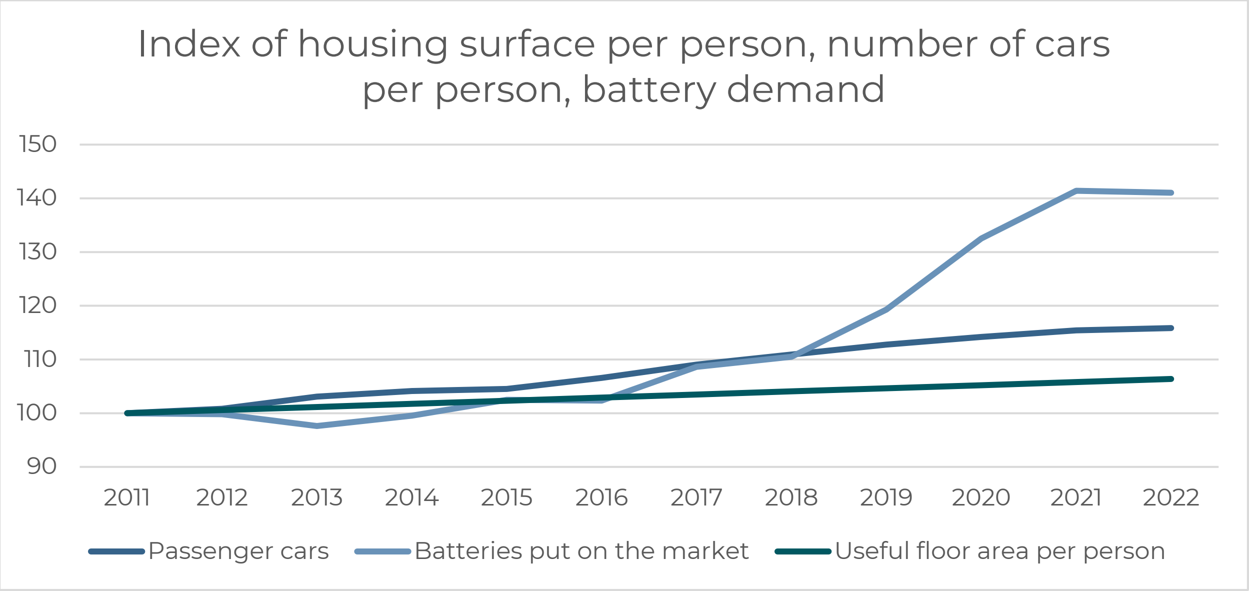
- Definition (components):
  - DMC data from Material flow accounts [env_ac_mfa]
  - Waste data from Treatment of waste by waste category, hazardousness and waste management operations [env_wastrt}
  - MISO data from https://boku.ac.at/miso/project
- Methodology (source and any data manipulation done):
  - DMC data is a sum of all MSs excluding Bulgaria for some years as this is confidential.
  - MISO: https://boku.ac.at/miso/project
- Metadata (Data source -weblink),
  - (Eurostat 2023). Contribution of recycled materials to raw materials demand - end-of-life recycling input rates (EOL-RIR). https://ec.europa.eu/eurostat/databrowser/view/cei_srm010/default/table?lang=en&category=cei.cei_srm
  - MISO (Wiedenhofer, D., Grammer, B., & Streeck, J. (2025). MAT_STOCKS Database extract for EU27 (1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15090142
- Units: DMC and waste treatment ktonnes/year. GAS and EOL (MISO) Gt/year
- Temporal coverage: DMC and waste treatment 2010-2022, MISO: 1970-2016
- Geographic coverage: EU 27

10.4.6. E.1 Index of Housing Surface per Person, Number of Cars per Person and Battery Demand

Metric

Index of housing surface per person, number of cars per person and battery demand

Demand, and demand intensity is increasing in terms of useful floor area per person, number of cars per person and number of batteries put on the market. All three of which are key areas for resource use.



*Coverage:*EU27

Source: Eurostat, Enerdata, EU Building Stock Observatory

Assessment

The data presents an index comparison of three variables: housing surface per person, number of passenger cars per person, and battery demand, all normalised to a base year of 2011 (=100). The trends indicate varying growth rates across these factors.

