The CIRCULARITY GAP REPORT Nations

Methodology Document

Circle Economy
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List of abbreviations and acronyms

CE: Circular economy

CGR: *Circularity Gap Report*

CM: Circularity Metric

EE-MRIOA: Environmentally-Extended Multi-Regional Input-Output Analysis

EW: Economy-wide

GDP: Gross domestic product

HSUT: Hybrid supply and use tables

IE: Industrial ecology

LCA: Life cycle assessment

EW-MFA: Economy-Wide Material Flow Accounting

NSI: National Statistical Institute

PSUT: Physical supply and use tables

RME: Raw material equivalents

SEM: Socioeconomic metabolism

SEEA: System of Environmental-Economic Accounting

SNA: System of National Accounts

SNAC: System of national account consistent

CIRCLE ECONOMY

Glossary

By-products: A product that is produced simultaneously with another product, but which can be regarded as secondary to that product, for example, gas produced by blast furnaces. In the context of measuring a circular economy, this refers to substances or objects resulting from a production process, the primary aim of which is not the production of that item. In this case, a substance or object may be regarded as being a by-product only if it is produced as an integral part of a production process, its further use is certain and lawful, and it can be used directly without any further processing other than normal industrial practice. By-products are not waste (source: SNA).

Circular economy: A circular economy is an economy where the value of materials in the economy is maximised and maintained for as long as possible; the input of materials and their consumption is minimised; and the generation of waste is prevented and negative environmental impacts reduced throughout the life-cycle of materials (source: OECD expert group and UNECE Task Force)

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

Domestic Material Consumption (DMC): An environmental indicator that covers the flows of products and raw materials alike by accounting for their mass. It can take an 'apparent consumption' perspective—the mathematical sum of domestic production and imports minus exports—without considering changes in stocks. It can also take a 'direct consumption' perspective, in that products for import and export do not account for the inputs—be they raw materials or other products—used in their production (source Sala et al. 2019)[1]

Ecological cycle: Also referred to as biological cycle, is the processes - such as composting and anaerobic digestion - that together help to regenerate natural capital. The only materials suitable for these processes are materials of biological origin or bio-based materials, excluding materials embedded in geological formations and/or fossilised (source: Ellen Mac Arthur Foundation Glossary)

Greenhouse gases (GHG) refers to a group of gases contributing to global warming and climate breakdown. The term covers seven greenhouse gases divided into two categories. Converting them to carbon dioxide equivalents (CO2e) through the application of characterisation factors makes it possible to compare them and to determine their individual and total contributions to Global Warming Potential (see below).[2]

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

[2] Eurostat (2016). Glossary: Greenhouse gas, Eurostat: Statistics explained. Retrieved from: [Eurostat website]

Global warming potential (GWP) The heat absorbed by any greenhouse gas in the atmosphere as a multiple of the heat that would be absorbed by the same mass of carbon dioxide (CO2). The GWP of CO2 is 1. For other gases, the GWP depends on the gas and the time frame considered (source: IPCC).[3]

Goods: Physical objects for which a demand exists, over which ownership rights can be established and whose ownership can be transferred from one institutional unit to another by engaging in transactions on markets; they are in demand because they may be used to satisfy the needs or wants of households or the community or used to produce other goods or services (source: SNA).

Material: Substances or compounds are used as inputs to production or manufacturing because of their properties. A material can be defined at different stages of its life cycle: unprocessed (or raw) materials, intermediate materials and finished materials. For example, iron ore is mined and processed into crude iron, which in turn is refined and processed into steel. Each of these can be referred to as materials (source EU Commission).[4]

Material footprint: The attribution of global material extraction to a country's final domestic demand. In this sense, the material footprint represents the virtual total volume of materials (in Raw Material Equivalents) required across the whole supply chain to meet final demand. The material footprint, as referred to in this report, is the sum of the material footprints for biomass, fossil fuels, metal ores and non-metallic minerals (source: UNSD).[5]

Material flows: The amounts of materials in physical weight that are available to an economy. These material flows comprise the extraction of materials within the economy as well as the physical imports and exports (*id est,* the mass of goods imported or exported). Air and water are generally excluded (source: Eurostat).[6]

Natural resources: include land, water, air and materials. They are seen as parts of the natural world that can be used for economic activities that produce goods and services. Material resources are biomass (like crops for food, energy and bio-based materials, as well as wood for energy and industrial uses), fossil fuels (in particular coal, gas and oil for energy), metals (such as iron, aluminium and copper used in construction and electronics manufacturing) and non-metallic minerals (used for construction, notably sand, gravel and limestone) (source: UNEP).[7]

Primary raw materials: Also known as virgin materials, are basic natural materials that are extracted from the ground or harvested and processed into new materials or products. For example, bauxite is the raw material that is processed into aluminium, petroleum for plastics manufacture, iron ore for steel manufacture and wood pulp for paper manufacture. Conversely, non-virgin materials, also referred to as "secondary materials" would include materials in products that have been reused, refurbished or repaired; components that have been remanufactured; materials that have been recycled (source: SEEA-CF).

Products: Goods and services exchanged and used for various purposes, as inputs in the production of other goods and services, as final consumption, or for investment. *Semi-finished products* are products that have undergone some processing but require further processing before they are ready

[3] Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., & Zhou, B. (eds.). (2021) *Climate change 2021: The physical science basis. Contribution of working group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press (In Press), Retrieved from: IPCC website

[4] European Commission. (n.d.). EU Science Hub, Raw Materials Information System (RMIS). Retrieved from: RMIS website

[5] United Nations Statistics Division. (2022). SDG Indicator Metadata. Retrieved from: UN statistics website

[6] Eurostat, Statistics explained. (2017) Glossary: Material flow indicators. Retrieved from: Eurostat website

[7] UN Environment Programme. (n.d.). Glossary. Retrieved from: Resource Panel Glossary

for use. They may be sold to other manufacturers or transferred to sub-contractors for further processing. Typical examples would include rough metal castings sold or transferred for finishing elsewhere (NACE Rev. 2). *Finished products or goods* consist of goods produced as outputs that their producer does not intend to process further before supplying them to other institutional units. A good is finished when its producer has completed their intended production process, even though it may subsequently be used as an intermediate input into other processes of production.

Raw materials: Natural resources which are converted into useful primary materials. Examples are ores (for metals), minerals (e.g. chalk, gravel, sand, stones), air and water, but also oil, natural gas, coal and biomass if they are used as matter (e.g. construction materials, lubricants). A distinction can be made between 'primary raw materials` and 'secondary raw materials (source: OECD MFA Guide)

Raw Material Equivalent (RME) A virtual unit that measures how much of a material was extracted from the environment, domestically or abroad, to produce the product for final use. Imports and exports in RME are usually much higher than their corresponding physical weight, especially for finished and semi-finished products. For example, traded goods are converted into their RME to obtain a more comprehensive picture of the 'material footprints'; the amounts of raw materials required to provide the respective traded goods (source: Eurostat).[8]

Raw Material Consumption (RMC) The final domestic use of products in terms of RME. RMC, referred to in this report as the 'material footprint', captures the total amount of raw materials required to produce the goods used by the economy. In other words, the material extraction necessary to enable the final use of products (source: Eurostat).[9]

Recovery: Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. It's a subcategory of "waste management" (source: EU Waste Framework Directive).

Recycling: Any activity by which materials are recovered from a waste stream for the purpose of providing material inputs for use in another production process (other than processes designed for energy recovery, the reprocessing into fuels or material for backfilling) (source: EU Waste Framework Directive).

Residuals: Flows of solid, liquid and gaseous materials, and energy that are discarded, discharged or emitted by establishments and households through processes of production, consumption or accumulation. The term "waste" can be understood as referring to any kind of residuals (source: SEEA-CF).

Reuse: Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived. Reusable products areUsed and end-of-life goods (including second-hand goods) diverted from the waste stream for re-use, remanufacturing, repair or trade (e.g. electrical and electronic equipment or its components that can be used for the same purpose for which they were conceived). Reusable products can be diverted from the waste stream after waste collection (thus ceasing to be waste), or before the products become waste (source: EU Waste Framework Directive).

Secondary materials: Materials that have been previously used and have been recovered or prepared for reuse. This includes materials in products that have been reused, refurbished, or repaired;

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[8] Eurostat, Statistics explained. (2017) Glossary: Material flow indicators. Retrieved from: Eurostat website

[9] Eurostat. (2022) Handbook for estimating raw material equivalents. Retrieved from: Handbook-country-RME-tool (europa.eu)

components that have been remanufactured; and materials that have been recycled. Synonym of "non-virgin materials" (source: Based on Ellen MacArthur Foundation and IRP).

Secondary raw materials: Materials recovered from recycling. This is a subcategory of "secondary material"`. The EU Extractive Waste Directive (2006/21/EC) and the legal definitions of waste and waste management hierarchy regulated by the EU Waste Framework Directive (2008/98/ EC) do not distinguish between "secondary material" and "secondary raw materials" (source: CES Waste Statistics Framework).

Sector: Any collective of economic actors involved in creating, delivering and capturing value for consumers, tied to their respective economic activity. We apply different levels of aggregation aligned with the classifications used in Exiobase V3. These relate closely to the European sector classification framework NACE Rev. 2.

Socio-economic metabolism (SEM): The self-reproduction and evolution of the biophysical structures of human society. It comprises the biophysical transformation processes, distribution processes and flows, that are controlled by humans for their purposes. Together, the biophysical structures of society ('in use stocks') and Socio-economic metabolism form the biophysical basis of society (source Pauliuk et al 2015).[10]

Stressor: In Input-Output Analysis, is defined as the environmental impact occurring within the region that is the subject of the analysis. There is, therefore, an overlap between the stressor and the footprint, as they both include the share of impact occurring within the region as a result of domestic consumption. Conversely, while the rest of the stressor is made of impacts occurring within the region as a result of consumption abroad (embodied in exports), the footprint includes impacts occurring abroad as a result of domestic consumption (embodied in imports).

Technical cycle: The processes that products and materials flow through in order to maintain their highest possible value at all times. Materials suitable for these processes are those that are not consumed during use - such as metals, plastics and wood (source: Ellen MacArthur Foundation Glossary). Material belonging to the technical cycle (technical materials) are non-bio-based materials stemming from non-renewable natural assets (see ecological cycle). In a circular economy their value is maintained by re-using (and repair of) products made from technical materials or material recycling.

Waste: Any material which the holder discards or intends or is required to discard. The term waste is understood to encompass all types of residuals (source: CES Waste Statistics Framework).

Waste collection: The gathering of waste, including the preliminary sorting and preliminary storage of waste for the purposes of transport (source: EU Waste Framework Directive and CES Waste Statistics Framework)

Waste disposal: Any operation which main purpose is not the recovery of materials or energy even if the operation has as a secondary consequence the reclamation of substances or energy. It includes incineration without energy recovery, deposit into or onto land (e.g. landfilling), deep injection, surface impoundment, release into water bodies and permanent storage (source: CES Waste Statistics Framework).

Waste management: Set of lawful activities carried out by economic units of the formal sector, both public and private for the purpose of the collection, transportation, and treatment of waste, including

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

final disposal and after-care of disposal sites. It refers to legal activities carried out by economic units of the formal sector (source: CES Waste Statistics Framework).

Waste prevention: Measures taken before a substance, material or product has become waste, that reduce (a) the quantity of waste, including through the re-use of products or the extension of the life span of products; (b) the adverse impacts of the generated waste on the environment and human health; or (c) the content of harmful substances in materials and products. To be understood as prevention of any kind of residuals, also including emissions to air and to water (source: EU Waste Framework Directive and CES Waste Statistics Framework.

Waste treatment: Recovery or disposal operations, including preparation prior to recovery or disposal. It's a subcategory of «waste management» (source: EU Waste Framework Directive).

Introduction

This document outlines the general methodology used in national *Circularity Gap Reports*, accompanied by Technical Annexes that offer additional insights into the research process. For a comprehensive understanding, this document should be read in conjunction with the Project Annexes.

To clarify terminology and abbreviations used in this methodology pack, please consult the Glossary and List of acronyms and abbreviations.

1. Research aims

Circularity Gap Reports aim to:

1. Identify how materials flow through and accumulate in the economy, providing an understanding of the Socioeconomic metabolism (SEM) of an economy and identifying hotspots to advance the circular economy;
2. Provide a snapshot of how circular a country is by implementing the Circularity Indicator Set (CIS), a systemic approach of indicators to monitor progress towards the circular economy, including the level of Circular Jobs;
3. Spotlight possible interventions within significant sectors and value chains that can drive the transition to circularity and reduce their material and carbon footprints;
4. Provide evidence-based recommendations and spotlight avenues for decision-makers within government and business to drive the circular economy transition and revamp production and consumption patterns.

2. Research approach

Circularity Gap Reports use a mixed research approach and integrate quantitative and qualitative research methods drawing from the *industrial ecology toolkit* to establish baseline circularity and model the effects of a set of circular strategies on the baseline circularity and carbon footprint.

We use two main methods to map how material resources are extracted, transformed and consumed: 1) Economy-Wide Material Flow Accounting (EW-MFA) and 2) Environmentally Extended Multi-Regional Input-Output Analysis (EE-MRIOA). These two tools help understand how material resources are extracted, used, and disposed of within an economy, as well as the GHG emissions, among other environmental impacts, associated with these processes. They are the foundations for the establishment of the Circularity Indicator Set (CIS).

Figure one presents a schematic depiction of the relationships between these methods and their outputs. A brief description of each is provided below in Box 1.1 and Box 1.2, respectively. See Annex A for more information on these approaches.

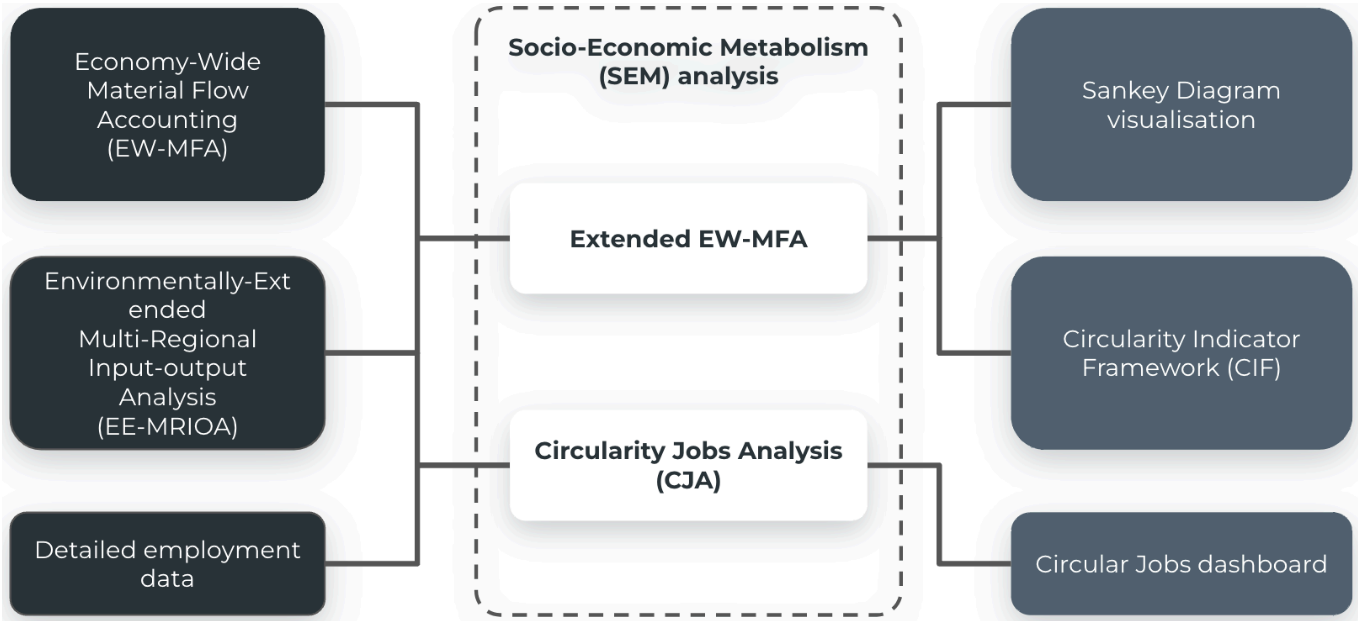

Figure one. Relationship between methods used and their outputs.

