# THE CIRCULARITY GAP REPORT 2023

## *Methods*

Circle Economy
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v 1.0

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# Abbreviations and acronyms

**C&DW:** Construction and demolition waste

**CE**: Circular economy

**CGR**: Circularity Gap Report

**CM**: Circularity Metric

**DE**: Domestic extraction

**D&D**: Demolition and discard

**DMC**: Domestic material consumption

**DMI**: Domestic material consumption

**DPO**: Domestic processed output

**EEIOA**: Environmentally-extended input-output analysis

**EE-MRIO**: Environmentally-extended multi-regional input-output

**EoL:** End-of-life

**EW**: Economy-wide

**GAS**: Gross additions to stocks

**LULCC:** Land use and land cover change

**MFA**: Material flow accounts

**MSW:** Municipal solid waste

**NAS**: Net additions to stocks

**PM**: Processed materials

**PRM**: Processed raw materials

**RMC**: Raw material consumption

**RME**: Raw material equivalents

**RMI**: Raw material input

**SEM**: Socioeconomic metabolism

**SM**: Secondary materials

**SW:** Special waste

**WaW:** What a Waste

# 1. Introduction

The concept of a Circular Economy (CE) is gaining increasing attention from policy makers, industry, and academia. There is a rapidly evolving debate on definitions, limitations, the contribution to a wider sustainability agenda, and a need for indicators to assess the effectiveness of circular economy measures at larger scales. Herein, we looked at previous research in an attempt to adapt and apply a framework for a comprehensive and economy-wide biophysical assessment of a CE at the global level. The *Monitoring Framework for Economy-wide Material Loop Closing,* developed for the EU28 by Mayer and colleagues (2019)[1] and Haas and colleagues (2020),[2] utilises and systematically links official statistics on resource extraction and use and waste flows in a mass-balanced approach. This framework builds on the widely applied framework of economy-wide material flow accounting and expands it on the one hand by 'opening up' the economy black box and, on the other, by integrating waste flows, recycling, and downcycled materials. A comprehensive set of indicators that measure the scale and circularity of total material and waste flows and their socioeconomic and ecological loop closing is built upon such a framework.

As shown in **Figure one**, the goal of the Circularity Metric calculation is three-fold. First, following the work by Haas and colleagues (2015, 2020),[3] the goal is to *implement* a set of socioeconomic metabolic indicators (including, but not limited to material circularity) at the global level. Differently to both studies, the assessment should be fully bottom-up so that the global indicator set is derived by summing up results for each individual country. Additionally, the framework has to allow for a year-by-year monitoring effort. These requirements have a great amount of influence on the analytical approach as well as on the eligibility of datasets and are the main determinant of the differences between the original framework and the one presented in this document.

Second, while previous studies have carried out the analysis up to the year 2015, we aim to *update* the indicator set for the most recent year possible by means of an extensive primary data gathering effort in combination with data extrapolation techniques. While this is expected to increase the uncertainty, it will also make the analysis more relevant in an increasingly rapidly changing global landscape.

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[1] Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., & Blengini, G. A. (2019). Measuring progress towards a circular economy: a monitoring framework for economy-wide material loop closing in the EU28. *Journal of Industrial Ecology, 23*(1), 62-76.

[2] Haas, W., Krausmann, F., Wiedenhofer, D., Lauk, C., & Mayer, A. (2020). Spaceship earth's odyssey to a circular economy-a century long perspective. *Resources, Conservation and Recycling, 163*, 105076.

[3] Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. *Journal of Industrial Ecology, 19*(5), 765-777.

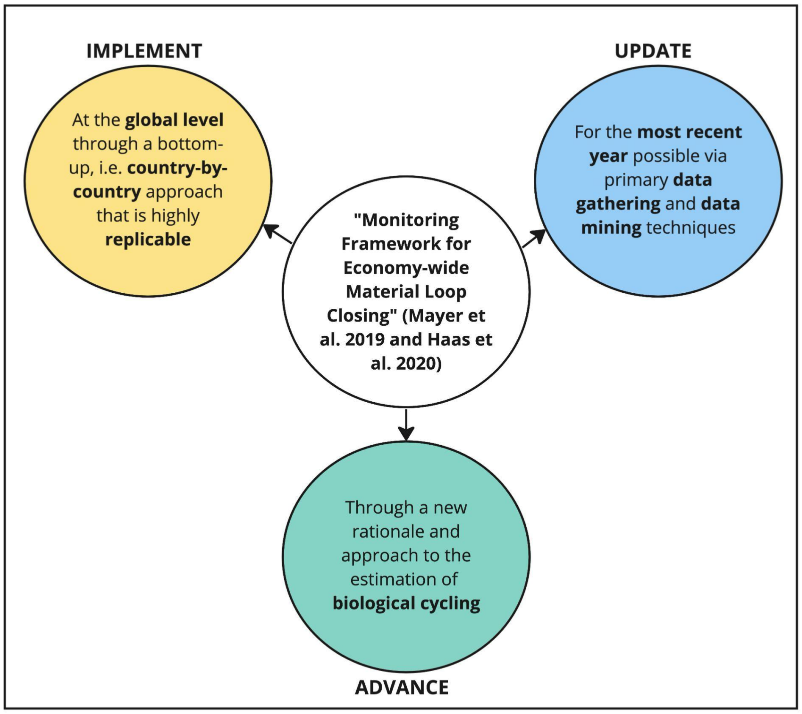

***Figure one***. *Triple goal of the CGR 2023 Circularity Metric calculation.*

Third, picking up from the recommendations by Haas and colleagues, we take steps to *advance* the framework by addressing the issue of defining criteria for ecological loop closing and the operationalization of circular biomass. Criteria to be considered refer to soil degradation, overexploitation of water resources, efficient management of plant nutrients and livestock manure and net carbon losses related to cultivation (Haas et al., 2020). At the present stage, the contribution of this work to the topic remains more theoretical than practical and lies in the development of a rationale and narrative for adopting a ‘nutrient cycles perspective’ to the indicator framework, the definition of system boundaries, processes and flows as well as the identification of a method and data sources for their quantification.

# 2. *Circularity Gap Report 2023* Monitoring Framework

For the CGR 2023, we developed a methodological approach for the quantification and tracing of material, energy, and waste flows through the socioeconomic system. This approach is based on the economy-wide monitoring framework of the circular economy as developed by Mayer and colleagues (2019), but adapted for the assessment of the global socioeconomic system and tracking material flows for our Circularity Indicator framework **(see Chapter 2.3).**

First, we describe the accounting framework by Mayer and colleagues, shown in **Figure two**. This framework is useful to trace materials by main material groups from their extraction to major uses within the socioeconomic system and towards discard and either material recovery or deposition to nature as wastes and emissions. The main physical stages of the flow of materials through the entire system are marked by throughput indicators, represented as boxes. These include the source of material inputs (for example, domestic extraction, imports), major material transformation processing stages within the system (for example, processed materials, energetic and material use, in-use stocks of materials, waste treatment, EoL waste) and the destination of outflows (for example, exports, domestic processed output to the environment). Flows of materials are displayed as arrows between these boxes; the colours of boxes indicate the type of data source.

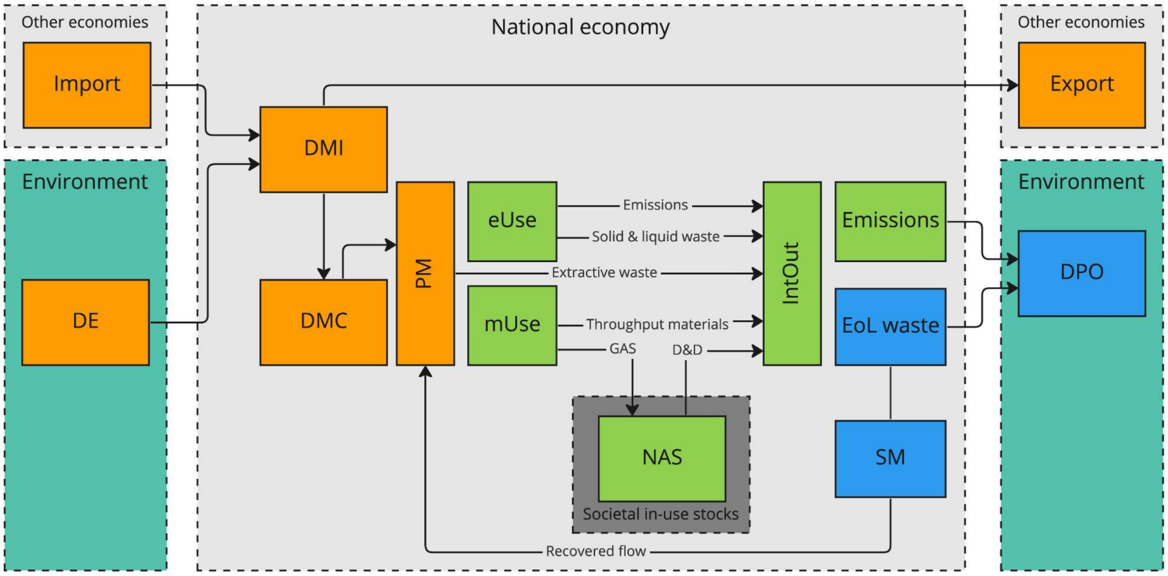

***Figure two.*** *Framework and throughput indicators for an economy-wide assessment of circularity. This framework can be used for 1) individual materials, such as corn or iron, 2) material groups, such as biomass, metal ores, fossil fuels or non-metallic minerals, or 3) all materials, represented by total domestic extraction. Each colour represents a different data source, with orange indicating official data from economy-wide material flow accounts, blue indicating official waste and emissions statistics, and green indicating mass-balanced modelling. Arrows in between (in some cases) indicate a combination of statistical data and modelling .*

Processed materials (PMs) are defined as the sum total of domestic material consumption (DMC) and secondary material (SM) inputs. PMs are allocated to either energetic or material use based on different data sources such as FAO food balances and assumptions. Energetic use (eUse) not only comprises materials used to provide technical energy (fuel wood and biofuels) but also feed and food, the primary energy sources for livestock and humans. Material use (mUse) was split into extractive waste, materials used for stock building (i.e., gross additions to in-use stocks of materials [GAS]), and throughput materials. Extractive waste refers to waste material that occurs during early stages of the processing of domestically extracted ores and directly goes from PM to interim output (IntOut).

Stock building materials comprise all materials that accumulate in buildings, infrastructures, or durable goods with a lifetime of more than one year (for example, concrete, asphalt, or steel). The share of stock-building materials in mUse is estimated based on information from industry and production statistics, results from material flow studies and assumptions. Throughput materials comprise materials that do not accumulate in in-use stocks, and can be split into two types of materials: first, materials used deliberately in a dissipative way such as salt or fertiliser minerals, and losses that occur during material processing (wastage, not reported in waste statistics); and second, short-lived products such as packaging or newspaper, manufacturing wastes, and food waste (reported in waste statistics).

All materials that are neither added to stocks nor recycled are converted into gaseous, solid, or liquid outputs within the year of extraction. Together with D&D from in-use stocks that have reached the end of their service lifetime, these outflows are denoted as interim outputs (IntOut). IntOuts are split into emissions, comprising all gaseous emissions (for example, carbon dioxide ($CO_2$), sulphur dioxide ($SO_2$), methane ($CH_4$)) including water vapour and into EoL waste, including all solid (and liquid) outputs. Emissions cannot be recycled and go straight into domestic processed output (DPO). A fraction of total EoL waste, reported as RCV B—(recovery other than energy recovery—backfilling) and RCV O (recovery other than energy recovery—except backfilling) in Eurostat waste statistics (env_wastrt), is reentering socioeconomic processes as secondary materials. The remaining EoL waste (after subtracting SM) is returned to the environment as DPO waste and either landfilled, incinerated, or deliberately applied (for example, manure, fertiliser). DPO emissions and DPO waste together form total DPO.

To close the material balance between input and output a combination of data from statistical reporting with modelling was used. This is done separately for eUse and for the mUse components in two balancing calculations. The following equations summarise the mass balancing for eUse (Equation 1) and mUse (Equation 2).

$$DPO\ emissions\ =\ eUse\ -\ solid\ and\ liquid\ wastes \quad 1)$$
$$Demolition\ and\ discard\ =\ EoL\ waste\ from\ mUse\ -\ throughput\ materials\ in\ waste \quad 2)$$

In the framework form Mayer and colleagues, it assumed that all materials used to provide energy were converted into DPO emissions (including water vapour) and solid waste within the year of extraction. DPO emissions are then calculated as the difference between eUse and the outflow of solid waste. The so-called balancing items (oxygen uptake from air during combustion and water consumed by humans and livestock) were excluded. This means that all outflows from eUse include only the materials contained in actual inputs as composed in PM (for example, $CO_2$ or $SO_2$ in terms of C or S content; excrements at the average water content of food and feed intake). Closing the mass balance for eUse in this way implies that all inaccuracies in statistical data and assumptions that result in inconsistencies between input and output flows accrued in DPO emissions (DPOe).

Because the actual size of most of the in-use stocks is unknown, the following approach to close the material balance is used: In a first step, a consistent split of total EoL waste from mUse into waste flows resulting from discard and demolition and throughput materials was required. Total EoL waste from mUse was derived from waste statistics. While waste statistics report information on construction and demolition waste, this waste flow was not fully consistent with EoL waste from discard and demolition, which also contains waste flows from discarded long-living products such as furniture, cars, or electric appliances. In a second step, the amount of discard and demolition (D&D) is calculated as the difference between EoL waste from mUse reported in waste statistics and the fraction of throughput materials (i.e. materials with a lifespan of less than one year) in mUse (for example, waste from packaging, paper, food waste, etcetera). In a third step, NAS were calculated as the difference between additions to stocks and discard and demolition. Closing the mass balance in this way implies that all inaccuracies in statistical data and assumptions that result in inconsistencies between input and output flows for mUse accrue in D&D flows as residual flow category, and consequently in the value for NAS.

In the **Global CGR 2023 monitoring framework, shown in Figure three**, inter-economy flows such as Gross Additions to Stocks (GAS), Demolition and Discard (D&D) and throughput materials are included in the system definition. Only key throughput indicators and flows that are directly used in the calculation of the headline indicators are quantified, such as the energy use of fossil fuels (eUse FF). This simplification reduces the amount of modelling and country-specific information required, at the cost of reintroducing a ‘black-box’ approach.

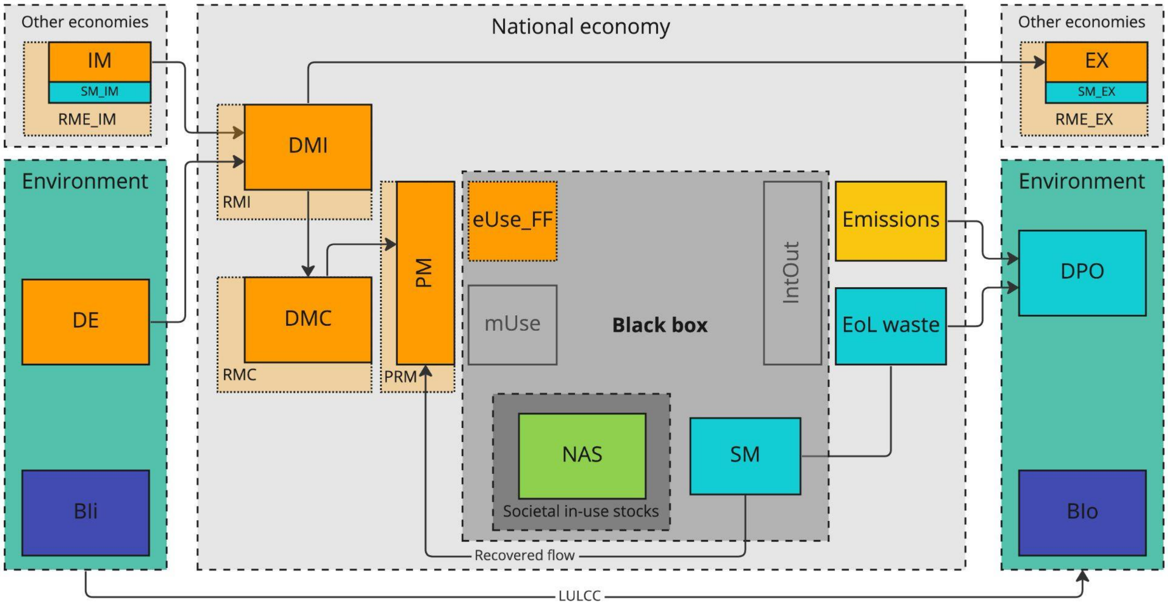

**Figure three.** *Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues (2019). Colours indicate data sources used: orange = economy-wide material flow accounts data, blue = estimated and calculated data, yellow = emissions statistics, green = mass-balance approach. Arrows in between in some cases indicate a combination of statistical data and modelling.*

NAS are calculated through the standard Economy-wide Material Flow Accounts (EW-MFA) balancing formula, that is as the residual of the material balance identity:

$$NAS = DE + IM + BIi - DPO - EX - BIo$$

Standard global EW-MFAs are based on simple material flow data sets that focus on direct flows such as material extraction, physical trade (i.e. imports and exports), waste and emissions. As mentioned, the direct accounts treat the national economy as a black box, but also exclude upstream and downstream material flows associated with trade. In the Global CGR 2023 framework these indirect flows related to trade, also known as Raw Material Equivalents (RMEs), were included. As a result, two versions of the indicator set were produced, one based on direct flows and indicators (i.e. DMC, PM) and one based on RMEs (i.e. raw material consumption (RMC), processed raw materials (PRM)). It is important to note that, because no trade exists when taking a global perspective (in fact at the global level $IM = EX$ and $RME\_IM = RME\_EX$ so that $PTB = 0$ and $RTB = 0$, thus $DMC = RMC = DE$), this is only relevant for the results at the country level.

In the framework by Mayer and colleagues (2019), only domestically recycled materials from official waste statistics are quantified. This means that the waste component of the system is not fully consistent with the material component, which takes a consumption-based perspective. To address this limitation, the Global CGR 2023 framework accounts also for the amount of waste, by-products and SMs imported ($SM_{imp}$) and exported ($SM_{exp}$) so that the 'Recovered flow' reflects the amount of SMs consumed rather than just domestically produced.

As such, the Global CGR 2023 framework can be considered a bottom-up accounting (or bookkeeping) approach where the amount of modelling—and thus the need for country-specific industry or production statistics and results from material flow studies—is limited. By following the standard EW-MFA approach more closely, the applicability and timeliness of the framework increases and makes it possible to apply a fully bottom-up approach that relies as much as possible on readily available and regularly updated international datasets.

## 2.2 Accounts and data sources

In this section, we describe the material flow concepts from a EW-MFA perspective based on definitions and nomenclatures from *UNEP's MFA Manual,*[4] and explain how these are integrated in the CGR 2023 monitoring framework.

