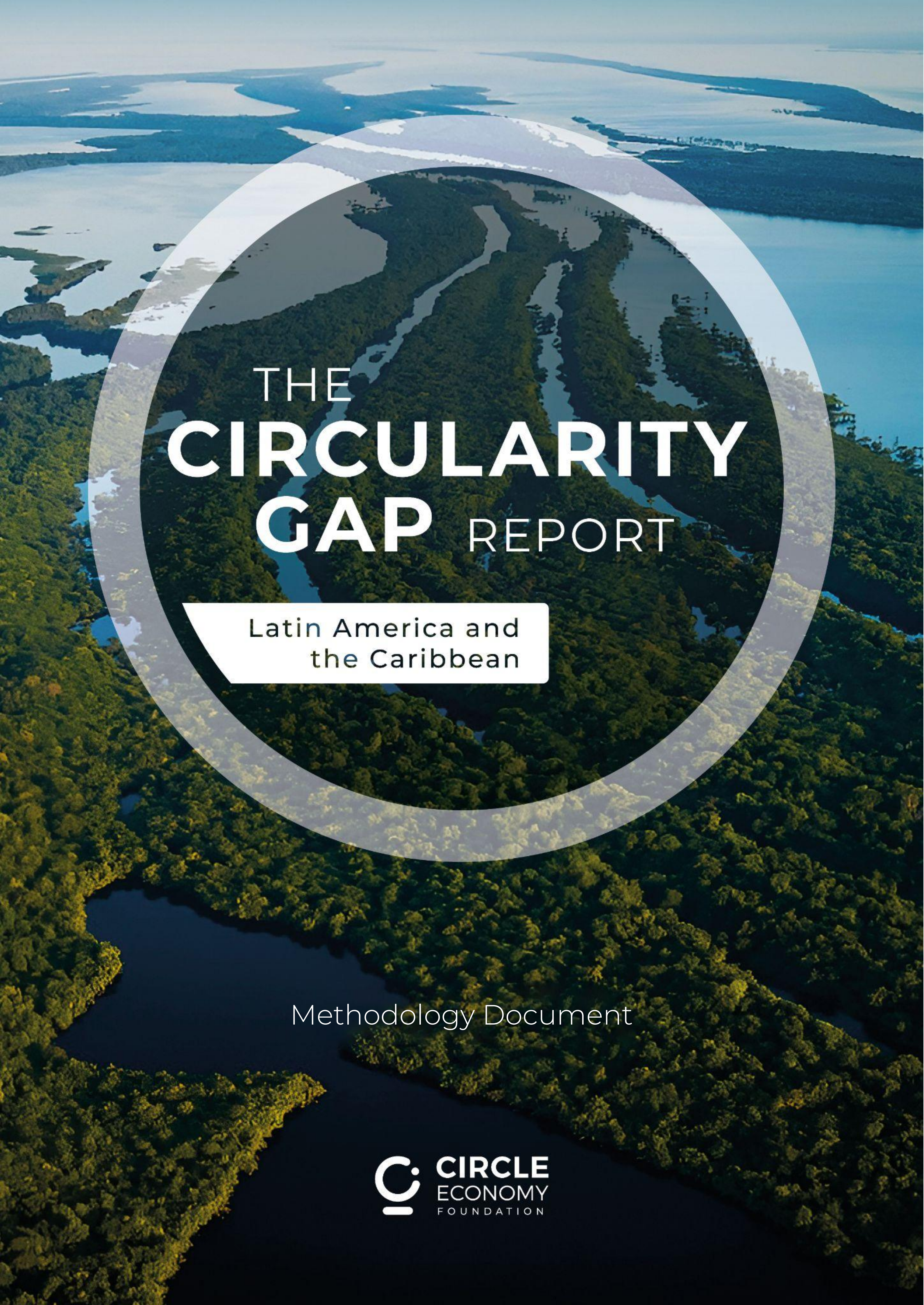

THE CIRCULARITY GAP REPORT

Latin America and the Caribbean

Methodology Document

CIRCLE ECONOMY FOUNDATION

Methodology Document

Circle Economy
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Abbreviations and acronyms

CGR: Circularity Gap Report
CE: Circular economy
LAC: Latin America and the Caribbean
EW-MFA: Economy-wide Material Flow Analysis
DE: Domestic Extraction
IMP: (Direct physical) Imports
EXP: (Direct physical) Exports
PTB: Physical Trade Balance
DMC: Domestic Material Consumption
DMI: Domestic Material Inputs
RME_IMP: Raw Material Equivalents of imports
RME_EXP: Raw Material Equivalents of exports
RTB: Raw Material Trade Balance
RMC: Raw Material Consumption
DPO: Domestic Processed Output
BI: Balancing Items
NAS: Net Additions to Stock
D&D: Demolition and discard
GAS: Gross Additions to Stock
EoL: End-of-Life
LULCC: Land Use, Land Use Change and Forestry
WAS_TRT: Waste treated
SM_TRD: Secondary materials traded
PM: Processed Materials
PRM: Processed Raw Materials
MF: Material Footprint (as classification system Material Flows)
AEA: Air Emissions Accounts
GMFD: Global Material Flow Database
HIC: High Income Countries
UMC: Upper-Medium Income Countries
LMC: Lower-Medium Income Countries
LIC: Low Income Countries
SW: Special Waste
MSW: Municipal Solid Waste
C&DW: Construction and demolition waste
GDP: Gross Domestic Product
PEFA: Physical Energy Flow Accounts
TPES: Total Primary Energy Supply
NCI: Non-circular Inputs
ITGS: International Trade in Goods Statistics
HS: Harmonised System
CN: Combined Nomenclature

Introduction

The concept of circular economy (CE) is gaining increased attention from policy makers, industry and academia. There is a rapidly evolving debate on the concept's definition, limitations, contribution to the wider sustainability agenda, and the need for indicators to assess the effectiveness of circular economy measures at larger scales. To this end, we build upon previous research in an attempt to adapt and apply a framework for a comprehensive and economy-wide biophysical assessment of CE at the global level. The *Monitoring Framework for Economy-wide Material Loop Closing*, developed for the EU28 by *Mayer et al. (2019)*[1] and *Haas et al. (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 (EW-MFA) 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.

Following the method developed for the *Circularity Gap Report 2023* (CGR),[3] the one employed for the CGR Latin America and the Caribbean (LAC) can be described as a ***bottom-up accounting (or bookkeeping) approach*** for the quantification of economy-wide material flows and indicators. It is *bottom-up* because it creates an aggregated set of indicators for the LAC region through the sum of individual countries, thus using statistics and modelling estimates at the national level. It is largely an accounting (or bookkeeping) approach because, differently from Mayer and colleagues, the material balance is closed using standard equations from the Material Flow Accounting framework. As it will be detailed in the following sections, while some key figures were calculated or estimated through this analysis, and modelling estimates from other datasets were used, this work has been primarily focused on data gathering, harmonisation and gap filling. Our approach is different from the more analytical and top-down one developed by Mayer and colleagues, which is rather focused on the systematic quantification of inter-economy material flows, despite our end-goal being to quantify the same set of indicators.

[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] Circle Economy. (2023). *The circularity gap report 2023: Methods (v 1.0)*. Amsterdam: Circle Economy. Retrieved from: CGRi website

Accounts and data sources

In this section, we describe the material flow concepts from an EW-MFA perspective based on definitions and nomenclatures from the United Nations Environment Programme's (UNEP) MFA Manual, and explain how these are integrated in the CGR LAC monitoring framework.

The implementation of the monitoring framework requires the development of a regional 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 region. 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_EX),
- Domestic Processed Output (DPO),
- Balancing Items (BIs);
- Land Use, Land Use Change and Forestry (LULUCF) 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)

The relationship between key MFA indicators is shown in ***Figure one***.

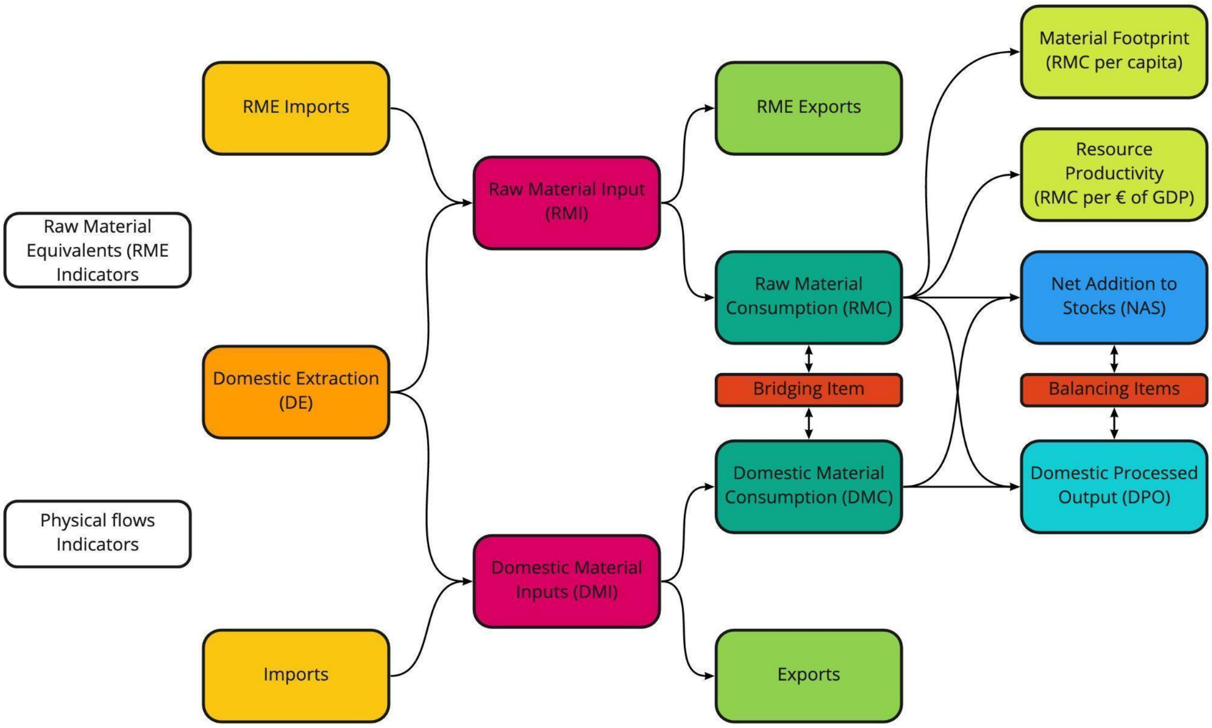

Figure one. Relationship between key MFA indicators.

Standard EW-MFAs are based on material flow datasets that focus on primary material extraction, physical trade (i.e. imports and exports), waste and emissions. These so-called 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:

- 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, land use change and forestry (LULUCF) 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). LULUCF 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 global accounts (***Table one***), of which the LAC region represents a subset.

Table one. High-level summary of the source used in the compilation of the CGR global accounts.