Data for this study was gathered through a combination of desktop research collaboration with project partners and consultation with coalition members. For a list of project-specific data sources, see the Project Annex. General data sources underlying Circle Economy's models are referenced throughout this document and its Annexes.

To ensure the robustness and comprehensiveness of the research findings, expert interviews, surveys and workshops were conducted with relevant stakeholder groups. These methods served to validate the data, refine the quantitative findings, and address any knowledge gaps identified during the research process.

Box one: Economy-wide material flow analysis (EW-MFA)

EW-MFA is a tool that quantifies physical material and energy flows and stocks in a system defined in a specific space and time.[11] In its traditional and highly standardised form, EW-MFA represents a robust framework for the compilation of direct material flow data sets that focus on primary material extraction, physical trade (that is, imports and exports), waste and emissions. The direct accounts treat the national economy as a black box and exclude upstream and downstream material flows associated with trade (that is, indirect flows) as well as recycling or reuse flows within the economy and mobilisation of materials that do not enter the economic process. EW-MFA results are also commonly presented as a set of six headline indicators, such as Domestic Material Consumption (DMC) and Domestic Material Input (DMI), that measure the resource burden for the economy (see Annex A of the Technical Annex document).

EW-MFA indicators can be compared to other ones related to the economy, as well as to each other. For example, resource productivity is a measure of the total amount of materials an economy uses in relation to Gross Domestic Product (GDP). Trends in resource productivity can be shown once EW-MFA indicators have been established. If material consumption reduces compared to GDP, this is known as decoupling. Decoupling may indicate the possibility

[11] These material flows exclude bulk water and air. The scale of water use is so significant that including its mass in MFAs obscures other resource use. For this reason, standard MFA practice only includes water mass contained in products e.g. agricultural produce and imported beverages. Water for other consumptive uses (cleaning or irrigation) and in situ uses (such as hydroelectric power), sometimes known as bulk water in MFAs, will be excluded from these accounts. It is important to highlight that while MFA typically emphasises material resources over water, it can also be effectively employed to analyse water resources.

Box two: Environmentally-Extended Multi-Regional Input-Output Analysis (EE-MRIOA)

Environmental Indicators

There are generally three types of methods used to calculate footprint indicators, including the RMC or material footprint :[12] (1) top-down approaches that start from the macroeconomic level and focus on national or regional economic structures and material extraction, (2) bottom-up approaches that use specific coefficients that represent the material input required per unit of product, and (3) hybrid approaches combining both top-down and bottom-up approaches.

Top-down approaches build on input-output analysis (IOA), which focuses on the economic structure of a country in the form of matrices that depict inter-industry flows, final consumption categories and factor inputs, known as Input-Output Tables (IOTs). Each column of an IOT can be interpreted as an inventory of production inputs. The environmental data on material use linked as environmental extensions (EE) to an IO table can be considered an inventory of environmental inputs such as raw materials, GHG emissions or employment.

[12] Lutter, S., Giljum, S., & Bruckner, M. (2016). A review and comparative assessment of existing approaches to calculate material footprints. Ecological Economics, 127, 1-10.

In general, two main types are distinguished: single-region and multi-regional input-output (MRIO) models. Single-region IO models assume that imported products are produced with the same technology as domestic products. In MRIO models, country IOTs are linked via bilateral trade data, which means they consider different technologies applied in each country. MRIO analysis allows product value chains and related environmental flows to be tracked along the various life cycle stages of all products and services, from material extraction to final demand, considering specific material intensities across countries.

As such, EE-MRIOA represents a macroeconomic tool with a number of advantages for the calculations of indirect flows: (1) it allows for the calculation of a broad range of footprints (such as material, emissions, employment) for all products and industries, including those with very complex global supply chains and (2) by following a top-down approach, MRIOA avoids double counting, and as a result, the global system is always consistent. Key disadvantages are: (1) the limited number of commodities and regions distinguished, which is determined by the sectoral or industrial and regional disaggregation of an IO model and (2) the assumption of homogenous environmental characteristics of all products within a product group.

An MRIO approach complements traditional territorial and production-based perspectives by looking at direct environmental flows (or direct material flows) with a consumption-based and life-cycle perspective. This enables practitioners to understand these activities in terms of impacts along and across global supply chains, including indirect environmental flows (that is, the RME of material flows).

For their headline indicators, *Circularity Gap Reports* employ a consumption-based and life-cycle approach, which ensures that environmental impacts are allocated to economies that drive production through consumption. In other words, it considers the environmental impact caused by the demand for products and services in a particular area, regardless of where those goods are produced and including indirect flows associated with them (See Annex A of the Technical Annex document for more information on the *CGR EE-MRIO model*).

Employment Indicators

Labour is also considered an input into the economy. As such, we can use labour satellite accounts in the input-output system to determine employment intensity factors (employment or economic output) per sector.

The level of sector granularity in the IO tables may not be sufficient to expose circular sectors. We utilise granular employment data to split out the national tables, and employment intensity factors are computed. In the Circular Jobs Analysis, estimates are made for the proportion of final demand, and consequent circular economic output is determined. This is used to determine the new circular employment intensities, which are applied back to total employment.

For more information on how sectors' circular activities are mapped, see Annex C. For more information on how circular activities and final demand are determined, see Section 4.2 of this methodology document.

3. Scope of circularity

3.1 Material perspective

To measure material circularity, we look at how economies use resources, focusing on the flow of materials through an economy—versus how they are used long-term—as a starting point. This approach, known as an extended Economy-Wide Material Flow Analysis (EW-MFA), studies the flows and stocks of materials and energy through a society's economic system. This method builds on and is inspired by the work of leading academics in the field.[13,14]

Our research takes a broad perspective on material circularity. Instead of focusing on a single metric (such as recycling), we have developed a monitoring system— CIS — that provides an overview of all inputs and outputs within an economy. The CIS broadly categorises these into circular inputs, linear inputs, and stock build-up.

To complement this overview of circularity, we summarise other aspects of SEM through the compilation of sectoral material and carbon footprint breakdowns, visualised by a Sankey diagram. This diagram illustrates the flow of embodied materials through the economy, tracing their journey from the source (national or imported) to provisioning systems and ultimately to their end-of-life handling or export (see Annex C in the Technical Annex document)

This material-focused perspective, together with the Circular Strategies (see Section 3.3), aligns with the 'Material life-cycle and values chain' building block of the UNECE/OECD conceptual framework[15]. This component reflects key features and major outcomes of the circular economy, considering the material basis and productivity of the economy, the efficiency of materials and waste management, the circularity of material flows, and the interactions with trade and globalisation (for more information on the relationship between the Circularity Gap Report and other circularity frameworks see Annex B of the Technical Annex document).

3.2 Socio-economic perspective

The transition to circularity will be driven by work and workers and must be just. While global material extraction and consumption can spur development, the benefits have yet to be distributed equally, leading to the exploitation of land, people and communities worldwide. The circular economy can offer a solution by fulfilling society's needs with less whilst reducing planetary impacts.

Our study considers circular jobs—that is, the share of the current workforce contributing to the circular economy—as an entry point to a broader socio-economic perspective. By first establishing the current sectors and workers that are employed in the circular economy, we can identify opportunities to boost circularity by creating more circular jobs in key sectors. We can begin to analyse and understand the quality and conditions of circular work versus work in the linear economy to ensure decent work in the circular economy.

This socioeconomic perspective, along with the Circular Strategies (see Section 3.3), aligns with the 'Socio-economic opportunities and Economic efficiency and social equity' building blocks of the

[13] Pauliuk, S., & Hertwich, E. G. (2015). Socio-economic metabolism as paradigm for studying the biophysical basis of human societies. Ecological economics, 119, 83-93.
[14] Haas, W., Krausmann, F., Wiedenhofer, D. & Heinz, M. (2015). How circular is the global economy? An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. *Journal of Industrial Ecology, 19*(5), 765–777. doi:10.1111/jiec.12244
[15] Guidelines for Measuring Circular Economy - Part A: Conceptual Framework, Indicators and Measurement Framework, ECE/CES/STAT/2023/5, UNECE/OECD

UNECE/OECD conceptual framework.[16] This framework focuses on creating socio-economic opportunities for a just transition and structures CE indicators around four themes: (i) market developments and new business models; (ii) trade developments; (iii) skills, awareness and behaviour; and (iv) inclusiveness of the transition. Specifically, the Circular Jobs Analysis aligns with (i) market developments and new business models—measured by jobs in CE sectors and the gross value added (GVA) of CE sectors—as well as with (iv) inclusiveness of the transition, which address the distributional aspects of CE policies.

3.3 Circular strategies

There are several conceptual frameworks which aim to classify the circular economy based on its core activities, such as lowering resource use, extending the lifespan of resources, and recycling materials. These frameworks include the 10R framework,[17] the Key Elements Framework,[18] the Bocken et al. (2016) model,[19] and the approaches developed by Ellen MacAuthur[20] and Aguilar-Hernandez et al. (2018).[21]

Table one. *Strategies compared across selected circular economy frameworks.*

<table>
<tr><th>10R framework</th><th>Key Elements Framework (Core Elements)</th><th>Bocken et al. (2016)</th><th>Ellen MacArthur Foundation</th><th>Aguilar-Hernandez et al. (2018)</th></tr>
<tr><td></td><td rowspan="4">Prioritise regenerative resources</td><td>Regenerate flows</td><td>Regenerate ecosystems</td><td></td></tr>
<tr><td>Refuse</td><td rowspan="3">Narrow flows</td><td rowspan="3">Design out waste</td><td rowspan="3">Resource Efficiency (RE)</td></tr>
<tr><td>Reduce</td></tr>
<tr><td>Rethink</td></tr>
<tr><td>Reuse</td><td rowspan="5">Stretch the lifetime</td><td rowspan="6">Close flows (use phase)

Slow flows (design phase)</td><td rowspan="5">Keep products in use for longer</td><td rowspan="5">Closing Supply Chains (CSC)

Product Lifetime Extension (PLE)</td></tr>
<tr><td>Repair (and maintenance)</td></tr>
<tr><td>Refurbish</td></tr>
<tr><td>Remanufacture</td></tr>
<tr><td>Repurpose</td></tr>
<tr><td>Recycle</td><td rowspan="2">Use waste as a resource</td><td>Design out waste</td><td rowspan="2">Residual Waste Management (RWM)</td></tr>
<tr><td>Recover</td><td></td><td></td></tr>
</table>

[16] Guidelines for Measuring Circular Economy - Part A: Conceptual Framework, Indicators and Measurement Framework, ECE/CES/STAT/2023/5, UNECE/OECD

[17] Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). Circular economy: measuring innovation in the product chain (No. 2544). PBL Publishers. Retrieved from: PBL website

[18] Circle Economy. (2021). The key elements of the circular economy. Retrieved from: Circle Economy website

[19] Bocken, N., 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

[20] Ellen MacArthur Foundation. (n.d.). What is a circular economy? Retrieved from: Ellen MacArthur Foundation website

[21] Aguilar-Hernandez, G.A., Sigüenza-Sanchez, C.P., Donati, F. Rodrigues, J. & Tukker, A. (2018). Assessing circularity interventions: a review of EEIOA-based studies. *Economic Structures, 7*. 14. doi.org/10.1186/s40008-018-0113-3

We base our circular strategy framework on the work of Bocken et al. (2016) and Aguilar-Hernandez et al. (2018). For communication purposes, the more immediate and accessible terminology created by Bocken and colleagues is used, whereas for modelling purposes, the more technical terminology adopted by Aguilar-Hernandez et al. (2018) is employed. As shown in the table above, the two frameworks are largely overlapping (see Section 4.3):

- **Narrow flows—Use less:** The amount of materials (including fossil fuels) used in the making of a product or in the delivery of a service are decreased. This is done through circular design, greater *resource efficiency (RE)* or increasing the usage rates of materials and products. In practice: Sharing and rental models, material lightweighting (mass reduction), multifunctional products or buildings, energy efficiency, digitisation.
- **Slow flows—Use longer:** Resource use is optimised as the *functional lifetime of products is extended (PLE)*. Durable design, materials and service loops that extend life, such as repair and remanufacturing, both contribute to slowing rates of extraction and use. In practice: Design for longevity, modular design and design for disassembly, design for recyclability (both technical and biological).
- **Regenerate flows—Make clean:** Fossil fuels, pollutants and toxic materials are replaced with regenerative alternatives, thereby increasing and maintaining value in natural ecosystems. In practice: Regenerative and non-toxic material use, renewable energy, regenerative agriculture and aquaculture.
- **Cycle flows—Use again:** The reuse of materials and products at end-of-life is optimised, facilitating *closed-loop supply chains (CLS)*. This is enhanced by the optimal cascading of resources, development of reverse logistics and take-back schemes, as well as improved *residual waste management* (RWM). In practice: Reuse, repair, remanufacturing, refurbishing, renovation and remodelling over building new structures, recycling.

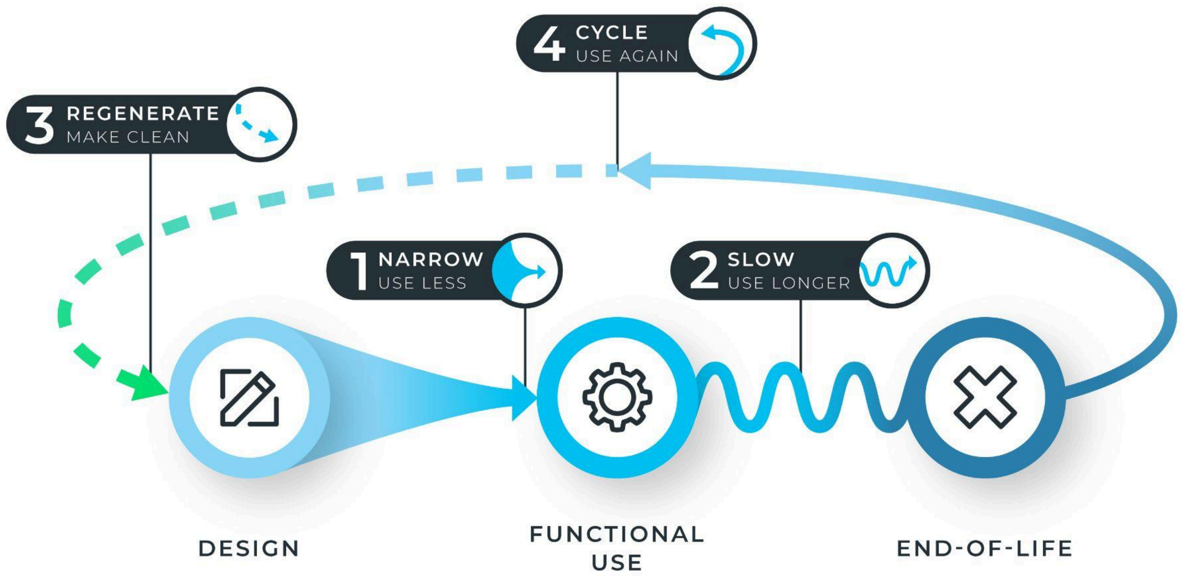

Figure two. *Four strategies to achieve circular objectives: narrow, slow, regenerate and cycle.*

4. Analyses

4.1 Circularity Indicator Set

The CIS is based on extended EW-MFA principles taken from the work of Mayer et al. (2018)[22], Haas et al. (2020)[23] and previous research.[24] [25] [26] The underlying measurement framework fully integrates waste flows, recycling and downcycled materials with traditional EW-MFA statistics. In Circle Economy's model, the approach is further extended to include indirect flows (see Annex A of the Technical Annex document for more details).