The implementation of the monitoring framework requires the development of a global MFA consistent with the principles of EW-MFA. The challenge is to build the MFAs required for the calculation while making the data gathering and processing simple and systematic, so that it can be easily applied to every country in the world. The key flows and indicators required are the following:

- Domestic Extraction (DE), Direct Physical Imports (IM) and Exports (EX),
- Raw Material Equivalents of imports (RME_IM) and exports (RME_EXP),
- Domestic Processed Output (DPO),
- Balancing items (BIs);
- Land Use and Land Cover Change and (LULCC) emissions,
- Share of energy use in DE of fossil fuels (eUSe_FF)
- Waste treated by waste stream and treatment option (WAS_TRT)
- Waste, by products and secondary materials traded by treatment option (SM_TRD)

Standard global EW-MFAs are based on simple material flow data sets that focus on primary material extraction, physical trade (i.e. imports and exports), waste and emissions. The direct accounts treat the national economy as a black box and exclude upstream and downstream material flows associated with trade as well as recycling or reuse flows within the economy, and mobilisation of flows that do not enter the economic process. They also do not provide estimates of the amounts of materials embedded in the stock of buildings and infrastructure. To make the difference between the direct material flow accounts and additional accounts clear, EW-MFA accounts are structured into four accounting modules that cover specific aspects of the interaction between the economy and natural resources. Additionally, an extra module is included to introduce additional data requirement needed for an extended monitoring framework:

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[4] UNEP. (2021). *The use of natural resources in the economy: A global manual on economy wide material flow accounting*. Nairobi, Kenya: UNEP. Retrieved from: SEEA website

- The *first module* is concerned with DE, IM and EX of materials;
- The *second module* focuses on indirect flows associated with imports and exports, i.e. RME_IM and RME_EX;
- The *third module* looks at the output side of the material flow accounts and reports DPO, i.e. flows of waste and emissions and the gateways through which they leave the economy towards the environment (landfill, soil, water and air);
- The *fourth module* allows for closing the material flow balance by linking inputs to outputs and introducing a set of balancing items on the input (BIi) and output (BIo);
- The *extra module* includes internal flows and Land Use and Land Cover Change (LULCC) emissions. Internal flows trace materials from their extraction to major uses within the socioeconomic system and towards discard and either material recovery or deposition to nature as wastes and emissions. Examples are the allocation of consumption of resources into material and energy use (for example, energy use of fossil fuels [eUse FF]) or recycling flows (one of the elements of WAS_TRT). LULCC are typically not recorded in standard EW-MFAs due to their fuzzy position in between the environmental and economic systems. In the present approach, they play an important role in the determination of the renewability and circularity of biomass.

In the following sections, each module is given a more detailed description of its elements as well as the sources and assumptions used in compilation of the CGR 2023 global accounts (**Table one**).

***Table one.*** *Overview of variables, datasets and related sources.*

| Module | Variable | | MF Code | Dataset | Source | Notes |
|---|---|---|---|---|---|---|
| 1 | Domestic Extraction | DE | MF.1.X to MF.4.X | de_tccc, env_ac_mfa | International Resource Panel, Eurostat | Available at both digit-1 and digit-4 level, the latter used for the compilation of BIs |
| 1 | Domestic Material Consumption | DMC = DE + PTB | | | | Available only at digit-1 level |
| 2 | Raw Material Trade Balance | RTB = RME_IM - RME_EX | | | | |
| 1 | Physical Trade Balance | PTB = IM - EX | | trade_tccc, env_ac_mfa | | Available at both digit-1 and digit-4 level, the latter used for the compilation of BIs |
| 3 | Emissions to air | DPO | MF.7.1 | Eora v199.82 | Eora | Cross-checking of multiple datasets (EDGARv6.0, PRIMAPHISTv2.3, env_ac_mfadpo) |

| | | | | | | |
|---|---|---|---|---|---|---|
| 3 | Waste disposal to environment | | MF.7.2 | What-a-Waste database, env_wastrt | World Bank, Eurostat | Updated by Circle Economy |
| 3 | Emissions to water, dissipative uses and losses | | MF.7.3<br>MF.7.4<br>MF.7.5 | - | - | Estimated through expert knowledge and rules of thumb |
| 4 | Net balancing item | BI = BIi -BIo | MF.8.1<br>MF8.2 | Trade_tccc, Faostat and EW_MFA Questionnaire | International Resource Panel, Faostat and Eurostat | Calculations based on digit-4 DMC, emissions, livestock and human heads in combination with standard average coefficients |
| Extra | Waste recycling | WAS_TRT | (not included) | What-a-Waste database, env_wastrt | World Bank, Eurostat | Updated by Circle Economy |
| Extra | Trade in waste, by-products and secondary materials | SM_TRD = SM_IM - SM_EX | | BACI database | CEPII | Application of Eurostat approach to international physical trade database |
| Extra | Land Use and Land Cover Change emissions | LULCC | | PRIMAPHIST v2.3.1 | PIK | - |
| Extra | Fossil fuels for energy and material use | eUse_FF<br>mUse_FF | | Energy balances | UNSTAT | - |

## 2.2.1 Module one: Domestic material extraction (DE), direct physical imports (IM) and exports (EX)

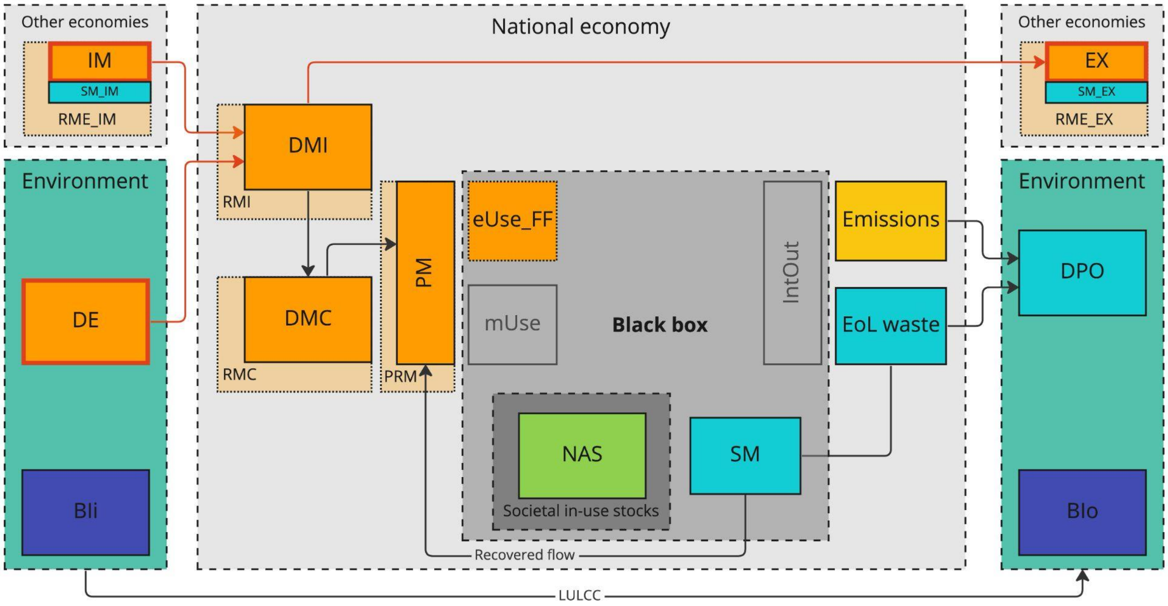

***Figure four.*** *Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues (2019) with Module 1 flows and indicators highlighted.*

### Domestic extraction

Module one is the core of a national material flow data set. **Figure four** highlights in red the components of this module. It includes the DE of materials that are further used in economic processes, usually accounted for at the point when the natural resource becomes commoditised and a price is attached. The aggregate flow DE covers the annual amount of solid, liquid and gaseous raw materials (except for water and air) extracted from the natural environment to be used as material factor inputs in economic processing. The term 'used' refers to the acquisition of value within the economic system. DE includes biomass, fossil fuels, metal ores and non-metallic minerals. It also covers IM and EX of goods measured at the volumes at which they cross national boundaries. IM and EX typically contain products at different stages of processing, including unprocessed primary products, processed primary products, simply transformed manufactures and elaborately transformed manufactures. With this information, additional indicators can be derived including a Physical Trade Balance (PTB) and Domestic Material Consumption (DMC) where:

$$PTB = IM - EX \text{ and } DMC = DE + PTB$$

At their most aggregate level (digit-1 level), they are recorded in terms of resource groups, namely Biomass, Metal Ores, Non-metallic Minerals and Metal Ores.

## Biomass (MF.1)

According to EW-MFA conventions, the DE of biomass includes all biomass of vegetable origin extracted by humans and their livestock, capture of wild fish, and the biomass of hunted animals (**Table two**). Biomass of livestock and livestock products (for example, milk, meat, eggs, hides) is not accounted for as domestic material extraction but considered as flows within the economic system. Within this CE framework, biomass flows are quantified at a more granular level (up to digit-4 level) due to the role they play in the generation of agricultural organic waste and the determination of balancing items.

***Table two.*** *Biomass flows in EW-MFA (highlighted in bold are those explicitly used or re-estimated within the current framework).*

| Level | Code | Label | DE | Import | Export | Notes |
|---|---|---|---|---|---|---|
| 1 | MF1 | Biomass | X | X | X | |
| 2 | MF11 | Crops (excluding fodder crops) | X | X | X | |
| **3** | **MF111** | **Cereals** | **X** | **X** | **X** | Under TCCC this is broken down into Rice, Wheat and Cereals nec |
| **3** | **MF112** | **Roots, tubers** | **X** | **X** | **X** | Used for calculation of MF.8.2.3 Step 2: Water content of biomass products |
| **3** | **MF113** | **Sugar crops** | **X** | **X** | **X** | |
| **3** | **MF114** | **Pulses** | **X** | **X** | **X** | |
| **3** | **MF115** | **Nuts** | **X** | **X** | **X** | |
| **3** | **MF116** | **Oil-bearing crops** | **X** | **X** | **X** | |
| **3** | **MF117** | **Vegetables** | **X** | **X** | **X** | |
| **3** | **MF118** | **Fruits** | **X** | **X** | **X** | |
| **3** | **MF119** | **Fibres** | **X** | **X** | **X** | |
| **3** | **MF11A** | **Other crops (excluding fodder crops) n.e.c.** | **X** | **X** | **X** | |
| 2 | MF12 | Crop residues (used), fodder crops and grazed biomass | X | X | X | |
| 3 | MF121 | Crop residues (used) | X | X | X | |
| **4** | **MF1211** | **Straw** | **X** | **X** | **X** | Used in recalculation of agricultural waste |
| **4** | **MF1212** | **Other crop residues (sugar and fodder** | **X** | **X** | **X** | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | **beet leaves, etcetera)** | | | | |
| 3 | MF12 | Fodder crops and grazed biomass | X | X | X | |
| **4** | **MF1221** | **Fodder crops (including biomass harvest from grassland)** | **X** | **X** | **X** | Used in recalculation of agricultural waste |
| **4** | **MF1222** | **Grazed biomass** | **X** | **X** | **X** | |
| 2 | MF13 | Wood | X | X | X | |
| 3 | MF131 | Timber (industrial roundwood) | X | X | X | |
| **3** | **MF132** | **Wood fuel and other extraction** | **X** | **X** | **X** | Used in calculation of MF.8.1.1 Step 2: Oxygen for combustion of hydrogen, MF.8.1.1 Step 3: Oxygen content, MF.8.2.1.1 Water vapour from moisture content of fuels and MF.8.2.1.2 Water vapour from the oxidised hydrogen components of fuels |
| 2 | MF14 | Wild fish catch, aquatic plants and animals, hunting and gathering | X | X | X | |
| 2 | MF15 | Live animals and animal products (excluding wild fish, aquatic plants and animals, hunted and gathered animals) | | X | X | |
| *2* | *MF16* | *Products mainly from biomass* | | X | X | |

## Straw (MF.1.2.1) and crop residues used (MF.1.2.2)

MFA accounts distinguish between two types of crop residues: *1.2.1 Straw of cereals*: all harvested straw of cereals including maize and *1.2.2 All other crop residues*: this can, for example, include tops and leaves of sugar crops.

In some cases, all or some harvested crop residues are accounted for in national agricultural statistics. However, neither FAOSTAT nor national agricultural statistics in most countries report any data on harvested crop residues. In cases where national statistics provide data on the used fraction of crop residues, these can directly be used for EW-MFA compilation without further processing. For most countries, however, crop-residue production and the fraction recovered for socioeconomic use will have to be estimated via the following steps:

- Step one: Identification of crops that provide residues for further socioeconomic use. In most cases, this will include cereals (1.1.1), sugar crops (1.1.3) and some oil bearing crops (1.1.6); only in exceptional cases will other crops have to be considered.
- Step two: Estimation of available crop residues via harvest factors. The harvest index, which denotes the share of primary crop harvest of total above-ground plant biomass, and the grain-to-straw ratio. These relations are specific to individual cultivars, and by using them it is possible to estimate total biomass residue from primary crop harvest (*Equation (1)*) . In the absence of national information, the average harvest factors for crops in different world regions can be used.

$$(1)\ Crop\ residues\ [t\ 15\%\ moisture]\ =\ primary\ crop\ harvest\ [t\ (as\ is\ weight)]\ *\ harvest\ factor$$

- Step three: Estimation of fraction of used residues. The fraction of residues used (recovery rate) can be estimated based on expert knowledge, or from country-specific studies on crop residue use. In cases where no reliable information is available, the recovery rates in different world regions can be used. The amount of used crop residues is calculated using *Equation (2)*.

$$(2)\quad Used\ crop\ residues\ [t\ 15\%\ moisture]\ =\ Crop\ residues\ [t\ 15\%\ moisture]\ *\ recovery\ rate$$

## Metal ores (MF.2)

Metal ores are best described as the deposits of metal compounds in the Earth's crust that can be processed to produce desired metals at an economically viable cost. Implicit in this definition of ore is the fact that 'ore' is as much an economic term as it is physical. If the market price for a metal increases, the concentration of contained metal (or 'grade') at which a rock can be considered ore will decrease. Ore deposits will generally be rock, but in certain important cases can be special soils or sand deposits as well.

An important concept when accounting for ore production is exactly what should be counted, and where. For EW-MFA purposes, only that portion of the excavated rock that is to be processed in some way, to obtain the desired metals, should be counted. This means that any soil or rock that is simply excavated and moved, to gain access to the metal ore itself, should not be counted as ore. Due to the limited ability of modern bulk mining methods to sharply delineate waste rock from ore, considerable mixing of waste rock and ores occurs in the mining process, with some waste rock being included in the flow to further processing, and some ore being discarded as waste, without further processing. For the purposes of EW-MFA this problem can be largely ignored by accounting for ore on a 'run of mine' (ROM) basis. ROM ore already includes the elements of waste rock that have been mixed in with the ore (ore 'dilution') in the mining process. Note that waste rock and waste dumps should not be confused with mine 'tailings'. Tailings are the main process waste left over after processing/beneficiation of the ore has taken place, and are included in EW- MFA accounts if the ore has been accounted for correctly. Tailings are composed mainly of the portions of the ore that are of little economic value, but that are too intimately associated with the valuable metal compounds to be separated in the initial excavation process.

Within the baseline CE monitoring framework, the accounting of metal ores is only carried out at the aggregated resource group level (digit-1), since a more detailed tracing of such flows throughout the economic system does not directly and significantly influence other flows or indicators. The estimation of industrial waste (see *'Waste generation, collection and treatment'*) could benefit from the calculation of excavated rocks (waste from unused extraction) and tailings (waste from used extraction) directly from metal ores extraction data. ***Table three*** provides an overview of the metal ores flow in EW-MFA.

***Table three.*** *Metal Ores flows in EW-MFA (highlighted in bold are those explicitly used or re-estimated within the current framework).*

| Level | Code | Label | DE | Import | Export | Notes |
|---|---|---|---|---|---|---|
| **1** | **MF2** | **Metal ores (gross ores)** | **X** | **X** | **X** | |
| 2 | MF21 | Iron | X | X | X | |
| 2 | MF22 | Non-ferrous metal | X | X | X | |
| 3 | MF221 | Copper | X | X | X | |
| 3 | MF222 | Nickel | X | X | X | |
| 3 | MF223 | Lead | X | X | X | |
| 3 | MF224 | Zinc | X | X | X | |
| 3 | MF225 | Tin | X | X | X | |
| 3 | MF226 | Gold, silver, platinum and other precious metals | X | X | X | |
| 3 | MF227 | Bauxite and other aluminium | X | X | X | |
| 3 | MF228 | Uranium and thorium | X | X | X | |
| 3 | MF229 | Other non-ferrous metals | X | X | X | |
| 2 | MF23 | Products mainly from metals | | X | X | |

## Non-metallic minerals (MF.3)

Non-metallic minerals are widely available worldwide, and are mostly domestically sourced. If accounted for by mass, the vast majority of the materials in this category are sand, gravel and clay used for construction, while the remainder are used either as decorative stones or for chemicals and fertilisers. ***Table four*** shows the proposed classification for non-metallic minerals. There is no clear distinction between those used for industrial purposes and those used for construction, since there is no clear and distinct differentiation between the two, and certain materials can be used for either industrial or construction purposes.

Within the baseline CE monitoring framework the accounting of non-metallic minerals is only carried out at the aggregated resource group level (digit-1) since a more detailed tracing of such flows throughout the economic system does not directly and significantly influence other flows or indicators.

***Table four*** *Non-metallic mineral flows in EW-MFA (highlighted in bold are those explicitly used or re-estimated within the current framework).*

| Level | Code | Label | DE | Import | Export | Notes |
|---|---|---|---|---|---|---|
| **1** | **MF3** | **Non-metallic minerals** | **X** | **X** | **X** | |
| 2 | MF31 | Marble, granite, sandstone, porphyry, basalt, other ornamental or building stone (excluding slate) | X | X | X | |
| 2 | MF32 | Chalk and dolomite | X | X | X | |
| 2 | MF33 | Slate | X | X | X | |
| 2 | MF34 | Chemical and fertiliser minerals | X | X | X | |
| 2 | MF35 | Salt | X | X | X | |
| 2 | MF36 | Limestone and gypsum | X | X | X | |
| 2 | MF37 | Clays and kaolin | X | X | X | |
| 2 | MF38 | Sand and gravel | X | X | X | |
| 2 | MF39 | Other non-metallic minerals | X | X | X | |
| 2 | MF3B | Products mainly from non metallic minerals | | X | X | |

## Fossil fuels (MF.4)

Fossil fuels are still the major energy carriers worldwide. They are materials formed from biomass in the geological past and comprise solid, liquid and gaseous materials. The largest share in worldwide energy production is provided via burning different kinds of coal. Petroleum resources are mainly used to provide energy, but they also serve as base materials for industrial processes (for example, for the production of organic chemical compounds and synthetic materials or fibres). Natural gas is used as an energy source for heating, cooking and electricity generation, but also as fuel for vehicles and for the manufacture of plastics and other commercially important organic chemicals.