<table>
<tr><th>Module</th><th colspan="2">Variable</th><th>MF Code</th><th>Dataset</th><th>Source</th><th>Notes</th></tr>
<tr><td>1</td><td>Domestic Extraction</td><td>DE</td><td rowspan="4">MF.1.X to MF.4.X</td><td rowspan="3">de_tccc, env_ac_mfa</td><td rowspan="4">International Resource Panel</td><td>Available at both digit-1 and digit-4 level, the latter used for the compilation of BIs</td></tr>
<tr><td>1</td><td>Domestic Material Consumption</td><td>DMC = DE + PTB</td><td rowspan="2">Available only at digit-1 level</td></tr>
<tr><td>2</td><td>Raw Material Trade Balance</td><td>RTB = RME_IM - RME_EX</td></tr>
<tr><td>1</td><td>Physical Trade Balance</td><td>PTB = IM - EX</td><td>trade_tccc, env_ac_mfa</td><td>Available at both digit-1 and digit-4 level, the</td></tr>
</table>

						latter used for the compilation of BIs
3	Emissions to air	DPO	MF.7.1	Eora v199.82	Eora	Cross-checking of different datasets (e.g. EDGARv6.0 and PRIMAPHISTv2.3)
3	Waste disposal to environment		MF.7.2	What-a-Waste database	World Bank	Updated by Circle Economy
3	Emissions to water, dissipative uses and losses		MF.7.3 MF.7.4 MF.7.5	-	-	Partially estimated or excluded
4	Net balancing item	BI = BIi -BIo	MF.8.1 MF8.2	Trade_tccc, Faostat and EW_MFA Questionnaire	International Resource Panel and Faostat	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	World Bank	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, Land Use Change and Forestry emissions	LULUCF		PRIMAPHIST v2.3.1	PIK	-
Extra	Fossil fuels for energy and material use	eUse_FF mUse_FF		Energy balances	UNSTAT	-

The Global Circularity Gap 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, divided into key resource groups, from their extraction to major uses within a socioeconomic system, all the way towards their discard and either material recovery or deposition to nature as waste 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, end-of-life (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.

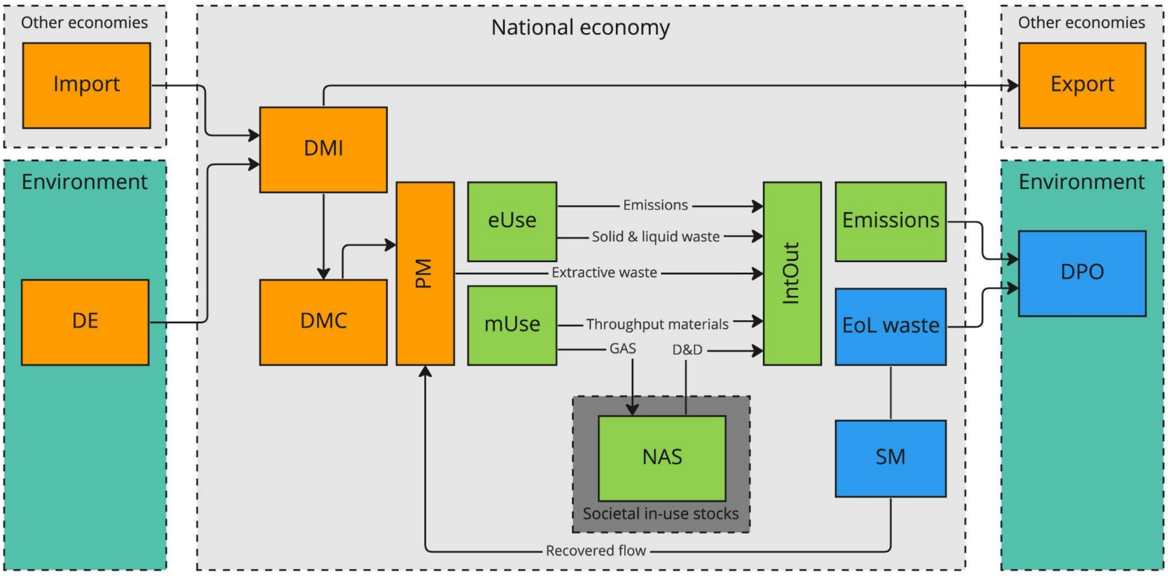

Figure two. Framework and throughput indicators for an economy-wide assessment of circularity. This framework can be used for 1) individual materials, such as corn or iron, 2) material groups, such as biomass, metal ores, fossil fuels or non-metallic minerals, or 3) all materials, represented by total 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) is 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 the 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, infrastructure 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 waste, 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 demolition and discard (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 re-entering socioeconomic processes as secondary materials. The remaining EoL waste (after subtracting SM) is returned to the environment as DPO waste and is either landfilled, incinerated or deliberately applied to the land (for example, manure and fertiliser). Together, DPO emissions and DPO waste form total DPO.

To close the material balance between input and output a combination of data from statistical reporting and 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 one) and mUse (Equation two).

$$DPO\ emissions\ =\ eUse\ -\ solid\ and\ liquid\ wastes\quad (Eq.\ one)$$
$$Demolition\ and\ discard\ =\ EoL\ waste\ from\ mUse\ -\ throughput\ materials\ in\ waste\quad (Eq.\ two)$$

In the framework from 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 are 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 was used: as 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. As a second step, the amount of D&D was 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). As a third step, net additions to stock (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 are accrued in D&D flows as residual flow category, and consequently in the value for NAS.

In the CGR LAC monitoring framework, shown in ***Figure three***, inter-economy flows such as GAS, D&D and throughput materials are *not 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.

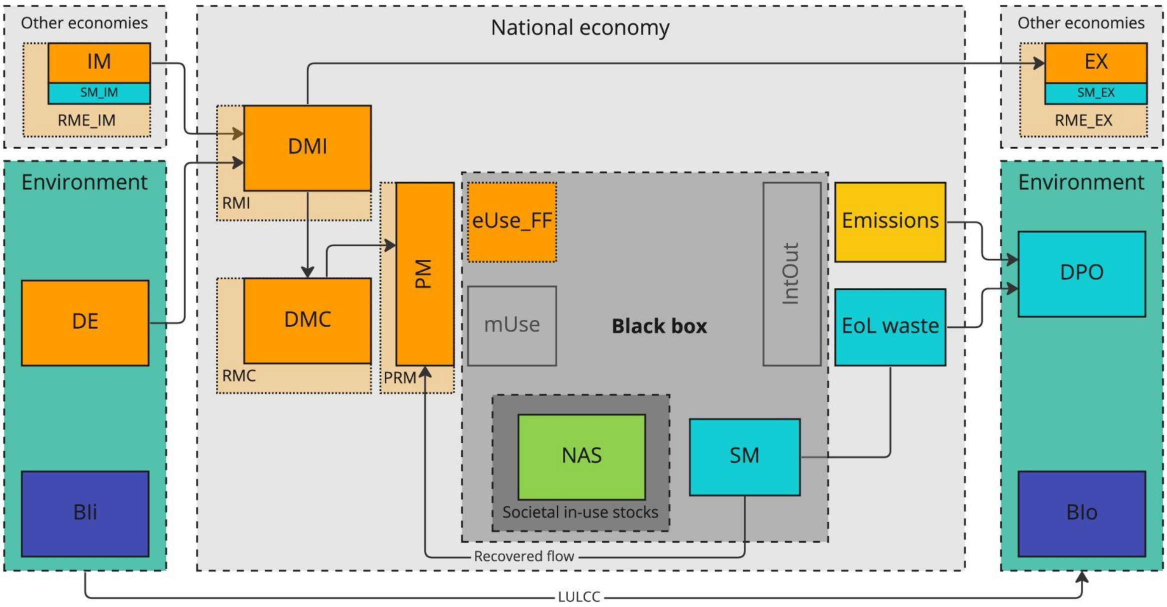

Figure three. Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues (2019). Colours indicate data sources used: orange = economy-wide material flow accounts data, blue = estimated and calculated data, yellow = emissions statistics, green = mass-balance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

NAS were calculated through the standard EW-MFA balancing formula, that is as the residual of the material balance identity:

$$NAS = DE + IM + BIi - DPO - EX - BIo \, (Eq.\ three)$$

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 economies as a black box, but also exclude upstream and downstream material flows associated with trade. In the Global CGR Monitoring 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 national or regional 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 Monitoring 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 waste domestically recycled.

As such, the Global CGR Monitoring Framework can be considered a bottom-up accounting (or bookkeeping) approach where the amount of modelling—and thus the need for country- or region-specific industry or production statistics and results from material flow studies—is limited. By incorporating selected elements of the extended framework by Mayer and colleagues (2019) while following more closely the standard EW-MFA approach, its applicability and timeliness increases and allows to apply a country-by-country approach that relies as much as possible on readily available and regularly updated international datasets.

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

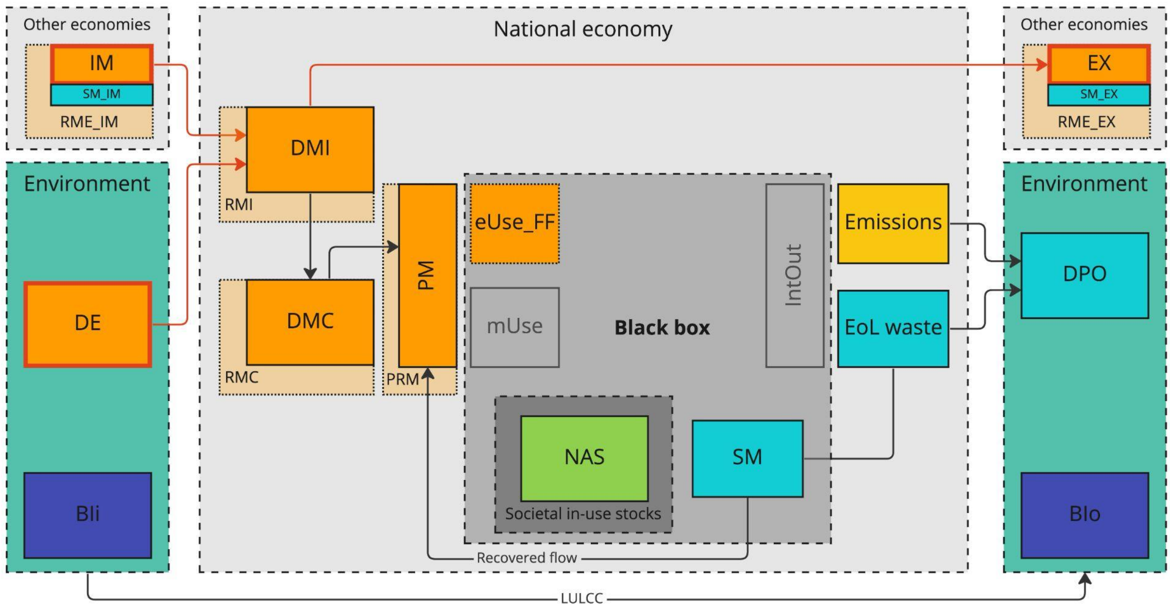

Figure four. Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues (2019) with Module one flows and indicators highlighted.