The number of passenger cars per person shows a steady, moderate increase from 2011 to 2022, suggesting a gradual rise in the intensity of car ownership. The useful floor area per person appears relatively stable, with only slight growth over time; however, this trend is based on extrapolated data from 2008 and 2020, meaning the actual pattern between these years may have varied. In contrast, the demand for batteries exhibits a much sharper increase, particularly from 2017 onward, surpassing 150 by 2022. This suggests a surge in battery usage, likely influenced by the increasing use of portable electronic devices like smartphones and laptops.

Background

The indicators reflect trends in resource consumption and efficiency across key sectors that generally have high resource demand. The housing surface per person provides insight into housing space utilisation, which impacts material use in construction and renovation. A stable or slightly increasing trend suggests limited expansion, aligning with circular economy principles that prioritise optimising existing infrastructure over continuous new construction.

The number of passenger cars per person and battery demand are crucial for understanding shifts toward sustainable mobility and demand patterns in consumer electronics and other battery using applications. A rise in battery demand also underscores the need for efficient battery recycling, reuse, and sustainable sourcing of raw materials. Monitoring these trends helps assess progress toward a circular system where resources are kept in use for longer, minimising waste and environmental impact.

Supporting information

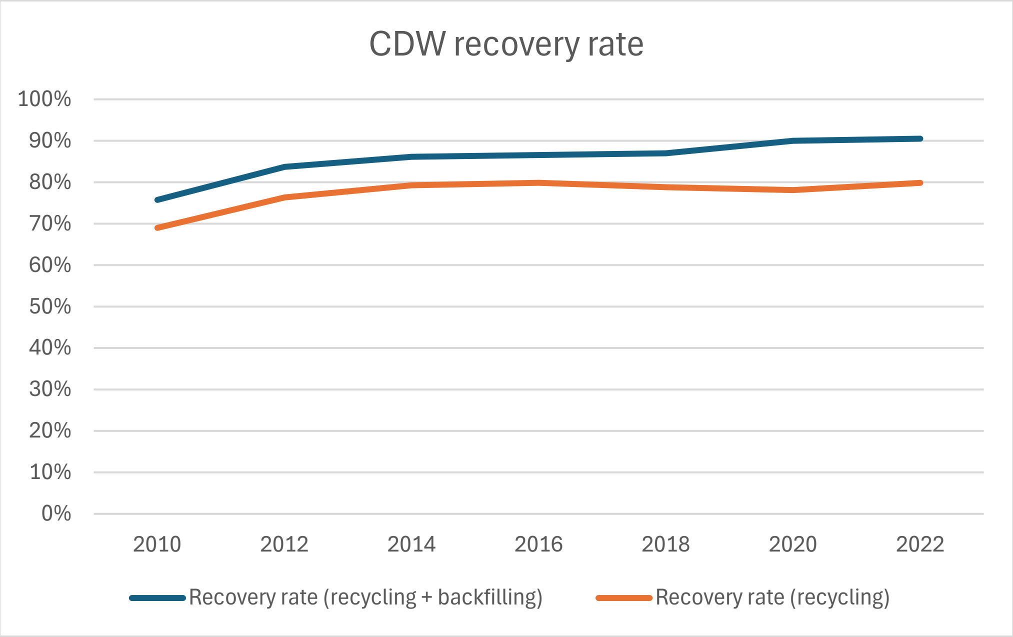
- Definition (components): The metrics show the housing surface per person, number of passenger cars per person, and battery demand, expressed as an index comparison of the three variables
- Methodology (source and any data manipulation done): The data presents an index comparison of three variables: housing surface per person, number of passenger cars per person, and battery demand, all normalized to a base year of 2011 (=100). Housing surface per person is based on primary residential floor area (m²) in 2008, sourced from a study by Enerdata, and 2020 data from the EU Building Stock Observatory, divided by EU-27 population data from Eurostat. An extrapolation was performed to estimate values for 2008 and 2020. The number of passenger cars per person is derived from data on passenger cars per thousand inhabitants. Battery demand is based on data for portable batteries and accumulators placed on the market mainly coming from EPR schemes.‘ This means any battery, button cell, battery pack or accumulator that is sealed, can be hand-carried and is neither an industrial battery or accumulator nor an automotive battery or accumulator.
- Metadata (Data source -weblink):
    - Enerdata https://entranze.enerdata.net/average-floor-area-per-capita.html
    - EU Building Stock Observatory https://building-stock-observatory.energy.ec.europa.eu/database/
    - Statistical Office of the European Union (Eurostat): Passenger cars - per thousand inhabitants, Sales and collection of portable batteries and accumulators, and Population change - Demographic balance and crude rates at national level
- Units: Index points (base year of 2011 =100).
- Temporal coverage (years x-y): 2011 - 2022
- Geographic coverage (e.g. EU 27): EU27