Energy statistics and energy balances such as those reported to the IEA provide a comprehensive illustration of the supply and use of all energy carriers. In EW-MFA, the domestic material extraction of energy materials/carriers is limited to the extraction of fossil energy carriers. Hence, primary renewable energy carriers, such as hydro, wind, solar and geothermal energy are not included. ***Table five*** shows the classification of material flows for the DE of fossil energy materials/carriers. Within this CE framework, fossil fuels flows are quantified at a more granular level of detail due to the role they play in the determination of balancing items as well as inherently non-circular flows (see *'Fossil fuels use for energy and material purposes'*).

***Table five*** *Fossil Fuels flows in EW-MFA (highlighted in bold are those explicitly used or re-estimated within the current framework).*

| Level | Code | Label | DE | Import | Export | Notes |
|---|---|---|---|---|---|---|
| 1 | MF4 | Fossil energy materials/carriers | X | X | X | |
| 2 | MF41 | Coal and other solid energy materials/carriers | X | X | X | |
| **3** | **MF411** | **Lignite (brown coal)** | **X** | **X** | **X** | Used in calculation of MF.8.1.1 Step 2: Oxygen for combustion of hydrogen, MF.8.1.1 Step 3: Oxygen content, MF.8.2.1.1 Water vapour from moisture content of fuels and MF.8.2.1.2 Water vapour from the oxidised hydrogen components of fuels |
| **3** | **MF412** | **Hard coal** | **X** | **X** | **X** | |
| **3** | **MF413** | **Oil shale and tar sands** | **X** | **X** | **X** | |
| **3** | **MF414** | **Peat** | **X** | **X** | **X** | |
| 2 | MF42 | Liquid and gaseous energy materials/carriers | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **3** | **MF421** | **Crude oil, condensate and natural gas liquids (NGL)** | **X** | **X** | **X** | Used in calculation of MF.8.1.1 Step 2: Oxygen for combustion of hydrogen, MF.8.1.1 Step 3: Oxygen content, MF.8.2.1.1 Water vapour from moisture content of fuels and MF.8.2.1.2 Water vapour from the oxidised hydrogen components of fuels |
| **3** | **MF422** | **Natural gas** | **X** | **X** | **X** | |
| 3 | MF423 | Fuels bunkered (Imports: by resident units abroad); (Exports: by non-resident units domestically) | | X | X | |
| 2 | MF43 | Products mainly from fossil energy products | | X | X | |

## Trade of materials

Also covered in module one are direct physical imports (IM) and exports (EX). Within the CE monitoring framework, physical trade data is sourced directly from the IRP global material flow database and it is not re-estimated starting from economic trade data due to the large uncertainties this process can entail. For EU28 countries, Eurostat data is used instead.

A major difference in assembling physical trade accounts compared to DE accounts is that there is little risk of multiple counting of the same materials in trade accounts. For example, when assembling DE accounts, care must be taken not to include wood when it is first harvested, then again possibly as sawn wood, wood chips or pulp, and possibly a third time as paper or other wood products. This is generally not a problem for trade, as once a product is exported in one form, it cannot logically be exported again in another (at least not unless it is re-imported first). As a result of this, the scope of materials and products accounted for in the EW-MFA trade accounts is much larger. Where DE only accounts for wood as it is extracted from the environment, the trade account will seek to include processed wood and wood products.

While the scope of products in the EW-MFA trade accounts is much broader than DE accounts, no attempt is made to account for the ‘embodiment’ of natural resources in physical trade, apart from the materials that are directly, physically traded. The tonnages of materials required to produce a product, but that are not a physical part of the final traded product, are not counted for in physical trade. Accounting for embodied materials in energy is the concern of different methodologies, notably of material footprinting. Materials that enter and leave a country merely *en route* to their destination are known as transit flows, and should not be counted in either import or export accounts.

The classification scheme used for physical trade corresponds as closely as possible with the categories used for domestic material extraction, but as can be seen from **Tables 3.1 to 3.4** there are a few additional categories. This is to allow the capture of additional goods that have been processed to some degree, and even some manufactured goods where they are dominated by specific material categories. This is mainly reflected in the categories that start with 'Products mainly from' and by the category 'Other products' (MF.5). In the context of direct accounts and indicators, these compounded products can be reallocated to different material flows based on their relative shares within the resource group. However, this should not result in negative consumption figures due to a too-large negative PTB. For this reason, this reallocation step is not performed in the context of this analysis.

### 2.1.2 Module two: Raw material equivalents of trade and material footprint

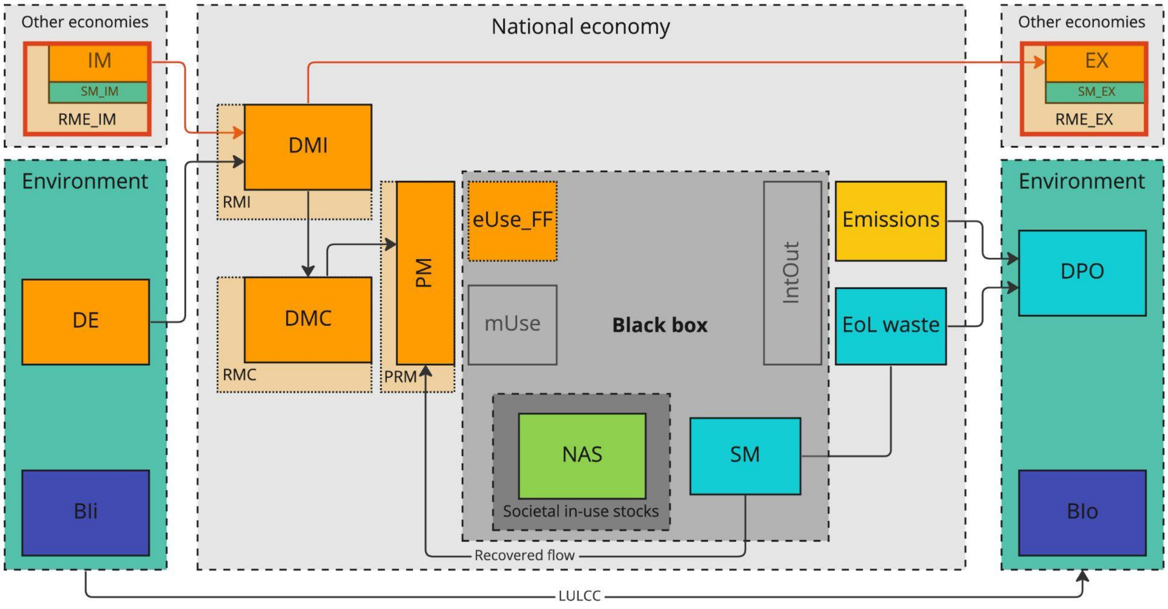

***Figure five.*** *Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues (2019) with Module two flows and indicators highlighted*

Module two focuses on a final demand perspective of material use. It measures the RME_IM and RME_EX, which are the upstream material requirements to produce direct imports and exports.

RMEs assume a similar system boundary (point of extraction and commodification) for domestic and traded materials. The Raw material Trade Balance (RTB) is established by subtracting RME_EX from RME_IM. With this information the Material Footprint of consumption (MF) or Raw Material Consumption indicator (RMC) is established. The MF attributes global material extraction (wherever it occurs and along the whole lifecycle of natural resources) to final demand in a country where:

$$MF = DE + RME\_IM - RME\_EX = DE + RTB$$

Environmental assessments generally apply a territorial—or production-based—perspective to analyse environmental pressures and impacts that occur within the borders of a country or region. Consequently, the monitoring of current environmental policies mostly relies on indicators applying this perspective. However, in the era of globalisation, supply chains are increasingly organised on the international level, thus disconnecting the location of production from final consumption. Various local environmental and social impacts in countries, which extract and process raw materials or manufactured products, are therefore often related to final demand in other countries. Production-oriented indicators cannot account for the totality of the actual environmental consequences induced by the consumption of certain products, as they do not include those impacts which are located in other world regions.

The indicator RMC (or MF) responds to this need to better understand these 'teleconnections' between distant places of production and consumption. The RMC indicator is calculated by transforming the weights of direct import and export flows into their respective RME. RME refers to the supply chain-wide primary material extractions required to produce a certain imported or exported product. For example, if a country imports a certain amount of beef, the respective RMEs refer, among other aspects, to the fodder plants that were required to feed the cattle. Or if a country imports cars, the RMEs comprise all primary raw material extractions that were required to produce the car (for example, crude iron or copper ore to produce steel or copper wires; crude oil to produce plastic parts).

The RMC (or MF) indicator thus corrects the national material balance for international trade, accounting for both domestic and foreign material extraction with the same system boundaries. Using DMC, dislocating material-intensive production from the domestic territory away to other world regions, while keeping final demand for products and services constant, will result in better apparent performance. In contrast, using RMC, net-importers cannot improve their performance just by outsourcing. At the same time, for net-exporting countries with small domestic final demand, RMC figures will be lower compared to the results for DMC.

Within the baseline CE monitoring framework, RME_IM, RME_EX and the resulting RMC (1-digit level) are sourced from release 055 of the GLORIA global environmentally-extended multi-region input-output (MRIO) database (Lenzen et al., 2022),[5] constructed in the Global MRIO Lab (Lenzen et

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[5] Lenzen, M., Geschke, A., West, J., Fry, J., Malik, A., Giljum, S., Milà i Canals, L., Piñero, P., Lutter, S., Wiedmann, T., Li, M., Sevenster, M., Potočnik, J., Teixeira, I., Van Voore, M., Nansai, K. & Schandl, H. (2022) Implementing the material footprint to

al., 2017).[6] GLORIA was built by the University of Sydney using the IELab infrastructure for the United Nations IRP in the context of the update of the material footprint accounts forming part of the UN IRP Material Flows Database Therefore, RMC figures are consistent with DE ones hosted within the same database.

## 2.2.3 Module three: Material outflows

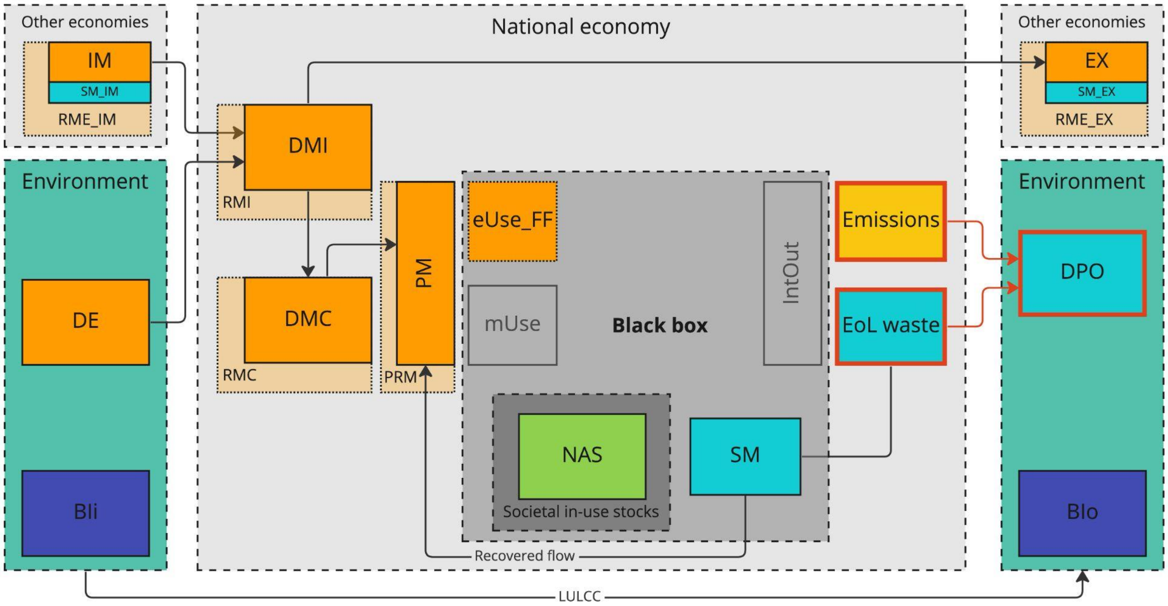

***Figure six.*** *Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues (2019) with Module 3 flows and indicators highlighted*

Module three covers the output side of EW-MFA and records the total weight of materials, extracted from the natural environment or imported, that have been used in the national economy before flowing to the environment. In **Figure six**, they are the boxes of Emissions, EoL waste, and DPO. DPO comprises all waste and emission flows that occur in the processing, manufacturing, use, and final disposal stages of the production-consumption chain. This includes:

- Emissions to air (MF.7.1);
- Industrial and household wastes deposited in uncontrolled landfills (MF.7.2 [whereas wastes deposited in controlled landfills are regarded as an addition to socioeconomic stock]):
- Emissions to water or material loads in wastewater (MF.7.3);
- Materials dispersed into the environment as a result of deliberate product use (MF.7.4) or undeliberate losses (MF.7.4.).

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measure progress towards Sustainable Development Goals 8 and 12. *Nature Sustainability, 5*, 157-166. doi:10.1038/s41893-021-00811-6

[6] Lenzen, M., A. Geschke, M.D. Abd Rahman, Y. Xiao, J. Fry, R. Reyes, E. Dietzenbacher, S. Inomata, K. Kanemoto, B. Los, D. Moran, H. Schulte in den Bäumen, A. Tukker, T. Walmsley, T. Wiedmann, R. Wood & N. Yamano (2017) The Global MRIO Lab - charting the world economy. , 158-186. doi:10.1080/09535314.2017.1301887

The first three categories (MF.71 to MF.73) refer to the three gateways through which materials are initially released to the environment, i.e. air, land and water, commonly referred to as emissions and waste in official statistics. The remaining two categories are residual categories, not fully attributable to a specific gateway but attributed to a type of release, dissipative or deliberate. Recycled material flows are considered flows within the economy (for example, of metals, paper, glass) and thus are not considered as outputs (nor inputs).

Common DPO accounts—as described above—follow a ‘bottom-up’ approach, which derives DPO data from waste and emission statistics. Consequently, DPO categories are oriented by gateway and type of release. However, there are still open issues and challenges to be solved, for example, inconsistent system boundaries between EW-MFA and waste/emission statistics and incomplete coverage of waste statistics. In recent years, biophysical stock accounts and circular economy initiatives have led to a different approach that has put more emphasis on flows within the socioeconomic system including recycling and reuse, and thus requires consistency between inputs and outputs as well as stocks. These studies require a clear structuring of DPO along material categories in order to consistently close the material balance. Waste statistics, however, do not always allow for the necessary detail and inconsistencies between input data and output data can prevent successfully closing the balance. To avoid these problems, methods are developed that consistently link input and output flows by focusing on corresponding material conversion processes and that take material stocks into account (this is the domain of ‘top-down modelling’). For further information on methods and empirical data see, for example, Haas and colleagues (2015).

## Emissions to air (MF.7.1)

Emissions to air are gaseous or particulate materials released to the atmosphere from production or consumption processes in the economy. In EW-MFA emissions to air comprise 14 main material categories at the 2 digit level, as shown in ***Table six.***

***Table six*** *Emissions to air flows in EW-MFA (highlighted in bold are those explicitly used or re-estimated within the current framework).*

| Level | Code | Label | Notes |
|---|---|---|---|
| **1** | **MF71** | **Emissions to air** | |
| **2** | **MF711** | **Carbon dioxide ($CO_2$)** | |
| **3** | **MF7111** | **Carbon dioxide ($CO_2$) from biomass combustion** | Only available for EU28 countries from env_ac_dpo |
| **3** | **MF7112** | **Carbon dioxide ($CO_2$) excluding biomass combustion** | Cross-checking includes EDGARv6.0, PRIMAPHIST v2.3.1, Eora v199.82 and Global Carbon Project |
| **2** | **MF712** | **Methane ($CH_4$)** | Cross-checking includes PRIMAPHIST v2.3.1, Eora v199.82 |
| **2** | **MF713** | **Dinitrogen oxide ($N_2O$)** | |

| | | | |
|---|---|---|---|
| **2** | **MF714** | **Nitrous oxides (NO$_x$)** | Only available from Eora v199.82 |
| 2 | MF715 | Hydrofluorocarbons (HFCs) | |
| 2 | MF716 | Perfluorocarbons (PFCs) | |
| 2 | MF717 | Sulphur hexafluoride | |
| **2** | **MF718** | **Carbon monoxide (CO)** | Only available from Eora v199.82 |
| 2 | MF719 | Non-methane volatile organic compounds (NMVOC) | |
| **2** | **MF71A** | **Sulphur dioxide (SO$_2$)** | Only available from Eora v199.82 |
| 2 | MF71B | Ammonia (NH$_3$) | |
| 2 | MF71C | Heavy metals | |
| 2 | MF71D | Persistent organic pollutants (POPs) | |
| 2 | MF71E | Particles (PM10, Dust) | |
| 2 | MF71F | Other emissions to air | |

** Note: All of the emissions accounted for are used in the estimation of MF.8.1.1 Oxygen for combustion processes.*

The primary source of data for compiling emissions are the Air Emission Accounts (AEA). AEAs record flows of gaseous and particulate materials (six greenhouse gases including CO$_2$ and seven air pollutants) emitted by the economy into the atmosphere. AEAs are consistent with the supply and use framework of the system of national accounts, broken down into 64 emitting industries plus households. By following the national accounts' residence principle, emissions by resident economic units are included even if these occur outside the territory (for example, resident airlines and shipping companies operating in the rest of the world). For this reason, AEAs are used in the compilation of environmental extensions for input-output tables.

Within the context of the global CGR monitoring framework, emissions to air were sourced from the environmental extension of the global multi-regional input-output database Eora. This database included information from different datasets which allowed for cross-checking and complementing partial information (see **Table six** for more detail on gases and pollutants covered by each dataset). CO$_2$ was the only gas covered by every dataset. A meta-analysis revealed a good degree of alignment in terms of overall global emissions, however considerable variations were found for individual countries' figures. The only dataset that covered extensively several greenhouse gases (Eorav199.82) was found to have disproportionately high values across all gases for small countries and to result in unrealistically high figures when calculating balancing items related to the combustion process (*see 'Module 4: Material balance and stock accounts'*). Despite covering only CO$_2$ emissions, the EDGAR v6.0 dataset[7] was deemed the most accurate and reliable of the datasets and selected as the source of

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[7] Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Lo Vullo, E., Solazzo, E., Monforti-Ferrario, F., Olivier, J., & Vignati, E. (2021): EDGAR v6.0 greenhouse gas emissions. European Commission. Retrieved from: [EDGAR - The Emissions Database for Global Atmospheric Research (europa.eu)]

data in this category. All datasets were found to fall short on reporting on $CO_2$ from biomass combustion (MF7.1.1.1) and additional data sources were used to fill in the gaps. Unfortunately, this was possible only for EU28 countries using the env_ac_dpo dataset which systematically reports this item. For all the other world countries, $CO_2$ from biomass combustion (MF7.1.1.1) could not be estimated and was replaced with the application of correction factors to balancing items.