The Circularity Indicator Set can be compared to and complemented with other indicators from monitoring frameworks on the circular economy such the one developed by ISO/DIS 59020 and UNECE/OECD. For more information on how the Circularity Indicator Set relates to these frameworks, see Annex B.

Due to different statistical definitions and system boundaries between the EW-MFA and waste statistics, coherence and compatibility is lacking, and *harmonisation* is needed when they are to be employed in the same analysis. Moreover, while the extended and traditional EW-MFA frameworks aim to quantify the same headline indicators using largely the same data, they do so using slightly different approaches. This often results in differing results, which require *reconciliation*. The processes of harmonising input data and reconciling output results are, therefore, critical in the development of integrated and comprehensive datasets that are also accurate and robust. For more information about the harmonisation and reconciliation efforts in this study, see Section 2.2 in the Project Annex.

The CIS distinguishes between scale indicators, which provide measures for the overall size of the SEM, and metabolic rates, which measure technical and ecological cycling relative to input and output flows. Providing independent measures for flows on both the input and output sides is necessary and insightful due to the delaying effect that in-use stocks of materials have on output flows. Inputs[27] expressed in absolute terms are used to measure the **scale** of circular and non-circular flows and can be distinguished as follows:

- Circular inputs:
    - **Secondary Material Inputs (SMIc)**: Accounts for all materials that were formerly waste but are cycled back into use, including recycled materials from both the technical cycle (such as recycled cement and metals) and recycled biological inputs (such as paper and wood). In its metabolic form, it refers to the share of secondary materials out of the total material consumption of an economy.

[22] Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., & Blengini, G. A. (2018). 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. doi:10.1111/jiec.12809

[23] 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.

[24] Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European Union and the World in 2005. *Journal of Industrial Ecology*, *19*(5), 765–777. doi:10.1111/jiec.12244

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

[26] 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*. JRC technical reports, EUR 28811 EN. Luxembourg: Publications Office of the European Union.

[27] Note: These are to be intended as inputs to final consumption (i.e. excluding exports)

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- Renewable Biomass Inputs (RBIc)
    - **Renewable Biomass Inputs (RBIc)**: Accounts for primary biomass (such as timber, food products or agricultural residues) that is *carbon-neutral*. Because it is carbon neutral, this biomass has the *potential* to be circular—and indeed, part of it is, and therefore *could* be considered under SMIc. However, due to data limitations, it is difficult to guarantee full nutrient cycling—the second criterion for biomass to be considered circular and renewable—allowing ecosystem biocapacity to remain the same.

- Linear inputs:
    - **Non-Renewable Biomass Inputs (NRBIc):** Accounts for primary biomass that is *not carbon neutral* as a minimum—yet not sufficient—criteria for renewability and circularity.
    - **Fossil Fuel Inputs (FFIc):** This category centres on fossil-based energy carriers, such as fuel oil, gasoline, diesel and natural gas, among others. These fuels are burned mainly for energy and, to a lesser extent, to produce chemicals and plastics. As they burn, they release GHG emissions into the atmosphere. These inputs cannot be cycled and are *inherently non-circular*. Here, the circular transition will naturally prevent emissions through actions that aim to directly reduce fossil fuel consumption.
    - **Recyclable Inputs (RIc):** Accounts for materials like metals, plastics, paper and glass found in everyday products. Contrary to SMIc, this category represents *materials that can potentially be cycled but are currently not*, whether within the country or abroad.

- Stock build-up:
    - **Net Additions to Stocks (NAS)**: Accounts for the material in products with a lifespan longer than one accounting year that are added to long-term in-use stocks in the form of buildings, infrastructure, machinery, equipment, inventories and so on.

On the other hand, absolute total material use can be measured in the following ways:

- On the input side, **Domestic Material Consumption (DMC),** also referred to as 'apparent consumption', 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. On the output side, **Domestic Processed Output (DPO)** measures the total amount of solid waste and emissions from a national economy;
- To capture the full amount of materials used in the production of finished products, a life-cycle indicator was included in the form of **Raw Material Consumption (RMC)** or material footprint;[28] a measure of global raw material use associated with domestic final consumption. No corresponding indicator on the output side is available at the moment of writing;
- To account for the use of secondary materials (which are usually not included in conventional EW-MFA indicators), the **Processed Materials (PM)** or **Processed Raw Materials (PRM)** are the sum total of DMC (or RMC) and SMIc. Similarly, on the output side, **Interim Outputs (IntOut)** measure End-of-Life (EoL) wastes and emissions before materials for recycling and downcycling are diverted. Even in industrial countries, stocks are growing. IntOut in a given year are thus much smaller than the amount of PM in that year, which inhibits loop closing at present. This produces a delaying effect on the potential recycling of these materials after their lifetime has ended in the future.

[28] Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2013). The material footprint of Nations. *Proceedings of the National Academy of Sciences*, *112*(20), 6271–6276. doi:10.1073/pnas.1220362110

Bringing together scale indicators for circular and linear flows with total materials use measured at the input- and output-side, five pairs of metabolic **rate indicators** can be calculated, which measure material flows relative to interim inflows (PM) and outflows (IntOut):

1. The Technical Cycling rates measure the contribution of SMIc to PM and PRM (**Input Technical Cycling rate [ITCr]**) and the share of IntOut that is diverted to be used as secondary materials (**Output Technical Cycling rate [OTCr]**). Recycled waste from material processing and manufacturing (such as recycled steel scrap from autobody manufacturing) is considered an industry internal flow and is not accounted for as a 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 underestimation 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 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 renewable biomass, as well as a lack of related data, we use the share of RBIc (that is., renewable biomass in DMC/RMC) in PM/PRM for the **Input Ecological Cycling rate potential (IECrp)** and the share of RBO (that is, renewable biomass in DPO) in IntOut for the **Output Ecological Cycling rate potential (OECrp)**. Because ecological cycling is a crucial part of CE strategies, data and adequate indicators must be developed so that technical and ecological cycling rates indicate the overall circularity of an economy. So far, neither robust criteria nor comprehensive indicators are available to identify the fraction of biomass production which 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. Conversely, the **Input Non-Renewable Biomass (INRBr)** and **Output Non-Renewable Biomass rate (ONRBr)** measure the share of NRBIc in PM/PRM and IntOut, respectively.

3. The **Input Non-Circular rate (INCr)** and **Output Non-Circular rate (ONCr)** measure the share of FFIc (that is, the energy use of fossil energy carriers) in PM/PRM and IntOut, respectively, thus quantifying the share of material flows that do not qualify for technical and ecological loop closing. Due to unreliable information on dissipation rates of fertilisers or salt for de-icing roads, for example, we did not allocate these materials to non-circularity flows.

4. The **Net Stocking rate (NSr)** measures the (NAS) that are not available for cycling during the current accounting period as a share of PM/PMR. It is only used as an input-side indicator.

5. The difference between 100% and the sum total of the four metabolic rates serves as a measure of the unexploited potential for technical cycling and represents the input and output of non-renewable materials available for cycling, namely the **Input Non-Renewable rate (INRr)** and **Output Non-Renewable rate (ONRr)**.

6. Finally, any difference between RMC and DMC is referred to as net extraction abroad (NEA), and it is considered a bridging item rather than an actual indicator (see Annex A for more detail on the meaning and purpose of net extraction abroad).

Table two. *Overview of the system of indicators for monitoring economy-wide loop closing.*

	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**)	Domestic Processed Output (**DPO**)	n.a.
	Interim flows	Processed Materials (**PM**) = DMC + SMIc	Processed Raw Materials (**PRM**) = RMC + SMIc	Interim Outputs (**IntOut**) = EoL waste + DPO emissions	n.a.
Metabolic rates (%)	Technical Cycling (TC)	Input Technical Cycling rate (**ITCr**) = Share of SMIc in PM	Input Technical Cycling rate (**ITCr**) = Share of SMIc in PRM	Output Technical cycling rate (**OTCr**) = Share of SMIc in IntOut	n.a.
	Ecological cycling potential (ECp)	Input Ecological Cycling rate potential (**IECrp**) = Share of DMC of primary renewable biomass in PM	Input Ecological Cycling rate potential (**OECrp**) = Share of DMC of primary renewable biomass in PRM	Output ecological cycling rate potential (**OECrp**) = Share of DPO renewable biomass in IntOut	n.a.
	Non-Renewable Biomass (NRB)	Input Non-Renewable Biomass rate (**INRBr**) = Share of DMC of primary non-renewable biomass in PM	Input Non-Renewable Biomass rate (**INRBr**) = Share of DMC of primary non-renewable biomass in PRM	Output Non-Renewable Biomass rate (**ONRBr**) = Share of DPO non-renewable biomass in IntOut	n.a.
	Non-Circularity (NC)	Input non-circularity rate (**INCr**) = Share of eUse of fossil energy carriers in PM	Input non-circularity rate (**INCr**) = Share of eUse of fossil energy carriers in PRM	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	n.a.	n.a.
	Net Extraction Abroad (NEA)	n.a.	Net extraction abroad rate (**NEAr**) = share of NEA in PRM (where NEA = RMC - DMC)	n.a.	Outputs from Net extraction abroad rate (**NEAr**) = share of NEA in PRM (where NEA = RMC - DMC)
	Non-renewabi	Input	Input	Output	Output

	lity (NR)	Non-Renewable rate (**INRr**) = 100 - (ITCr + IECrp + INRBr + INCr + NSr)	Non-Renewable = rate (I**NRr**) = 100 - (ITCr + IECrp + INRBr + INCr + NSr + NEAr)	Non-Renewable rate (**ONRr**) = 100 - (OTCr + OECrp + ONRBr **+** ONCr)	Non-Renewable rate (**ONRr**) = 100 - (OTCr + OECrp + ONRBr **+** ONCr + NEAr)

*Mass-based circular economy indicators include two types of measurements: scale indicators, which measure the absolute size of input and output flows in tonnes, and metabolic rates, which measure the cycling and linearity of these flows as a percentage relative to input and output. (n.a. = not applicable). For more information on the variables used to calculate these indicators, refer to Annex A. Note that not all indicators listed in the table may be included in the final report.

It should be noted that for simplicity, so far, we have considered the net trade balance of secondary materials as part of SMIc despite these flows being explicitly quantified and treated in Circle Economy's EW-MFA model. The estimation of imported and exported secondary materials is based on the methodology developed by Eurostat and used in calculating the CMUr (see Boxes three and four).[29]

Box three: Computations behind Input Technical Cycling rate (ITCr)

Let's consider *ITCr* — the share of secondary materials in PRM — and re-write it in mathematical terms:

$$ITCr = SMIc/PRM$$

Where:

$$PRM = RMC + SMIc$$

$$SMIc = RCV\_R\_B_{cons} + BP_{cons} + RP_{cons}$$

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

In principle, this indicator can measure either 1) a country's capacity to produce and consume secondary raw materials and 2) its effort to collect waste for recovery. In a closed economy, with no imports or exports, both are one and the same. However, in reality, countries are open economies with flows of imports and exports of waste collected in one country but treated and used in another. **In that case, the production and consumption (of secondary raw materials) and collection effort (of waste for recycling) in one country may not be one and the same. Therefore the ITCr rate must focus on one or the other.** This is a design choice. The ITCr rate indicator may come with a different specification, depending on the approach sought.

In this respect, it was decided that the ITCr rate measures a country's effort to deploy secondary materials. This perspective credits the country's effort to produce and consume secondary material from recycled waste instead of gathering waste bound for recovery. Producing and consuming secondary materials more directly contributes to the worldwide supply of secondary materials and hence avoids primary material extractions.

Aligned with the definition adopted by the UNECE and OECD[30], **secondary materials** are defined as "*Materials that have been previously used and have been recovered or prepared for reuse. This includes materials in products that have*

[29] Eurostat. (2018). *Circular material use rate: calculation method.* Eurostat manuals and guidelines. Luxembourg: Publications Office of the European Union, 2018. Retrieved from: Eurostat website

[30] Conference of European Statisticians Guidelines for Measuring Circular Economy- Part A: Conceptual Framework, Indicators and Measurement Framework ECE/CES/STAT/2023/5, UNECE/OECD, 2023

been reused, refurbished, or repaired; components that have been remanufactured; by-products; and materials that have been recycled (also referred to as secondary raw materials)".

The ITCr rate indicator is based as much as possible on official statistics. In the EU context, these are compiled by Member States and reported to Eurostat under legal obligations:

- **Waste statistics:** Regulation (EC) No2150/2002 on waste statistics (WStatR) is a framework for harmonised Community statistics in this domain. The WStatR requires EU Member States to provide data on the generation, recovery and disposal of waste every second year. Data set on waste treatment (env_wastrt) are used (or compiled based on such regulation) for the calculation of ITCr rate;

- **Economy-wide material flow accounts:** As already mentioned, EW-MFA describes the interaction of the domestic economy with the natural environment and the rest of the world economy in terms of flows of materials (excluding water and air). EW-MFA is a statistical framework conceptually embedded in environmental-economic accounts and fully compatible with concepts, principles, and classifications of national accounts — thus enabling a wide range of integrated analyses of environmental, energy and economic issues e.g. 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 countries. 'Goods' means all movable property, including electricity. ITGS are the official harmonised source of information about the EU's exports, imports and trade balances. Data is extracted from the COMEXT website for European member states, while data is extracted from the BACI database for non-European member states. The main classifications for ITGS are the Combined Nomenclature (CN) and Harmonised System (HS).

The ITCr can then be approximated by three components: the amount of waste recycled in domestic recovery plants, indirectly or directly substituting raw materials (W_RCV), by-products (BP) and reused products (RP). However, all these types of secondary materials can also be corrected by imports and exports. These two aspects are developed below.

Amount of domestic secondary materials

The **first component of ITCr** - W_RCV - is measured from waste statistics and includes residual material legally declared as waste which is recovered and, after treatment, fed back to the economy (material flowing through the legally demarcated waste management system). It represents the amount of materials recycled in domestic plants.

While waste statistics measures the input of waste into recovery operations and not the amount of secondary raw materials that result from these operations; an analysis by Eurostat concluded that the input to recovery plants is an acceptable proxy for the output from recovery plants. However, it should be notes that this assumes that the sorting and processing losses during recycling operations are negligible Based on 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 into 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 ITCr rate indicator, it is concluded that the best option is to include recycling and backfilling (code: RCV_R_B), (i.e., excluding energy recovery). While backfilling often involves low-value recycling applications and can arguably be considered as a circular flow, it should be noted that the exclusion of waste from UDE (most notably W126 Soils and

W127 dredging spoils) prevents low-value backfilling from overly weighting on the ITCr as almost the totality of it relates to W121 mineral waste from construction and demolition.

The **second component of ITCr** - BP - includes residual material outside the legal waste coverage (outside the waste management system), generated e.g. as an incidental or secondary 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

As specified by the UNECE and OECD, in the context of measuring a circular economy, by-products refer to substances or objects resulting from a production process, the primary aim of which is not the production of that item. In this case, a substance or object may be regarded as being a by-product only if it is produced as an integral part of a production process, its further use is certain and lawful, and it can be used directly without any further processing other than normal industrial practice. By-products are not waste and therefore not covered by conventional waste statistics.

The **third component of ITCr** - RP - includes re-used/re-usable products which are used and end-of-life goods (including second-hand goods) diverted from the waste stream for re-use, remanufacturing, repair or trade (e.g. electrical and electronic equipment or its components that can be used for the same purpose for which they were conceived). Reused/re-usable products are not waste and therefore not covered by conventional waste statistics.