10.4.7. E.2 Construction & Demolition Waste (CDW) Recovery

Metric

Percentage of CDW recovered

The percentage of construction and demolition waste (CDW) that is recovered appears high but there are some concerns about the accuracy and nature of the data.



Coverage: EU27

Source: Eurostat

Assessment

The figure illustrates the percentage of Construction and Demolition Waste (CDW) that has been recovered over time from 2010 to 2022. The graph features two lines:

- The blue line represents the percentage of CDW that has been recovered including both recycling and backfilling, showing a steady increase from 76% in 2010 to about 91% in 2022.
- The red line represents the percentage of CDW that has been recovered only including recycling, showing a more gradual increase from around 69% in 2010 to about 80% in 2022.

It is important to note that backfilling is a relatively low-grade use of materials. Additionally, construction and demolition waste (CDW) data is often based on surveys, leading to gaps in accuracy.

In 2020, the EU-27 generated 333 Mt of CDW (excluding soils and dredged materials), making it the largest waste stream by weight in the EU. Although recycling rates are high, current waste management practices often result in downcycling, where materials lose quality and value (EEA, 2024).

Background

The percentage of Construction and Demolition Waste (CDW) recovered indicates how effectively materials from demolished or renovated buildings are being reused, recycled, or repurposed instead of being sent to landfill. Higher recovery rates enhance resource efficiency by reducing the demand for virgin raw materials, conserving natural resources, and minimising waste disposal. This, in turn, lowers landfill usage, decreases environmental pollution, and reduces the carbon footprint by cutting emissions associated with extracting and processing new materials.

The key legislation in the context of CDW recycling is the EU Waste Framework Directive, which sets the basic concepts and definitions related to waste management. It also mandates that EU Member States achieve a target of 70% CDW recovery by 2020. This directive aligns with broader EU sustainability goals, reinforcing the shift towards a circular economy by promoting selective demolition, material reuse, and improved recycling practices.

Supporting information

- Definition (components): Metric shows recovery rate of CDW, expressed in percentages of total CDW
- Methodology: Raw data were sourced from Eurostat under the category "Treatment of Waste by Waste Category, Hazardousness, and Waste Management Operations" for mineral waste from construction and demolition. The analysis was based on Eurostat's aggregated data for the EU-27. The dataset includes information on waste treatment and waste recovery, with recovery further categorised into recycling & backfilling and recycling alone. To determine the annual recovery rate, the total amount of recovered waste (in tonnes) was divided by the total waste treatment (in tonnes) for each available year.
- Metadata (Data source): Statistical Office of the European Union (Eurostat) https://ec.europa.eu/eurostat/databrowser/view/env_wastrt__custom_15995116/default/table?lang=en
- Units: Percentage
- Temporal coverage (years x-y): biennially from 2010
- Geographic coverage (e.g. EU 27): EU 27

10.4.8. E.3 Level of Building Renovation

Metric

Useful floor area with corresponding renovation rate

The level of building renovation differs per country and sector, but there is a lack of data availability