As mentioned in Chapter 2, air emissions constitute the largest part of DPO and can be used to estimate the rest of the category using information on their relative share. In this analysis, such information could only be found for EU28 countries through Eurostat's EW-MFA handbook[8] and was deemed representative only for High Income Countries (HIC). Countries belonging to the other income groups may present a very different DPO profile, for instance one where the volume of uncontrolled landfill disposal (MF.7.2) takes up a much larger part of DPO. For countries belonging to these groups, correction factors and other assumptions were therefore applied to other elements of DPO such as uncontrolled disposal (MF.7.2.) and to the output balancing item (BIo).

### MFA conventions

*Oxygen content.* Oxygen is drawn from the atmosphere during fossil-fuel combustion and other industrial processes. Overall, oxygen uptake from the atmosphere during production and consumption is substantial and accounts for approximately 20% by weight of material inputs to industrial economies. In EW-MFA, this atmospheric oxygen is not included in the totals on the input side (DE, DMC and DMI) but it is included in the totals on the output side (DPO). The reason is that oxygen is a constituent part of the pollutants and greenhouse gases, and these emissions are usually reported and analysed with their oxygen content. To arrive at a full mass balance, the missing oxygen on the input side is reported as an input balance item.

## Waste landfilled (MF.7.2)

By definition, waste refers to materials that are of no further use to the generator for production, transformation or consumption. Waste may be generated during the extraction of raw materials, during the processing of raw materials to intermediate and final products, during the consumption of final products, and in the context of other activities.

In industrialised countries, most waste flows are deposited to controlled landfills, which are subject to management and treatment. A landfill is defined as a deposit of waste into or onto land, both in the form of a specially engineered landfill and of temporary storage for over one year on a disposal site. A controlled landfill is one whose operation is subject to a permit system and to technical control procedures under the national legislation in force. For the purposes of EW-MFA, waste flows into controlled landfills are considered flows within the socioeconomic system and are not accounted for in DPO. Only waste disposed of outside of these controlled sites should be accounted for, i.e. uncontrolled land deposits or 'wild' open dumping. The respective quantities are considered small in industrialised countries due to strict regulations, but can be significant in other countries. In

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[8] Item 298 in EUROSTAT. (2018). *Economy-wide material flow accounts HANDBOOK 2018 edition*. doi.org:10.2785/158567

contrast, controlled, i.e. maintained, landfills must be considered part of the socioeconomic system. Therefore, wastes deposited in controlled landfills should be accounted for as an addition to stock.

While this distinction between controlled and uncontrolled landfills is accepted on conceptual grounds, there are reasons to take account of controlled landfills as a memorandum item. First, it might be difficult to separate controlled from uncontrolled landfills in national statistics. In that case, information on both might help in estimating a time series of waste to uncontrolled landfills. Second, data on total amount of waste produced provides valuable information for estimations in the DPO data compilation process (for example, estimations of DPO to air and water from landfills, etcetera) as well as in material stock accounts. It might nourish secondary analysis, for example on recycling and reuse rates, serving as a reference for policies addressing environmental issues related to waste generation and treatment. Within the context of this framework and analysis, net material additions to controlled landfills are accounted for but excluded from the indicator NAS.

**Construction and demolition waste** includes rubble and other waste material arising from the construction, demolition, renovation or reconstruction of buildings or parts thereof, whether on the surface or underground. It consists mainly of building materials and soil, including excavated soil. It includes waste from all origins and from all economic sectors. For the requirements of EW-MFA, special attention has to be paid to avoid double counting but also to include all relevant flows to arrive at a comprehensive data set. This applies, in particular, to excavated soils: on the input side, excavated soil or earth represents unused domestic material extraction, which is not part of the direct material inputs to the economy. Consequently, excavated soil has to be omitted from the domestic processed output of the economy as well. Only used parts of excavated soil need to be included both on the EW-MFA input side as well as the output side.

Within the CE monitoring framework, disposal of waste to landfill and more in general municipal and industrial waste collection and treatment are estimated through a custom procedure. It combines primary data gathering via a survey and desk research with extrapolations based on waste generation intensities and monetary data on waste management activities. The procedure is extensively explained in chapter *'Waste generation, collection and treatment'*. To distinguish between controlled and uncontrolled disposal, the following treatment types are considered:

- Controlled landfill (specified)
- Unspecified landfill (uncontrolled)
- Open dump (uncontrolled)
- Sea dump (uncontrolled)
- Sanitary landfill with gas system (controlled)

Furthermore, 'Other' waste treatment, 'Unaccounted' and 'Uncollected' waste are all assumed to be disposed of in an uncontrolled way.

## Emissions to water (MF.7.3)

Emissions to water are materials which cross the boundary from the economy back into the environment with water as a gateway. They include substances and materials released to natural waters by human activities after or without passing wastewater treatment. This category more or less includes outflows from municipal or industrial sewage treatment plants.

Accounting for only 1%, emissions to water represent the smallest category of DPO (Matthews et al., 2000)[9] and are therefore not explicitly accounted for within the CE monitoring framework.

## Dissipative use of products (MF.7.4)

Some materials are deliberately dissipated into the environment because dispersal is an inherent quality of product use or quality and cannot be avoided (Matthews et al., 2000). Products used in a dissipative role are listed in ***Table seven***.

***Table seven.*** *Dissipative flows in EW-MFA (highlighted in bold are those explicitly used or re-estimated within the current framework, in italic those for which a provision for future estimation is made).*

| Level | Code | Label | Notes |
|---|---|---|---|
| **1** | **MF74** | **Dissipative use of products** | |
| *2* | *MF741* | Organic fertiliser (manure) | Partially estimated from livestock heads and metabolic parameters, but not included |
| 2 | MF742 | Mineral fertiliser | |
| *2* | *MF743* | Sewage sludge | - |
| *2* | *MF744* | Compost | - |
| 2 | MF745 | Pesticides | |
| 2 | MF746 | Seeds | |
| 2 | MF747 | Salt and other thawing materials spread on roads | |
| 2 | MF748 | Solvents, laughing gas and other | |

Within the CE monitoring framework, none of the most relevant digit-2 flows are explicitly calculated, however a provision for future estimation is made. These flows are organic fertiliser (manure, MF.7.4.1), sewage sludge (MF.7.4.3) and compost (MF.7.4.4) and further described in the sub-sections below. As a provisional solution, the volume of agricultural waste is included as a proxy for this category under the assumption that a large part of it consists of crops residues, organic fertiliser and compost applied to land. Correction factors are applied to the different income groups to account for the share of agricultural waste that is not re-applied to land as an amendment, but rather open burned in fields. **Table eight** summarises the correction factors applied and the

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[9] Matthews, E., C. Amann, M. Fischer-Kowalski, S. Bringezu, W. Hüttler, R. Kleijn, Y. Moriguchi, et al. (2000). The weight of nations: material outflows from industrial economies. Washington D.C.: World Resources Institute. Retrieved from:

assumptions behind them. It is important to stress that such correction factors are assumed mostly to compensate for extremely low or negative figures for NAS resulting from the balancing identity, and are not based on actual statistics or literature.

***Table eight.*** *Correction factors for agriculture waste as a proxy for Dissipative Uses (MF.7.4).*

| Income group | Correction factor | Note |
|---|---|---|
| High-income countries (HIC) | 0 | Agricultural waste is not used as proxy for MF.7.4 because the correction factor is already applied to MF.7.1.1.2 |
| Upper-medium income countries (UMC) | 1 | 100% of agricultural waste is used as proxy for MF.7.4 |
| Lower-medium income countries (LMC) | 0.5 | 50% of agricultural waste is used as proxy for MF.7.4 under the assumption that the remaining 50% is incinerated |
| High-income countries (HIC) | 0 | 0% of agricultural waste is used as proxy for MF.7.4 under the assumption that the remaining 100% is incinerated |

## 2.2.4 Module four: Material balance and stock accounts

Module four is about the ‘physical growth of the economy’, i.e. the quantity (weight) of new construction materials accumulating in buildings and infrastructure, as well as materials used for durable goods with a lifetime of more than one year such as cars, industrial machinery and household appliances. This information is a first step towards physical stock accounts, as it allows us to calculate additions to and outflows from stocks, and is a proxy for potential future material flows that may become secondary raw materials or waste. NAS are therefore calculated as a statistical balance between inputs and outputs using information from modules one and three (see **Figure seven**).

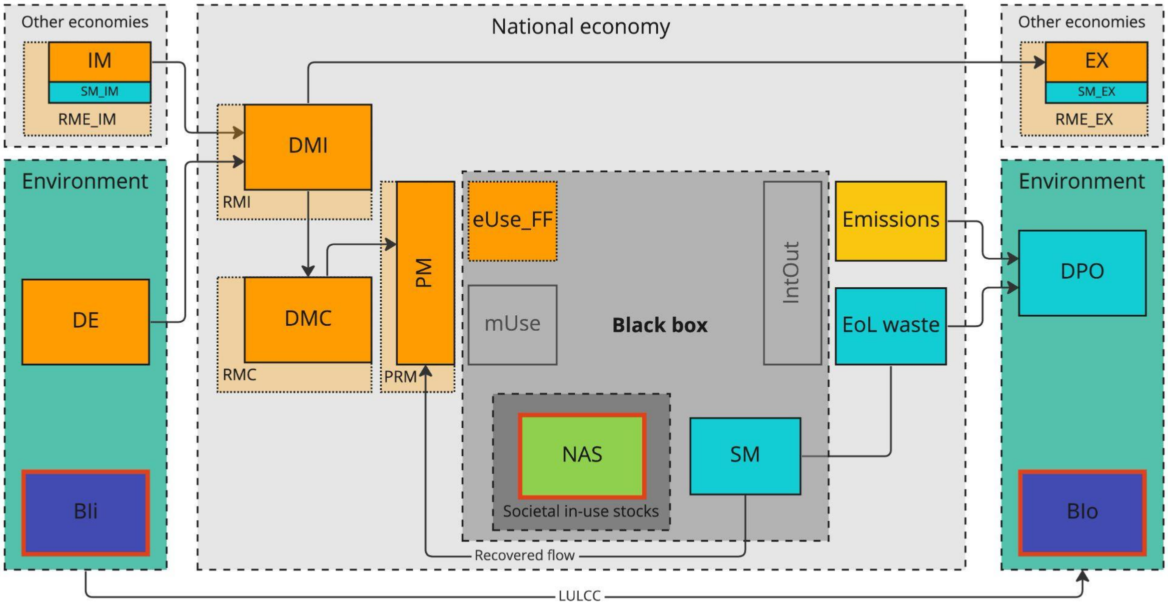

***Figure seven.*** *Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues et al. (2019) with Module four flows and indicators highlighted.*

Although bulk water and air flows are excluded from EW-MFA, material transformations during processing may involve water and air exchanges which significantly affect the mass balance. Balancing Items (BIs) are estimations of these flows, which are not part of DE, DPO or NAS, because they are not included in the definition of these flows. Balancing items mostly refer to the oxygen demand of various combustion processes (both technical and biological ones), water vapour from biological respiration, and from the combustion of fossil fuels containing water and/or other hydrogen compounds. In the compilation of these flows, only a few quantitatively important processes are taken into account and the flows are estimated using generalised stoichiometric equations. **Table nine** summarises the BIs included in standard EW-MFA.

***Table nine.*** *Balancing Items included in EW-MFA (highlighted in bold are those explicitly used or re-estimated within the current framework).*

| Level | Code | Label | Notes |
|---|---|---|---|
| 1 | MF81 | Balancing items: input side | |
| **2** | **MF811** | **Oxygen for combustion processes** | Estimated by applying average coefficients from the EW-MFA Questionnaire to air emissions (MF.7.1 data) |
| **2** | **MF812** | **Oxygen for respiration of humans and livestock; bacterial respiration from solid waste and wastewater** | Estimated by applying average coefficients from the EW-MFA Questionnaire to livestock data from FAOSTAT and population data from the |

| | | | |
|---|---|---|---|
| | | | UN Population Prospects |
| 2 | MF813 | Nitrogen for Haber-Bosch process | |
| 2 | MF814 | Water requirements for the domestic production of exported beverages | |
| 1 | MF82 | Balancing items: output side | |
| **2** | **MF821** | **Water vapour from combustion** | Estimated by applying average coefficients from the EW-MFA Questionnaire to DMC at 4-digit level from IRP |
| **2** | **MF822** | **Gases from respiration of humans and livestock, and from bacterial respiration from solid waste and wastewater** | Estimated by applying average coefficients from the EW-MFA Questionnaire to livestock data from FAOSTAT and population data from the UN Population Prospects |
| **2** | **MF823** | **Excorporated water from biomass products** | Estimated by applying average coefficients from the EW-MFA Questionnaire to DMC at 4-digit level from IRP |

A limitation of organising environmental statistics employing an MFAapproach that includes inputs and outputs is the inability for coherence checks of individual data sets by establishing a material balance of inputs and outputs. In principle, the sum of inputs equals the sum of outputs corrected for changes in stock. The material balance is established by adding domestic material extraction, imports, NAS and balancing items, which equal exports, DPO and balancing items.

$$DE + IM + BIi = EX + DPO + BIo + NAS$$

In practice, NAS would be calculated as the residual of the material balance identity. As a consequence, NAS would contain all calculation errors. It is possible to calculate material stock and changes in material stock directly using a combination of bottom-up and top-down accounting principles which would allow to run quality checks on the material balance. The material balance also reveals important relationships among the different indicators and provides a sense of whether an economy invests in establishing physical stocks or is fuelled by a large throughput of materials.

Oxygen for combustion processes (MF.8.1.1) is by far the quantitatively most important balancing item on the input side (ca. 90%)[10] while water vapour from combustion (MF.8.2.1) is by far the quantitatively most important balancing item on the output side (more than 60%).[11] When including also ‘MF.8.1.2 Oxygen for respiration of human and livestock; bacterial respiration from solid waste

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[10] Item 478 in EUROSTAT. (2018). *Economy-wide material flow accounts HANDBOOK 2018 edition*. doi:10.2785/158567

[11] Item 501 in EUROSTAT. (2018). *Economy-wide material flow accounts HANDBOOK 2018 edition*. doi:10.2785/158567

and wastewater' and 'MF.8.2.2 Gases from respiration of humans and livestock, and from bacterial respiration from solid waste and wastewater', more than 95% of the balancing items on both sides can be estimated.

Within the CE monitoring framework, the compilation tool provided within the EW-MFA questionnaire is used to estimate all the balancing items with reasonable accuracy based on the available data, data already reported in the accounts, and data provided within the tool. In particular, data on the DMC of biomass and fossil fuels products at the digit-3 and digit-4 level can serve as the initial data source for a reasonably robust estimation of combustion-related items. The FAOSTAT crops and livestock products dataset can serve as the initial data source for a reasonably robust estimation of respiration-related items. For a detailed description of the stepwise approach to the calculation of balancing items, refer to the Eurostat MFA Handbook.

## 2.2.5 Module five: Internal flows and LULCC

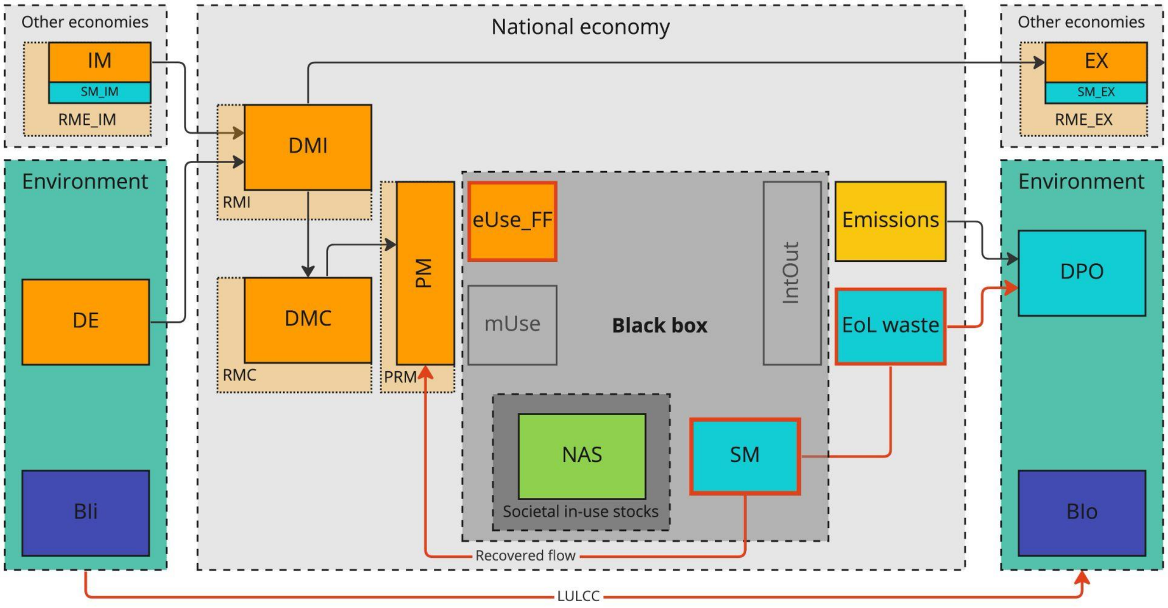

***Figure eight.*** *Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues (2019) with Extra Module flows and indicators highlighted.*

Major material uses, as well as recycled flows, are considered material flows within the economy and thus are not considered as outputs (nor inputs). LULCC, on the other hand, are considered as a flow from the environment (land compartment) to the environment (air compartment) and are therefore also not included in EW-MFA as they do not cross the economy border. The CE monitoring framework takes a novel approach by including flows of secondary materials and emissions from land use to allow for the monitoring of socioeconomic and ecological loop closing in national economies (Haas et al., 2015).

## Waste generation, collection and treatment

Recycled flows, hereafter referred to as secondary materials (SM), refer to materials recovered through all forms of recycling, reuse and remanufacturing but also downcycling (for example, backfilling) or cascadic use. In this document, the two terms are used interchangeably, as a study carried out by Eurostat concluded that the input to recovery plants is an acceptable proxy for the output from recovery plants.[12] The monitoring framework was built upon a systems and material perspective of the economy, and based the assessment as far as possible on statistical data from national (i.e. statistical offices) and international (i.e. FAOSTAT, IRP) official environmental reporting systems. While recovered materials were either reported in waste statistics or could be directly quantified, this was not possible for other CE strategies such as the extension of product lifetimes, reuse and remanufacturing, or sharing. In our framework, these strategies would result in an increase of the service lifetime of in-use stocks and potentially a stabilisation of in-use stock growth, as indicated by the NAS. Thus, even though these strategies are difficult to measure directly, their effects on the size of inflows, additions to stock, and outflows can be substantial and are observable via this CE monitoring framework.