Adjusting circular use of material for trade balance

ITCr focuses on representing a country's effort to produce and consume secondary materials, including waste collected in another country and later imported for domestic deployment. Consequently, the total amount of secondary materials is adjusted as follows:

$$RCV\_R\_B_{cons} = RCV\_R\_B_{dom} + RCV\_R\_B_{imp} - RCV\_R\_B_{exp}$$

$$BP_{cons} = BP_{dom} + BP_{imp} - BP_{exp}$$

$$RP_{cons} = RP_{dom} + RP_{imp} - RP_{exp}$$

with:

X_{imp}: amount of imported waste bound for recovery, by-products or reused products and

X_{exp}: amount of exported waste bound for recovery, by-products or reused products

$RCV\_R\_B_{cons}$ equals 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 contributing to the worldwide saving of primary raw materials. This perspective is closer to the national accounts' logic in which most re-attributions are directed towards final use.

To calculate the amounts of imported waste and by-products ($RCV\_R\_B_{imp}$, BP_{imp}) and exported waste and by-products ($RCV\_R\_B_{exp}$, BP_{exp}), Eurostat has identified the CN codes that can be considered such[31]. For application to non-EU

[31] Eurostat. (2022). *List of CN-codes used to approximate imports and exports of waste destined for recycling.* Retrieved from: Eurostat website

countries, CE has developed a mapping table between the CN and HS classification that allows it to replicate the methodology on international trade databases such as BACI.

It is important to note that for EU countries, the main source for $RCV\_R\_B_{cons}$, the env_wastrt dataset[32], measures waste bound for recovery at the recycling plant, thus already including imported waste for recycling and excluding exported waste for recycling. Furthermore, while BP_{imp} and BP_{exp} can be estimated using list of codes and international trade databases, BP_{dom} as well as RP_{cons} are currently lacking reliable systematic estimation approaches and therefore needs to rely on ad-hoc data collection which often missing

Box four: An overview of economy-wide circularity indicators

With the increasing number of indicators aimed at measuring progress towards the circular economy, it is more important than ever to understand what each is measuring as well as how they differ. Eurostat reports on at least three physical 'ratio' indicators that are relevant to the circular economy.

The ***Traditional Recycling Rate*** is expressed as the ratio between the volume of waste collected for recycling (RCV_R or RCV_R_B items in the env_wastrt[33] or env_was_oper dataset[34]) over the total volume of treated waste. Since this indicator measures how much of the total waste that is collected ends up at recycling plants, it is an **output-side indicator**. Its denominator is the total amount of waste treated, which can be seen as an outflow of the production and consumption system. It's important to note that the numerator—the amount of waste collected for domestic recycling—does not represent the actual amount of recycled (secondary) materials produced by the plant, as sorting and processing losses may occur during the recycling process. The difference between the env_wastrt and env_was_oper datasets is that, while the former measures waste destined for recycling within national borders (consequently including imported and excluding exported waste), the latter focuses on national waste treated regardless of the country in which the treatment takes place (consequently including exports and excluding imports of waste).

The ***End-of-Life Recycling Input Rate (EOL-RIR)*** is expressed as the ratio between the input into the production system that comes from the recycling of 'old scrap' (or 'end-of-life scrap')—for instance, scraps and waste derived from the treatment of products at their end-of-life—and the total input to the production system requires for a particular raw material. Since its denominator is the total amount of inputs into a process of a raw material's supply chain, for instance, processing or manufacturing, this is considered an **input-side indicator**. Contrary to the Traditional Recycling Rate, the EOL-RIR explicitly takes imports of secondary materials into account.

The ***Circular Material Use Rate (CMUR)***, reported by Eurostat, is expressed as the ratio between waste destined for recycling and the total raw materials and manufactured products used by an economy expressed as Domestic Material Consumption (DMC). As with the EOL-RIR, since the denominator is the total input into the economy, this is considered an **input-side indicator**. The CMUR adds the amount of exports of waste destined for recycling abroad to the traditional domestic recycling (R_RCV from env_wastrt) while subtracting the amount of imports destined for domestic recycling. The resulting figure thus represents the amount of waste collected for either domestic or foreign recycling. In the CMUR, the input of waste into recovery operations is deemed an acceptable proxy for the amount of secondary materials produced as a result of the same recovery operations.

The difference between input- and output-side indicators is key to understanding why different indicators may vary so

[32] Eurostat. (n.d.). Waste generation and treatment (env_wasgt). Metadata. Retrieved from: [Eurostat website]
[33] ibid
[34] Eurostat. (n.d.). Management of waste excluding major mineral waste, by waste management operations (env_wasoper). Metadata. Retrieved from: [Eurostat website]

much. In fact, material outputs are usually much smaller compared to their counterparts on the input side due to material accumulation in long-term stocks as well as dissipation during use—for example, when fossil fuels are combusted and become emissions. What's more, the distinction between collected waste destined for recycling, by-products and secondary materials, as well as the different perspectives on imports and exports, can play a significant role in the final figures as well as on their interpretation.

The ***Input Technical Cycling rate*** (also referred to as Circularity Metric), as calculated in *Circularity Gap Reports,* is expressed as the ratio between waste destined for recycling and the total raw material equivalents used by the economy, which is known as Raw Material Consumption (RMC) or the consumption-based Material Footprint (MF). When it comes to trade in waste, the *Circularity Gap Report* methodology distinguishes between waste collected for recycling and by-products and uses this distinction to refine the allocation of trade. **The ITCr is an input-side indicator, like the CMUR**, but with some key differences:

- Firstly, the ITCr is a life-cycle indicator based on Raw Material Consumption (RMC), while the CMUR is based on Domestic Material Consumption (DMC). DMC represents the physical weight of material consumption and imports and exports, while RMC represents all the raw materials used for each component of the DMC in terms of Raw Material Equivalents (RMEs). For example, a smartphone may weigh only a couple hundred grams but requires far more resources to produce. The CMUR does not account for this;
- Secondly, while the CMUR credits collection efforts (deducting imports and adding exports), the ITCr credits waste processors/consumers (adding imports and subtracting exports of by-products). This perspective is closer to the national accounts' logic, in which most re-attributions are directed towards final use. It discourages the export of waste abroad (often seen as 'problem shifting') and encourages the development of local waste treatment capacity;
- Thirdly, the ITCr includes backfilling (RCV_R_B) and not just recycling (RCV_R). While backfilling often involves low-value recycling applications and can arguably be considered as a circular flow, it should be noted that the exclusion of waste from UDE (most notably W126 Soils and W127 dredging spoils) prevents low-value backfilling from over weighting on the ITCr as almost the totality of it relates to W121 mineral waste from construction and demolition;
- Finally, the ITCr is part of a wider set of indicators, while the CMUR is a stand-alone metric. The ITCr should be viewed in the context of the other indicators that make up the CIS. While highlighting the share of secondary raw material consumption in the economy is crucial, so is knowing the proportion of materials going into stocks, of carbon-neutral and non-carbon-neutral biomass inputs or of fossil fuel inputs, which are inherently non-recyclable.

4.2 Circular Jobs Analysis

In addition to the material perspective, we estimate the circular jobs in select sectors of the economy as per the Circular Jobs Methodology developed by Circle Economy, International Labour Organisation and International Financial Corporation.

To estimate the extent of circular employment within a country, the building block methodology provides a structured approach that classifies economic sectors in International Standard Industrial Classification of All Economic Activities (ISIC) (Revision 4), based on their contribution to the circular economy. This approach distinguishes between fully circular and partially circular sectors, allowing for tailored measurement depending on the nature of economic activities.

- **Fully circular sectors** are those where all employment is assumed to contribute directly to the circular economy by virtue of the occupational functions involved. These include sectors such as repair and maintenance, waste collection and material recovery (excluding landfill and incineration), sewerage, renting and leasing activities, remediation services, the retail sale of second-hand goods, and wholesale of waste and scrap. In addition, a subset of the transport sector—urban and suburban passenger land transport (ISIC H4921)—is also considered fully circular due to its role in shared access and reducing car dependency. Employment in these sectors can be directly counted using national labour force or sectoral employment data.

- **Partially circular sectors** are those where only a portion of employment is considered circular, given the coexistence of linear and circular activities. These include material- and resource-intensive sectors such as agriculture, mining, manufacturing, and construction. Since employment datasets in ISIC do not distinguish between circular and non-circular activities within these sectors, our estimates rely on modelling.
    - For agriculture, biological circularity is proxied by the proportion of cropland under organic agriculture.
    - For mining, economic circularity is proxied by the sector's contribution to the recycling sector through domestic sales and exports.
    - For manufacturing and construction, circularity is estimated using an average of material circularity (the share of secondary, i.e. non-virgin inputs in the sector's material inputs) and economic circularity (the sector's contribution to the recycling sector through domestic sales and exports).

The methodology also accounts for informal employment, which is critical in many national contexts, particularly in the Global South. When labour statistics are disaggregated by formality status, circular employment in each sector is split into formal and informal categories based on the sector's informal employment share. In cases where such disaggregation is unavailable, the methodology imputes values using country income group-based averages.

In applying this methodology at the national level, the highest level of employment data resolution is used, ideally at ISIC four-digit level. Where such granularity is unavailable, aggregated data is supplemented with imputations drawn from country income group averages. Gender-disaggregated estimates can also be included, either directly from national data or inferred from income group averages.

While the methodology provides a replicable and scalable approach to measuring circular employment, it is important to acknowledge certain limitations. Existing statistical systems and input–output models are often built around linear economic assumptions and may not fully capture informal, small-scale, or non-standard circular activities. In many countries, data on informal employment remains incomplete or inconsistently classified, and the assumptions within input–output databases (such as Eora) may not reflect sectoral diversity or local production structures. As a result, estimates derived from this methodology should be interpreted as indicative rather than exhaustive, with results likely underestimating the true scope of circular employment. Nevertheless, this methodology offers a robust starting point for countries to quantify, analyse, and track their circular employment landscape[35].

[35] For a more extensive explanation refer to the circular employment methodology document

The list of economic sectors along with the indicator used for determining circular employment has been listed in Annex C.

4.3 Scenario modelling

Environmentally extended input-output analysis (EEIOA) can be applied to assess the economic and environmental impacts of implementing circular economy strategies and interventions.[36] IOA, in its various forms, is a static structural model that provides detailed insights into sectoral and economic composition, making 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 by applying exogenous changes. One of the advantages of this approach is the transparency of its assumptions, which is crucial for CE impact assessments, as the variety of methodologies can make comparing studies difficult.

As a first step, we developed a CE policy modelling framework based on the work of Aguilar et al. (2018) and Donati et al. (2020) and integrated additional literature on circular strategies frameworks.[37] [38] [39] We begin by asserting that the objective of a CE policy is always the implementation of the circular economy paradigm, which can be achieved through various strategies. In this study, we use a three-strategy classification: Resource Efficiency (RE), Change Consumption Patterns (CCP) and Closing Supply Chains/Product Lifetime Extension (CSC/PLE). Compared to four strategies outlined by Aguilar et al. (2018), CSC and PLE are grouped together due to their overlapping nature while Residual Waste Management (RWM) is not included due limitations in modelling waste treatment interventions through monetary IOTs (for more details on waste management scenarios see Scenario modelling section in Annex A). This classification serves as the overarching terminology for modelling the 10Rs strategies outlined by Potting et al. (2017)[40] and closely aligns with the Bocken framework, which is primarily used for communication purposes (see **Table one**). The main difference is that the three strategy classification lacks the 'regenerate' element, which addresses the elimination of toxic inputs and the use of more renewable materials. While regenerate strategies are extremely important and a core element of the circular economy, they are not included due to limitations in modelling 'qualitative' aspects of material flows (e.g. toxicity and renewability) through monetary IOTs.

We define strategies as sets of policy interventions and improvement options (or simply interventions). For example, PLE can be achieved, among others, by reusing and remanufacturing or delaying product replacement.[41] 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. We further distinguish between a general description of interventions and specialised interventions. An intervention (such as reuse and remanufacturing) is specialised when it refers to a specific product or application (such as increased lifetime

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[36] 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). doi:10.1186/s40008-018-0113-3

[37] Blomsma, F., Pieroni, M., Kravchenko, M., Pigosso, D. C. A., Hildenbrand, J., Kristinsdottir, A. R., … McAloone, T. C. (2019b). 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

[38] Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, *153*, 104553. doi:10.1016/j.resconrec.2019.104553

[39] Reike, D., Vermeulen, W. J. V., & 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

[40] Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: measuring innovation in the product chain (No. 2544).* PBL Publishers. Retrieved from: PBL website

[41] Cullen, J. M., Allwood, J. M., & Borgstein, E. H. (2011). Reducing energy demand: What are the practical limits? *Environmental Science & Technology*, *45*(4), 1711–1718. doi:10.1021/es102641n

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 lifetime of vehicles, the primary change would be a reduction in 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 higher good utilisation. We show this conceptual approach in **Figure three**.

Figure three. *Conceptual approach to scenario modelling.*

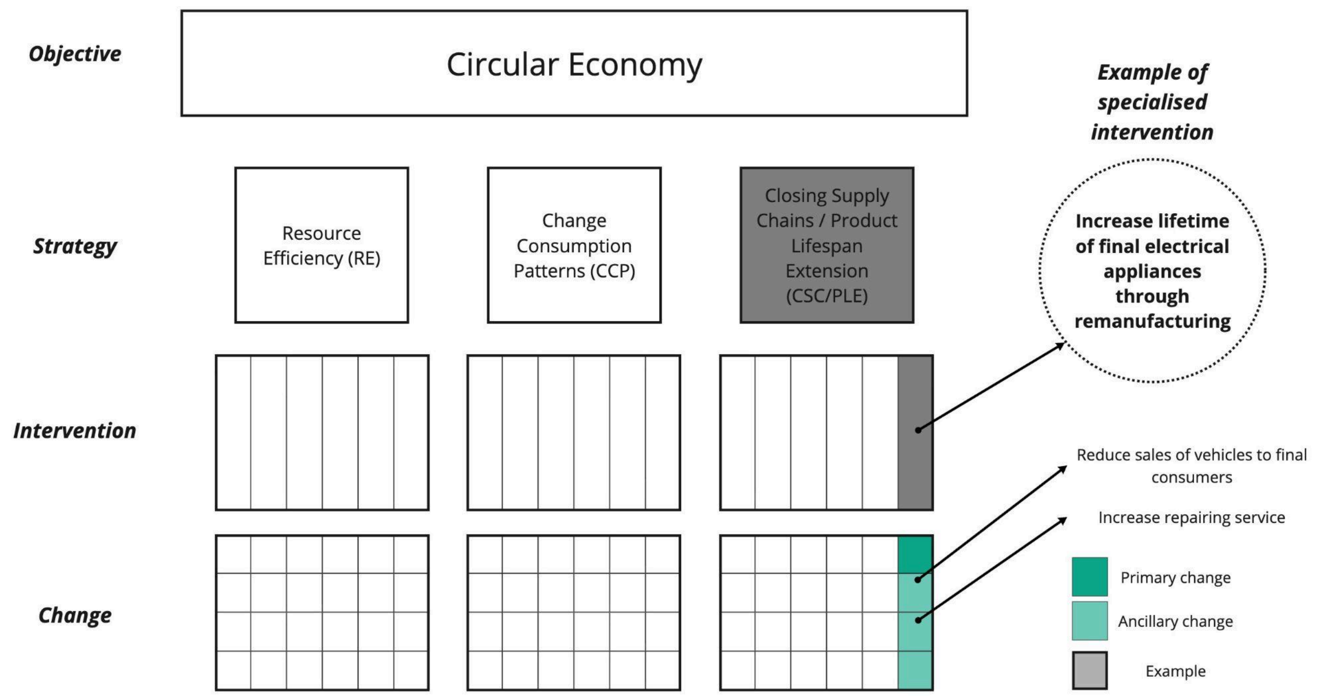


Table three summarises the strategies and interventions as they relate to each provisioning system. Local data and modelling assumptions are researched and applied to each strategy (See section 2.3 in the Project Annex).