Sector	**Residential**			**Service**		
EU Member State	Useful floor area (in million m^2)	Useful floor area renovated (in million m^2)	Renovation rate (in %)	Useful floor area (in million m^2)	Useful floor area renovated (in million m^2)	Renovation rate (in %)
Austria	536.3	21.2	4.0%	119.4	3.5	2.9%
Belgium	706.1	54.6	7.7%	151.4	20.0	13.2%
Bulgaria	359.8	39.0	10.8%	66.9	7.9	11.8%
Croatia	204.4	21.9	10.7%	39.8	2.6	6.4%
Cyprus	103.0	2.7	2.6%	7.9	1.3	17.0%
Czechia	433.5	25.2	5.8%	84.3	6.5	7.7%
Denmark	382.7	14.5	3.8%	123.2	5.6	4.5%
Estonia	30.7	1.1	3.6%	109.2	3.4	3.1%
Finland	452.3	14.4	3.2%	99.8	4.3	4.3%
France	3,454.2	173.5	5.0%	884.2	29.9	3.4%
Germany	4,266.1	178.9	4.2%	1741.1	63.5	3.6%
Greece	646.4	19.4	3.0%	144.5	9.0	6.2%
Hungary	338.4	14.2	4.2%	99.9	4.2	4.2%
Ireland	139.7	5.0	3.6%	61.9	1.1	1.7%
Italy	3,790.9	171.9	4.5%	440.2	44.8	10.2%
Latvia	71.0	2.3	3.3%	17.3	0.7	3.9%
Lithuania	91.1	2.5	2.8%	31.1	0.7	2.2%
Luxembourg	32.1	0.7	2.2%	7.2	0.3	4.1%
Malta	13.7	0.4	3.2%	4.0	0.3	8.7%
Netherlands	789.6	39.9	5.0%	238.9	12.4	5.2%
Poland	1,178.9	89.0	7.6%	383.7	26.0	6.8%
Portugal	691.6	56.0	8.1%	127.7	16.2	12.7%
Romania	464.6	52.3	11.3%	83.9	7.3	8.7%
Slovakia	186.6	7.6	4.1%	35.9	3.1	8.8%
Slovenia	71.2	3.7	5.2%	27.7	1.7	6.2%
Spain	3241.1	26.6	0.8%	349.5	24.7	7.1%
Sweden	542.8	26.5	4.9%	152.1	11.3	7.5%
Total EU27	***23,218.9***	***1,065.2***	***4.6%***	***5,632.3***	***312.1***	***5.5%***

Total EU27 (residential and services		
Useful floor area (in million m^2)	Floor area renovated (in million m^2)	Renovation rate (in %)
28,851.2	1,377.2	4.8%

Coverage: EU27

Source: EU Building Stock Observatory

Assessment

The table represents the useful floor area (m²) for various countries, alongside their renovation rates and useful floor area renovated (m²) for residential and service sectors. Data is only available for the renovation rate and useful floor area renovated in 2016, which represents a significant data gap.

Bulgaria, Croatia, and Romania have the highest renovation rates for residential buildings, while Bulgaria, Belgium, Italy, Portugal, and Cyprus lead in the service sector. The data shows no clear correlation between larger floor area and higher renovation rates.

The EU27 has a total of 28.851 million m² of useful floor area, mostly from pre-1970 buildings, with a peak between 1946–1969. Construction sharply declined in the 1970s, likely due to shifts in policy or urban development. Since 1980, floor area has remained stable with minor fluctuations. The steep decline in buildings from 2011–now indicates limited new construction. Renovation appears to be an approach to maintaining the existing building stock, as large-scale demolition would lead to more recent buildings making up a larger portion of the data.

Background

The data highlights the relationship between the existing building stock, renovation rates, and the focus on maintaining rather than replacing buildings. In a circular economy, the goal is to maximize the lifespan of resources, reduce waste, and promote reuse. Renovating older buildings instead of demolishing them aligns with these principles by reducing the need for new materials, conserving energy, and minimizing construction waste. The data suggests that renovation plays a significant role in sustaining the built environment, which is a key aspect of the circular economy.

While renovations offer social, economic, and environmental benefits, they also increase material consumption, requiring careful trade-offs. Demolition generates vast amounts of construction and demolition waste—333 million tonnes in the EU-27 in 2020, making it the largest waste stream by weight. Although recycling rates are high, much of the waste is downcycled, missing opportunities for resource conservation and emissions reductions (EEA, 2024).