Tracing the transformation of materials from their extraction until their end-of-life requires the integration of EW-MFA and waste statistics. The latter, however, are lacking in many countries and need to be estimated based on available data. One of the most comprehensive databases on waste management is the What-a-Waste (WaW) v2.0 database by the World Bank (Kaza et al., 2018).[13] This was used as the starting point for the estimation of waste generation, collection and treatment for all countries in the world. While the main advantage of this database is the wide coverage across countries and indicators, the completeness and time coverage of the data points can vary greatly and requires extensive data gaps filling and extrapolation. We first provide a general description of the database and then present the step-by-step procedure used to improve it.

The WaW database compiled solid waste management data from various sources and publications for analytical purposes. The database mainly focuses on Municipal Solid Waste (MSW), which encompasses residential, commercial and institutional waste. Special Waste (SW), which encompasses industrial, medical, hazardous, electronic, and construction and demolition waste is also compiled to the extent possible. Actual values rather than estimates or projections are prioritised even if that requires the use of older data. The data reported are predominantly from 2011–17, although overall data span about two decades. Within a single country, data availability may cut across several years. Furthermore, when a year range is reported in the original source, the final year of the range is provided in this document's data set. Overall, this translates into highly fragmented and heterogeneous data points from a temporal perspective. Waste collection coverage data are reported according to multiple definitions: amount of waste collected, number of households served, population served or geographic area covered. Waste treatment and disposal

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[12] Circular Material Use Rate calculation method 2018 edition, Eurostat

[13] Kaza, Silpa; Yao, Lisa C.; Bhada-Tata, Perinaz; Van Woerden, Frank. (2018). *What a waste 2.0 : a global snapshot of solid waste management to 2050*. Washington, DC: World Bank. Retrieved from:

includes recycling, composting, anaerobic digestion, incineration, landfilling, open dumping and dumping in marine areas or waterways. Given the variability of types of landfills used, data were collected for three types of landfills: sanitary landfills with landfill gas collection systems, controlled landfills that are engineered but for which landfill gas collection systems do not exist or are unknown and uncategorised landfills. In cases where disposal and treatment percentages did not add up to 100% or where a portion of waste is uncollected, the remaining amount is categorised as waste 'unaccounted for.' Waste not accounted for by formal disposal methods, such as landfills or recycling, was assumed to be dumped. Waste that is disposed of in waterways and that is managed in low- and middle-income countries in 'other' manners was also assumed to be dumped. Reported collection and treatment rates refer to MSW only.

Hereafter, the step-by-step approach for data gaps filing and extrapolation is presented:[14]

- *Step one—Primary data collection and integration:* Two approaches were used to perform an initial update of waste generation and treatment based on the collection of primary data and statistics. For European countries, env_wasmun,[15] env_wasgen[16] and env_wastrt[17] datasets for the target year were used to update MSW and SW generation and treatment, respectively. The env_wasgen dataset was reformatted to the five SW categories recorded by the WaW database based on the nature of the waste stream rather than the generating sector. The env_wastrt dataset was reformatted under the following assumptions: 1) All landfilled waste is considered to be disposed of in a controlled way, 2) Recycling includes also backfilling and 3) Waste from unused extraction (dredging spoils and soils) was excluded. For non-European countries, a waste data collection survey was developed and distributed to the statistical offices and environmental agencies of the major world economies. Countries for which useful information was gathered include India, United States, China, Brasil, Indonesia, Russia, Mexico, Japan, Nigeria, Turkey, Pakistan, Thailand, Canada, South Africa, South Korea and Australia;

- *Step two—MSW generation adjustment:* This analysis assumes that MSW generation grows primarily based on population. Time series of population from the UN's World Population Prospects[18] were used to calculate MSW generation intensities (tonnes per capita) for the source years (various) and multiplied by the historical population level for the target year. If MSW data were available for 2018, the original data were used;

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[14] Target year refers to the baseline year for which it was decided to estimate the indicator framework based on data availability across all databases employed in the analysis. The target year for the global CGR 2023 is 2018.

[15] Eurostat. (n.d.). Municipal waste by waste management operations. Retrieved from: Eurostat website

[16] Eurostat. (n.d.). Municipal waste by waste management operations. Retrieved from: Eurostat website

[17] Eurostat. (n.d.). Municipal waste by waste management operations. Retrieved from: Eurostat website

[18] UN World Population Prospect 2019 extracted from File POP/1-1: Total population (both sexes combined) by region, subregion and country, annually for 1950-2100 (unit thousands persons)

- *Step three—SW generation adjustment*: This analysis assumes that SW generation grows primarily based on sectoral gross output.[19] Time series of agricultural, construction and manufacturing industry output from the Eora database were used to calculate SW generation intensities (tonnes per million €) for the source years (various) and multiplied by the historical gross sectoral output for the target year. Hazardous waste was assumed to be linked to the manufacturing industry output. E-waste and medical waste were instead assumed to be linked to population and extrapolated based on historical population levels. If SW data were available for 2018, the original data were used;

- *Step four—Gap filling for SW data:* Individual countries were classified into income groups. Average SW generation intensities for each group and waste category were calculated. The averages were calculated as the sum of available waste volumes (after removing outliers) divided by the sum of the respective sector's gross output. Countries for which no primary data were available were attributed the average waste generation intensity of their income group and multiplied by the historical gross output for the target year;

- *Step five—Gap filling for collection rates data:* Weighted average collection rates were calculated for each income group and used to estimate the amount of generated waste that is treated in countries for which no primary data was available. Collection rates as a share of total population were used for the estimation of treated MSW while collection rates as a share of total waste generation were used for the estimation of treated SW. *It is important to note that for the lack of more detailed data, collection rates for MSW were applied to SW fractions under the assumptions that the two types of waste were collected alike.* From this step onwards, agricultural waste was excluded from the calculations to avoid overlap and double counting between the socioeconomic and ecological cycling indicators (see '*Headline Indicators*');

- *Step six—Treatment rates data gaps filling:* Weighted average waste treatment rates were calculated for each income group and used to estimate waste treatment rates in countries for which no primary data was available. *It is important to note that for the lack of more detailed data, treatment rates for MSW were applied to SW fractions under the assumptions that the two types of waste were treated alike.* This was the case for all but European countries for which instead specific rates for MSW and SW were available;

- *Step seven—Calculation of scaling factors for waste treatment rates:* Time series of gross output for waste treatment sectors were gathered from the Input-Output database Exiobase v3.8.1.[20] Based on the source year for which mass-based waste treatment rates were available, (monetary-based) scaling factors were calculated as the ratio between gross output in the source and target year. Matching tables of WaW treatment types and countries

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[19] Gross Output is defined as the measure of total economic activity in the production of new goods and services in an accounting period. In the context of this analysis, it is calculated from Input-Output Tables as the sum of interindustry (or intermediate) and final sales by sector.

[20] Stadler, K., Wood, R., Bulavskaya, T., Södersten, C., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J., Theurl, M., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K., … & Tukker, A. (2021). EXIOBASE 3 (3.8.1) [Data set]. Zenodo. doi:10.5281/zenodo.4588235

to Exiobase waste treatment sectors and regions were developed and the monetary-based scaling factors were used to scale the mass-based waste treatment rates. For instance, if the aggregated gross output of all re-processing sectors of a country in Exiobase increased by 10% between the source and target year (i.e. a scaling factor of 1.1), then the physical volume of the recycling flows also increased by 10%. *It is important to note that this assumes full linearity between the monetary gross output of a waste treatment sector and the physical volume treated by the same. This assumption was not empirically tested*. If waste treatment rates were available for 2018, the original data were used;

- *Step eight—Recalculation of waste treatment rates:* The scaling factors were used to scale treated waste volumes and treatment rates were re-estimated. The updated rates were applied to the original waste generation figures to avoid a change in total waste generation compared to the baseline figures.

As a result of this process, a comprehensive and fairly harmonised database covering MSW and SW generation, collection and treatment and suitable for the estimation of recycling as well as controlled and uncontrolled disposal flows was developed. Despite the best efforts to guarantee the quality and reliability of the figures in the database, they should be used with great care due to the extensive use of assumptions and the shortcomings underlying this approach. The main limitations and avenues for future improvement are listed below:

- The choice of population as the only determinant of change in MSW generation could be improved by the use of a better factor, such as, for instance, GDP per capita.
- The choice of gross output and more generally monetary data to extrapolate SW has many shortcomings such as the exclusion of the waste generation by the informal economy and the overestimation of waste generation for geographically small countries with high GDP. Agricultural waste generation could be better estimated using data from FAOSTAT (see 'Biomass (MF.1)' and 'Dissipative use of products (MF.7.4)') while construction and demolition waste using a dynamic stock and flow model.
- The application of the same collection and treatment rates for MSW and SW could be improved by the use of specific rates for each type.
- The use of waste treatment sectors' gross output in the development of scaling factors for waste treatment rates could be improved by the selection of a more specific factor such as investment in waste treatment technologies.

## Fossil fuels use for energy and material purposes

In the original CE monitoring framework by Mayer and colleagues (2019), all primary and secondary materials consumed are accrued in the throughput indicator Processed Materials (PMs) are assigned to either material (mUse) or energetic use (eUse) through the use of specific coefficients. These were developed for each resource group by looking at major uses of different materials within each group and complemented with external sources and assumptions. This is a key step in the quantification of key flows for some headline indicators, including GAS and D&D for the calculation of NAS. Since within the current framework, NAS is estimated as the residual item of the material balance identity (see *'Material Balance and Stocks Accounts'*), we only estimate the mUse and eUse of the fossil fuels resource group as these flows are used in the calculation of the Non-Circular Inputs (NCI) indicator (see *'Headline Indicators'*).

Major uses of fossil fuels cannot be deduced directly from the DMC even at the most detailed 3-digits level. When detailed Physical Energy Flow Accounts are not available, to split the use of fossil fuels into either eUse or mUse we make use of energy balances. The UNSTAT energy balances cover the supply and use of nine different energy carriers, both material and not, for all countries in the world. The item 'Non energy use' within 'Final energy demand' is assumed to be a good proxy for the material use of fossil fuels, so that the share of material uses is calculated as the ratio of 'Non energy use' to the 'Total primary energy supply' (TPES) of a country. Only material energy carriers within TPES are considered (this excludes nuclear energy, heat and electricity) and converted from energy (TJ) to material (ton) units using average calorific values from the IEA Energy Statistics Manual.[21] The typical use of fossil fuels for energy purposes ranges between 90–95% and this share is used to split the DMC of fossil fuel into either mUse and eUse.

## Land-use and land-cover change emissions

LULCC emissions are central in the determination of the Ecological Cycling Potential (see *'Headline Indicators'*). However, estimates vary strongly between different datasets and the methodologies used can be very different. There are also changes in methodologies within datasets, which again introduce sudden emissions changes into time series. To gather country-by-country data on LULCC, we used the PRIMAP-hist v2.3.1 database[22] and adjusted the figures from a territorial- to a consumption-based principle based on the work by Bhan and colleagues (2021)[23]. This adjustment is crucial for countries in tropical regions, such as the LATAM region, because the majority of positive LULCC emissions originate from deforestation (and other practices occurring in these regions) as a result of final consumption happening abroad.

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[21] IEA, EUROSTAT & OECD. (2004). *Energy statistics manual*. Retrieved from: Eurostat website

[22] Gütschow, J. & Pflüger, M. (2021). The PRIMAP-hist national historical emissions time series (1850-2019) v2.3.1. Zenodo. doi:10.5281/zenodo.5494497

[23] Bhan, M., Gingrich, S., Roux, N., Le Noë, J., Kastner, T., Matej, S., ... & Erb, K. H. (2021). Quantifying and attributing land use-induced carbon emissions to biomass consumption: A critical assessment of existing approaches. *Journal of Environmental Management, 286*, 112228. doi:10.1016/j.jenvman.2021.112228

## 2.3 Headline indicators

The indicators presented here are based on the EW-MFA framework presented in the previous chapters and are taken from the work of Mayer and colleagues (2019) and previous research.[24][25][26] It distinguishes between scale indicators, which provide measures for the overall size of the socioeconomic metabolism (SEM), and metabolic rates, which measure socioeconomic and ecological cycling relative to input and output flows. Providing independent measures for flows on both the input and output sides is necessary because of the delaying effect that in-use stocks of materials have on output flows. Three pairs of indicators are used to measure the scale of material and waste flows:

1. DMC measures all materials directly used in a national production system, and is regarded as a proxy for the aggregated pressure the economy exerts on the environment. DPO measures the total amount of outflow of wastes and emissions from a national economy;

2. In order to be able to capture displacement effects related to imports and exports, a consumption-based indicator was included in the form of RMC, or material footprint;[27] a measure of global material use associated with domestic final consumption. No corresponding indicator on the output side was available at the moment of writing;

3. The final pair of scale indicators takes the flow of secondary materials into account, which is not presented in conventional EW-MFA indicators: On the input side, the indicator PM (or PRM) measures the sum total of DMC (or RMC) plus the input of secondary materials, and on the output side, IntOut measures wastes and emissions before materials for recycling and downcycling are diverted. Even in industrial countries, stocks are growing and interim outflows in a given year are much smaller than the amount of PM in that year, which further inhibits loop closing at present, producing a delaying effect for potential recycling of these materials after their lifetime has ended in the future.

Five pairs of metabolic rates were proposed as indicators for the degree of loop closing that has been achieved. These measure material flows relative to interim flows PM and IntOut:

1. The socioeconomic cycling rates measure the contribution of secondary materials to PM (**Input Socioeconomic Cycling rate [ISCr]**)—calculated based on both DMC and RMC—and the share of IntOut that is diverted to be used as secondary materials (**Output**

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[24] Haas, W., F. Krausmann, D. Wiedenhofer, & M. Heinz. (2015). How circular is the global economy? An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. *Journal of Industrial Ecology 19*, 765– 777. doi:10.1111/jiec.12244

[25] Kovanda, J. (2014). Incorporation of recycling flows into economy-wide material flow accounting and analysis: A case study for the Czech Republic. *Resources, Conservation and Recycling 92*(Supplement C), 78–84. doi:10.1016/j.resconrec.2014.08.006

[26] Nuss, P., G.A. Blengini, W. Haas, A. Mayer, V. Nita, & D. Pennington. (2017). *Development of a Sankey diagram of material flows in the EU economy based on Eurostat data, EUR 28811 EN*. JRC technical reports. Luxembourg: Publications Office of the European Union. doi:10.2760/362116

[27] Wiedmann, T.O., H. Schandl, M. Lenzen, D. Moran, S. Suh, J. West, & K. Kanemoto. (2015). The material footprint of nations. *Proceedings of the National Academy of Sciences, 112*(20), 6271–6276.

**Socioeconomic Cycling rate [OSCr]**). Differently from Mayer's model, in this accounting framework, secondary materials do not originate exclusively from discarded material stocks. For instance, recycled waste from material processing and manufacturing (for example, recycled steel scrap from autobody manufacturing), while being considered an industry internal flow, was accounted for as secondary material as long as it is legally declared as waste. Energy recovery (electricity, district heat) from the incineration of fossil or biomass waste was not considered as recycling since it does not generate secondary materials;

2. For biomass, derived circularity indicators are more intricate. Due to the absence of a clear definition and recognised criteria for sustainably produced biomass, as well as a lack of related data, we use the share of primary biomass (i.e., biomass DMC/RMC) in PM/PRM for the **Input Ecological Cycling rate potential (IECrp)** and the share of DPO from biomass in IntOut for the **Output Ecological Cycling rate potential (OECrp)**. Because ecological cycling is a crucial part of CE strategies, data and adequate indicators have to be developed so that socioeconomic and ecological cycling rates indicate the overall circularity of an economy. So far, neither robust criteria nor comprehensive indicators are available that enable the identification of the fraction of biomass production that qualifies as sustainable ecological cycling. As a first approximation for renewable biomass, we only consider carbon neutral biomass. We interpret this as a minimum requirement: more comprehensive assessments should be developed. It can therefore be stated that the IECr relates to the circularity of terrestrial carbon stocks. To estimate the flow of primary biomass that cannot be regarded as carbon neutral, we deducted the biomass related net-emissions of carbon from LULCC from socioeconomic biomass flows, consistently re-estimated as tonnes of carbon content. To calculate the amount of circular and non-circular biomass, the flow of primary biomass through the economy was converted into dry matter using appropriate information on moisture content of different biomass types, and further into C assuming a carbon content of 50% in dry matter biomass. The share of biomass that does not qualify for ecological cycling in a specific year is then calculated as the ratio of net-emissions of C from LULCC to the C content of primary biomass inputs and to the C content of the output of wastes and emissions from biomass use, respectively, in that year. These shares are than applied to split the biomass flow into fresh weight circular and non-circular biomass on the input and output side;

3. The **Input Non-Circularity rate (INCr)** measures the share of eUse of fossil energy carriers in PM and IntOut, thus quantifying the share of material flows that do not qualify either for socioeconomic and ecological loop closing. Due to unreliable information on dissipation rates of fertilisers or salt for de-icing roads, for example, we did not allocate these materials to non-circular flows;

4. The **Net Stocking rate (NSr)** quantifies the amount of materials being added to long term material reserves and not available for cycling during the current accounting period; it is used both as an input- and an output-side indicator;

5. The difference between 100% and the sum total of the four metabolic rates serve as a measure for the unexploited potential for socioeconomic cycling, and represents the input and output of non-renewable materials available for cycling; namely the **Input Non-Renewable material rate (INRr)** and **Output Non-Renewable material rate (ONRr)**;
6. Finally, the difference between RMC and DMC is referred to as net extraction abroad (NEA), which is used as a bridging item rather than an actual indicator. The reason for this is that while the original indicator framework is calculated over PMs, in CGRs this is also done over PRMs. The latter has the advantage of taking a life-cycle perspective and reallocating raw material extraction to the point of final consumption; however it has the disadvantage of introducing an overlap in the system boundary definition that is not straightforward to reconcile. Calculating indicators on PRM the same way as on PM would mean extending assumptions that are valid for a specific material flow within the economy under analysis to broader raw material equivalent flows originating from all the other economies. As an example, let's consider the estimation of the non circular flows: The eUse fraction of fossil fuels in PM is made of the actual fuels (for example, gasoline, diesel, kerosene) produced and imported that are being burned (consumed), so the identification of their use is straightforward. However, the eUse fraction of fossil fuels in PRM accounts for the raw materials (for example, petroleum) across all kinds of products and applications, thus not necessarily related eUse. Furthermore, for traded commodities, within these raw material equivalents extracted abroad and consumed locally (or vice versa, extracted locally and consumed abroad) there are also flows that are not materially embedded into the traded commodity, but rather transformed into waste and emissions during processing, transportation and other supply chain steps. At the moment of writing, there was no suitable methodology to differentiate and track the fate of such flows with the aim of reconducting them to one of the input- or output-side indicators mentioned above. Therefore, we introduced a bridging item and refer to it as the **Net Extraction Abroad rate (NEAr)**. When NEAr is negative, it means that the economy under study extracts more resources to satisfy final demand abroad than those extracted abroad to satisfy domestic final demand and vice versa. For a lack of better information, we assume that all NEA is made of non-renewable inputs and thus accrues in the NRIr.