Domestic extraction

Module one is the core of a national or regional material flow data set. ***Figure four*** highlights the components of this module in red. 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 and is a very relevant criteria in the definition of system boundaries on the input as much as on the output side. The alignment of system boundaries for input- and output-side data through the identification of waste from unused (for example, excavated earths, overburden, dredging spoils, etcetera) and used (for example, extractive ore waste, tailings, etcetera) extraction is addressed in the section *Waste generation, collection and treatment*.

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:

$$PTB = IM - EX \text{ and } DMC = DE + PTB \; (Eq.\ four)$$

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

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 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).

<table>
<tr><th>Level</th><th>Code</th><th>Label</th><th>DE</th><th>Import</th><th>Export</th><th>Notes</th></tr>
<tr><td>1</td><td>MF1</td><td>Biomass</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>2</td><td>MF11</td><td>Crops (excluding fodder crops)</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>3</td><td>MF111</td><td>Cereals</td><td>X</td><td>X</td><td>X</td><td>Under TCCC this is broken down into Rice, Wheat and Cereals nec</td></tr>
<tr><td>3</td><td>MF112</td><td>Roots, tubers</td><td>X</td><td>X</td><td>X</td><td rowspan="5">Used for calculation of MF.8.2.3 Step 2: Water content of biomass products</td></tr>
<tr><td>3</td><td>MF113</td><td>Sugar crops</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>3</td><td>MF114</td><td>Pulses</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>3</td><td>MF115</td><td>Nuts</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>3</td><td>MF116</td><td>Oil-bearing crops</td><td>X</td><td>X</td><td>X</td></tr>
</table>

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 beet leaves, etcetera)**	**X**	**X**	**X**	
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 five*) . In the absence of national information, average harvest factors for crops in different world regions can be used (UNEP, 2021).

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

- **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 (UNEP, 2021). The amount of used crop residues is calculated using *Equation six*.

$$Used\ crop\ residues\ [t\ 15\%\ moisture]\ =\ Crop\ residues\ [t\ 15\%\ moisture]\ *\ recovery\ rate\ (Eq.\ six)$$

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. ***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	

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. This operation could also support the alignment of mismatches between the DE and IMP/EXP accounts for metal ores.

As reported in ***Table four***, within the CGR LAC project, such mismatches were evident especially for the extraction-intensive countries of Chile and Perú. For these two countries in particular, the ratio of metal ores exported versus those extracted and imported was found to be completely different from what was expected, considering that these two countries are known to be top metal exporters worldwide. From the *Technical annex for Global Material Flows Database—2021 edition,*[4] it is clear that the DE and trade accounts for metal ores were put together using different approaches and data sources, potentially resulting in different principles being applied to each account. In this respect, a first attempt was made to systematically resolve this discrepancy by back-calculating and applying content-to-ore factors to the traded metal volumes for a variety of ores using the *Intermediate data files from the compilation of Economy-wide Material Flow Accounts for the Domestic Extraction of abiotic materials*.[5] However, the application of these factors did not provide reliable enough results across all metals and countries and a more tailored approach based on primary data was applied instead.[6]

Table four. Extraction, import and export of metal ores in extraction-intensive Chile and Perú.

Country	DE [Mtonne]	IMP [Mtonne]	EXP [Mtonne]	EXP/(DE + IMP) [%]
Chile	860.1	3.7	22.9	2.7%
Perù	459.7	3.1	31.2	6.7%

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 five*** 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.

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

[5] Liebo, M. (2022). Intermediate data files from the compilation of Economy-wide Material Flow Accounts for the Domestic Extraction of abiotic materials [Data set]. Zenodo. doi:10.5281/zenodo.6618340

[6] For Chile, a 97.7% ratio of exports-to-domestic extraction was applied (personal communication with ECLAC). For Perú, no exports-to-extraction ratio was available. National reports on metal ores extraction and trade were also consulted, but it was not possible to derive reliable enough figures from the data within.

Table five. 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 six*** 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 six. Fossil Fuels flows in EW-MFA (those highlighted in bold are 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**	**Other products mainly from fossil fuels e.g. plastics**		**X**	**X**	Used in the estimation of the parameters fossil fuels for energy (eUse) and

						material (mUse) purposes

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 GMFD and it is not re-estimated starting from economic trade data due to the large uncertainties this process can entail. In comparison, 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 (proportioning principle). However, this should not result in negative consumption figures due to an overly negative PTB.

Module two: Raw material equivalents of trade and material footprint

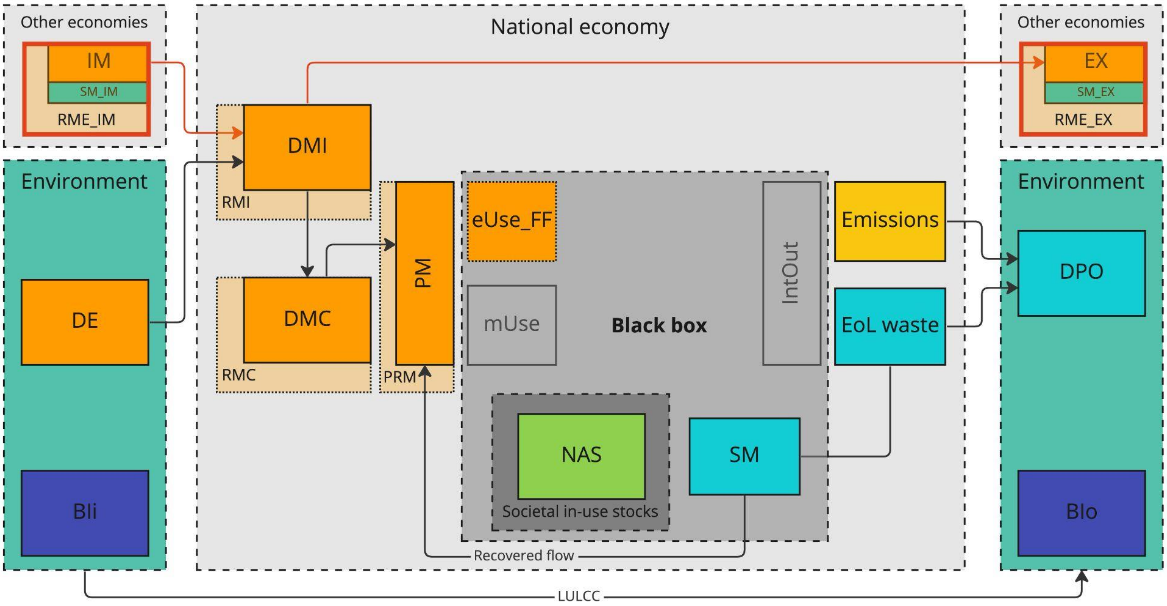

Figure five. Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues (2019) with Module two flows and indicators highlighted.

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:

$$MF = DE + RME\_IM - RME\_EX = DE + RTB \; (Eq.\ seven)$$

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),[7] constructed in the Global MRIO Lab (Lenzen et al., 2017).[8] 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 Global Material Flows Database (GMFD). Therefore, RMC figures are consistent with DE ones hosted within the same database.

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

[8] 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. *Economic Systems Research*, 29, 158-186. doi:10.1080/09535314.2017.1301887

Module three: Material outflows

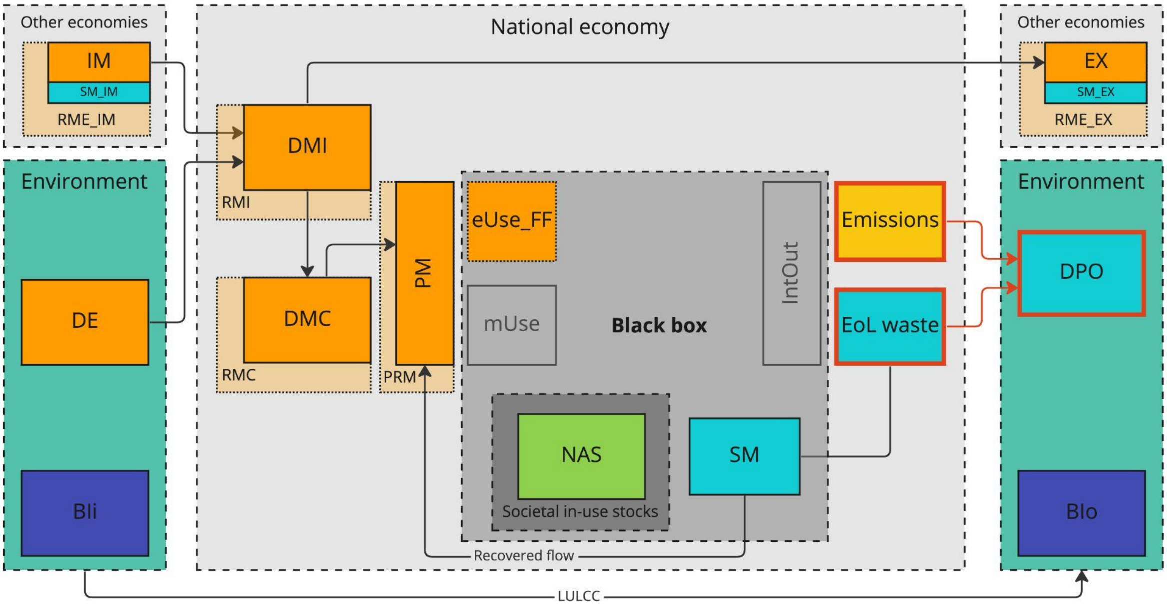

Figure six. Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues (2019) with Module three flows and indicators highlighted.

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.7.5).

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 and 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 seven.***

Table seven. 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**	Tentatively estimated
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 seven*** 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 extensively covered 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 four: Material balance and stock accounts*). Despite covering only CO_2, CH_4 and N_2O emissions, PRIMAPHIST v2.3.1[9] was deemed the best option since it also covered LULUCF emissions (*see Module five: Internal flows and LULUCF)*. All datasets were found to fall short on separately reporting CO_2 from biomass combustion[10] (MF7.1.1.1) and a tentative estimation method was applied.

First, following the approach by Mayer and colleagues, we carried out a sanity check between the selected CO_2 emissions figures and the DMC of fossil fuels. The following steps were performed:

1. CO_2 (MF7.1.1) emissions were converted into carbon contained in the fuel at the point of extraction using stoichiometric ratios;
2. DMC of fossil fuels (MF4) was converted into dry matter content by deducting the vapour generated during combustion as the water vapour form moisture content of fuels (MF8.2.1.1) and water vapour from oxidised hydrogen components of fuels (MF8.2.1.2) (see *Module four: Material balance and stock accounts)*. Standard moisture contents for the material groups and sub-groups were applied;
3. Finally, fossil fuels emissions from dry matter derived from the calculation in step two and emissions to air from PRIMAPHIST v2.3.1 excluding oxygen calculated in step one were compared.