Supporting information

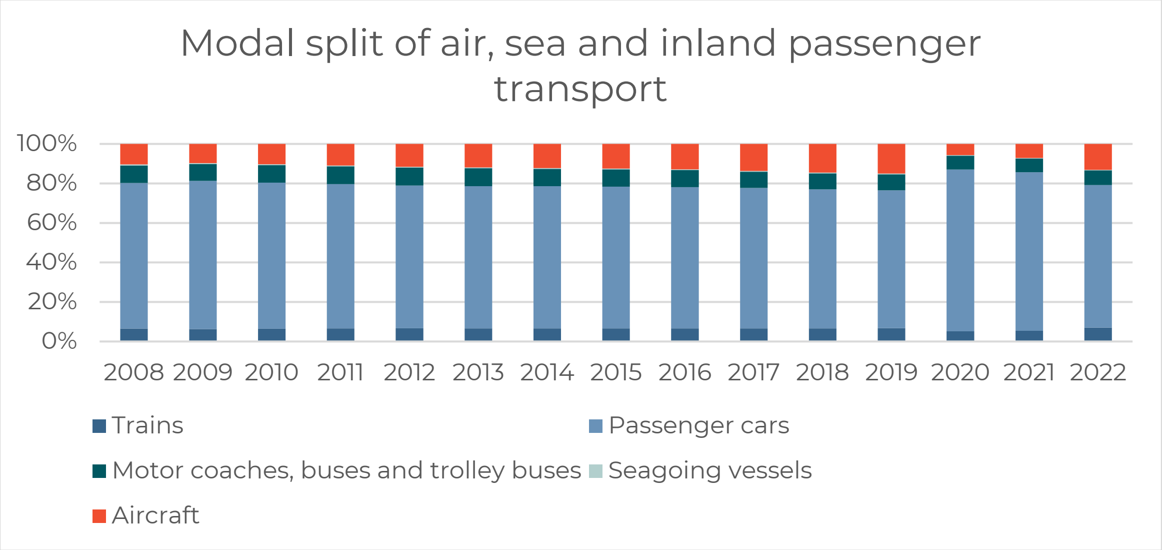
- Definition (components): Metric shows the residential and service sector useful floor area with corresponding renovation rate per country
- Methodology: Raw data the renovation rate and useful floor area renovated (2016) were sourced from the EU Building Stock Observatory. The data on useful floor area renovated is categorized by sector (residential and service) and per country. The total useful floor area was calculated by dividing the useful floor area by the renovation rate.
- Metadata (Data source -weblink): EU Building Stock Observatory https://building-stock-observatory.energy.ec.europa.eu/database/
- Units: Useful floor area (renovated) in m² and renovation rate in %
- Temporal coverage): 2016
- Geographic coverage: EU 27

10.4.9. E.4 Modal Shift

Metric

Passenger cars continue to dominate personal transport in Europe

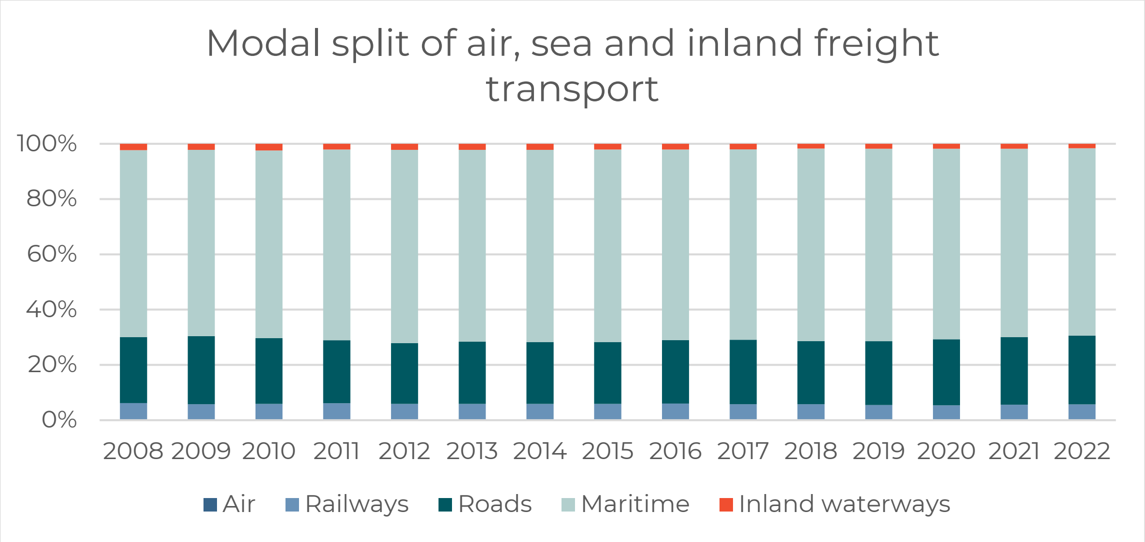
Figure 1: Modal split of air, sea and inland passenger transport in percentages