Table three. *High-level summary of circular Interventions and strategies.*

1. HOUSING		
Strategy	Intervention	Examples
RE	**Occupancy increase -** More intensive use of buildings involves actions to reduce the demand for floor area per person compared to an expected increase	Co-housing, multi-functional spaces, smart and adaptable floor plans, peer-to-peer lodging, trendy smaller homes and replacing single family homes with multi-family homes
RE	**Downsizing and lightweighting -** Designing lighter and smaller products that deliver the same service, reducing the amount of materials incorporated in the product and often the energy required to operate it	Leaner and lighter buildings such as tiny or geodetic houses enabled by 3D printing technologies. Reduction in the use of and, where possible substitution of steel and concrete with wood or bio-concrete.

CSC/PLE	**Structural renovation -** Renovation of structural elements with the main aim of extending the building's lifetime,without delivering significant energy efficiency improvements (<5%)	Strengthening and reinforcing load-bearing elements, creating open spaces, building additions and conversions, enhancing roofing.
RE	**Energy renovation -** I.e. refurbishment or retrofitting is the implementation of changes to the building facades (i.e. walls and frames) or technological system (i.e. HVAC systems) with the aim of increasing the building's energy efficiency	Measures to improve the building envelope (high performance insulation, double-glazed windows), smart building technology (smart meters), efficient systems and appliances (HVAC systems , LED lighting) or integration of renewable energy sources
2. NUTRITION		
Strategy	Intervention	Examples
CCP	**Diet shift -** Changing dietary consumption patterns towards less meat-intensive or meat-free diets	Increase in the share of population following a vegan, vegetarian or flexitarian diet compared to the standard national base diet (varies depending on the nation)
CCP	**Balanced diet -** Reduction of the actual caloric intake to an average healthy sufficiency level of 2250 kcal/pp/day	Change in caloric intake - in most cases a reduction, but possibly an increase in undernourished countries - can occur with or without change in diet composition.
RE	**Reduce avoidable food waste -** Reduction of pre- and post-consumer avoidable food losses and waste	Improved technologies in production and storage, supply- and demand-side negotiations (to avoid waste of imperfect or damaged food), improved logistics, meal planning and smart shopping, improve date labels and food information, leftovers resume, education campaigns
CCP	**Sustainable agriculture -** Changing both production and consumption patterns to local, seasonal and organic food products	Community Supported Agricultural (CSA) programs, farmers markets, home gardens, education campaigns
3. MOBILITY		
Strategy	Intervention	Examples
RE	**Occupancy increase -** Natural development in vehicle occupancy due to socio-economic as well as urban planning developments	Demographic changes, Transit-Oriented Development (TOD), Vehicle ownership taxation
RE	**Downsizing and lightweighting -** Reducing material demand for vehicle production through shifting from a larger sized vehicle to a smaller one and substituting steel with lighter materials for certain vehicle parts	Incentivise micro-cars, minivans and other downsized vehicle types over SUVs and conventional cars, use of new materials such as aluminium, carbon fibre, magnesium or high-strength steel
CLS/PLE	**Lifetime extension and stock modernisation -** Shift from internal combustion engines to fully electric and hybrid powertrains and implementation of repair- and remanufacturing-oriented business models for this new generation vehicles	Government incentives on e-vehicles, expansion of charging infrastructure, car subscription services, predictive maintenance services, reuse components markets

CCP	**Car-sharing and ride-sharing -** Increase average vehicle occupancy by decoupling use from ownership and increasing the utilisation rate	High-Occupancy Vehicles and High-Occupancy Toll lanes, improved peer-to-peer platforms for car pooling, increase organisational buy-in
4. MANUFACTURING		
Strategy	Intervention	Examples
CLS/PLE	**R-strategies for machinery and equipments -** Remanufacturing, refurbishment, repair and upgrade and reuse applied to industrial machinery and household and work equipment	Design for longevity and disassembly, "machine-as-a-service" business models, predictive maintenance services, repair cafès and workshops
RE	**Fabrication yield improvements and scrap diversion -** Fabrication yield improvements entail the reduction of selected metals going to the scrap market from their primary production/ from manufacturing industries and an equal reduction in the consumption of the primary metal across all categories / in the same sector, respectively.	Lean manufacturing techniques, Ai-driven digital twins,process automation, equipment optimisation (e.g. computer numerical control), smart inventory methods, industrial symbiosis
5. LIFESTYLES & SERVICES		
Strategy	Intervention	Examples
CCP	**Material sufficiency lifestyles -** Promote different lifestyles oriented to self-sufficiency and reduced consumption in contrast with consumeristic lifestyles	Do-it-yourself culture, C2C business models, non-market and community initiatives (e.g. time banks, local currencies)

Technical Annex

Annex A: Industrial ecology toolkit

Economy-Wide Material Flow Accounting

Table one. *Summary of traditional and extended MFA variables with description and formulas (greyed out cells means that the variable is not included in the approach, empty cells means that the variable is input data with no calculation needed)*

Label	Code	Description	Traditional	Extended
Domestic extraction	DE	Extraction of raw materials from the domestic environment		
Physical Imports	IMP	Imports of raw materials, semi-finished and finished products		
Raw Material Equivalents of Imports	RME_IMP	Indirect flows or upstream raw material requirements related to imports		
Physical Exports	EXP	Exports of raw materials, semi-manufactured and manufactured products		
Raw Material Equivalents of Exports	RME_EXP	Indirect flows or upstream raw material requirements related to exports		
Domestic Material Input	DMI	Primary material inputs into an economy	$DE + IMP$	$DE + IMP$
Raw Material Input	RMI	Primary inputs into an economy expressed in raw material equivalents	$DE + RME\_IMP$	$DE + RME\_IMP$
Domestic Material Consumption	DMC	Primary material or apparent consumption of an economy	$DMI - EXP$	$DMI - EXP$
Raw Material Consumption	RMC	Primary consumption into an economy expressed in raw material equivalents	$RMI - RME\_EXP$	$RMI - RME\_EXP$

Recycled waste for domestic consumption	$RCV\_R\_B_{cons}$	Domestic (excl. exports) and imported waste recycled in domestic recovery plants. It does not include waste from unused extraction. Recycling includes backfilling.		$RCV\_R\_B_{dom} + RCV\_R\_B_{imp} - RCV\_R\_B_{exp}$
By-products for domestic consumption	BP_{cons}	Domestic (excl. exports) and imported by-products for domestic consumption		$BP_{dom} + BP_{imp} - BP_{exp}$
Reused products for domestic consumption	RP_{cons}	Domestic (excl. exports) and imported reused for domestic consumption		$RP_{dom} + RP_{imp} - RP_{exp}$
Secondary material inputs consumed	$SMIc$	Secondary material consumption of an economy		$RCV\_R\_B_{cons} + BP_{cons} + RP_{cons}$
Processed Materials	PM	Primary and secondary material consumption of an economy		$DMC + SMIc$
Processed Raw Materials	PRM	Primary and secondary material consumption of an economy where primary material consumption only is expressed in raw material equivalents[42]		$RMC + SMIc$
Energetic use	$eUse$	Fraction of PM that is used to provide energy. Comprises not only technical energy but also feed for livestock and food for humans		Calculated based on coefficients from material flow database and Mayer et al. (2018)
Material use	$mUse$	Fraction of PM that is used for material purposes. Comprises all metals and non metallic minerals, fractions of biomass and fossil energy carriers		
Gross additions to stock	GAS	Materials used to build up in-use stocks of materials (life span >1 yr)		
Reported waste from energetic use	W_eUse	Solid waste from combustion of fuels and excrements of humans and livestock at the water content of biomass intake (i.e. excluding water uptake by humans and livestock) as reported in official statistics		All waste assumed to originate from material use (see
Reported waste from material use	W_mUse	Solid waste from discarded stocks (life span >1 yr), short-lived products (life span <1 yr) and processing and manufacturing waste		

[42] Methodological issues related to the estimation of secondary materials in raw material equivalents can be found in this Technical Note

Reported End-of-Life waste	EoL_r	Total end of life waste comprises all solid waste from $eUse$ and $mUse$, including throughput materials reported in waste statistics.		$W\_eUse + W\_mUse$
Short-lived material use of crop residues	Crp	Crops residues for feed and deliberative dissipative uses (fertilisers)		Based on Mayer et al. (2018)
Extractive waste	Ext	Waste rock from domestic mining		Calculated based on material flow statistics
Unreported waste from material use	Wu_mUse	Waste from material uses not fully reported in waste statistics. This can include country-specific under- or mis-reported waste fraction required for mass balancing (Wu)		$Crp + Ext + Wu$
Unreported waste from energetic use	Wu_eUse	Excrements generated from food and feed intake not fully reported in waste statistics		Calculated based on material flow statistics and Mayer et al. (2018)
Unreported End-of-Life waste	EoL_u	Total waste not reported in waste statistics		$Wu\_eUse + Wu\_mUse$
Total End-of-Life waste	EoL_t	Total reported and unreported waste from		$EoL_r + EoL_u$
Demolition and Discard	$D\&D$	Solid waste from discarded in-use stocks. Comprises construction and demolition waste but also all other discarded long living products		$W\_mUse - (mUse - GAS - Wu\_mUse)$
Domestic processed output from energy (emissions)	DPO_e	All gaseous outputs including vapour from combustion and human and animal respiration; oxygen input from air is excluded.		$eUse - W\_eUse - Wu\_eUse$
Domestic processed output from materials	DPO_w	All EoL waste excluding materials recovered for re- and downcycling. All liquid and solid outputs including moisture content as included in extracted material but excluding extra added water (e.g during industrial processes or drinking water)		$EoL_t - RCV\_R\_B_{dom}$
Domestic processed output	DPO	Total waste and emissions released to the environment		$DPO_e + DPO_w$
Interim outputs	$IntOut$	Total wastes and emissions after the use phase		$EoL_t + DPO_e$

Balancing items input-side	BI_{in}	Mostly oxygen demand for combustion and respiration processes		All variables are pre-calculated at the net of the balancing items
Balancing items output-side	BI_{out}	Mostly water vapour generated from combustion processes, gases from respiration and evaporated water from biomass products		
Net additions to stock	NAS	Measure of the "physical growth of the economy", i.e. the quantity (weight) of new construction materials accumulating in buildings, infrastructure and materials incorporated into durable goods (life span >1 yr)	$DMC + BI_{in} - BI_{out} - DPO$	$GAS - D\&D$
Land Use and Land Use Change emissions	$LULUCF$	Technically not part of the EW-MFA framework as this is an environment-to-environment flow. Included in the extended approach for calculations related to the biological cycle		

Traditional approach

EW-MFA is a statistical accounting framework describing the physical interaction of the economy regarding material flows with the natural environment and the rest of the world economy. It represents a useful framework for deriving a high-level overview and understanding of the SEM of the system under analysis[43]. EW-MFA records the throughput of materials (excluding bulk flows of water and air) at the input and output sides of the national economy based on a conservation of mass principle. The mass balance principle is used to check the consistency of the accounts. It also provides one possibility to estimate the net accumulation of materials also known as stocks. The mass balance principle can be formulated as:

$$Inputs = outputs + additions\ to\ stocks - removals\ from\ stocks = outputs + net\ stock\ changes$$

Material inputs into national economies include:

- Domestic Extraction of material originating from the domestic environment;
- Physical Imports (all goods) originating from other economies;
- Balancing Items on the input side

Material outputs from national economies include:

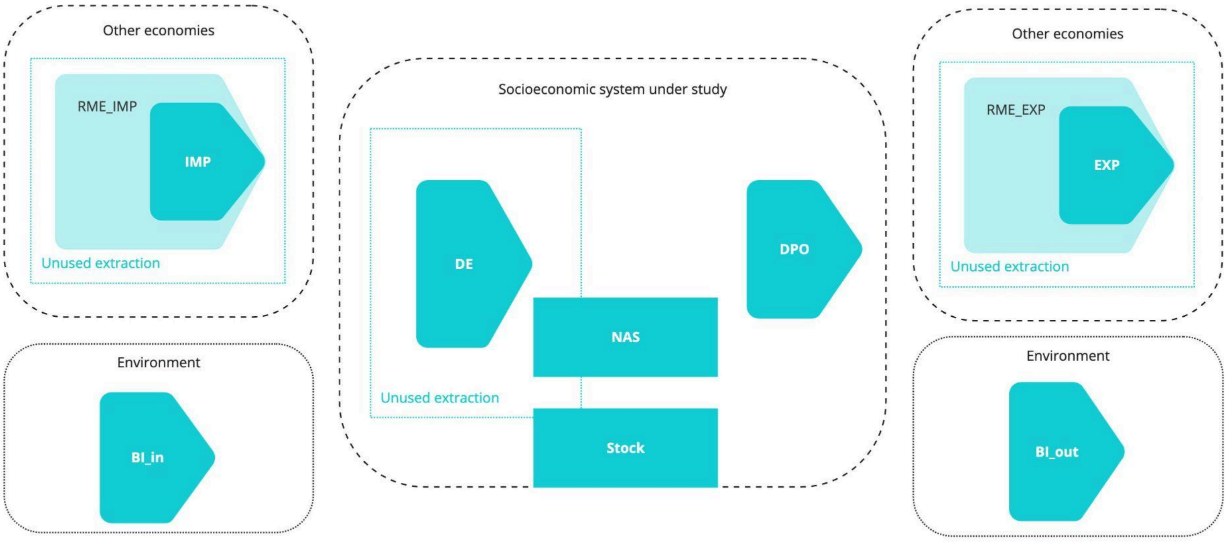
- Domestic Processed Output to the domestic environment;
- Physical Exports (all goods) to other economies;
- Balancing Items on the output side

In most national economies, the amount of physical input exceeds the physical output. The difference between inputs and outputs corresponds to the net accumulation of material in the economy in the form of,

[43] Nairobi, K. (2021). The use of natural resources in the economy: A Global Manual on Economy Wide Material Flow Accounting.

e.g. buildings and infrastructures, machinery and durable goods. In EW-MFA, this material accumulation in a single year is called net additions to stock (NAS). **Figure one** depicts a traditional EW-MFA system.

Figure one. *Traditional EW-MFA system, also referred to as the "black-box" approach.*



Domestic Extraction (DE). This includes 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 acquiring value within the economic system. Domestic extraction is categorised into four groups in most MFAs:

1. Biomass which comprises agriculture harvest, timber, animal grazing, and fishing;
2. Metal ores which include ferrous and non-ferrous metals;
3. Non-metallic minerals, sometimes divided into construction and industrial minerals); and
4. Fossil energy materials/carriers which comprises coal, natural gas and crude oil.

Imports (IMP) and Exports (EXP). This covers all imported or exported commodities in tonnes. Traded commodities comprise goods at all stages of processing from basic commodities to highly processed products.

Domestically Processed Outputs (DPO). Comprises all waste and emission flows that occur in the processing, manufacturing, use, and final disposal stages of the production-consumption chain. Recycled material flows are considered flows within the economy (e.g. of metals, paper, glass) and thus are not considered as outputs (nor inputs, "black-box" approach[44]). DPO includes:

- Direct emissions to air and water;
- Industrial and household wastes deposited in uncontrolled landfills (whereas wastes deposited in controlled landfills are regarded as an addition to socioeconomic stock);
- Dissipative use of products (where materials are dispersed into the environment through their use) e.g. fertiliser application; and

[44] Krausmann, F., Lauk, C., Haas, W., & Wiedenhofer, D. (2018). From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. Global environmental change, 52, 131-140.

- Dissipative losses e.g. emissions to air from automobile tyre; and brake wear and road abrasion.

The scale of water use is so significant that including its mass in MFAs obscures other resource use. For this reason, standard MFA practice only includes water mass contained in products e.g. agricultural produce and imported beverages. Water for other consumptive uses (cleaning or irrigation) and in situ uses (such as hydroelectric power), sometimes known as bulk water in MFAs, will be excluded from these accounts.