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

[10] This sub-category includes combustion of biodiesel and bioethanol, biogas for producing electricity and heat, biomass for electricity and heat (mainly wood and agricultural harvest residuals and traditional biomass burning (firewood and residuals). It does not include land use and land use changes (considered flows within the environment).

It was found that emissions to air from step one were consistently larger than those from step two for many LAC countries, and the difference for the whole LAC region was 11.7%. Because in principle the two should match, it was concluded that CO_2 emissions from PRIMAPHIST v2.3.1 (as integrated into Eora's environmental extension) were likely to also include non-fossil fuels related ones, namely CO_2 from biomass combustion (MF7.1.1.1). This resulted in an estimated 220 million tonnes of CO_2 from biomass combustion for the whole LAC region. It should be noted, however, that although the figure at the aggregated regional level seems reasonable, single countries' results are not always positive and consistent. Furthermore, there is a degree of variability between DMCs fossil fuels within the very same IRP GMFD and the choice over the figure to be used influences these results (***Table eight***).

Table eight. Comparison between DMC of fossil fuels from different datasets and as re-estimated based on air emissions (highlighted in bold is the figure used in this analysis).

Dataset	Value (Mt)	Notes
Mfa4_export reallocation	651.5	IRP GMFD dataset at material category (1-digit) level. Complex and mixed products are reallocated according to the proportioning principle (see section *Trade of materials)*
Mfa4_ export no reallocation	592.7	IRP GMFD dataset at material category (1-digit) level without reallocation of complex and mixed products
maxCombinedRawTrade_TCCC	**590.5**	**IRP GMFD dataset at material sub-group (4-digit) level without reallocation of complex and mixed products.**
Re-estimation based on emissions to air	629.4	Re-estimated figure based on air emissions data from PRIMAPHIST v2.3.1. Note that this figure would assume that the entirety of reported emissions are related to the combustion of fossil fuels and not biomass.

As mentioned in Chapter two, air emissions constitute the largest part of DPO. In the global approach, this was used to estimate total DPO using correction factors based on their relative share within the broader group. However, such information could only be found for EU28 countries through Eurostat's EW-MFA handbook[11] 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 LAC countries, no correction factor was applied meaning that the total DPO may be slightly underestimated (*see also sections Emissions to water (MF.7.3) and Dissipative use of products (MF.7.4)*)

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

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

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 disposal to the environment (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 or processing of raw materials to intermediate and final products, during the consumption of final products, and in the context of other activities. Waste generated from the treatment of waste, also referred to as secondary waste, is not accounted for in the context of this framework as it would translate into double counting (Mayer et al., 2019).

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 contrast, controlled, i.e. maintained, landfills must be considered part of the socioeconomic system. Therefore, waste 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 account for 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. Within the context of this framework and analysis, net material additions to controlled landfills are accounted for but excluded from the indicator NAS.

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)
- Sanitary landfill with gas system (controlled)
- Unspecified landfill (uncontrolled)

- Open dump (uncontrolled)
- Sea dump (uncontrolled)
- Other treatment (controlled)

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

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 mineral waste from 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 as well as dredging spoils represents unused domestic material extraction, which is not part of the direct material inputs to the economy. Consequently, excavated soil and dredging spoils 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.

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 into natural water systems through 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)[12] 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 nine***.

Table nine. Dissipative flows in EW-MFA (highlighted in bold are those explicitly used or re-estimated within the current framework, the remaining ones are currently excluded).

Level	Code	Label	Notes
1	MF74	Dissipative use of products	
2	**MF741**	**Organic fertiliser (manure)**	**Estimated from livestock heads and metabolic parameters**
2	MF742	Mineral fertiliser	
2	MF743	Sewage sludge	

[12] 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: WRI website

2	MF744	Compost	Approximated by the item 'short-lived material use of crop residues' (Mayer et al., 2019).
2	MF745	Pesticides	
2	MF746	Seeds	
2	MF747	Salt and other thawing materials spread on roads	
2	MF748	Solvents, laughing gas and other	
1	MF75	Dissipative losses	

Within the global CGR approach, the volume of agricultural waste (estimated based on the monetary output of the agricultural sector) is used as a proxy for both categories under the assumption that a large part of it consists of crops residues, organic fertiliser and compost applied to land. Correction factors are then 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.

Within the CGR LAC approach, two of the material classes (2-digit) are estimated, namely organic fertiliser (manure, MF.7.4.1) and compost (MF.7.4.4). For the former, country-level livestock data from FAOSTAT for five types of animals in combination with standard factors for manure production and moisture content were used. All manure was assumed to be spread on land and thus dissipated into the environment. For the latter, the item 'short-lived material use of crops residues',, as described in Mayer et al. (2019) was used as a proxy. In turn, this was calculated as the sum of Straw (MF1.2.1.1) and Other crops residues (MF1.2.1.2) in dry matter content. Average 'as harvested' moisture contents of 14% and 85%, respectively, were applied. The average moisture content considering both flows was estimated at 40%, which is in line with the 45% used by Mayer and colleagues for the EU28 economy. The excorporated water content was then added as a balancing item on the output side (see *Module four: Material balance and stock accounts*).

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***).

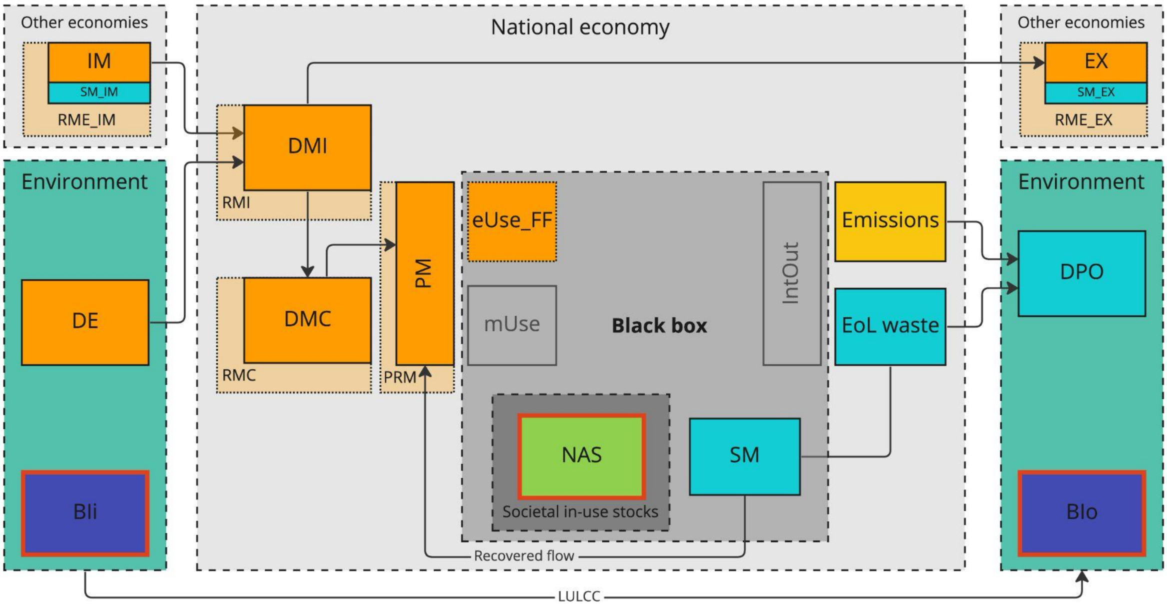

Figure seven. Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues et al. (2019) with Module four flows and indicators highlighted.

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 their definitions. BIs 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 ten*** summarises the BIs included in standard EW-MFA.

Table ten. Balancing Items included in EW-MFA (highlighted in bold are those explicitly used or re-estimated within the current framework, the remaining ones are currently excluded).

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 (incl. residues)**	Estimated by applying average coefficients from the EW-MFA Questionnaire to DMC at 4-digit level from IRP. Bulk water from beverage imports is excluded

Oxygen for combustion processes (MF.8.1.1) is by far the quantitatively most important balancing item on the input side (ca. 90%),[13] 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%).[14] When including also 'MF.8.1.2 Oxygen for respiration of human and livestock; bacterial respiration from solid waste 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 3-digit and 4-digit 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.

A limitation of organising environmental statistics employing an MFA approach 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 and balancing items on the input side—which equal exports, DPO, NAS and balancing items on the output side.

$$DE + IM + BIi = EX + DPO + NAS + BIo \, (Eq.\ eight)$$

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

[13] Item 478 in EUROSTAT. (2018). *Economy-wide material flow accounts HANDBOOK 2018 edition*. doi:10.2785/158567
[14] Item 501 in EUROSTAT. (2018). *Economy-wide material flow accounts HANDBOOK 2018 edition*. doi:10.2785/158567

top-down accounting principles, which would allow to run quality checks on the material balance.[15] 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.

Module five: Internal flows and LULUCF

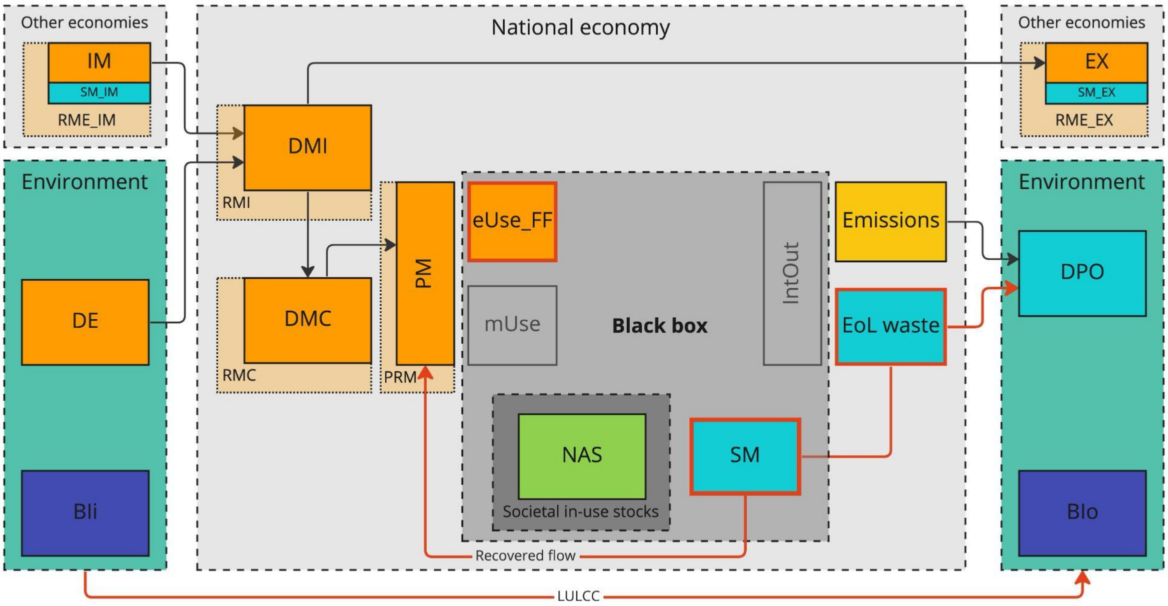

Figure eight. Framework and throughput indicators for a global economy-wide CE assessment based on Mayer and colleagues (2019) with Extra Module flows and indicators highlighted.