***Table ten.*** *Summary of system indicators for monitoring economy-wide loop closing. Mass-based circular economy indicators where scale indicators measure the absolute size of input and output flows in tonnes and circularity rates measure socioeconomic and ecological cycling relative to input and output flows in percentages (n.a. = not applicable).*

| **Dimension** | | **Input-side indicator** | | **Output-side indicator** | |
|---|---|---|---|---|---|
| | | **Direct** | **Life-cycle** | **Direct** | **Life-cycle** |
| **Scale indicators (t)** | **In- and output flows** | Domestic material consumption (**DMC**) | Raw material consumption (**RMC**) = DMC + NEA | Domestic Processed Output (**DPO**) | n.a. |
| | **Interim flows** | Processed Materials (**PM**) = DMC + secondary materials consumed (SM) | Processed Raw Materials (**PRM**) = RMC + secondary materials consumed (SM) | Interim outputs (**IntOut**) = EoL waste + DPO emissions | n.a. |
| **Metabolic rates (%)** | **Socioeconomic cycling (SC)** | Input socioeconomic cycling rate (**ISCr**) = Share of secondary materials consumed (SM) in PM | Input socioeconomic cycling rate (**ISCr**) = Share of secondary materials consumed (SM) in PRM | Output socioeconomic cycling rate (**OSCr**) = Share of secondary materials in IntOut | n.a. |
| | **Ecological cycling potential (EC)** | Input ecological cycling rate potential (**IECrp**) = Share of DMC of primary biomass in PM | | Output ecological cycling rate potential (**OECrp**) = Share of DPO biomass in IntOut | n.a. |
| | **Non-circularity (NC)** | Input non-circularity rate (**INCr**) = Share of eUse of fossil energy carriers in PM | | Output non-circularity rate (**ONCr**) = Share of eUse of fossil energy carriers in IntOut | n.a. |
| | **Net additions to stocks (NAS)** | Net stocking rate (**NSr**) = Share of NAS in PM | Net stocking rate (**NSr**) = Share of NAS in PRM | Net stocking rate (**NSr**) = Share of NAS in IntOut | n.a. |
| | **Net Extraction** | n.a. | Net extraction abroad rate | | n.a. |

| | | | | | |
|---|---|---|---|---|---|
| | **Abroad (NEA)** | | (**NEAr**) = share of NEA in PRM | | |
| | **Non-renewable input (NR)** | Non-renewable input rate (**NRIr**) = 100 - (ISCr + IECrp + INCr + NSr) | Non-renewable input rate (**NRIr**) = 100 - (ISCr + IECrp + INCr + NSr + NEAr) | Non-renewable output rate (**NROr**) = 100 - (OSCr + OECrp + ONCr + NSr) | n.a. |

It should be noted that for simplicity, so far we have considered net the amount of traded secondary materials as part of DMC despite these flows being explicitly quantified and treated in the monitoring framework. The estimation of imported and exported secondary materials is based on the methodology developed by Eurostat and used in the calculation of the circular material use rate (CMUr).[28] Let's consider ISCr—the share of secondary materials in PRM—and re-write it in mathematical terms:

$$ISCr = SM/PRM$$

Where:

$$DMC = DE + IMP + SM_{imp} - EXP - SM_{exp}$$

$$PRM = DMC + NEA + SM$$

$$SM = SM_{dom} + SM_{imp} - SM_{exp}$$

To avoid double counting we rewrite DMC in its normal form:

$$DMC = DE + IMP - EXP$$

then $ISCr$ can be rewritten as:

$$ISCr = \frac{SM_{dom} + SM_{imp} - SM_{exp}}{DMC + NEA + SM_{dom} + SM_{imp} - SM_{exp}}$$

A higher ISCr rate value means that more secondary materials substitute for primary raw materials, thus reducing the environmental impacts of extracting primary material. The numerator and denominator of the equation above can be measured in different ways depending on considerations of analysis and data sources.

In principle, this indicator measures both the capacity of a country to produce secondary raw materials and its effort to collect waste for recovery. In a closed economy, with no imports or exports, both are one and the same. However, in reality, countries are open economies with flows of imports and exports of waste collected in one country but treated and recycled in another one. In

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[28] Eurostat. (2018). *Circular material use rate.* Retrieved from: Eurostat website

that case, the production (of secondary raw materials) and collection effort (of waste for recycling) in one country may not be one and the same. Therefore the ISCr rate must focus on one or the other. This is a design choice. Depending on the approach sought, the ISCr rate indicator may come with a different specification. In this respect, it was decided that the ISCr rate measures a country's effort to deploy secondary materials. This perspective credits the country's effort to produce secondary material from recycled waste as opposed to gathering waste bound for recovery which indirectly contributes to the worldwide supply of secondary materials and hence avoidance of primary material extractions. Remarkably, this is the opposite perspective than the one taken by the Eurostat’s CMUr.

The ISCr rate indicator is based on either official statistics compiled by individual countries under legal obligations or by data gathered or estimated through a variety of methods including desk research, sampling and modelling. The former include:

- **Waste statistics:** For European countries, Regulation (EC) No2150/2002 on waste statistics (WStatR) is a framework for harmonised Community statistics in this domain. The WStatR requires EU Member States to provide data on the generation, recovery and disposal of waste every second year. Dataset on waste treatment (env_wastrt) are used (or compiled based on such regulation) for the calculation of ISCr rate. For non-European countries, waste treatment is estimated using the approach outlined in section *‘Waste generation, collection and treatment’*.

- **Economy-wide material flow accounts:** As already mentioned, EW-MFA describes the interaction of the domestic economy with the natural environment and the rest of the world economy in terms of flows of materials (excluding water and air). EW-MFA is a statistical framework conceptually embedded in environmental-economic accounts and fully compatible with concepts, principles, and classifications of national accounts—thus enabling a wide range of integrated analyses of environmental, energy and economic issues for example, through environmental-economic modelling. For European countries, the collection of EW-MFA data is based on Regulation (EU) 691/2011 and the dataset used (or compiled) is (or is based on) the env_ac_mfa data set. For non-European countries, the collection of EW-MFA data may or may not be regulated and these are retrieved from the global material flow database by IRP which is built using a mix of primary data and modelling estimates.[29]

- **International trade in goods statistics (ITGS)** measures the value and quantity of goods traded between the countries. ‘Goods’ means all movable property including electricity. ITGS is the official harmonised source of information about exports, imports and the trade balances of the EU. For EU Member States, data is extracted from the COMEXT website while for non-European countries, data is extracted from the BACI database. The main classifications for ITGS are the Combined Nomenclature (CN) and Harmonised System (HS).

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[29] CSIRO. (2021). *Technical annex for global material flows database (2021 edition)*. Retrieved from: Resource Panel website

The ISCr can be approximated by the amount of waste recycled in domestic recovery plants and thereby indirectly or directly substituting primary raw materials. But recycled amounts of waste in treatment operations can be also corrected by imports and exports of waste destined for treatment. These two aspects are developed below.

### 2.3.1 Amount of waste recycled in domestic recovery plants

The first component of ISCr—$SM_{dom}$—is measured from waste statistics. It may be decomposed into the following components (cases):

- Residual material legally declared as waste which is recovered and after treatment fed back to the economy (material flowing through the legally demarcated waste management system).
- Residual material, outside the legal waste coverage (outside the waste management system), generated, for example, as by-product during certain production processes, and fed back into the economy. This category can further be distinguished into:
    - Residual material subject to economic transactions between establishments;
    - Intra-establishment flows.

Only residual material legally declared as waste is included in ISCr, thus the indicator only represents the contribution of the waste management system to the circular economy. Excluded is any circular use of residual material which does not touch the waste management system and which is currently infeasible to quantify based on statistics. In the future, the non-waste part of circular material flows may increase because of their increasing value. In other words, one may expect that retaining some value of residual materials and their circular flows will increasingly be integrated into the ordinary economy, i.e. become intermediate use. This would not show as circular use but would reduce the need for primary raw materials.

While waste statistics measures the input of waste into recovery operations and not the amount of secondary raw materials that result from these operations; an analysis by Eurostat concluded that the input to recovery plants is an acceptable proxy for the output from recovery plants. On the basis of the treatment operations defined in the WaW database, a distinction is made in treatment types, namely:

- Uncontrolled disposal: This includes disposal to unspecified landfill (D1), open dumping (D1), release into sea and water bodies (D6, D7), unaccounted and uncollected waste;
- Controlled disposal: This includes disposal to controlled and sanitary landfill (D5, D12) and other treatment (D2-4, D8, D9, D11, D12-15);

- Incineration: This include both with (R1[30]) and without energy recovery (D10);
- Recovery: This includes composting and anaerobic digestion (R3) and recycling together with backfilling (R2, R4-11), but excluding that of waste originating from unused extraction.

For the purpose of the ISCr rate indicator only recovery is condeired, i.e. excluding energy recovery.

### 2.3.2 Adjusting circular use of material for net imports of waste

The focus of ISCr is to represent a country's effort to produce secondary materials, including waste collected in another country and later imported for domestic deployment. Consequently, the total amount of recycled waste in treatment operations is adjusted as follows:

$$SM = SM_{dom} + SM_{imp} - SM_{exp}$$

with:

$SM_{imp}$: amount of imported waste bound for recovery, and

$SM_{exp}$: amount of exported waste bound for recovery

The amount of waste recycled in domestic recovery plants, plus imported waste destined for recovery, minus exported waste destined for recovery abroad. When adjusting the amounts of recycled waste in treatment operations by imports and exports of secondary material, the country which uses the secondary material (recovered from former waste) gets the 'credit' for the contribution to the worldwide saving of primary raw materials. This perspective seems to be closer to the national accounts' logic in which most re-attributions are directed towards final use.

In order to calculate the amounts of imported waste ($SM_{imp}$) and exported waste ($SM_{exp}$), Eurostat has identified the CN-codes which can be considered trade in waste.[31]

CE has developed a mapping table from CN 8-digits to HS 6-digits codes and applied the same methodology to international trade databases such as COMTRADE and BACI to quantify bi-lateral trade in waste for recycling and by-products between all countries in the world. A cross-analysis of the results between the COMEXT and BACI database for EU28 countries has shown the suitability of such a mapping table for analysis at the international level.

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[30] This code refers to the treatment operations as defined in the EU Waste Framework Directive 75/442/EEC.

[31] EUROSTAT (2021). List of CN-codes used to approximate imports and exports of waste destined for recycling. Retrieved from: cei_srm030_esmsip_CN-codes.pdf (europa.eu)

## 2.3.3 Comparison with previous Circularity Metrics

A one-on-one comparison between the metric as calculated in the latest update (global CGR 2020) and the current one is not possible because of the radical changes introduced by the new methodology and indicators. These are summarised in **Table eleven**.

**Table eleven.** Key differences between the CGR 2020 Circularity Metric and the CGR 2023 Socioeconomic Cycling Rate.

| Variable | Circularity Metric (CGR 2020) | Socioeconomic cycling (CGR 2023) |
|---|---|---|
| Cycled flow ($SM$) composition | Includes both technical and biological materials returned to the environment (for example, manure, compost, digestate applied on land) similar to traditional recycling rates | Includes technical materials only, biological materials fall under the ecological cycling potential |
|  | Includes energy recovery (efficiency > 65%) | Only includes forms of recovery that generates secondary materials |
| Primary source of waste generation and treatment data | Exiobase Hybrid Supply and Use Tables (Merciai et al., 2018)[32] waste accounts | What-a-Waste database by the World Bank (Kaza et al., 2019) |
| Scope of the update | Update limited to EU28 countries using Eurostat statistics | Update for all major world economies using several data sources such as Surveys, data from national statistical offices and extrapolations |

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[32] Merciai, S., & Schmidt, J. (2018). Methodology for the Construction of Global Multi-Regional Hybrid Supply and Use Tables for the EXIOBASE v3 Database. *Journal of Industrial Ecology*, *22*(3), 516–531.doi: 10.1111/jiec.12713

# 3. Planetary boundaries

The Planetary Boundaries framework, firstly developed by Rockström and colleagues (2009),[33] and updated by Steffen and colleagues (2015),[34] is a well-known concept that defines the 'safe operating space' for human development, based on the planet's bio-physical processes. It provides a science-based reference of the risks that human interventions will substantially alter the Earth's system. The Planetary Boundaries framework thus considers nine among the Earth system processes, each of them embracing one or several Sustainable Development Goals. Each of the Earth's processes is associated with a defined ecological limit at global or regional level, set according to the precautionary principle and allowing for acceptable societal development. Limits are measured through control variables, namely metrics that quantify the state, pressure or driving forces of the environment depending on the Earth processes. It is acknowledged that methods to implement the Planetary Boundaries framework in sustainability assessments remains a challenge. To overcome such limitations, new initiatives to use the planetary boundaries have been developed to contribute to the current discussion.

The Planetary Boundaries framework consists of nine earth systems: 1. Climate change, 2. Novel entities,[35] 3. Stratospheric ozone depletion, 4. Atmospheric aerosol loading, 5. Ocean acidification, 6. Biogeochemical flows (nitrogen and phosphorus), 7. Freshwater use, 8. Land-system change and 9. Biosphere integrity (functional diversity and genetic diversity).

In 2009, Rockström and colleagues proposed the limits of each earth system and a way to quantify with the exception of Atmospheric aerosol loading and Chemical pollution. A few years later, in 2015, Steffen and colleagues proposed a regional boundary for atmospheric aerosol loading.

At the time of writing, Rockstrom and colleagues (2009) identified that three of the nine planetary boundaries were overshot, while latest developments show that five of these boundaries have now been transgressed. We were able to confirm the transgression of four of these boundaries in our assessment.

After the work of Rockström and colleagues, new ways to measure the planetary boundaries have been proposed, as well as ways to measure their transgression, such as the work of Steffen and colleagues (2015) and Wang-Erlandsson and colleagues (2022).[36] For example, Rockstrom and

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[33] Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472–475. doi: 10.1038/461472a

[34] Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223). doi:10.1126/science.1259855

[35] In Rockström et. al. (2009), this is named 'Chemical pollution'.

[36] Wang-Erlandsson, L., Tobian, A., van der Ent, R. J., Fetzer, I., te Wierik, S., Porkka, M., Staal, A., Jaramillo, F., Dahlmann, H., Singh, C., Greve, P., Gerten, D., Keys, P. W., Gleeson, T., Cornell, S. E., Steffen, W., Bai, X., & Rockström, J. (2022). A planetary boundary for green water. *Nature Reviews Earth and Environment, 3*(6), 380–392.doi:10.1038/s43017-022-00287-8

colleagues set the boundary of Land-system change as ao 15% loss of the world's dry land converted to cropland. This approach differs from the boundaries proposed by Steffen and colleagues in 2015, where Land-system change boundaries are expressed as a percentage of forested land compared to the original forest area and takes into account three types of forests: tropical, temperate and boreal, each with their own range of actual area vs original area. Moreover, Ryberg and colleagues (2018)[37] developed impact characterisation factors of a catalogue of emissions to air and water for different earth systems. This acts as a tool to enable the measurement of the transgression levels of different planetary boundaries. Finally, Wang-Erlandsson and colleagues added to a model approach to measure the green water boundary, adding to the blue water boundary by previous authors.

Keeping the latest developments in mind, we developed an impact assessment model for the planetary boundaries, which we used to measure the transgression of seven of nine of the boundaries of the framework proposed by Rockstrom and colleagues (2009).[38] In the following sections, we describe how we measured these transgressions, the main data used, our impact assessment model, and its integration with our scenario modelling framework.

### 3.2.1 Circle Economy's Planetary Boundary Impact Assessment Model

For the assessment of the transgression of the planetary boundaries, we developed a life-cycle-impact-assessment model[39] based on the EEIOA modelling framework using EXIOBASE 3.8.1[40] and the impact characterisation factors of emissions on the earth systems developed by Ryberg and colleagues.[41] We call this model Circle Economy´s Planetary Boundaries Impact Assessment Model (CEPBIAM). With this model, we measured the impacts on the following planetary boundaries:

1. Climate change
2. Ocean acidification
3. Nitrogen cycle

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[37] Ryberg, M. W., Owsianiak, M., Richardson, K., & Hauschild, M. Z. (2018). Development of a life-cycle impact assessment methodology linked to the Planetary Boundaries framework. *Ecological Indicators*, *88*, 250–262. doi:10.1016/j.ecolind.2017.12.065

[38] Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472–475. doi: 10.1038/461472a

[39] Heijungs, R., & Suh, S. (2002). *The computational structure of life cycle assessment*. Springer Netherlands. doi:10.1007/978-94-015-9900-9

[40] Stadler, K., Wood, R., Bulavskaya, T., Södersten, C. J., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Maerciai, S., Schmidt, J., Theurl, M., Plutzar, C., Kastner, T., Eisenmenger, N., Erd, K. H., Koning, A., & Tukker, A. (2020). EXIOBASE 3. doi:10.5281/zenodo.4277368

[41] Ryberg, M. W., Owsianiak, M., Richardson, K., & Hauschild, M. Z. (2018). Development of a life-cycle impact assessment methodology linked to the Planetary Boundaries framework. *Ecological Indicators*, *88*, 250–262. doi:10.1016/j.ecolind.2017.12.065

4. Phosphorus cycle
5. Atmospheric aerosol loading
6. Freshwater use
7. Land-system change

## 3.2. Establishing the boundaries

The boundaries for each earth system we measured are available in **Table twelve.**

***Table twelve.*** *Planetary boundaries or control variables.*

| Item | Impact category (Earth System) | Impact category (control variable in PB-framework) | Planetary boundary |
|---|---|---|---|
| 1 | Climate change | Atmospheric $CO_2$ concentration [ppm $CO_2$] | 350 (1) |
| 2 | Ocean acidification | Carbonate ion concentration, with respect to aragonite saturation state [OMEGA arag] | 2.75 (1) |
| 3.a | Biogeochemical flows | Global: Phosphorus flow fertilisers to erodible soils [Tg P yr-1] | 26.2 (2) |
| 3.b | Biogeochemical flows | Global: Industrial and intentional biological fixation of nitrogen [Tg N yr-1] | 62 (2) |
| 4 | Atmospheric aerosol loading | Aerosol optical depth (AOD) Asian control value as global control value | 0.25 (3) |
| 5 | Land-system change | Total forest cover loss [Mkm2] | 16 (4) |

NOTES: (1). Rockstrom et al. (2009), (2). Ryberg et al. (2018), (3) We used the boundary known for Asia for the rest of the world. (4). Circle Economy's approach on land-system change.