Balancing Items (BIs) and Material Accumulation (NAS). The input and output sides of the MFA are balanced to ensure all materials flowing into an economy in one year are accounted for. Balancing items on the input side mainly include oxygen requirements for combustion processes and respiration, nitrogen for ammonia production, and water requirements for the domestic production of exported beverages. Balancing items on the output side mainly include water vapour generated from combustion processes, gases from respiration and evaporated water from biomass products.

After adding the balancing items to input and output flows, the remaining materials are classified as material accumulation (or Net Additions to Stocks). This includes materials which are retained within the economy in the form of buildings, infrastructure and longer-life products (e.g. furniture, and electronics). Landfilled waste is also considered a stock since the material is permanently stored in a human-controlled environment.

Indirect Flows and Hidden Flows. Indirect flows measure the upstream quantity of materials associated with the imports of semi-finished and finished goods into the economy. They are needed to estimate the raw material requirements (RME) of traded commodities in an MFA. For example, to produce a tonne of imported canned fish, the upstream raw material requirements are the fish, metal cans, and the fossil fuel energy used to produce the canned fish. As these upstream raw material requirements are not exactly known, they are estimated based on input coefficients for different production processes, also known as RME coefficients. These coefficients are averaged factors for various inputs. Similar indirect flows can be defined for exports of semi-finished and finished products.

The domestic extraction of “unused materials” is classified as hidden flows. Examples of hidden flows are unused extraction from mining and quarrying (also known as overburden), discarded material from harvesting (e.g. wood harvesting losses), and soil and rock moved due to construction and dredging. Like indirect flows, these are also estimated using coefficients for biomass and minerals extraction processes.

Neither flow enters the focal socioeconomic system but the first, unused extraction remains within the natural system, and the second, RME remains in foreign economies. Both indirect and hidden flows are acknowledged but rarely quantified in traditional EW-MFA.

Having defined these material flow categories, we now can write a national material balance equation in EW-MFA terms:

$$DE + IMP + BI_{in} = EXP + DPO + BI_{out} + NAS$$

Extended approach

At both the Global and European level, nation-states report on a variety of statistics such as the production and trade of manufactured goods annually (known as ProdCom[45], ComExt[46] and Comtrade[47]), the production of agricultural products such as crops and livestock (FAOSTAT[48]) or the supply and use of energy carriers (UNSD Energy Statistics Database[49]. These detailed databases give consistency to nation EW-MFAs, allowing great comparability. The Eurostat's and UNEP's MFA Questionnaires[50][51] are fully functioning templates for conducting traditional EW-MFAs.

While the traditional approach provides a standardised way to quantify key material flows and stocks and related indicators, it sometimes falls short in describing and reconciling the link between all the datasets employed. The extended framework for an economy-wide CE assessment developed by Mayer et al. (2018)[52] is "*a framework for a comprehensive and economy-wide biophysical assessment of a CE, utilising and systematically linking official statistics on resource extraction and use and waste flows in a mass-balanced approach*" . Built upon traditional EW-MFA, it extends by discerning high-level material uses and by integrating waste flows, recycling and downcycling materials, that is by opening up the "black box" and uncovering flows within the economy (**Figure two**). Based on such a framework, a comprehensive set of indicators that measure the scale and circularity of total material and waste flows and their technical and ecological loop closing is developed.

The rationale for applying this framework to the standard EW-MFA data is to monitor progress towards a CE from an economy-wide perspective at the national or subnational scale. In fact, only at these levels it is possible to also capture system-wide effects such as displacement or rebound effects and to assess whether absolute reductions in resource use and waste flows were achieved. The novelty of the approach is the expansion of the EW-MFA boundaries by including flows of secondary materials and systematically mass-balance material inputs with waste, and secondary materials flows reported in the different statistical sources.

[45] Eurostat. (n.d.). Prodcom - Statistics by products - Overview. Available online at ProdCom
[46] Eurostat. (n.d.). Focus on Comext. Available online at ComExt
[47] Statistic Division of the United Nations (n.d.) UN COMTRADE. International Merchandise Trade Statistics. Available online at http://comtrade.un.org/
[48] Food and Agriculture Organization of the United Nations (n.d.). FAOSTAT statistical database. Available online at https://www.fao.org/faostat/en/#home
[49] Statistic Division of the United Nations (n.d.). UN ESD. Energy Statistic Database. Available online at https://unstats.un.org/unsd/energystats/data/
[50] Eurostat. (2024). Questionnaire for economy-wide material flow accounts. Available online at EW-MFA Questionnaire
[51] Environmental Programme of the United Nations (n.d.). UNEP. Questionnaire for economy-wide material flow accounts. Available online at EW-MFA Questionnaire
[52] Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., & Blengini, G. A. (2018). 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. doi:10.1111/jiec.12809

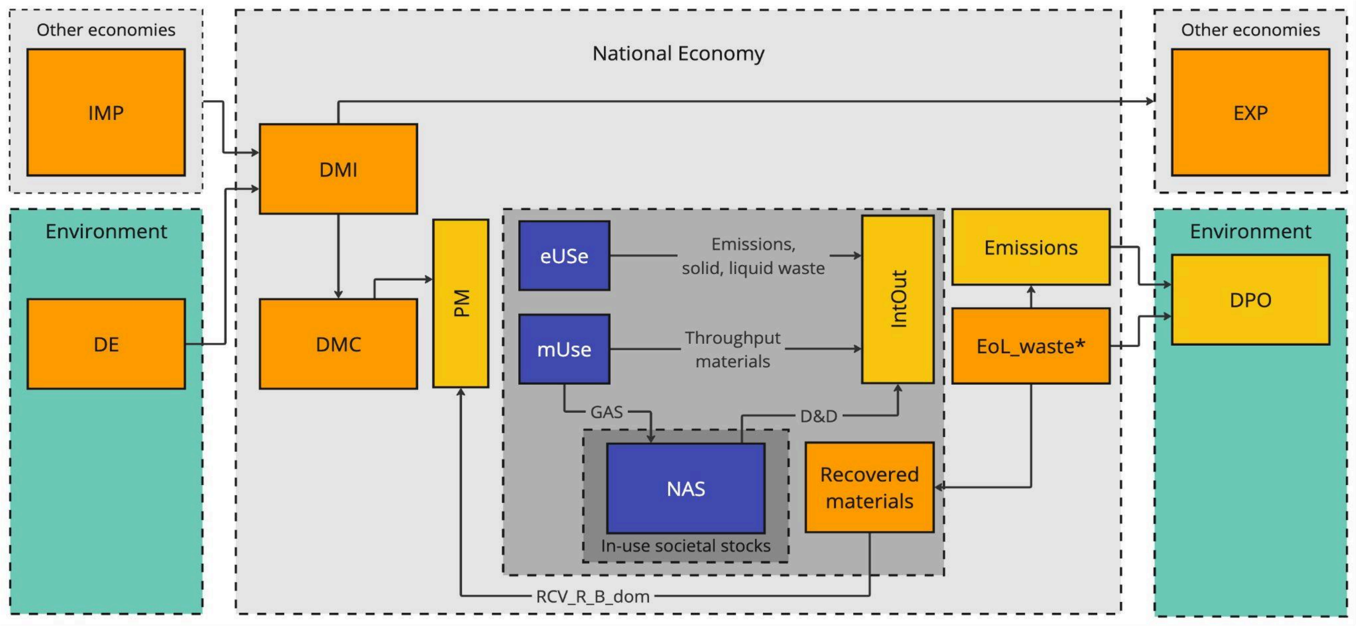


Figure two. *Simplified extended EW-MFA framework based on Mayer et al. (2018). This framework applies from individual materials (e.g., DE of corn or iron) to aggregated material categories (e.g., PM of biomass, fossil energy carriers) to the total material level (e.g., total DE). Colours indicate data sources used: Orange = reported data (e.g. official statistics), blue = mass-balanced modelling, yellow = mix of statistical and modelling approach. Note that compared to the traditional framework, Balancing Items on both sides are not included as all the flows and indicators are computed already at the net of such items.* *** *EoL waste excludes any flow related to Unused Domestic Extraction*

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

Processed materials (PM) were defined as the sum total of DMC and waste recycled in domestic plants ($RCV\_R\_B_{dom}$). PMs were allocated to either energetic or material use based on coefficients from material flow database and Mayer et al. (2018) - see table five in Project Annex. Energetic use ($eUse$) comprises materials used to provide technical energy (fuel wood and biofuels) and feed and food, the primary energy sources for livestock and humans. mUse was split into extractive waste, materials used for stock building (i.e., gross additions to in-use stocks of materials [GAS]), and throughput materials. Extractive waste refers to waste material that occurs during 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, infrastructures, or durable goods with a lifetime of more than one year (e.g., concrete, asphalt, or steel). The share of stock-building materials in mUse was estimated based on information from industry and production statistics, results from material flow studies and assumptions (see table five in Project Annex). Throughput materials comprise materials that do not accumulate in in-use stocks. They can be split into two types of materials: first, materials used deliberately in a dissipative way, such as salt or fertiliser minerals, and losses that occur during material processing (wastage, not reported in waste statistics); and second, short-lived products such as packaging or newspaper, manufacturing wastes, and food waste (reported in waste statistics).

All materials that are neither added to stocks nor recycled are converted into gaseous, solid, or liquid outputs within the year of extraction. Together with demolition and discard ($D\&D$) from in-use stocks that have reached the end of their service lifetime, these outflows were denoted as interim outputs ($IntOut$) in figure two. IntOuts were split into emissions, comprising all gaseous emissions (e.g., carbon dioxide [CO2], sulphur dioxide [SO2], methane [CH4]), 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_R_B (Recovery - Recycling and backfilling (excluding energy recovery) is reentering socioeconomic processes as secondary materials. The remaining EoL waste (after subtracting RCV_R_B) is returned to the environment as DPO waste and either landfilled, incinerated, or deliberately applied (e.g., manure, fertiliser). DPO emissions and DPO waste together form the total DPO.

To close the material balance between input and output flows, we combine data from statistical reporting with modelling. This was done separately for eUse and for the mUse components in two balancing calculations. The following equations summarise the mass balancing for eUse (equation 1) and mUse (equation 2).

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

Note that these two equations are equivalent to the ones reported in table one. We assumed that all materials used to provide energy were converted into DPO emissions (including water vapour) and solid waste within the year of extraction. We used data for solid waste from combustion reported in waste statistics and estimated the amount of solid waste from human and animal metabolism (excrements) by applying appropriate coefficients reflecting the non-digestible fraction of food and feed intake (Wu_eUse). DPO emissions were then calculated as the difference between eUse and the outflow of solid waste (Wu_eUse and Wu_mUse). Note that 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 (e.g., CO2 or SO2 in terms of C or S content; excrements at the average water content of food and feed intake). Closing the mass balance for eUse in this way implies that all inaccuracies in statistical data and assumptions that result in inconsistencies between input and output flows accrued in DPO emissions ($DPOe$). For the combustion of fossil energy carriers we cross-check the calculated DPO emissions with data from emission statistics. If the difference is found to be significant (negative difference or positive difference >10%), either model parameters or input data are modified to reconcile the results.

Due to a lack of knowledge of actual in-use stocks, we used the following approach to close the material balance: In the first step, a consistent split of total EoL waste from mUse Wu_mUse into waste flows resulting from discard and demolition ($D\&D$) and throughput materials was required. Total EoL waste from mUse (EoL_r) was derived from waste statistics. While waste statistics report information on construction and demolition waste, this waste flow was not fully consistent with EoL waste from discard and demolition, which also contains waste flows from discarded long-living products such as furniture, cars, or electric appliances. In a second step, we calculated the amount of discard and demolition as the difference between EoL waste from mUse reported in waste statistics and the fraction of throughput materials (i.e., materials with a life span < 1 year) in mUse (e.g., waste from packaging, paper, food waste, etc.). In the third step, NAS were calculated as the difference between additions to stocks and discard and demolition. Closing the mass balance in this way implies that all inaccuracies in statistical data and assumptions that result in inconsistencies between input and output flows for mUse accrue in demolition and discard flows as residual flow category, and consequently in the value for NAS. The fact that NAS are therefore calculated by balancing additions to stock and stock depletion rather than as a statistical balance between inputs and outputs represents one of the key differences between the traditional and extended EW-MFA approaches.

All flows and indicators were calculated for the four main material groups distinguished in EW-MFA. The calculation at the level of material groups on the output side was challenging due to the heterogeneity of solid, liquid and gaseous waste flow. Waste materials reported in one category typically comprise multiple material categories in EW-MFA, which requires conceptually linking them to flows on the input side and allocation to resource groups via composition coefficients. Moreover, waste flows reported in waste statistics needed adjustments to the system boundaries used in EW-MFA to ensure that input and output flows could be mass balanced (see table three in the Project Annex).

The extended EW-MFA framework by Mayer and colleagues brings considerable improvements to the traditional approach, by systematically linking material flow, waste and emission statistics in a mass-balanced approach. The economy "black box" is opened up and flows that are considered within the economy - such as recycling, fossil fuels used for energy purposes, non renewable and (potentially) renewable material inputs - and that are key for monitoring progress towards circularity are exposed and quantified. However, the extended approach still falls short on a number of elements:

1. Trade flows of secondary materials are not included, preventing a fully consistent consumption-based metric for technical cycling. Secondary materials include recyclable (or recycled) waste ($RCV\_R\_B_{imp}$ and $RCV\_R\_B_{exp}$) , by-products (BP_{imp} and BP_{exp}) and reused products (RP_{imp} and RP_{exp});
2. Some flows within the economy which are typically not covered by statistics such as generation of by-products for domestic consumption (BP_{dom}) and domestically reused products (RP_{dom}) are not included;
3. Indirect flows or upstream raw material requirements of trade flow (RME_{imp}, RME_{exp} and RMC) are not included.

All three issues are addressed by Circle Economy in its EW-MFA model.

Circle Economy's approach

Circle Economy's CGR EW-MFA model is used for calculating the CIS, a comprehensive set of indicators that measure the scale and rate of technical and ecological circularity - as well as the circularity gap - at the national level[53]. Built on top of the extended framework, the CGR EW-MFA model adds four important improvements:

[53] With some methodological adjustments, the model allows also for sub- and supra-national assessments

1. Trade flows of waste destined to recycling ($RCV\_R\_B_{imp}$ and $RCV\_R\_B_{exp}$) and by-products (BP_{imp} and BP_{exp}) are systematically included using the Eurostat's CMUR methodology[54] (see box three of the general methodology document). Trade flows of reused products (RP_{imp} and RP_{exp}) are included, if available from national sources;
2. By-products for domestic consumption (BP_{dom}) and domestically reused products (RP_{dom}) are included, if national sources are available;
3. Indirect flows or upstream raw material requirements of trade flow (RME_{imp}, RME_{exp} and RMC) are included and a set of indicators calculated on both apparent consumption (DMC) and material footprint (RMC). The estimation of indirect flow is based on the EE-MRIOA (see section Environmentally Extended Multi-Regional Input-Output Analysis - The Weavebase model)
4. Results from the traditional and the extended approach are cross-checked and reconciled to ensure the consistency and robustness of the results. Hidden flows are excluded at this time as data, thus far, remains insufficient.