Major material uses, as well as recycled flows, are considered material flows within the economy and thus are not considered as outputs (nor inputs). LULUCF, 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

[15] For instance, refer to Mayer et al. (2019) for an approach to NAS calculation through a coefficient-based static model or Haas et al. (2020) for one based on a dynamic stock-flow MEFA model.

plants is an acceptable proxy for the output from recovery plants.[16] 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).[17] 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 includes 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 it requires the use of older data. The data reported are predominantly from 2011–2017, 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 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 was 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

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

[17] 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: World Bank website

‘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:[18]

- **Step one—Primary data collection and integration:** This entailed the preparation and dissemination of a waste data survey through the CGR LAC stakeholders network. Relevant sources included national waste management reports and outlooks, reports from international bodies (for example, UNEP[19]) or foreign agencies (for example, RVO[20]) and the Inter-American Development Bank (IADB[21]) database. Both the waste survey template and the final waste generation, collection and treatment dataset are included in *Annex one*;

- **Step two—MSW generation adjustment:** This analysis assumes that MSW generation grows primarily based on population and affluence. Following the approach used by Kaza and colleagues (2018), a regression formula based on GDP per capita was used to estimate the development of MSW generation per capita for each country between the source and target years. Population figures from the UN’s World Population Prospects[22] were then used to estimate total MSW generation for the target year. If MSW data were available for 2018, the original data were used;

- **Step three—SW generation adjustment:** This analysis assumes that SW generation grows primarily based on sectoral gross output.[23] Time series of construction and manufacturing industry output from the Eora database were used to calculate SW generation intensities (tonnes per million euros) for the source years (various) and multiplied by the historical gross sectoral output for the target year. Hazardous, E-waste and medical waste were not included due to their relatively small contribution within total SW volumes. Agricultural waste was estimated separately as the sum of Crops residues (MF1.2.1) and Manure (MF7.4.1) consistently re-estimated in dry matter content. Compared to the estimation method based on monetary output applied in the global CGR, this approach found agricultural waste to be 13% larger (1013 million tonnes versus 912 million tonnes). If reported SW data were available for 2018, the original data were used—however, this was the case for only a few countries (***Table eleven***);

- **Step four—Gap filling for SW data:** Based on the available data, regional average SW generation intensities for construction and industrial waste were calculated.

[18] Source year refers to the latest year for which reported data was available, 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 CGR LAC is 2018.
[19] Savino, A., Solorzano, G., Quispe, C., & Correal, M. C. (2018). Waste management outlook for Latin America and the Caribbean. UNEP, https://wedocs. unep. org/bitstream/handle/20.500, 11822, 26448.
[20] Van Eijk, F., Huisman, H., Keesman, B., Breukers, L., (2021). Waste management in the LATAm region. Business opportunities for the Netherlands in the Waste/Circular Economy sector in eight countries of Latin America. RVO, Holland Circular Hotspot.
[21] Hub Residuos Sólidos y Circulares. (2021). Datos - Hub Residuos Sólidos y Circulares. Retrieved from: Hub Residuos Sólidos y Circulares website
[22] 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).
[23] 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.

The averages were calculated as the sum of available waste volumes 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 and multiplied by the historical gross output for the target year;

Table eleven. Overview of countries for which plausible figures on reported SW generation were gathered and regional average intensities used for countries with data gaps.

Country	Construction output (M$)	C&DW (ktonne)	C&DW generation intensity (tonne/k$)	Manufacturing output (M$)	Industrial waste (ktonne)	Industrial waste generation intensity (tonne/k$)
Brasil	144490	56981	0.39			
Barbados	558	185	0.33			
Chile	37795	7000	0.19	178795	10434	0.06
Colombia	51739	25000	0.48	172682	5641	0.03
Costa Rica	3194	800	0.25			
Mexico	166088	10153	0.06	736450	36287	0.05
Perù				123879	1719	0.01
Uruguay	9140	668	0.07			
LAC average			**0.24**			**0.04**

- **Step five—Gap filling for collection rates data:** Based on the available data, a weighted average collection rate for the LAC region was calculated. 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*;

- **Step six—Treatment rates data gaps filling:** For each country within the LAC region, treatment rates for a source year were gathered. Within the context of this framework, rates for anaerobic digestion and composting were not included since organic waste flows are accounted for in the ecological cycling potential rate rather than the socioeconomic cycling (see section *Headline indicators). 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;*

- **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.[24] 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 of the waste treatment sectors in the source and target year. Matching tables of WaW treatment types and countries 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 flow 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. The generalised formula for the calculation of waste treated volumes is the following:

$$was_{trt}(ton) = was_{gen}(tonne) * was_{coll}(\%) * was_{trt}(\%) \; (Eq.\ nine)$$

Where the volume of waste treated $was_{trt}(tonne)$ is the product of the volume of waste generated $was_{gen}(tonne)$, the average collection rate $was_{coll}(\%)$ and the average treatment share $was_{trt}(\%)$ for a particular waste treatment type. For most countries, the sum of the waste treatment rates does not add up 100%: the remainder is assumed to be unaccounted waste. Unaccounted waste was found to represent just 5% of all generated waste. Both uncollected and unaccounted waste are assumed to be disposed of in an uncontrolled way, which is the case for 30% of all reported waste generated. For non biological waste—i.e construction waste, industrial waste and the non organic fraction of MSW—we carried out a sanity check over the amount of unreported/accounted waste since this is recognised to be a preeminent issue in many countries of the LAC region. We compared the ratio of non-organic waste generation over DMC excluding biomass and found this figure to be extremely low compared to the global benchmarks (***Table twelve***). While the link between a lower ratio and larger volumes of unreported waste is not unambiguous—as it may also relate to larger shares of NAS or emissions—it is still significant. Because most countries in the LAC region are UMCs, and some major economies such as Argentina and Chile are HICs, it is expected that the ratio would be substantially higher, therefore suggesting a much larger volume of unreported waste.

[24] 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

Table twelve. Comparison of inert waste generation and DMC of non organic materials across selected geographical entities.

Entity	Inert waste generation (Gtonne)	DMC excl. Biomass (Gtonne)	Was_gen/DMC
High Income Countries (HIC)	13.5	19.0	71.1%
Upper-Medium Income Countries (UMC)	9.0	37.9	23.7%
Lower-Medium Income Countries (LMC)	1.1	10.0	10.9%
Low Income Countries (LIC)	0.1	0.8	13.5%
Global (GLO)	***23.7***	***67.7***	***35.0%***
Latin America and the Caribbean (LAC)	0.54	4.2	12.8%

Despite 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 gross output, and more generally, monetary data to extrapolate SW has many shortcomings: for example, the exclusion of the waste generation by the informal economy and the overestimation of waste generation for geographically small countries with high GDP. Construction and demolition waste could be better estimated 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 monetary output for the development of scaling factors 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), and 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*).

When detailed Physical Energy Flow Accounts (PEFAs) are not available, two sources to split the use of fossil fuels into either energetic or material are available, namely energy balances and material flow accounts:

1. 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 (tonne) units using average calorific values from the IEA Energy Statistics Manual.[25]

2. The MFA accounts at the TCCC level from the IRP GMFD include the item 'Other products mainly from fossil fuels e.g. plastic' (corresponding to the MF4.3 item), which can be used to estimate the material use of fossil fuels. However, it should be noted that this item is only reported for the imports and export accounts and not for domestic extraction, one as material use of fossil fuels is related to processed products rather than raw materials. In this case, consumption would exclude processed fossil fuels products that are domestically produced and consumed.

Despite being less comprehensive, in the context of this analysis, the second approach was used because it was deemed more coherent with the rest of the data (i.e. not relying on yet another database) and less time consuming. For some major economies with potentially significant domestic production and consumption of fossil fuel products—such as Argentina, Brasil, Chile, Colombia, Mexico, Perù and Venezuela—data from the UNSTAT energy balances was used to allocate domestic extraction of 'Crude Oil' and 'Natural gas liquids' (corresponding to MF4.2.1). Overall, the material use (mUse) of fossil fuels ranged between 86% and 99%, while for major economies the range is reduced to between 92% and 98%.

Land-use and land-cover change emissions

LULUCF emissions are central to determining 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 LULUCF, we used the PRIMAP-hist v2.3.1 database[26] and adjusted the figures from a territorial- to a consumption-based principle based on the work of Pendrill and colleagues (2020)[27] and using the script developed by Richard Wood (2021).[28] This adjustment is crucial for countries in tropical regions, such as the LAC region, because the majority of positive LULUCF emissions originate from deforestation (and other practices occurring in these regions) as a result of final consumption happening abroad. This analysis found LULUCF emissions calculated from a consumption-based

[25] IEA, EUROSTAT & OECD. (2004). *Energy statistics manual*. Retrieved from: Eurostat website
[26] Gütschow, J. & Pflüger, M. (2021). The PRIMAP-hist national historical emissions time series (1850-2019) v2.3.1. Zenodo. doi:10.5281/zenodo.5494497
[27] Pendrill, F., Persson, U. M., Kastner, T., & Wood, R.. (2022). Deforestation risk embodied in production and consumption of agricultural and forestry commodities 2005-2018 (1.1) [Data set]. Zenodo. doi:10.5281/zenodo.5886600
[28] Available here.

perspective to be almost 30% lower than those accounted for from a production-based perspective.

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 et al. (2019) and previous research.[29] [30] [31] They distinguish between scale indicators, which provide measures for the overall size of the socioeconomic metabolism, 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.

1. Three pairs of indicators are used to measure the scale of material and waste flows: 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 raw material consumption (RMC), or material footprint;[32]; a measure of global material use associated with domestic final consumption. No corresponding indicator on the output side is 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.

As indicators for the degree of loop closing that has been achieved, five pairs of metabolic rates are proposed, which measure material flows relative to interim flows PM and IntOut:

1. The socioeconomic cycling rate, referred to as the 'Circularity Metric' in CGR LAC, 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 socioeconomic cycling rate [OSCr]**). Recycled waste from material processing and manufacturing

[29] Haas, W., F. Krausmann, D. Wiedenhofer, and 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.
[30] 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.
[31] Nuss, P., G.A. Blengini, W. Haas, A. Mayer, V. Nita, and 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, November 7.
[32] Wiedmann, T.O., H. Schandl, M. Lenzen, D. Moran, S. Suh, J. West, and K. Kanemoto. 2015. The material footprint of nations. Proceedings of the National Academy of Sciences 112(20): 6271–6276.