Coverage: EU27

Source: Eurostat

Figure 2: Modal split of air, sea and inland freight transport in percentages



Coverage: EU27

Source: Eurostat

Assessment

Figure 1 shows the modal split of air, sea, and inland passenger transport in percentages from 2008 to 2022. Passenger cars have consistently held the largest share of the modal split, with a notable increase in 2020 and 2021, likely due to COVID-19, as travellers favoured private vehicles over public transport. Train travel has remained relatively stable, though it declined during the pandemic due to lockdowns. Similarly, buses and trolleybuses saw a temporary dip but continue to play a key role in personal mobility. Seagoing vessels hold a smaller share but have shown a gradual increase over time. Air travel, despite a sharp drop in 2020–2021, has since rebounded, reflecting renewed demand.

Figure 2 shows the modal split of air, sea, and inland freight transport from 2008 to 2022. Maritime transport consistently holds the largest share, reflecting its dominance in long-distance freight due to its cost-effectiveness and ability to handle large volumes. Road transport maintains a significant share, crucial for short to medium distances and connecting inland areas to ports and rail terminals. Railways have a smaller but stable share, essential for bulk goods and long-distance inland transport, offering efficiency and lower environmental impact compared to road transport. Air transport has the smallest share, primarily used for high-value, time-sensitive goods despite its higher costs. Inland waterways show a small share, reflecting their niche role in regions with navigable rivers and canals. Overall, maritime transport remains dominant, while road and rail play steady roles in logistics, and air and inland waterways serve more specialised needs.

Background

The modal split shows the distribution of different transport modes, which has a significant impact on resource efficiency, emissions, and overall environmental sustainability. Different modes of transport use resources at different rates, with rail and maritime transport generally being more resource-efficient than road transport. This is because they can move goods or passengers in larger volumes with less fuel per unit. Despite this, road freight transport has remained the dominant mode. On the passenger side, public transport, such as buses and trains, is more energy and resource efficient and less carbon-intensive per person kilometre compared to private cars. However, private cars continue to be the primary mode of transport for passengers. Shifting towards a greater share of sustainable transport modes would help reduce emissions, and would require less resources, supporting the circular economy's objective of minimising environmental impact.

Supporting information

- Definition (components): Metric shows modal split of air, sea and inland passenger and freight transport in percentages of total transport use
- Methodology: Raw data were sourced from Eurostat under the categories “Modal Split of Air, Sea, and Inland Freight Transport” and “Modal Split of Air, Sea, and Inland Passenger Transport.” The analysis was based on Eurostat’s aggregated data for the EU-27. The dataset includes information on the percentage of passenger transport modes (trains, passenger cars, motor coaches, buses, trolley buses, seagoing vessels, and aircraft) and freight transport modes (air, railways, roads, maritime, and inland waterways).
- Metadata (Data source -weblink): Statistical Office of the European Union (Eurostat) https://ec.europa.eu/eurostat/databrowser/view/tran_hv_ms_psmod__custom_16000735/default/table?lang=en https://ec.europa.eu/eurostat/databrowser/view/tran_hv_ms_frmod__custom_16000963/default/table?lang=en
- Units: Percentage
- Temporal coverage: Annually from 2008 to 2022
- Geographic coverage: EU 27