Figure three shows a simplified depiction of the CGR EW-MFA measurement framework and model. In the context of CGRs, there are three instances of model use:

1. *All traditional EW-MFA datasets and headline indicators are already available at the required level of detail.* This is the case for most EU28 nations. Minimal additional data collection is required to deploy the CGR EW-MFA model. [***This is the case of country X***];
2. *Some traditional EW-MFA datasets and headline indicators are unavailable or available but not at the required level of detail:* This is the case of countries where, for instance, DMC is available but DPO or NAS are not. Here, a *streamlined approach* can be taken whereby DPO and BIs are only estimated using the best available data to derive NAS. [***This is the case of country X***];
3. *No traditional EW-MFA datasets and headline indicators are available:* This is often the case in assessments at the sub-national level or for data poor countries, where only basic production and trade statistics are available. Here, two approaches can be taken:

   3.1. The *integral approach* entails building the accounts from scratch following the international or European handbooks' guidelines and apply the CGR EW-MFA framework integrally[55] [***This is the case of country X***];

   3.2. The *simplified approach* entails using internationally available data sources and a combination of traditional and extended EW-MFA approaches together with simplified "rules of thumb" and assumption to quantify only variable that are strictly necessary for the calculation of the CIS [56] [***This is the case of country X***]

[54] Eurostat. (2018). *Circular material use rate: calculation method.* Eurostat manuals and guidelines. Luxembourg: Publications Office of the European Union, 2018. Retrieved from: Eurostat website
[55] For more detail on the methodology for sub-national assessment see [document WIP]
[56] For more detail on the methodology for supra-national assessment see CGR LAC methodology. Note that terminology and variable names can differ from the current document

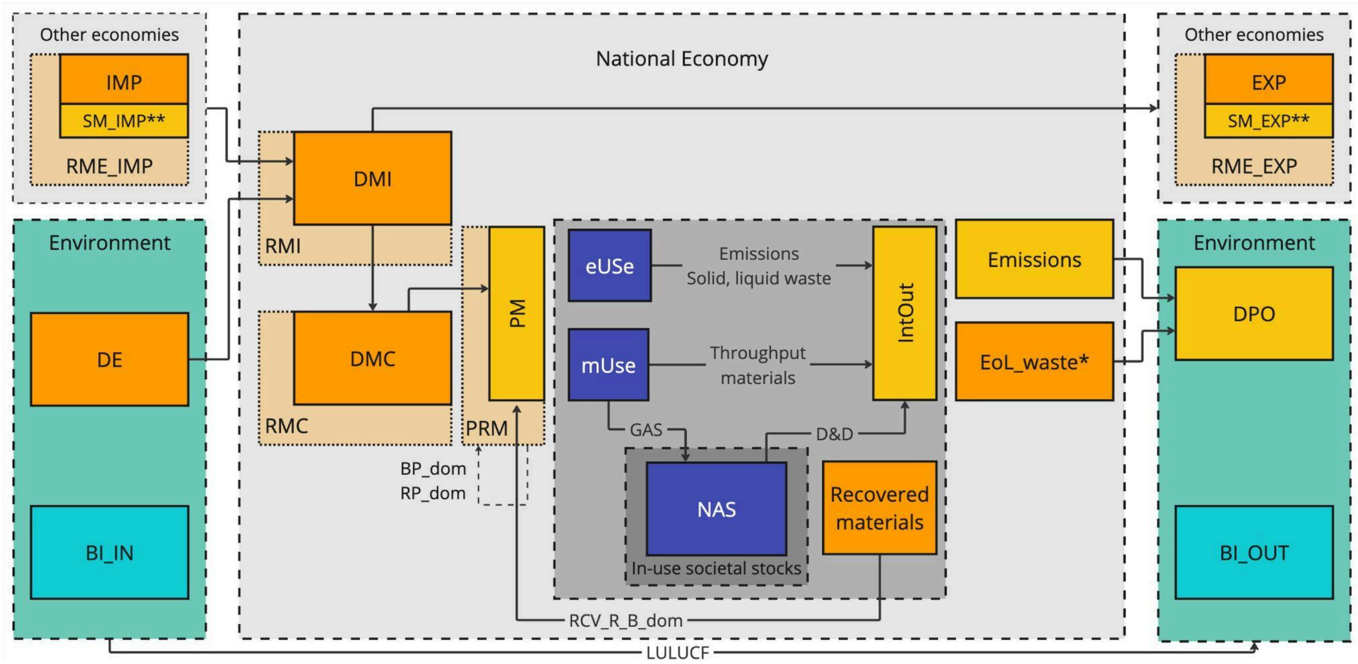


Figure three. *Simplified CGR EW-MFA framework. Differences with the extended EW-MFA framework are marked in bold. Blue = official statistics, yellow = mass-balanced modelling, purple = mix of statistical and modelling approach. Note that compared to the traditional framework, Balancing Items on both sides are not included as all the flows and indicators are computed already at the net of such items.* ***** *EoL waste excludes any flow related to Unused Domestic Extraction.* ****** *For simplicity,* SM_{imp} *and* SM_{exp} *are assumed to include both* BP_{imp} *and* BP_{exp}*,* $RCV\_R\_B_{imp}$ and $RCV\_R\_B_{exp}$

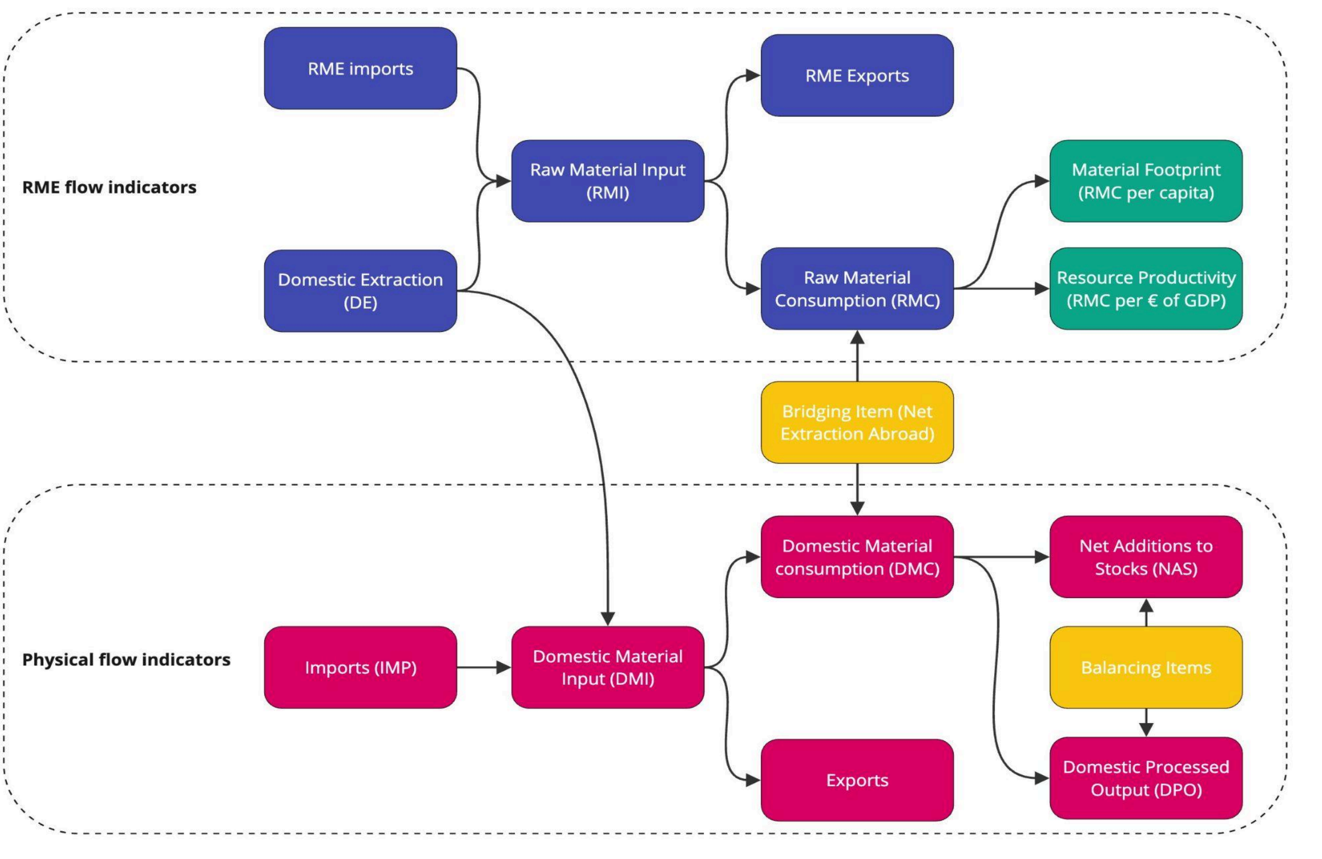
The extended MFA approach, particularly the process of harmonisation of systems boundaries across the EW-MFA and waste statistics, often generates headline indicators results that differ from those of the traditional approach. In order to minimise this difference, a manual iterative reconciliation process is performed. The objective is to minimise the difference between the two figures NAS and DPO indicators by changing values of particular coefficients in the extended MFA framework (e.g. share of mUse in DMC and share of stock additions in mUse - for the full list refer to table three of the Project Annex). Whenever the difference between indicators cannot be reconciled to satisfactory levels, an additional estimation of unreported waste is introduced (it should be noted the treatment route of such unreported waste remains unspecified).

The Bridging Item issue

CGRs typically report the CIS indicator based on PRM while indicators based on PM are calculated but not reported. PRM-based indicators have the advantage of taking a life-cycle perspective by reallocating raw material extraction to the point of final consumption; however, this 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 defined system boundary (the socioeconomic system under study) to outside of it (all the other economies). For 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 (e.g. petroleum) across all kinds of products and applications, thus not necessarily related eUse. In other words, direct physical flows - IMP and EXP - and derived indicators DMC and PM are conceptually different from upstream material requirements expressed in RMEs - RME_IMP and RME_EXP - and derived indicators RMC

and PRM. The application of the extended approach to the latter requires proper consideration. Therefore, we introduce a bridging item calculated as $RMC - DMC$ and refer to it as net extraction abroad (NEA) as shown in figure four.

Figure four. *Position of NEA as bridging item between RME and Physical flow indicators. Blue = Indicators expressing quantities of actual or "virtual" raw materials only. Purple = Indicators expressing quantities of a mix of actual raw materials, semi-finished and finished products. Yellow = special bridging and balancing items. Green = indicators expressing normalised physical quantities.*



When the NEA rate is negative, it means that the economy under study extracts more resources to satisfy final demand abroad than those extracted abroad to satisfy domestic final demand and vice versa. In case of *positive NEA,* the difference is arbitrarily added to the NRI indicator due to the difficulty of tracing their fate and thus allocating these flows to the rest of the indicators. This pinpoints another limitation in the use of RMEs rather than physical flows, that is the difficulty to track the fate of raw materials extracted abroad that are either embedded into the traded commodity or transformed into waste and emissions during processing in the foreign country. Conversely, in case of *negative NEA* the difference is subtracted from the NRI thereby, reducing it. For more project-specific information on this see section 2.2.4 of the Project Annex.

The Renewable Biomass issue

Ecological cycling is commonly assumed, but hardly operationalized in CE assessments. However, using biomass does not automatically imply safe ecological loop closing, as negative environmental impacts from land-use indicate. So far, neither robust criteria nor comprehensive indicators are available which enable identifying the fraction of biomass production which qualifies for sustainable ecological cycling[57]. 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, as we elaborate in the discussion section. To estimate the flow of primary biomass which cannot be regarded as carbon neutral, we deduct the net emissions of carbon from deforestation caused by land use change[58] [59] 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 the 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 deforestation 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.

$$BIO_{ren} = DMC_{bio} * BIO_{ren\%}$$

$$BIO_{ren\%} = 1 - ((LUC * 0.27) / (DMC_{bio} * DM_{avg\_bio\%} * 0.5))$$

Where DMC_{bio} is the fresh weight of biomass consumed, LUC are the CO2 emissions from deforestation caused by land use change embodied in trade, 0.27 is the molar ratio of elemental carbon to CO2, $DM_{avg\_bio\%}$ is the average dry matter share of biomass (calculated by subtracting the average water content at harvest from each biomass MF code) and 0.5 is the average elemental C content in dry biomass.

Box five: LULUCF vs deforestation

We have chosen to use deforestation emissions embodied in trade to proxy non-circular biomass. While previous iterations of this methodology used LULUCF, this data is notoriously unreliable to use and as such not included in the emissions databases by default. On a more practical note, LULUCF is also not easily linked to non-circular biomass as its emissions may be negative in the case of huge carbon sink territories (e.g. Brazil). Especially when combined with a CBA approach, this opens up the question on which parts of LULUCF emissions may be exported for the benefit of the importing territory. This approach had the additional side effect of theoretically allowing the import of negative emissions, which is illogical from an environmental perspective.

Instead, we have chosen to use deforestation emissions embodied in trade, developed by Singh & Persson (2024), which attributes deforestation - and related emissions - across the world to the expansion of cropland, pastures and forest plantation, and the commodities produced on this land. This, by definition, attributes the negative changes (deforestation) in land use change to the consumption of commodities, and thus more accurately reflects the non-circular use of biomass, globally.

[57] Navare, K., Muys, B., Vrancken, K. C., & Van Acker, K. (2021). Circular economy monitoring–How to make it apt for biological cycles?. Resources, Conservation and Recycling, 170, 105563.

[58] Pendrill, F., Persson, U. M., Kastner, T. & Wood, R. (2022). Deforestation risk embodied in production and consumption of agricultural and forestry commodities 2005-2018. Chalmers University of Technology, Senckenberg Society for Nature Research & Norwegian University of Science and Technology (NTNU). https://zenodo.org/records/5886600

[59] Singh, C. & Persson, U. M. (2024). Global patterns of commodity-driven deforestation and associated carbon emissions. Earth ArXiv. https://doi.org/10.31223/X5T69B

Environmentally Extended Multi-Regional Input-Output Analysis - Weavebase model

Environmentally-extended input-output analysis (EE-MRIOA) 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. EEIOA 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.

Of the available Multi-Regional EEIO databases (EE-MRIO), EXIOBASE stands out as a database compatible with the SEEA with a high industrial detail matched with multiple social and environmental satellite accounts. EXIOBASE represents the production and consumption of 164 industries and/or 200 economic goods for 43 countries and 5 rest-of-the-world (ROW) regions. Satellite accounts for resources and emissions are available for each sector and country. The original EXIOBASE 3 data series ended in 2011. However, in later releases, nowcasting procedures have been applied based on a range of auxiliary data, but mainly trade and macro-economic data which go up to 2022 when including International Monetary Fund projections.

Another prominent EE-MRIO is Eora26, which boasts highly detailed regional coverage with 189 regions, but only 26 high level sectors. Eora uses the national accounts for each region, and while the full version has the original sector coverage as originally reported, this database is neither symmetric nor easy to harmonise , and we instead opt for the simplified Eora26 database.

Given the requirements of having global regional coverage, whilst supporting detailed sectoral breakdowns, we have developed a robust, authoritative, and highly resolved MRIO database for analysing environmental footprints related to the circular economy. The database utilises the high sectoral disaggregation of EXIOBASE's 163 sectors to augment Eora26 while keeping the high regional resolution of the latter (188 countries after dropping the historic USSR). The high level sector (26) totals adhere to the Eora26 monetary database, and are not too dissimilar to the EXIOBASE linkages where regions are identical (with mostly minor differences due to total industrial output differences between databases). However, in the case of the 5 EXIOBASE ROW regions, the relative shares of the sub sectors are shared among these regions, but applied to their national high level sector totals. This results in a database with Eora26 regions and EXIOBASE sectors, which adheres to the Eora26 monetary totals.

This method is in fact the opposite of the approach implemented by Cabernard et al. (2021)[60] in which Exiobase was used as the baseline and regionally expanded using Eora. We argue that it is more beneficial to increase sectoral resolution while preserving original country-specific information for a vast amount of nations than to increase regional resolution while preserving "black box" "Rest of the World" region totals.

For the extensions, we start with using the EXIOBASE satellite and apply the opposite method as described above: we instead retain the EXIOBASE extension, but extended regionally using Eora26 satellites. EXIOBASE is used much more commonly for environmental impact assessment, and we found that retaining its satellite structure was beneficial in this regard.