## Circle Economy's Planetary Boundary (and Material Footprint) Impact Assessment Model

The general model approach for assessing the trespass of the planetary boundaries of the global economy is:

$$h = C^{'} e$$

Where $h$ is a vector of total impacts on each planetary boundary, $C$ is the characterisation factor matrix of stressors for each earth system, and $e$ is a vector of stressors, derived from the results of the global socioeconomic metabolism. The symbol ' denotes transposition.

To calculate the transgression level in percentage of each boundary, except for land-system change of forest areas,[42] we simply compare the total impacts on each earth system with the control value or boundary so that:

$$h_{transgression} = \left(h\, d^{-1} - i\right) \cdot 100$$

Where $h_{transgression}$ is a vector of values of the transgression in % of each planetary boundary, $d$ is a vector with the control values or boundaries of each earth system (**see Table twelve)**, $i$ is a column vector of ones, and the symbol • represents a dot product.

Furthermore, the emissions and stressors $e$ are calculated with standard EEIOA model approaches so that

$$e = S\, x + (S^{Y} Y')_{i}$$

Where $S$ is the interindustry stressor intensity matrix, $x$ is the total output vector, SY is the final demand stressor intensity matrix, and Y is the final demand, while the subscript $_{i}$ denotes summation of columns equivalent to $i$ is a column vector of ones to perform summation of columns.

This model approach was applied to the baseline and all scenarios and in function of the demands and total outputs calculated for each scenario, so that:

$$h(s) = C^{'} e(s)$$

$$\text{And}$$

$$e(s) = S\, x(s) + (S^{Y} Y'(s))_{i}$$

Where s represents every scenario modelled in our analysis. The total outputs $x(s)$ and final demands $Y(s)$ In function of each scenario (s) are the resulting outputs and demands from all the

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[42] The total land use transgression level is calculated in the way described. We applied a different method for the boundaries of Forest losses, including boreal forest, temperate forest and total forests, also described in this document.

changes in parameters and variables implementing our **scenario modelling approach, described in more detail in Section 3.1.2.**

Lastly, the material footprints are calculated as:

$$m = M^{'}e$$

Where $m$ is a vector of material footprints, and $M$ is a correspondence matrix of materials for four material categories: metals, minerals, biomass, and fossil fuels. This model was also implementation to calculate the resource uses for every scenario, wit the new variables obtained each scenario, thus implementing the model in function of all the scenarios, so that:

$$m(s) = M^{'}e(s)$$

## Impact characterisation factors for planetary boundaries

To make the impact assessment model operational, we created an impact characterisation matrix with Ryberg and colleagues that corresponds with environmental stressors of EXIOBASE. We matched the 1,123 elementary flows in EXIOBASE with 87 characterisation factors for 63 environmental flows of Ryberg and colleagues, considering emissions to different compartments such as air, land/soil, and water as necessary, as well as the consumption of resources, such as blue water and land.

With this approach, we were able to assign a characterisation factor for most of the emissions and stressors in EXIOBASE for each of the seven impacts measured. For climate change, we assigned a characterisation factor to all climate change-related emissions in EXIOBASE. While Ryberg and colleagues provide climate change characterisation factors to emissions of $NF_3$ and $CO_2$ from land transformation, these are not available as environmental extensions in EXIOBASE.

For Atmospheric aerosol loading, we assigned ten of the 13 characterisation factors of Ryberg to the environmental stressors in eXIOBASE. Neither dimethyl sulphate nor PM1 are present in EXIOBASE. However, EXIOBASE has PM2 which includes any particulate matter equal in size or smaller than PM2. At the same time, to emissions of 'carbon black' in EXIOBASE, we assigned the characterisation factor of generic carbon aerosols by Ryberg and colleagues.

For Biogeochemical flows, we assigned a characterisation factor to all emissions related to P and N cycles in EXIOBASE. While Ryberg and colleagues provide characterisation factors for emissions of P to groundwater and $NO_3$ to freshwater, these environmental extensions and compartments are not found in the list of environmental stressors in EXIOBASE. However, all of Ryberg's CFs of emissions of N to air were fully matched with EXIOBASE's emissions of N to air ($NO_x$ and $NH_3$), while all emissions of P of fertilisers to soil were matched completely with the characterisation factors of Ryberg.

For Freshwater use, we based our assessment with the characterisation factors of blue water consumption of Ryberg and colleagues and matched it with all the blue water consumption in EXIOBASE.

For Ocean acidification, the seven characterisation factors of Ryberg were matched with the emissions in EXIOBASE.

For Ozone depletion, only one ozone depletion-related gas is represented in EXIOBASE, while Ryberg and colleagues provide characterisation factors for 16 different gases.. For this reason, the assessment of the ozone layer depletion is not in the scope of our analysis.

For Land-system change, Ryberg and colleagues provide four different boundaries and characterisation factors for land-system change: tropical, temperate, and boreal forests, and total forest cover area. While EXIOBASE does not have these four types of forest areas or depletion of forest areas, we developed a different approach to measure the impact on land-system change. This is described in the following section.

## Circle Economy's Land-system change approach

The boundaries of Land-system change by Ryberg and colleagues is expressed as a percentage of original forest area that remains intact. We transformed these percentages into net forest cover areas in millions of square kilometres (Mkm2) to determine the maximum losses of forest areas that would be considered safe. These areas then become our control variables or boundaries, representing the maximum permissible forest losses in Mkm2 considered safe, consistent with the boundaries proposed by Steffen and Ryberg and colleagues.

To establish the total area of boreal, temperate, and tropical forests we used data from FAOSTAT of 2018. We then estimated the present net forest areas that have disappeared, and the boundaries of these biomes in terms of maximum forest area losses. We calculated the baseline values with data from the Forest Resource Assessment (FRA) report.[43] **Table thirteen** contains the forest areas measured with our data, and the boundaries for each biome and land-system change as well as the results of the baseline assessment.

***Table thirteen.*** *Land-system change boundaries.*

| Forest type: | Original forest area (Mkm$^2$) | 2020 forest area (Mkm$^2$) | Forest area lost (2020) | Boundary (minimum forest area in percentage of original forest) | Boundary minimum forest area (Mkm2) | Boundary (maximum safe loss of forest area) | Boundary transgression in % (2020) |
|---|---|---|---|---|---|---|---|
| ***Boreal*** | *22.5* | *11.1* | *11.39* | *85%* | *19.1* | *3.41* | *237%* |
| ***Temperate*** | *19.0* | *18.3* | *7.85* | *50%* | *9.5* | *9.50* | *-17%* |

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[43] FAO. (2020). *Global forest resources assessment 2020: Main report.* Rome: FAO. Retrieved from: FAO website

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ***Tropical*** | *22.7* | *11.15* | *4.36* | *85%* | *19.3* | *3.38* | *28%* |
| ***Land-system change total*** | *64.2* | *40.6* | *23.61* | *75%* | *47.9* | *16.05* | *47%* |

To measure the transgression levels of land-systems in the scenarios, we assumed that any savings in total land-use (calculated with EXIOBASE and our scenario modelling framework) would be transformed into new forest areas proportionally to the shares of forest loss of each forest type. After this operation, we calculated new forest areas in each scenario, and then calculated the counterfactual, net forest cover loss to calculate the transgression of the land system.

### 3.1.2 Scenario modelling framework

Our scenario modelling approach is based on EEIOA and the circular economy scenarios modelling framework proposed by Donati et al. (2018).[44] These techniques allow us to instantly introduce technological changes and recalculate the total intermediate and final outputs of the system. These scenarios represent new hypothetical systems, for which we can calculate effects on material use among other environmental pressures. These scenarios are counter-factual, or 'what-if' scenarios: they are not time-specific, and thus, they do not represent a specific year in the future, but rather a new steady state of the global economy.

This modelling framework allows us to model circular economy strategies that can be classified as Product Lifetime Extension (PLE); Resource Efficiency (RE); Closing Supply Chains (CSC); Residual Waste management operations strategies,[45] or close, narrow, slow, and regenerate strategies.[46] Modelling one specific circular economy strategy is conceptually simple: changes can be made in the exchanges between industries, representing technological changes, or in the final demands of households and governments, representing changes in consumption patterns. They can also be combined. In addition, parameter changes can be applied with different penetration levels for each industry and region, selectively. Although the concept is simple, one single strategy can entail from hundreds to thousands of changes in the variables of our model due to its topological architecture, which consists of five regions, 163 industries for each region, and seven final demands for each industry, as well as 1,123 environmental stressors.

To systematically determine changes in parameters and variables for each intervention in a systematic way, we have developed a set of 'physical layers' or **blueprints** to translate individually designed circular economy strategies into the necessary parameters and variables' changes to represent every intervention or combination of them. This flexibility of our modelling approach

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[44] Donati, F., Aguilar-Hernandez, G. A., Sigüenza-Sánchez, C. P., de Koning, A., Rodrigues, J. F., & Tukker, A. (2020). Modeling the circular economy in environmentally extended input-output tables: Methods, software and case study. *Resources, Conservation and Recycling, 152*, 104508. doi:10.1016/j.resconrec.2019.104508

[45] Aguilar-Hernandez, G. A., Sigüenza-Sanchez, C. P., Donati, F., Rodrigues, J. F., & Tukker, A. (2018). Assessing circularity interventions: a review of EEIOA-based studies. *Journal of Economic Structures, 7*(1), 1-24. doi:10.1186/s40008-018-0113-3

[46] Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. doi:10.1080/21681015.2016.1172124

allowed us to model circular interventions with different penetration levels for each variable change, with different penetration levels for individual regions. In this *Circularity Gap Report*, we considered five world regions: Europe, North America, Latin America, Asia & Oceania, and Africa, due to their relatively homogeneous conditions in areas like housing, nutrition, mobility, consumption and energy technologies.

# Scenarios

In the *Circularity Gap Report 2023*, we described the results of our scenarios in four overarching circular economy strategies: 1. Transform the global food system, 2. Build a circular built environment, 3. Achieve circular manufactured goods and consumables, and 4. Drive forward circular mobility and transport. In addition, we modelled a set of interventions for the transformation of the global energy system. All these strategies and interventions were then combined in one single scenario, discarding any overlapping interventions and thus avoiding issues such as double-counting or double dis-counting. In the following pages we describe the main strategies and assumptions behind our scenarios organised in four circular economy concepts: narrow, slow, close and regenerate.

## 1. Transform the global food system

***Narrow.*** As part of this group of interventions, we modelled a 50% reduction in food waste globally. This intervention reflects the target of one of the current Sustainable Development Goals (SDGs) of the United Nations.[47] As the baseline, we used the current shares of waste published by food product categories by the FAO.[48] These shares are categorised food product categories including: cereals, roots/tubers, oilseeds and pulses, fruits and vegetables, meat, fish and seafood, and dairy products and by the five world regions: Europe, Asia & Oceania, North America, Latin America and Africa.

This scenario also models the impact of *healthy diets.* This intervention is based on the dietary scenarios by Vita et. al. (2019),[49] which measures the impact of a vegetarian diet, vegan diet, mediterranean diet, and a healthy diet. It does so by adapting the caloric intake of particular food products as needed for each diet. The dietary changes modelled for this scenario are those proposed by Vita and colleagues for the vegan diet: a substitution of animal food products with plant-based products. In addition, we eliminated the caloric intake of low nutrition foods like sugars and sugary beverages, and substituted this intake with fruits, vegetables and nuts. In these substitutions, we considered the caloric intake requirements of proteins, carbohydrates and fats, maintaining the caloric intake recommendations by the FAO for these nutrient groups, which

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[47] United Nations. (2022.). *The sustainable development goals report*. Retrieved from: UN website

[48] FAO Statistics Division. (2023). FAOSTAT. Retrieved from: FAO website

[49] Vita, G., Lundström, J. R., Hertwich, E. G., Quist, J., Ivanova, D., Stadler, K., & Wood, R. (2019). The environmental impact of green consumption and sufficiency lifestyles scenarios in Europe: Connecting local sustainability visions to global consequences. *Ecological Economics*, *164*. doi:10.1016/j.ecolecon.2019.05.002

average 2,920 calories per person per day. Like the previous intervention, these dietary changes were adjusted according to the latest data on caloric intake by food and nutrient groups in the five world regions in our framework.

***Narrow and Regenerate.*** The last of this scenario's interventions models the impact of going *local, seasonal, and organic*. In modelling these interventions, we assume a 50% reduction in the transportation of selected food products due to increased preference for local products. This intervention results in a 30% reduction in fossil fuel and electricity use by the vegetable sectors. Lastly, chemical N and P fertilisers were eliminated to represent an organic agriculture system, a modelling approach proposed by Vita and colleagues (2019).

## 2. Build a circular built environment

***Narrow and Regenerate.*** Based on Vita and colleagues' (2019) parameters for passive houses and their impacts, we assume that energy use is reduced between 6% and 25% for all regions for different energy carriers. We also model the impact of low-carbon construction, doubling the use of wood in new housing, and a reduction of 15% in the use of steel, aluminium and cement. In turn, wood use is increased by 200%.

We also modelled energy savings by making changes in the energy efficiencies of washing machines, tumble dryers and irons. We also assumed that the population reduces the number of washing and drying cycles by better loading home appliances, and implementing smart metering solutions[50] at home. On average, we assumed a 20% reduction in the electricity consumption of European and North American households based on a report by the European Consumer organisation.[51] Moreover, Levke and colleagues calculated that 36 lifestyle strategies can lower GHG emissions up to 58%; this translates to a net 24% reduction when taking rebound effects into account.[52] Based on these two sources, we modelled additional energy savings of 24% for households in all world regions.

We also modelled the lightweighting of structures and reduced material intensities for new builds. We assumed a 15% reduction in the use of steel for new construction,[53] and substituted it with wood proportionally to structural strength of both materials, therefore not considering the new building's structural safety and integrity. This intervention was also supported by the assumption that many new structures are built with up to 40% excess steel in some regions.[54] We also modelled an 18% reduction in the use of concrete. This reduction is based on the material savings by new

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[50] Grigoras, G. (2018). Impact of smart meter implementation on saving electricity in distribution networks in Romania. *Application of Smart Grid Technologies: Case Studies in Saving Electricity in Different Parts of the World*, 313–346. doi:10.1016/B978-0-12-803128-5.00009-X

[51] Klopfert, F.,& Wallenborn, G. (2011). *Empowering consumers through smart metering.* Brussels: The European Consumer Organisation. Retrieved from: BEUC website

[52] Lekve Bjelle, E., Steen-Olsen, K., & Wood, R. (2018). Climate change mitigation potential of Norwegian households and the rebound effect. *Journal of Cleaner Production*, *172*, 208–217. doi.org:10.1016/j.jclepro.2017.10.089

[53] Circle Economy & Bain & Company. (2022). A circular future for the European construction sector: Commercial and residential buildings. Amsterdam: Circle Economy. Retrieved from: Circle Economy website

[54] Moynihan, M. C., & Allwood, J. M. (2014). Utilization of structural steel in buildings. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 470*(2168). doi:10.1098/rspa.2014.0170

construction materials and technologies such as innovations in materials for bricks and modular construction technologies.[55] These improvements in construction and reductions of materials are also in line with the previous work of Vita and colleagues (2019) and Donati and colleagues (2020).[56]

The final narrow strategy was the development of a local construction supply chain. Similar to modelling a local market of agricultural products, we modelled this intervention by assuming a 50% reduction of the construction sector's transportation requirements by air, water, and land. We also assumed that common construction materials are substituted by other construction materials sourced locally. Locally sourced materials result in the substitution of 18% of cement and manufactured metallic and mineral products for construction with stone, brick, sand and clay in all world regions.

***Cycle.*** For the cycle strategies in the built environment, we modelled the elimination of the incineration of C&DW in all world regions. We assumed that C&DW is diverted from incineration and is instead recycled and reused. This led to reduced demand for primary materials for construction of diverting 1.2% in Asia and Oceania, 2.1% in Africa, and 3.2% in Europe and North America.

## 3. Achieve circular manufactured goods and consumables

***Narrow.*** We model a reduction in the consumption of textile products and household goods and appliances. At the industrial level, *narrow* strategies manifest as interventions such as optimising industrial processes and semi-manufactured product yields.

***Cycle.*** One of the cycle strategies is the use of recycled fibres in textiles. To model this strategy, we reduced the demand of primary resources by 10%, based on the findings of Moran and colleagues (2018).[57] Industrial symbiosis is another cycle strategy. In modelling industrial symbiosis, the production of metal scraps is optimised by reintegrating metal scraps as in a semi-open loop system, preventing scraps from reaching large recycled-metal markets and directly reducing the demand of primary metals *in situ*. Therefore, the reduction of the flows of selected metals going to recycling from their primary production is equal to the reduction in the consumption of the primary source across all industries that produce scrap. In addition, improvements in efficiency and cuts in yield losses are applied to most semi-manufactured product industries. The resulting reductions in primary material demand range between 7% and 33%, with steel, copper and aluminium observing the largest savings. This strategy was applied to all regions. No differentiation in prices between primary and secondary materials was considered.

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[55] LYTAG concrete. (2017). Standard insulated wall system. Retrieved from: Aggregate Industries website

[56] Donati, F., Aguilar-Hernandez, G. A., Sigüenza-Sánchez, C. P., de Koning, A., Rodrigues, J. F. D., & Tukker, A. (2020). Modeling the circular economy in environmentally extended input-output tables: Methods, software and case study. *Resources, Conservation and Recycling*, *152*, 104508. doi:10.1016/j.resconrec.2019.104508

[57] Moran, D., Wood, R., Hertwich, E., Mattson, K., Rodriguez, J.F.D., Schanes, K., & Barrett, J. (2018). Quantifying the potential for consumer oriented policy to reduce European and foreign carbon emissions. *Climate Policy*. doi:10.1080/14693062.2018.1551186

***Slow.*** For textiles, we assumed that the general population shifts to a culture of repair and maintenance culture marked by a '*sufficiency*' and *less is more* mindset. To model this strategy, we assumed a reduction in the purchase of clothes and apparel. Vita and colleagues (2019) previously modelled this intervention as a net reduction of 80% in the consumption of apparel products. We used this parameter as a reference, and then applied different penetration rates for different textile and apparel products, resulting in net reductions in apparel consumption of between 10% and 16% in all *Shift* and *Grow* regions, except Africa (Europe, North America, Europe, Asia and Oceania).

To model slow strategies for other durable products, we applied reductions in the consumption of durable products as modelled by Vita and colleagues, but with different penetration rates for selected product categories and regions. The net reductions modelled in the consumption of durable products ranged from 24% to 40% for household products, and between 2.5% and 42% for machinery and equipment consumed by industries. The reductions of selected finished products for households, and machinery and equipment for industries, occurs as an effect of extending product lifetimes mainly through repair and maintenance. At the household level, the savings in the purchase of durable products was reallocated to leisure and recreation activities. Similarly, at the industrial level, the savings in the purchase of new machinery and equipment were partially re-allocated to products and services to represent increased repair and maintenance activities. This intervention was applied to all world regions.