(for example, recycled steel scrap from autobody manufacturing) is considered an industry internal flow and not accounted for as secondary material. In this model of the physical economy secondary materials originate from discarded material stocks only. The outflows from the dissipative use of materials and combusted materials (energy use) can, by definition, not be recycled. This assumption may lead to a minor under-estimation of downcycled materials, when solid wastes from the combustion of fossil materials are used in construction. Energy recovery (electricity, district heat) from the incineration of fossil or biomass waste is 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 circular economy 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 for sustainable ecological cycling. As a first approximation for renewable biomass, we only consider carbon neutral biomass. We interpret this as a minimum requirement, while more comprehensive assessments should be developed. It can therefore be stated that the IECrp relates to the circularity of terrestrial carbon stocks. To estimate the flow of primary biomass that cannot be regarded as carbon neutral, we deduct the biomass-related net-emissions of carbon from LULUCF from socioeconomic biomass flows, consistently re-estimated as tons of carbon content. To calculate the amount of circular and non-circular biomass, the flow of primary biomass through the economy is 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 then applied to split the biomass flow in 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 deicing roads, for example, we did not allocate these materials to non-circularity 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) and it is used as a bridging item rather than an actual indicator (see ***Figure one***). 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 which is not straightforward to reconcile. Calculating indicators on PRM the same way as on PM would imply extending assumptions that are supposedly valid only within the system boundary definition (the economy under analysis), outside of it (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 (e.g. gasoline, diesel, kerosene) that are being burned 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. Therefore, we introduce 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. Another issue related to using RMEs rather than physical flows is that it is hard to track the fate of raw materials extracted abroad and that are not embedded into the traded commodity, but rather transformed into waste and emissions during processing.

Table thirteen. Mass-based circular economy indicators where scale indicators measure the absolute size of input and output flows in tons and circularity rates measure socioeconomic and ecological cycling relative to input and output flows in percentage (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	Processed Raw Materials (PRM) = RMC + secondary materials	Interim outputs (IntOut) = EoL waste + DPO emissions	n.a
Metabolic rates (%)	**Socioeconomic cycling (SC)**	Input socioeconomic cycling rate (ISCr) = Share of	Input socioeconomic cycling rate (ISCr) = Share of	Output socioeconomic cycling rate (OSCr) = Share	n.a

		secondary materials in PM	secondary materials in PRM	of secondary materials in IntOut	
	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 Abroad (NEA)	n.a.	Net extraction abroad rate (NEAr) = share of NEA in PRM		n.a
	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 CE's MFA model. 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).[33] Let's consider ISCr—the share of secondary materials in PRM—and re-write it in mathematical terms:

$$ISCr = SM/PRM \ (Eq. ten)$$

Where:

$$DMC = DE + IMP + SM_{imp} - EXP - SM_{exp} \ (Eq.\ eleven)$$

$$PRM = DMC + NEA + SM$$

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

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

$$DMC = DE + IMP - EXP \ (Eq.\ twelve)$$

[33] Eurostat (2018). *Circular material use rate: Calculation method*. Retrieved from: Europa website

then $ISCr$ can be rewritten as:

$$ISCr = \frac{SM_{dom} + SM_{imp} - SM_{exp}}{DMC + NEA + SM_{dom} + SM_{imp} - SM_{exp}} \quad (Eq.\ thirteen)$$

A higher ISCr rate value means that more secondary materials are substituted for primary raw materials, thus reducing the environmental impacts of extracting primary materials. 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 and regions are open economies with flows of imports and exports of waste collected in one country but treated and recycled in another one. In 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 as much as possible on official statistics compiled by National States and reported under legal obligations. Data gaps are filled in with estimates and extrapolations based on the best available data, expert knowledge and assumptions:

- **Waste statistics:** Regulations on waste statistics in Latin American countries are deployed at the national level with no obligations to report on any supra-national entity, such as for example the European Community (EC) through its centralises statistical body Eurostat. For instance, (EC) No2150/2002 on waste statistics (WStatR) is a framework for harmonised Community statistics in this domain that requires EU Member States to provide data on the generation, recovery and disposal of waste every second year. In that context, the harmonised data set on waste treatment (env_wastrt) are used (or in special cases compiled based on such regulation) for the calculation of ISCr rate;

- **Economy-wide material flow accounts:** As already mentioned in Chapter one, 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. 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;

- **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 are the official harmonised source of information about exports, imports and the trade balances of the EU. For European Member States, data is extracted from the COMEXT website while for non-European member states data is extracted from the BACI database. The main classifications for ITGS are the Combined Nomenclature (CN) and Harmonised System (HS).

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.

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 that 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), is generated for example As a 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. Any circular use of residual material that does not touch the waste management system and that is currently infeasible to quantify based on statistics is excluded. 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 measure 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 Waste Framework Directive 75/442/EEC, a distinction is made in treatment types, namely:

- Recovery—energy recovery (RCV_E). Operation R1 corresponds with the treated amount of waste used principally as fuel or other means to generate energy.

- Recovery—recycling and backfilling (RCV_R_B). RCV_R_B breaks down in RCV_R (Recovery—recycling) and RCV_B (Recovery—backfilling). RCV_R is the waste recycled in domestic recovery plants and it comprises the recovery operations R2 to R11—as defined in the Waste Framework Directive 75/442/EEC.

For the purpose of the ISCr rate indicator it is concluded that the best option is to include recycling and backfilling (code: RCV_R) i.e., excluding energy recovery.

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:

$$SM = SM_{dom} + SM_{imp} - SM_{exp} \; (Eq.\ fourteen)$$

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.[34] Circle Economy 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 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.

[34] Eurostat. (2021). List of CN-codes used to approximate imports and exports of waste destined for recycling. Retrieved from: Europa website

Macroeconomic scenario modelling

Environmentally extended input-output analysis (EE-IOA) provides a simple and robust method for evaluating the linkages between economic consumption activities and environmental impacts, including the harvest and degradation of natural resources. EE-IOA is now widely used to evaluate the upstream, consumption-based drivers of downstream environmental impacts and to evaluate the environmental impacts embodied in goods and services that are traded between nations.

EE-IOA can be applied to assess the economic and environmental implications of a transition towards a circular economy.[35,36,37] IOA, in its various forms, is a static structural model that provides a high resolution of sectors and structural economic composition and makes it a useful tool for the impact assessment of supply chains. As such, it is a suitable model for the creation of 'what-if' scenarios through the application of exogenous changes, which can also be named *nowcasting*. One of the advantages of this type of approach is the level of transparency in its assumptions. This is especially important for circular economy impact assessment as the variety of approaches makes it difficult to compare studies. Previous studies have tried to categorise types of interventions within a circular economy, their fundamental waste management models and indicators. However, further and continuous development of assessment methods is still necessary to improve their application as policy tools.

As the first step, building on the work of Aguilar-Hernandez and colleagues (2018) and Donati and colleagues (2020) and integrating it with additional literature on circular strategies frameworks,[38] [39] [40] [41] a new comprehensive circular economy policy modelling framework was developed. We begin by asserting that the objective of a circular policy is always the implementation of the circular economy paradigm. In order to achieve this objective, different strategies exist. There are various categorisations of circular strategies such as ReSOLVE.[42] [43] However, in this study we integrate the the four-strategy classification of Aguilar-Hernandez and colleagues (2018), which consists of: Product

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[35] 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
[36] Wood, R., Moran, D., Stadler, K., Ivanova, D., Steen-Olsen, K., Tisserant, A., & Hertwich, E. G. (2018). Prioritizing consumption-based carbon policy based on the evaluation of mitigation potential using input-output methods. Journal of Industrial Ecology, 22(3), 540-552.
[37] 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, 106322.
[38] Blomsma, F., Pieroni, M., Kravchenko, M., Pigosso, D. C., Hildenbrand, J., Kristinsdottir, A. R., ... & McAloone, T. C. (2019). *Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation*. Journal of Cleaner Production, 241, 118271. doi:10.1016/j.jclepro.2019.118271
[39] Morseletto, P. (2020). *Targets for a circular economy*. Resources, Conservation and Recycling, 153, 104553. doi:10.1016/j.resconrec.2019.104553
[40] Reike, D., Vermeulen, W. J., & Witjes, S. (2018). *The circular economy: new or refurbished as CE 3.0?—exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options*. Resources, Conservation and Recycling, 135, 246-264. doi:10.1016/j.resconrec.2017.08.027
[41] 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
[42] McKinsey & Company. (2016). *The circular economy: Moving from theory to practice.* Retrieved from: McKinsey website
[43] Bocken, N. M., 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

Lifetime Extension (PLE), Resource Efficiency (RE), Closing Supply Chains (CSC) and Residual Waste Management (RWM)—with a variation of the 10Rs framework developed by Potting and colleagues (2017).[44]

We define interventions as sets of strategies and improvement options (or simply interventions). For example, PLE can be achieved, among others, by reuse and remanufacturing, or by delaying products' replacement. In other words, while these two interventions aim at the same objective—the extension of the product's life—the way they are implemented is different.[45] We further distinguish between a general description of interventions and specialised interventions. An intervention (for example, reuse and remanufacturing) is specialised when it refers to a specific product or application (for example, increased lifetime through reuse and remanufacturing in final consumers' vehicles). Interventions are modelled through sets of changes that affect the production and consumption systems. We further distinguish between primary and ancillary changes. For instance, if the intervention concerns increasing the life-time of vehicles, the primary change would be a reduction of sales of vehicles resulting from fewer consumers needing to replace their vehicles. A corresponding ancillary change would be the potential increase in repairing services caused by a higher utilisation of the good. We show this conceptual approach in ***Figure nine***.

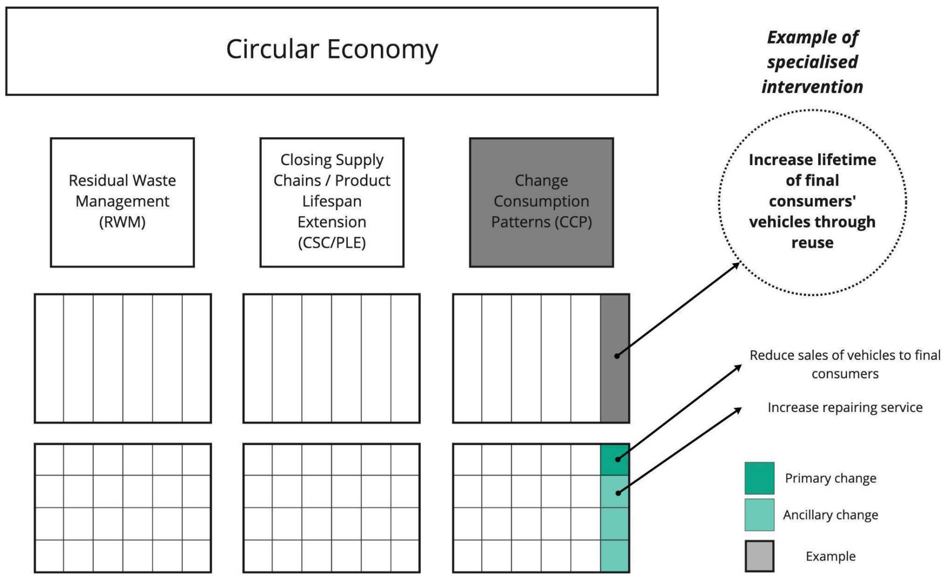

Figure nine. Circular economy policy modelling framework (from Donati et al. 2020).