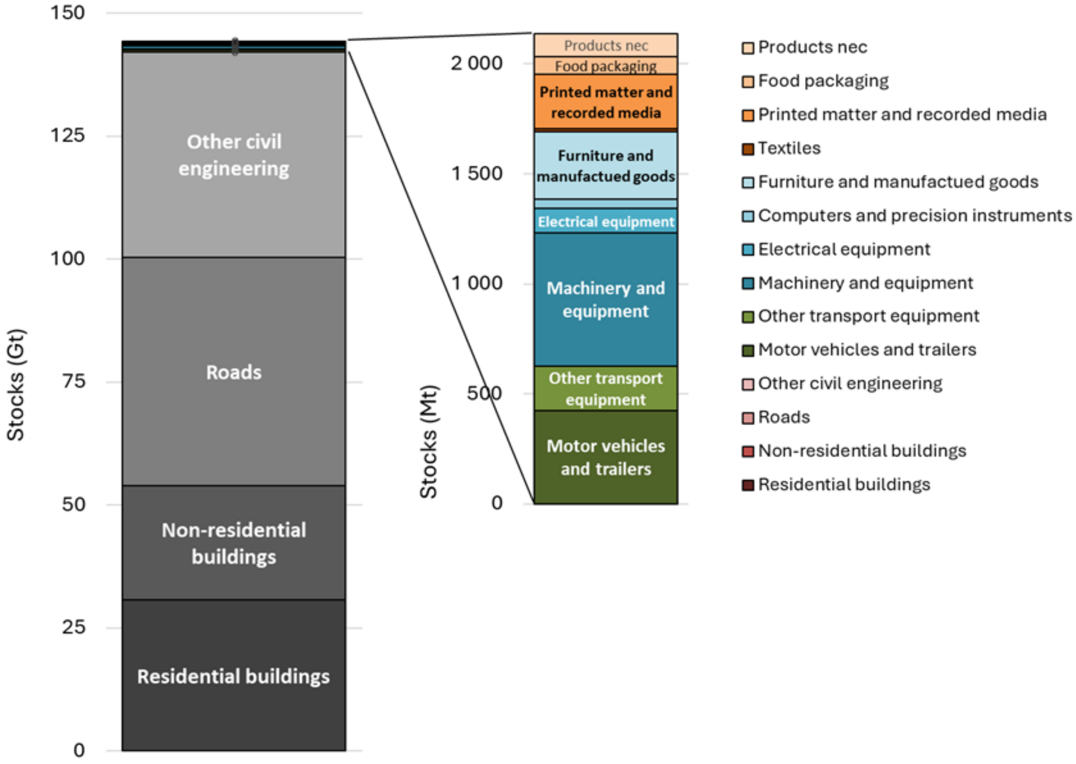
10.4.10. E.5 Total EU stocks by end use (2016)

Metric

chart/graph. With Title: Coverage: Source:

Total EU stocks by end use (2016)

Buildings and infrastructure dominate the material stock by end use



*Coverage:*EU27

Source: MISO2 (Wiedenhofer et al., 2024; Wiedenhofer, Grammer, et al., 2025)

Assessment

Next to the biggest groups, i.e. roads, other civil engineering, residential and non-residential buildings, the figure zooms into the smaller end-uses, which includes different kinds of machinery, vehicles and other durable consumer products. Among these, we find machinery and equipment (600 Mt), motor vehicles and trailers (425 Mt), other transport equipment (200 Mt), furniture and other manufactured goods (310 Mt), printed matter (250 Mt), as well as small amounts of electrical equipment (110 Mt), food packaging (80 Mt), textiles (12 Mt), computers and precision instruments (4 Mt) and products not specified elsewhere (105 Mt).

The detailed perspective by end use reveals the importance of construction activities producing buildings, mobility- and other infrastructure. 99% of the material stocks are concerned with buildings, roads and other civil engineering (railways, bridges, tunnels, water supply pipes, harbours, dams, power plant construction, etc.).

The use of materials differs between end-uses, with non-metallic minerals mainly used in buildings, roads, and other civil engineering, whereas metals are used across all end-use categories except for roads.

Background

Stocks and their use are considered major leverage points for a sustainable CE. Stock related CE measures include:

1. the reduction of the weight of new anthropogenic material stocks (narrowing);
2. the increase of stock lifetimes (slowing), and
3. the use of secondary materials in stock-building (closing).

The data presented here shows that the importance of measures designed to improve the material efficiency of construction and civil engineering and those that might reduce the need for new roads and the maintenance of existing roads.

Supporting information

- Definition (components): https://boku.ac.at/miso/project
- Methodology: https://boku.ac.at/miso/project
- Metadata: (Wiedenhofer, D., Grammer, B., & Streeck, J. (2025). MAT_STOCKS Database extract for EU27 (1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15090142
- Units: tons
- Temporal coverage: 2016
- Geographic coverage: EU 27

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10.6. Annex F. Data files

The data files containing the figures supporting the graphs related to the MISO2 model, and the complete results of the MISO2 model supporting this study, are accessible at:

Wiedenhofer, D., Grammer, B., & Streeck, J. (2025). MAT_STOCKS Database extract for EU27 (1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15090142

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