***Regenerate.*** Based on the lifestyle changes scenarios by Vita and colleagues (2019) we substituted 90% of fossil-fuel-based textiles and apparel products and replaced them with natural fibres. This intervention was applied to Europe, North America, Europe, Asia, and Oceania (*Shift* and *Grow* regions, except Africa).

## 4. Drive forward circular mobility and transport

***Narrow.*** Our first narrow strategy for this scenario is a car-free lifestyle. We modelled this intervention for the regions of Europe, North America, and Oceania, for which the car ownership per 1,000 inhabitants exceeds the threshold of 250.[58] [59] [60] [61] We modelled the change to a car-free lifestyle by calculating the reduction of kilometres driven[62] by the rural and urban populations of the regions that passed the car ownership threshold. The penetration of these changes affect 40% of the urban population and 10% of the rural population in these regions. The rationale behind these penetration rates is that urban populations will not give up entirely their cars: passenger vehicles will still be used for private transportation. Similarly, this intervention affects only 10% of rural populations, as rural areas have longer commuting distances, and these populations will remain

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[58] ACEA European Automobile Manufacturers' Association (ACEA). (2022). Vehicles in use in Europe.. Retrieved from: ACEA website

[59] World Health Organization. (2022). Registered vehicles data by country. *Global Health Observatory Data Repository*. Retrieved from: WHO website

[60] Center for Sustainable Systems, U. of M. (2022). Personal transportation factsheet. Retrieved from: CSS website

[61] Enerdata. (2021). Sectoral profile-transport energy consumption. *ODYSSEE-MURE*. Retrieved from: Odyssee Mure website

[62] United Nations Economic Commission for Europe (UNECE). (2020). *2020 inland transport statistics for Europe and North America.* Retrieved from: UNECE website

highly dependent on passenger cars to fulfil their transportation needs. The reduction in passenger kilometres travelled by private car was partially substituted by bikes, and walking (modelled as a reduction of 30% of total passenger kilometres) and partially substituted by car sharing (70% of the total passenger-kilometres reduction).

Other transportation modality shifts were modelled for Europe, North America and Oceania. This consisted of a lifestyle change by the population preferring public transport: buses and trains, both urban and extra-urban. We assumed that passenger kilometres travelled by car were substituted with public transport (buses and trains, both urban and extra-urban), without exceeding the current public transport capacities of each region. This capacity was assumed to be 20/50 for buses and 600/1200 for trains based on previous research. These assumptions resulted in a reduction of the passenger-car kilometres of 32% in Europe, and 12% in North America and Oceania. These reductions and substitutions of transportation modes were modelled as changes in households' direct fuel consumption and increases in the output of public transportation-related sectors in our model.

Another intervention considered was *flex-work,* or working from home. We modelled this intervention by assuming a 50% increase in work from home for *Shift* regions such as Europe, North America, and Oceania and 20% in *Grow* regions, including Asia and Latin America, assuming that half of the transportation needs of households is for commuting to work.[63] As an ancillary change, a reduction in 20% and 50% of the need of office floor area was modelled as reductions in real estate services to selected sectors in the industrial group *services.*

For the *fleet electrification* intervention, we assumed that 50% of passenger cars and 100% of the public transport fleet is electrified in all five world regions. This first assumption leads to a reduction in the expenditure in fossil fuels for these transportation modes. We then calculated the corresponding energetic value of these savings, and transformed them into expenditures on electricity carriers for households and public transport companies, using data on the electricity consumption of electric vehicles. This was based on electric vehicle profiles and data from the International Energy Agency (IEA).[64] [65] [66]

For the *Vehicle design and lightweighting* intervention was applied to all regions, and consists of a reduction in the amount of metals, including steel and aluminium components. Metals for private cars and vans were reduced by 50%, and steel, copper, and aluminium for trains, were reduced by

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[63] Eurostat. (2021). Passenger mobility statistics. Retrieved from: Eurostat Statistics Explained website https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Passenger_mobility_statistics

[64] Electric Vehicle Database. (2022). Energy consumption of electric vehicles cheatsheet - EV Database. Retrieved from: EV Database website

[65] International Energy Agency (IEA). (2019). *Fuel economy in major car markets: technology and policy drivers 2005–2017*. Retrieved from: IEA website

[66] International Energy Agency (IEA). (2019). *Fuel economy in major car markets: technology and policy drivers 2005–2017*. Retrieved from: IEA website

17%. These reductions are based on the previous work of Allwood, Cullen and colleagues.[67] [68] Subsequent improvements in fuel consumption due to the lightweighting of vehicles were modelled as an ancillary change. Our final intervention, *Reduced air travel*, was modelled by capping the number of trips supplied by airports and airlines for the *Shift* regions,[69] and the corresponding reduction in aviation fuel consumption, considering an average 1,500 kilometres per trip.[70] [71] Asia, Latin America and Africa were not affected as the air travel in these regions is smaller than one trip per capita per year.

***Narrow* and *regenerate*.** In this CGR, we modelled the impact of favouring renewables in the energy system. This intervention aligns with SDG 7: Affordable and Clean Energy. While the United Nations set the annual share growth of renewable energy to 2.6% by 2030, in 2021, the renewable energy supply grew nearly 7% despite the increase in energy demand in the same period, according to the International Energy Agency.[72] Based on the current growth rates, we modelled the phase-out of 75% of the electricity produced with fossil energy carriers: coal, coke, gas, oil and oil derivatives. These reductions are first quantified as economic flows from electricity producing sectors to electricity consumption sectors. Using data from the five world regions on the prices of electricity by energy source and carrier, and the total supply of energy in terajoules (TJ) of each electricity technology (fossil and renewable), we calculated the new demands of the production of electricity by solar photovoltaic (PV), using electricity production by solar photovoltaic technology as a proxy for all renewable energy sources.[73] [74] [75] [76] [77] These changes resulted in an increased economic output of the solar PV sector between 918% for Europe and 2,968% for Africa, with a global average of 931%. After the application of this intervention, 25% of the electricity was still assumed to be produced with fossil energy carriers. While virtually all sectors in our model were affected by this intervention, we isolated hard-to-abate industries such as fossil fuel extraction, and the production of fossil fuel products, steel, cement and transport from this intervention.[78]

Similarly, we reduced the demand for coke, gas and coal for the hot water supply sector at the interindustry level by 75% for all regions. The rationale behind this intervention was the contribution

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[67] Allwood, J.M., Cullen, J.M., Carruth, M.A., & UIT Cambridge Limited. (2012). *Sustainable materials: with both eyes open*. Engineering and Technology.

[68] Cullen, J. M., Allwood, J. M., & Bambach, M. D. (2012). Mapping the global flow of steel: from steelmaking to end-use goods. *Environmental Science & Technology*, *46*(24), 13048–13055. doi:10.1021/es302433p

[69] World Bank Group. (2022). DataBank | World Development Indicators. Retrieved from: World Bank website

[70] Graver, B., Zhang, K., & Rutherford, D. (2019). *CO2 emissions from commercial aviation, 2018*. The International Council of Clean Transportation. Retrieved from: ICCT website

[71] Our World in Data. (2020). Per capita international aviation passenger kilometers, 2018. Retrieved from: Our World in Data website

[72] IEA. (2022). *Renewables*. Paris: IEA. Retrieved from: IEA webiste

[73] Ritchie, H., Roser, M., & Rosado, P. (2022). Energy. *Our World in Data*. Retrieved from: Our World in Data website

[74] IEA. (2020). Levelised cost of electricity calculator. Paris: IEA. Retrieved from: IEA webiste

[75] Energy Information Administration. (2022). *Levelized costs of new generation resources in the annual energy outlook 2022*. Retrieved from: EIA website

[76] Fraunhofer-Institut für Solare Energiesysteme ISE. (2018). *Stromgestehungskosten erneuerbare energien - März 2018*. Retrieved from: ISE website

[77] LAZARD. (2020). *Levelized cost of energy and of storage 2020*. Retrieved from: Lazard website

[78] The effects of the energy transition in the electrification of transport are reflected in the combined scenario.

of heat and steam supply to climate change in our baseline assessment. Although deep reductions in fossil fuel use for hot water production were predicted, the benefits of this intervention are marginal.

The United Nations estimated in its Sustainable Development Goals Report (2022) that 2.4 billion people still use polluting cooking systems, which pose threats to health and the environment. To tackle this issue, we modelled a 75% reduction in the direct consumption of fossil fuels, such as coke and coal, and refinery products by households worldwide.

## 4. Interpretation of results

**For the planetary boundaries, Table fourteen** shows the baseline assessment and scenario results behind **Figure three** on pages 20-31 in the main report. These results show the transgression level of seven planetary boundaries for the baseline and for each scenario modelled, expressed in percentages of transgression. All the planetary boundary control variables have been normalised to 0%. When the impacts on each earth system are larger than the control variable, it is expressed with a positive percentual value, whereas if the impacts are lower than the control variable, the transgression level will be negative.

An earth system is considered to be transgressed when the measurement of the impacts is larger than the boundary itself. When the transgression percentage is larger than 0%, it means that the boundary of an earth system is transgressed. Mathematically, transgression levels can go to +infinity (%) and -infinity (%).

***Special notes on climate change:*** The ppm concentration measured represents the steady-state concentration of $CO_2$ in ppm that would be reached if the current yearly emissions of GHG remained constant for an indefinite time.

***Special notes on land-system change:*** In Land-system change, moving from 47% above the boundary to -151% below the boundary means that in this scenario, the allowance of forest loss equivalent to 16 million km2, considered to be the boundary, as well as 6.9 million km2 of additional forest area of different types (boreal, temperate, and tropical) could be recovered or regenerated. This sums 24 million km2 of original forests known to be lost.

**Table fifteen** shows the **material footprints results** for the baseline and for each of the scenarios in the main report. The material footprints of the baseline assessment were normalised to 0%. Therefore, positive results in percentages in the scenarios represent higher material footprints than the baseline results and negative percentages represent reductions relative to the baseline material footprints.

***Table fourteen.*** *Planetary boundary results: baseline and scenarios.*

| | ***Planetary Boundaries*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***Climate change*** | ***Ocean acidification*** | ***N cycle (air)*** | ***P soil*** | ***Atmospheric aerosol loading*** | ***Freshwater use*** | ***Land-system change*** |
| **Boundary** | *350.00 ppm [CO2]* | *2.75 [CO3+]* | *62 Mt/yr* | *26.2 Mt/year* | *0.25 Atmospheric aerosol depth (AOD)* | *4 Mm3/year of bluewater consumption* | *16.06 Mkm2 loss of forest cover area* |
| **Baseline Absolute Value** | ***1,018.50*** | ***3.1*** | ***98.9*** | ***34.8*** | ***0.03*** | ***1.6*** | ***23.61*** |
| **Baseline Transgression % of PBs** | **191%** | **13%** | **59%** | **33%** | **-87.00%** | **-59.00%** | **47.00%** |
| **Combined Scenario (absolute)** | **510.7** | **1.6** | **59.8** | **22.6** | **0.02** | **1.5** | **-6.9** |
| **Combined Scenario Transgression** | **46%** | **-43%** | **-3%** | **-14%** | **-93.00%** | **-62.00%** | **-143.00%** |
| Transform the global food system | 180.67% | 9% | 27.84% | -7% | -87.12% | -58.47% | -65.52% |
| Build a circular built environment | 146.98% | -4% | 48.68% | 32% | -88.91% | -59.82% | 38.75% |
| Achieve circular manufactured goods And consumables | 150.00% | -3% | 43.00% | 27% | -89.00% | -62.00% | -4.00% |
| Drive forward circular mobility And transport | 187.40% | 11.77% | 60.34% | 31.74% | -86.98% | -59.54% | 31.95% |
| Transition to a renewable energy system | 113.94% | -16.80% | 49.99% | 32.09% | -88.58% | -59.63% | 36.48% |

***Table fifteen.*** *Material footprint model approach results: baseline and scenarios.*

| | ***Material Footprints*** | | | | |
|---|---|---|---|---|---|
| **Scenarios** | ***Biomass*** | ***Metals*** | ***Non-metallic minerals*** | ***Fossil fuels*** | ***Total*** |
| **Baseline (modelled, Gt)** | **25.5** | **9.7** | **44** | **15.9** | **95.1** |
| **Combined Scenario (Gt)** | **18.3** | **5.6** | **33.4** | **5.9** | **63.2** |
| **Combined Scenario** | **-28%** | **-43%** | **-24%** | **-63%** | **-34%** |
| Transform the global food system | -1% | -10% | -8% | -13% | -7% |
| Build a circular built environment | -4% | -31% | -11% | -14% | -12% |
| Achieve circular manufactured goods And consumables | *25.5* | *9.7* | *44* | *15.9* | *95.1* |
| Drive forward circular mobility And transport | -28% | -43% | -24% | -63% | -34% |
| Transition to a renewable energy system | -1% | -3% | -1% | -13% | -3% |

# Glossary

**Consumption** refers to the usage or consumption of products and services meeting (domestic) demand. In environmental assessments, *consumption* refers to 'using up' products or services, while *use* refers to the act of employing a product or service. *Intermediate consumption* is an economic concept that refers to the monetary value of goods and services consumed or 'used up' as inputs in production by enterprises, including raw materials, services, and various other operating expenses. *Final consumption* is the expenditure by resident institutional units—including households and enterprises whose main economic centre of interest is in that economic territory—on goods or services that are used for the direct satisfaction of individual needs or wants or the collective needs of members of the community. *Absolute consumption* refers to the total volume of either physical or monetary consumption of an entity. *Relative consumption* refers to the volume consumed by an entity in relation to the unit of another variable, for instance population (*per-capita consumption*) or Gross Domestic Product (*consumption intensity*). Expressing consumption in 'per unit of another variable'—that is in relative terms—enables cross-entity comparisons due to the introduction of a common scale (normalisation).

**Domestic Material Consumption (DMC)** is an environmental indicator that covers the flows of products and raw materials alike by accounting for their mass. It can take an ‘apparent consumption’ perspective—the mathematical sum of domestic production and imports, minus exports—without considering changes in stocks. It can also take a ‘direct consumption’ perspective, in that products for import and export do not account for the inputs—be they raw materials or other products—used in their production. [79]

**Materials**, substances or compounds are used as inputs to production or manufacturing because of their properties. A material can be defined at different stages of its life cycle: unprocessed (or raw) materials, intermediate materials and finished materials. For example, iron ore is mined and processed into crude iron, which in turn is refined and processed into steel. Each of these can be referred to as materials. [80]

**Material footprint** is the attribution of global material extraction to the domestic final demand of a country. In this sense, the material footprint represents the virtual total volume of materials (in Raw Material Equivalents) required across the whole supply chain to meet final demand. The material footprint, as referred to in this report, is the sum of the material footprints for biomass, fossil fuels, metal ores and non-metallic minerals.[81]

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[79] Sala S., Benini L., Beylot A., Castellani V., Cerutti A., Corrado S., Crenna E., Diaconu E., Sanyé-Mengual E, Secchi M., Sinkko T., Pant R. (2019) Consumption and Consumer Footprint: methodology and results. Indicators and Assessment of the environmental impact of EU consumption. Luxembourg: Publications Office of the European Union, ISBN 978-92-79-97256-0, doi:10.2760/98570, JRC 113607

[80] EU Science Hub. (n.d.). Raw materials information system. Retrieved from: European Commission wesbite

[81] UN Stats. (2022). *SDG indicator metadata*. Retrieved from: UN website

**Material flows** represent the amounts of materials in physical weight that are available to an economy. These material flows comprise the extraction of materials within the economy as well as the physical imports and exports (*id est,* the mass of goods imported or exported). Air and water are generally excluded. [82]

**Non-circular inputs** are material inputs that are inherently not circular, such as fossil fuels destined to combustion.

**Non-renewable inputs** are non-renewable material inputs that are available for cycling. Metals and minerals represent the majority of these inputs. Fossil fuel based materials may also fall in this category, such as plastic bottles for recycling.

**Products** are goods and services exchanged and used for various purposes, as inputs in the production of other goods and services, as final consumption or for investment. *Semi-finished products* are products that have undergone some processing, but require further processing before they are ready for use. They may be sold to other manufacturers or transferred to sub-contractors for further processing. Typical examples would include rough metal castings sold or transferred for finishing elsewhere (NACE Rev. 2). *Finished products or goods* consist of goods produced as outputs that their producer does not intend to process further before supplying them to other institutional units. A good is finished when its producer has completed their intended production process, even though it may subsequently be used as an intermediate input into other processes of production. Thus, inventories of coal produced by a mining enterprise are classified as finished products, although inventories of coal held by a power station are classified under materials and supplies. Inventories of batteries produced by a manufacturer of batteries are finished goods, although inventories of the same batteries held by manufacturers of vehicles and aircraft are classified under materials and supplies.

**Raw Material Equivalent (RME)** is a virtual unit that measures how much of a material was extracted from the environment, domestically or abroad, to produce the product for final use. Imports and exports in RME are usually much higher than their corresponding physical weight, especially for finished and semi-finished products. For example, traded goods are converted into their RME to obtain a more comprehensive picture of the 'material footprints'; the amounts of raw materials required to provide the respective traded goods.[83]

**Raw Material Consumption (RMC)** represents the final domestic use of products in terms of RME. RMC, referred to in this report as the 'material footprint', captures the total amount of raw materials required to produce the goods used by the economy. In other words, the material extraction necessary to enable the final use of products.[84]

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[82] Eurostat. (n.d.). Glossary, material flow indicators. Retrieved from: Eurostat website

[83] Eurostat. (n.d.). Glossary, material flow indicators. Retrieved from: Eurostat website

[84] Eurostat. (2022). Handbook for estimating raw material equivalents. Retrieved from: Europa website

**Resources** include land, water, air and materials. They are seen as parts of the natural world that can be used for economic activities that produce goods and services. Material resources are biomass (like crops for food, energy and bio-based materials, as well as wood for energy and industrial uses), fossil fuels (in particular coal, gas and oil for energy), metals (such as iron, aluminium and copper used in construction and electronics manufacturing) and non-metallic minerals (used for construction, notably sand, gravel and limestone).[85]

**Secondary materials** are materials that have already been used and recycled. It refers to the amount of the outflow which can be recovered to be re-used or refined to re-enter the production stream. One aim of dematerialisation is to increase the amount of secondary materials used in production and consumption to create a more circular economy.[10]

**Socioeconomic metabolism** constitutes the self-reproduction and evolution of the biophysical structures of human society. It comprises the biophysical transformation processes, distribution processes and flows, that are controlled by humans for their purposes. Together, the biophysical structures of society ('in use stocks') and socioeconomic metabolism form the biophysical basis of society.[86]

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[85] UNEP. (n.d.). Glossary. Retrieved from: Resource Panel website

[86] Pauliuk, S. & Hertwich, E. (2015). Socioeconomic metabolism as paradigm for studying the biophysical basis of human societies. *Ecological Economics, 119,* 83-93. doi:10.1016/j.ecolecon.2015.08.012