[44] Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: measuring innovation in the product chain*. The Hague: PBL Publishers, 2544. Retrieved from: Netherlands Environmental Assessment Agency website
[45] Allwood, J. M., & Cullen, J. M. (2015). *Sustainable materials without the hot air: making buildings, vehicles and products efficiently and with less new material*. UIT Cambridge Limited.

All basic IO calculations are performed using the open-source tool for analysing global EE-MRIOs, **pymrio**.[46] Production- and consumption-based accounts are calculated using a standard set of IO formulas as specified in ***Table fourteen.***

Table fourteen. Description of main pymrio variables.

Variable name	Symbol	Description
Consumption-based accounts	$D^i_{cba} = D^i_{pba} + D^i_{imp} - D^i_{exp}$	Footprint of consumption
Production-based accounts	$D^i_{pba} = Fe + Ge$	Footprint of production or territorial accounts
Imports accounts	$D^i_{imp} = MY_t$	Footprint of imports or factors of production occurring abroad (embodied in imports) to satisfy domestic final demand
Exports accounts	$D^i_{exp} = M\hat{Y}_t e$	Footprint of exports or factors of production occurring domestically (embodied in exports) to satisfy final demand abroad
Factor production	F_e	Factors of production: extension plus value added block
Final demand factors	G_e	Factors of production: extension of final demand
Multipliers	$M = SL$	–
Leontief inverse	$L = (I - Z\hat{x}^{-1})^{-1}$	Total requirements matrix
Factor production coefficients	$S = F\hat{x}^{-1}$	–
Gross output	$x = Z_e + Y_e$	–
Transaction matrix	Z	Matrix of interindustry flows or intermediate transaction matrix
Final demand matrix	Y	Final demand matrix, including demand of imports, exports and domestic demand
Final demand matrix to satisfy factors of production abroad	$Y_t = Y - Y_{i,j} \mid i$	Final demand matrix with domestically satisfied final demand $Y_{i,j} \mid i$ subtracted, and Y_t represents the demand of UK's products and sectors from abroad

Note: the $\hat{}$ symbol represents the diagonalised vector, the e symbol represents a summation vector of ones.

Hereby, we present systematic methods to build complex circular economy counterfactual ('what-if') scenarios with EE-IOA. The basic Leontief demand-driven model

[46] Stadler, K. (2021). Pymrio – a Python based multi-regional input-output analysis toolbox. *Journal of Open Research Software*, 9(1), 8. doi:10.5334/jors.251

can be framed such that a stimulus vector of final demand leads to a set of impacts occurring in each production sector as:

$$D^{i}_{cba} = \hat{S}\,(I - A)^{-1} \quad (Eq.\ fifteen)$$

Note that (Eq. fifteen) is another expression of D^{i}_{cba} in ***Table fourteen***, where D^{i}_{cba} is a resulting column vector of impacts occurring in each production sector (the response variable) and Y^{i}_{e} is the column vector of final demand of products delivered by each sector (the control variable). The parameters of the model are the column vector S^{i} of environmental intensities (environmental pressure per unit of economic output) and A is a matrix of technical coefficients (whose entry ij is the volume of inputs from sector i that are required to generate one unit of output of sector j). For some environmental pressures (for example, global warming) there are direct emissions resulting from final consumption activities (for example, the combustion of fossil fuels by households leads to the emission of greenhouse gases). When this is the case it is necessary to include emissions from final demand to obtain total emissions, Ge.

$$D_{cba,\,tot} = D^{'}_{cba}e + Ge \ (Eq.\ sixteen)$$

In the previous expression, prime (') denotes transposition. If more information is available, the intensity of final consumption environmental pressures can, in principle, be disaggregated by product category. Note that the application the system uses is multi-regional. That is, each entry identifies not only a row and/or column economic sector or final demand category but also a region (for example, LAC, EU or Rest of the World).

To assess the environmental or socioeconomic impact of implementing a circular economy policy, we compare the impact that occurs in the baseline and the impact that occurs in a counterfactual scenario in which the changes corresponding to the circular intervention and strategy have been implemented. More formally, the impact of the circular policy is $\Delta D_{cba} = D^{*}_{cba} - D_{cba}$, where D_{cba} is the impact in the baseline scenario, and D^{*}_{cba} is the impact in the counterfactual scenario, defined as:

$$\hat{S}^{*}\,(I - A^{*})^{-1}\,Y^{*}_{e} \quad (Eq.\ seventeen)$$

If there are final consumption pressures, we can further define:

$$\Delta D_{cba,tot} = D^{*}_{cba,tot} - D_{cba,tot} \qquad \text{where:}$$

$$D^{*}_{cba,tot} = (D^{*})^{'}_{cba}e + Ge^{*}$$

A counterfactual scenario (an object adjoined with *) is constructed by adjusting specific elements in the objects that define the baseline EE-IO system—S, A, Y (and possibly Ge) with this adjustment being as faithful as possible to the concepts underlying the policy intervention, subject to the limitations of the data and model.

The counterfactual scenario is constructed by adjusting only a (possibly) small set of values of some of the matrix objects that define the EEIO system. All other entries remain identical in both scenarios. With the current methods, we do not perform any automatic rebalancing of the counterfactual scenario, as such the system may become unbalanced when changes are applied to the technical coefficient matrix A (i.e., total outputs differ from total inputs).

The edit of a particular entry ij of an arbitrary T matrix object from the baseline to the counterfactual scenario, is performed by the **pycirk**[47] software as:

$$M^{*}_{ij} = M_{ij} (1 - k_a) \; (Eq.\ eighteen)$$

The change coefficient (k_a) expresses the magnitude by which a value in the IO system is modified. It is obtained as the product of a technical change coefficient (k_t) which describes the intervention's maximum potential effect, and of a market penetration coefficient (k_p) describing the size of the given market affected so that:

$$k_a = k_t k_p \quad (Eq.\ nineteen)$$

Furthermore, there might exist a substitution relation between edits in different entries. For example, a reduction in the volume of a particular material (for example, steel) used in a production process might be compensated by an increase of another (for example, aluminium). This type of relation is modelled as:

$$M^{*}_{ij} = M_{ij} + \alpha(M^{*}_{mn} - M_{mn}) \; (Eq.\ twenty)$$

Here mn are the coordinates of the original change (for example, reduction in steel) and ij are the coordinates of the substitution (for example, increase in aluminium). α is a substitution weighing factor accounting for differences in price and physical material properties between products, materials or services.

This modelling approach considers the impact of actions at the margin, if taken tomorrow—namely, counterfactual scenarios or 'what-if' scenarios. This approach differs from the method of modelling the efficacy of interventions that would be adopted gradually at different points in time, which is far more complex. The sequencing would create many different path-dependent trajectories: while some changes considered would affect the volume of a particular stock, others would affect yearly flows (for example, the carbon footprint of electric vehicles depends strongly on the carbon intensity of the electricity used to fuel them). With our counterfactual modelling techniques, we considered the impact of a particular behaviour change in terms of yearly impact in a future year in which the relevant stock has been fully replaced. For example, the impact of improving building insulation is based on a comparison between the status quo and a hypothetical situation where a given fraction of existing buildings, and the same fraction of new construction, has improved insulation. In other words, we compare the baseline scenario against a future steady-state situation in which the relevant stock has been replaced following the change. Rebound effects due to re-spending are not considered[48]. In ***Table fifteen***, we list the main set of drivers used for modelling the

[47] 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

[48] Moran, D., Wood, R., Hertwich, E., Mattson, K., Rodriguez, J. F., Schanes, K., & Barrett, J. (2020). Quantifying the potential for consumer-oriented policy to reduce European and foreign carbon emissions. Climate Policy, 20(sup1), S28-S38.

scenarios (*see Annex II for a more detailed description and parameterisation of the scenarios).*

Table fifteen. High-level assumptions and drivers behind the modelling of the scenarios for the CGR LAC.

Scenarios	Interventions
Nutrition	• Whole population moves towards a more 'Mediterranean' diet substituting 80% of meat consumption towards fish, grains and vegetables • Reduction of 50% of the avoidable food waste produced by households. • Caloric intake per capita reduced towards average sufficiency level for European populations estimated at 2,700 calories/capita/day. • 50% reduction in mineral fertiliser use, 50% reduction of transport use for food logistics (more local food consumption) and 30% increase in seasonal food consumption

Manufacturing and Consumer goods	• *Process improvements:* Reduction of raw materials needed in the fabrication of finished products. The original intervention modelled by Donati and colleagues (2020) as a 28% reduction of aluminium and steel into specific products was extended to all metals, chemicals and wood.
	• *Industrial symbiosis*: limited to metals in this specific case and it consists of two similar interventions:
	  ○ Scrap diversion to other uses. Reduction of the amount of selected metals going to recycling from manufacturing industries (scrap) and equal reduction to the consumption of the primary source across other selected sectors. Scrap substitution is assumed to apply to selected sectors based on the fact that the scrap reduction concerns the production of manufactured products for specific industries;
	  ○ Reduce yield losses. Reduction of the flows of selected metals going to recycling from their primary production and equal reduction to the consumption of the primary source across all categories. Yield losses are assumed to apply to all the sectors since the reduction of yield losses concerns specifically the production of semi-manufactured products for many industries.
	• *R Strategies:* Application of the strategies is the same across all product categories and is split as follows: 50% remanufacturing/refurbishment, 12.5% repair/maintenance, 12.5% upgrade, 25% reuse. Repair/maintenance, upgrade and reuse are applied at both the inter-industry and final demand levels.

It should be noted that the changes calculated using the IOA model reflects exclusively on RMC (or D^i_{cba}***) and not on*** SM***. Changes on the direct physical volumes of*** SM ***are modelled mostly through high-level assumptions due to the lack of an integrated direct (as opposed to 'virtual' embodied) physical and monetary modelling system***.

System visualisation

Sankey diagrams are used to visualise flows of materials and energy in many applications, to aid understanding of losses and inefficiencies, to map out production processes and to give a sense of scale across a system. As available data and models become increasingly complex and detailed, new types of visualisation may be needed. A systematic method was adopted for generating different hybrid Sankey diagrams from a dataset, with an accompanying open-source Python implementation called Floweaver.[49] Underlying the Python library, a common data structure for flow data was defined, through which this method can be used to generate Sankey diagrams from different data sources such as material flow analysis, life-cycle inventories or directly measured data.[50]

The generation of the Sankey relies on the same input data used in the analysis in the form of Exiobase v3.8.2 with the updated environmental extension. In the first step, all four footprint accounts D^i_{cba}, D^i_{pba}, D^i_{imp} and D^i_{exp} were extracted and a fifth matrix of embodied resources through industries is calculated according to the following formula: $Zm = Z * M$. In the second step, a cut-off was defined in order to exclude smaller flows from the visual that would increase the image cluttering. In the third step, the five datasets were rearranged in the table format that is required from the Floweaver library to automatically generate the Sankey. The table format includes four different columns with the following labels: 'source' can be either the environment, a domestic industry or a foreign industry; 'target' can be a domestic industry, a foreign industry or a societal need; 'type' refers to one of the four resource groups and 'value' is an integer.

For entries in the D^i_{pba} dataset, 'source' is always set to the environment as these are all inputs coming from domestic extraction, meanwhile the 'target' is the extractive industries. For entries in the Zm dataset, both 'source' and 'target' are domestic industries as this matrix represents the resources embodied in domestic inter-industry transactions. For entries in the D^i_{imp} dataset, 'source' is always set to the exporting foreign region while the 'target' is the importing domestic industry. For entries in the D^i_{exp} dataset, 'source' is always the domestic exporting industry while 'target' is the importing foreign region. Finally, for entries in the D^i_{cba} dataset, the 'source' is the domestic industry whereas the 'target' is the societal need under which the material footprint was categorised. The categorisation of the material footprint by societal need follows the approach used by Ivanova and colleagues in 2017[51] through a concordance matrix describing the assignment of EXIOBASE product sectors across consumption domains at the final demand level.

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[49] FloWeaver. (n.d.). floWeaver generates Sankey diagrams from a dataset of flows. Retrieved from: [Sankey Review website]

[50] Lupton, R. C., & Allwood, J. M. (2017). *Hybrid Sankey diagrams: Visual analysis of multidimensional data for understanding resource use*. Resources, Conservation and Recycling, 124, 141-151. doi:10.1016/j.resconrec.2017.05.002

[51] Ivanova, D., Vita, G., Steen-Olsen, K., Stadler, K., Melo, P. C., Wood, R., & Hertwich, E. G. (2017). *Mapping the carbon footprint of EU regions*. Environmental Research Letters, 12(5), 054013. doi:10.1088/1748-9326/aa6da9

Job creation potential analysis

Drawing inspiration from recent literature on environmental and social taxation, such as the Ex'Tax project and the Circular Taxation Framework, the methodology developed by Circle Economy aims to estimate the Job Creation Potential of diverse circular economy strategies, with the assumption that a differential fiscal regime will shift the tax burden from circular to linear activities. Through this fiscal reform, wealth accumulation (through dividends and property) is systematically prevented in linear sectors and is redistributed to those activities that improve environmental and social performances.

The methodology follows a three-step approach to measure the job creation potential of circular policy interventions:

1. Firstly, we rethink the regional fiscal system and incentives. While the tax instruments and different sources that could increase the fiscal capacity are discussed qualitatively, the quantitative change is calculated for each country after fixing the tax revenue as a share of Gross Domestic Product (GDP) to the average OECD level.
2. The additional monetary resources are allocated through a multi-criteria prioritisation system across different sectors and interventions. Three criteria have been used for the allocation between sectors (material footprint, carbon footprint, and workforce size). For the allocation within each sector, we consider the implementation cost of the proposed interventions, classifying each of them according to the implications for reskilling, demand modulation, and capacity building.
3. Finally, we estimate the job creation potential of interventions that require capacity building investments. The monetary expenditure for those interventions and the employment multipliers of the Exiobase sectors affected by them are used to estimate the net creation of jobs.

Apart from the second step, that we discuss in detail hereafter, the other two steps consist of very simple mathematical operations. In the first step, we assume that all countries in LAC increase their fiscal capacity up to the average level of OECD countries, that is, tax revenues are fixed to 33.5% of GDP. This scenario implies additional tax revenues for all countries that reported a lower percentage in the year 2018. The only country with a tax capacity above the OECD average was Cuba (42.3%) which is excluded from the calculation. Summing up the additional tax revenues for all LAC countries, we get the total change in the budget available for circular investments in the region (delta scenario 2 in the calculation sheet). The monetary change is the numerical input that will be used in the second step of the methodology.

Allocation method to circular economy interventions

The budget available for public spending on circular economy strategies needs to be allocated across different sectors for the implementation of 15 circular interventions. Before discussing the criteria for the allocation, it is necessary to understand the definition of each intervention. The list of interventions specified in the table below consists of standard CGR intervention scenarios with a slightly adjusted definition.

Sector	Intervention code and name	Description
Built Environment	BE1: Regulate stock expansion	New directives for construction and demolition waste set a limit to the amount of virgin material that can be used for new building construction. While this intervention can boost new jobs in activities such as urban mining, material scouting, and general construction waste sorting activities, it can reduce the amount of workforce needed for new constructions. We therefore do not assume associated job creation potential for this policy intervention
	BE2: Renovation and space optimisation *	Urban planners increase their take on maintenance and renovation of public spaces. At the same time, subsidies to households are granted to incentivize the upgrading of heating and cooling systems and to improve the energy efficiency of buildings. Besides the reskilling of the workforce, the increasing demand for renovation activities could bring to a net job creation.
	BE3: Resource efficiency	This strategy aims to transform the way construction works are planned. Architects, engineers, and construction workers will need to adapt their processes to achieve higher resource efficiency in the sector. Training and incentives are granted to professionals to reduce material inputs without reducing durability of buildings.
Agrifood	AF1: Dietary habit change	The fiscal reform will incentivize the consumption of healthier alternatives, while awareness campaigns and a free consultation to the nutritionists can help the population to improve their dietary habits and avoid over-consumption. An increase in public awareness and the gradual adjustment of the prices can shift or slightly reduce the demand for food products and therefore only hold potential for transformation of the workforce.
	AF2: Sustainable agriculture	Local, organic and seasonal food cooperatives are stimulated by subsidies to be more competitive in the food market. Training on sustainable farming is provided to promote the use of biological inputs and other practices that maximise the yield of crops and aquaculture while minimising the ecosystem disruption in the long-run. Despite sustainable agriculture practices being more labour intensive, the fiscal reform could bring job losses in other food chains (e.g. non-seasonal food production).
	AF3: Reduce food loss and avoid food waste *	Waste prevention can occur both for the avoidable food loss and the unavoidable food waste stream. In the first case, jobs can be created in the distribution chain of food close to expiry. The second stream can become a resource for innovative enterprises that valorize biomass waste and use it as a resource for the processing of products, such as biofuel and bio-packaging production.
Mobility	MO1: Reduce car ownership	The suggested fiscal reforms will reduce the sales of new cars while promoting the use of car sharing services in peripheral as well as urban areas. While this intervention could reduce the employment in retail and manufacture of new vehicles, it can also bring a transformation of the automotive sectors toward shared mobility solutions

		fostering employment in related services.
	MO2: Increase public transport *	Subsidies and private investment in public transport can foster employment in the construction of new infrastructures, in the operation of the additional vehicles in the public fleet and their maintenance, as well as creating jobs in station services.
	MO3: Fleet electrification	Incentives for the electrification of public and private fleets can stimulate employment in R&D for sustainable mobility (e.g. biofuel and hydrogen). However, employment can be lost in the production and the sales of traditional fuel products.
	MO4: Lightweight vehicles	A tax relief on income of repair technicians and VAT on second-hand sales and upgrading of vehicles can encourage the shifting and reskilling of workers automobile technicians.
Manufacturing	MA1: Sustainable textile	The fiscal reform can bring to a reduction of first-hand production and sales in the textile sector, while incentivizing the collection and sales of second-hand clothing. The transformation of the sector requires a re-skilling of workers for the production of organic garments and a shift of the workforce employed in manufacturing and retail activities to the sorting and recycling of clothing.
	MA2: Longer life equipment	Tax relief/break for all jobs/activities in Repair, Maintenance, Upgrading, and Re-manufacturing will bring to a reduction in new sales of new machinery and equipment while extending the lifetime of those in use. This intervention will require a re-skilling of the manufacturing enterprises and technicians to be able to perform those activities.
	MA3: Industrial symbiosis	Training of employees is provided to promote industrial symbiosis with recycling strategies for enterprises operating in large industrial poles. The intervention only aims to train workers on these solutions but without subsidising the hiring of experts in industrial recycling strategies.
	MA4: Recycling infrastructure *	Investments and subsidies are required to expand the recycling infrastructure and to improve the activities of collection and sorting of disposed materials. This intervention holds a big potential for job creation (due to new facilities) as well as “formalisation” of informal workers in the waste sector through Negative Income Tax and other incentives.
	MA5: Immaterial lifestyle	Fiscal incentives, such as differential VAT and income tax, can shift production and demand from material to immaterial goods (e.g. recreational services), bringing to a reduction in the demand for manufactured goods and to a bigger demand for entertainment services and membership activities. Part of the workforce in the manufacture and retail sector could transition towards the provision of immaterial goods without necessarily bringing to jobs losses.

*Note: the * symbol represents the interventions that we deem to hold potential for capacity building and net job creation*

The allocation of resources between different sectors and purposes has no unique solution as several criteria can be used by local stakeholders and experts to determine the distribution across the aforementioned sectors and interventions. Hereby, we propose a multi-criteria approach to allocate the budget across different sectors based on their material and carbon footprint, and their workforce size. The following equation is used to calculate the score for each sector to determine the budget allocation:

$$S_i = (0.5\, MF_i + 0.5\, CF_i) + WS_i$$

where MF_i *is the material footprint of sector i,*
CF_i *is the carbon footprint of sector i,*
and WS_i *is the workforce size of sector i*

Hence, the score of each sector includes a component representing its potential for footprint impact reduction (with equal weight assigned to material and carbon footprint) and another element that refers to the size of the investment that is required to reskill and support the transformation of the sector's workforce. Finally, the share of the investment destined to sector *i* is given by S_i/S_{tot}. For simplicity, the three criteria have been scored with High (with value 3), Medium (2), and Low (1), but the use of actual indicators is advised for future applications of the method.

Following the description of the interventions listed in the table, another classification has been made to describe their expected implementation cost and to determine the allocation of resources within the sector.

1. Interventions that imply only a reskilling of the workforce and a Negative Income Tax get value 1 (Low cost);
2. When the intervention also require demand modulation through other taxes and subsidies (e.g. Sustainable agriculture and textile), the associated value is 2 (Medium cost);
3. For the interventions that require capacity building and infrastructure investment, in addition to expenses on skilling and demand modulation, the value assigned is 3 (High cost).

All interventions hold transformative potential[52] for the labour market but only a few are deemed to hold potential for capacity building[53] (as indicated in the table above) which are the ones considered in the estimation of net job creation. Finally, the monetary resources allocated to the 4 sectoral strategies that require capacity building have been split equally across the Exiobase industries that are instrumental to the implementation of the strategy. Using the employment multipliers for each Exiobase industry (from matrix M), we estimate net job creation per sector, strategy, and grand total.

[52] Transformative potential is taken to mean that an overall demand reduction would be compensated by a shift towards other services and activities. No net job creation potential is considered overall for these interventions.
[53] Capacity building potential is taken to mean that the intervention would lead to the generation of new net activities on the market.

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