Given that the satellite is based on EXIOBASE, as of v3.8.2,[61] the end years of real data points used are: 2015 energy, 2019 all GHG (non-fuel, non-CO2 are nowcasted from 2018), 2013 material, 2011 most others such as land and water. Due to the relatively outdated nature of the material accounts, CE has developed its own

[60] Cabernard, L., & Pfister, S. (2021). A highly resolved MRIO database for analyzing environmental footprints and Green Economy Progress. Science of the Total Environment, 755, 142587.

[61] Exiobase v3. (2020). Exiobase 3, version 3.8. doi:10.5281/zenodo.4277368

version where materials extraction is updated to the latest year available on a country-by-country basis using the high-resolution Global Material Flow Database - 2024 edition compiled using the Common Compilation Categories and provided under request by the International Resource Panel (IRP)[62]. The IRP database is based mostly on reported data until 2019-2020 and modelling estimates for later years[63]. Industry allocations of the baseline year 2011 have been applied under the assumption that the structure of the extractive industries has not radically changed in the last decade. This operation allows us to calculate reasonably robust material footprint accounts up until the year 2019-2020, under a defined set of assumptions (e.g. nowcasted monetary data from 2011 or industry allocation shares for material extraction).

Similarly, the emissions data has been updated to the base year using EDGAR v8.0. Due to imprecisions in the sectoral and direct emissions split of the Eora environmental extension used for the regional disaggregation of Exiobase's extension, a recalculation routine was introduced. For Annex-I countries, UNFCCC reported data is used, as it exposes sub-categories that relate to direct households directly. Given these coefficients, the shares for CRF categories 1.A.3 ("Transport") and 1.A.4 ("Other Fuel Combustion") that relates to household emissions can be estimated. To further extend this logic to non Annex-I countries, the same vehicle car use shares to 1.A.3 transport as GLORIA, sourced from Pomponi et al (2021) is applied. Finally, for category 1.A.4, the share "household" over "other consumption" from the UNSTAT energy balances is used to estimate the share of emissions from residential heating. Any leftover regions in EDGAR that we do not cover in the MRIO are redistributed so as to adhere to the global total (this is a minute difference).

In Europe, due to the high quality and granular data available in Eurostat, we additionally update the materials and emissions using "env_ac_mfa" and "env_ac_ainah_r2" respectively.

We update the employment extensions using data from the ILO to the given year, whilst adding additional employment indicators related to types of employment, (in-)formality, and more.

Lastly, to enable environmental impacts assessment (LCIA), we characterise the EXIOBASE stressors using IW+.

All calculations are performed using the open-source tool for analysing global EE-MIOTs, **pymrio.**[64] Production- and consumption-based accounts are calculated using a standard set of IO formulas as specified below and in **Table 3.**

$$D^i_{cba} = D^i_{pba} + D^i_{imp} - D^i_{exp}$$
$$D_{pba} = Fe + Ge$$
$$D_{imp} = MY_t$$
$$D_{exp} = M\hat{Y}_t e$$

Table 3. Description of main Pymrio variables

Variable name	Symbol	Description
Consumption-based accounts	D^i_{cba}	Footprint of consumption

[62] International Resource Panel. (n.d.). Global material flows database. Retrieved from: IRP website
[63] CSIRO. Technical annex for Global Material Flows Database - 2024 edition. Available online at: IRP website
[64] Pymrio. (n.d.). pymrio - Multi regional input output analysis in python. Retrieved from: pymrio website

Production-based accounts	D^{i}_{pba}	Footprint of production or territorial accounts
Imports accounts	D^{i}_{imp}	Footprint of imports or factors of production occurring abroad (embodied in imports) to satisfy domestic final demand
Exports accounts	D^{i}_{exp}	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	$L = (I - A)^{-1}$	Total requirements matrix
Factor production coefficients	$S = F\hat{x}^{-1}$	–
Gross output	$x = Z_{e} + Y_{e}$	–
Transaction matrix	Z_{e}	Matrix of interindustry flows or intermediate transaction matrix
Technology matrix	$A = Z\hat{x}^{-1}$	Matrix of technical coefficients, the amount of input from industry i needed to produce one unit of output from industry j
Final demand matrix	Y_{e}	–
Final demand matrix to satisfy factors of production abroad	$Y_{t} = Y - Y_{i,j} \| i = j$	Final demand matrix with domestically satisfied final demand set to zero

Note: the ^ symbol represents the diagonalised vector, the e symbol represents a summation vector of 1s

Scholars and practitioners have extensively discussed the merits and drawbacks of different input-output database structures, compilation and manipulation techniques.[65,66,67,68,69] According to Tukker and colleagues and Wiedmann and colleagues[70,71,72], there are several approaches to calculate footprints.

When possible, we employ a variation of method six (the SNAC approach[73]), in which flows are not rebalanced after the nesting of national data into the multi-regional system. This is not critical for a national analysis, and updating the global database for the national lens ensures that discrepancies related to global harmonisation are not going to impact the results for a national analysis. The SNAC approach consists of updating the domestic monetary blocks using bottom-up (national) IOTs. However, in order to keep the MRIO symmetrical, the sectoral classification system is remapped to the EXIOBASE sectors, or vice-versa, aggregating and disaggregating any sectors where needed. Imports and exports in the national IOT are used to correct the linkages with other regions in the MRIO.

However, note that the environmentally-extended (EE) part of the MRIO is not often updated, and still contains emission and material use intensities based on the EXIOBASE sectors. In rare cases, this may cause unintended results. For example, if a sector (e.g. Research and Development) has a low monetary value in EXIOBASE its emission intensity may be relatively high without much impact, but when the national IOT suddenly reports a much bigger monetary value in this sector it will use the high intensity factor from EXIOBASE and thus create a large impact out of "thin air". These cases cannot be easily predicted and arise from the nature of MRIOs in and of themselves.

Scenario modelling - A macroeconomic approach

In section *"4.3 Scenario modelling"*, we outlined the overall conceptual framework under which the *intervention blueprints* are developed. An intervention blueprint is defined as a standardised way of modelling a circular economy measure through a set of parameters to be applied in a macroeconomic (EE-MRIOA) model. For explanatory purposes, the process of parametrising the interventions listed in table three of the *"4.3 Scenario modelling"* section is hereafter divided into two parts, namely approach and data and mathematical formulation.

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[65] Schoer, K., Wood, R., Arto, I., & Weinzettel, J. (2013). *Estimating raw material equivalents on a macro-level: comparison of multi-regional input–output analysis and hybrid LCI-IO*. Environmental science & technology, 47(24), 14282-14289. doi:10.1021/es404166f
[66] Giljum, S., Lutter, S., Wieland, H., Eisenmenger, N., Wiedenhofer, D., Schaffartzik, A., & West, J. (2015). *An empirical assessment comparing input-output based and hybrid methodologies to measure demand-based material flows*. Paris: Organisation for Economic Co-operation and Development.
[67] Bruckner, M., Fischer, G., Tramberend, & S., Giljum, S. (2015). *Measuring telecouplings in the global land system: A review and comparative evaluation of land footprint accounting methods*. Ecological Economics 114, 11-21. doi:10.1016/j.ecolecon.2015.03.008
[68] Kovanda, J., Weinzettel, J., & Schoer, K. (2018). *What Makes the Difference in Raw Material Equivalents Calculation Through Environmentally Extended Input-Output Analysis?*. Ecological economics, 149, 80-87. doi:10.1016/j.ecolecon.2018.03.004
[69] Giljum, S., Wieland, H., Lutter, S., Eisenmenger, N., Schandl, H., & Owen, A. (2019). *The impacts of data deviations between MRIO models on material footprints: A comparison of EXIOBASE, Eora, and ICIO*. Journal of industrial ecology, 23(4), 946-958. doi:10.1111/jiec.12833
[70] Tukker, A., de Koning, A., Owen, A., Lutter, S., Bruckner, M., Giljum, S., ... & Hoekstra, R. (2018). *Towards robust, authoritative assessments of environmental impacts embodied in trade: Current state and recommendations*. Journal of Industrial Ecology, 22(3), 585-598. doi:10.1111/jiec.12716
[71] Tukker, A., Giljum, S., & Wood, R. (2018b). *Recent progress in assessment of resource efficiency and environmental impacts embodied in trade: An introduction to this special issue.* Journal of Industrial Ecology, 22(3), 489-501. doi:10.1111/jiec.12736
[72] Wiedmann, T., Chen, G., Owen, A., Lenzen, M., Doust, M., Barrett, J., & Steele, K. (2021). *Three-scope carbon emission inventories of global cities*. Journal of Industrial Ecology, 25(3), 735-750. doi:10.1111/jiec.12736
[73] Edens, B., Hoekstra, R., Zult, D., Lemmers, O., Wilting, H., & Wu, R. (2015). *A method to create carbon footprint estimates consistent with national accounts*. Economic Systems Research, 27(4), 440-457

Approach and data

The general CGR approach for scenario modelling relies on the transformation of physical and activity data from a variety of sources into a standardised set of parameters for application in monetary EE-MRIOTs. The key data sources for each provisioning system, are as follows:

- Housing: ODYM v2.4 Database, MAT_STOCKS database, EXIOBASE pxp
- Mobility: ODYM v2.4 Database, EXIOBASE pxp
- Nutrition: FAOSTAT Food Balances, Vita et al. (2019)
- Manufacturing: ODYM v2.4 Database, CE research
- Lifestyles: Vita et al. (2019)

The numerical parameters - namely technical (k_t), market penetration (k_p) and substitution (skw) coefficients (for more details see the mathematical formulation section) - are derived as the ratio of physical (e.g. ton, joule) or activity (m^2, km) data between a baseline and target year and, therefore, are unitless. As mentioned, the coefficients are applied to a monetary framework, hence the underlying assumption is one of proportionality between changes in physical or activity flows and related monetary transactions. This assumption avoids the need to use prices for conversion with all the complications of the case. **Table 4** summarises the database resolution over five key modelling dimensions:

Table 4. *Scenario model's input data resolution*

Dimension	Resolution
Time and age-cohorts	Time frame: 2015-2060 Reporting: Variable baseline year - 2050 (2032 as intermediate result)
Systems	5 provisioning systems: Housing, Mobility, Nutrition, Manufacturing and Services (Lifestyles)
Regions	Varies by system and parameter, typically: 20 for mobility and housing, 163 for nutrition and 1 (global region) for manufacturing and services
Materials	13 engineering materials aggregated to 7 material groups: Iron and steel, aluminium, copper, zinc, plastic, cement, concrete and wood
Products	Vehicles: 6 powertrains, 4 ownership types and 8 design segments Buildings: 4 size archetypes, 4 energy efficiency standards, 2 design segments Energy: 6 energy carriers Nutrition: Up to 95 food products aggregated to 6 food categories
Scenarios	3 socioeconomic, 2 climate change and 3 waste management scenarios

The modelling approach is semi-static: Time-series of input data (foreground system) are used to develop time-dependent coefficients as the ratio between a target and baseline year ($1 - n_{tx}/n_{t0}$) which are applied to a static EE-MRIOT framework (background system). While this is different from a fully-fledged dynamic approach where the outputs are the result of differential equations producing year-on-year results, the time-dependency of the foreground system allows to take into account underlying changes in the systems, though in a simplified way.

Based on the IPAT equation, the CGR modelling approach conceptualises impacts as the product of population, affluence and technology. While the representation of these aspects can slightly vary and adapt from one intervention blueprint to the other, generally speaking technological and affluence aspects are captured by the technical change coefficients while population and ambition levels are captured by the market penetration coefficients. Therefore, if the objective is to evaluate counterfactual scenarios where the effect of the interventions is calculated at the margin, datasets representing the underlying changes (e.g. residential floor area, person-km travelled or caloric intake) can be normalised by population with fixed values between the baseline and target year for parameters affected by changes in affluence (GDP/capita). Else, if the objective is to evaluate the projected effect of the interventions, datasets representing the underlying changes will be expressed in absolute terms (subjected to population growth) with floating values between the baseline and target year for parameters affected by changes in affluence.

The input data (foreground system) is specified for a number of scenarios. We distinguish between 3 types: Socioeconomic, climate change and waste management scenarios. Input data for socioeconomic and climate change scenarios determine changes to production- (RMI) and consumption-based (RMC) material footprint results while waste management scenarios determine changes to secondary material consumption. In this respect, it should be noted that the model is only partially-linked, that is not all elements of the model are interdependent. In particular, changes in material footprint are not linked to changes in secondary material consumption as the two modelling domains - economic transactions linked to material extraction and waste management system, respectively - are not part of a single fully integrated model and thus treated separately.

Data related to the three socioeconomic and two climate change scenarios is sourced directly from the ODYM model. For the waste management scenarios, high-level assumptions and projections are sourced from the Global WMO[74], adapted and applied to waste generation and treatment data from the global CGR 2025 database. These scenarios are widely used and adopted within the environmental modelling community, including the IPCC[75]:

- **Climate change scenarios**:
    - Baseline (unmitigated) - is a "Business-as-usual" scenario in regards to specific climate change mitigation and adaptation strategies;
    - Representative Concentration Pathway 2.6 (RCP2.6)[76] - is the most optimistic of the RCPs scenarios that envisions a future with significant reductions in greenhouse gas emissions, leading to a smaller increase in global temperatures compared to the other RCPs
- **Socioeconomic scenarios**:
    - Low Energy Demand (LED)[77] - is a "Sustainability and resource efficiency" scenario that explores a pervasive transformation of the demand side of resource systems. It integrates a number of emerging trends centered around digitalization, device convergence, the sharing, and circular economy, and associated waste minimization strategies. New technological, organizational, and business model innovations, combined with behavioral changes revolutionize service provisions in direction of highest levels of resource efficiency;

[74] https://www.unep.org/resources/global-waste-management-outlook-2024
[75] https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter04.pdf
[76] https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome
[77] https://iiasa.ac.at/models-tools-data/led

- Shared Socioeconomic Pathway 1 (SSP1)[78] - is a "Sustainability" scenario characterized by inclusive development that respects predicted environmental boundaries. Consumption is oriented toward low material growth and lower resource and energy intensity;
- Shared Socioeconomic Pathway 2 (SSP2) - is a "Business-as-Usual" scenario in which the world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines;

- **Waste management scenarios**:
  - Waste Management as Usual (WMaU) - is a scenario in which waste generation continues to increase with economic growth. Investment in infrastructure is limited; collection, recycling and disposal practises remain unchanged (fixed treatment rates);
  - Waste under Control (WuC) - is a scenario in which waste generation is decoupled from economic growth by 2030. Investments in waste prevention and management increase; by 2050 collection coverage increases to 100% and uncontrolled disposal ends. Diverted waste is treated equally across the other waste treatment types;
  - Circular Economy (CE) - is a scenario in which waste generation falls back to 2020 level by 2050. Collection coverage reaches 100% and uncontrolled waste disposal ends by 2050 and recycling (efficiency) reaches 60% by the same year

The intersection of these climate change, socioeconomic and waste management scenarios generates 18 combinations, three of which are selected to determine the final results range (**Table 5**).

Table 5. *Scenario combinations used for range definition*

Scenario	**Pessimistic**	**Middle**	**Optimistic**
Socioeconomic	SSP1	SSP2	LED
Climate change	Unmitigated	Unmitigated	RCP2.6
Waste management	WMaU	WuC	CE

Results are presented at 3 different aggregation levels: individual intervention (e.g. occupancy increase), provisioning system (e.g. housing) and combined (all provisioning systems together).

There are three main limitations that are important to consider when using and interpreting these scenarios:

- Waste management are global economy-wide scenarios and are only applied at the combined level. This means that impact at the level of individual interventions and provisioning systems is only presented in terms of change in Raw Material Consumption (RMC) and not as a change in the ITCr. The modelling secondary material consumption at the individual intervention and provisioning system level requires global waste generation and treatment data at the sectoral level which is currently not available;
- The impacts of interventions are calculated over RMC and applied in relative terms to DMC. Consequently, only changes on the ITCr and not on the rest of the indicators can be quantified;
- Impacts on the consumption-based GHG footprint are partial and only consider supply chain (indirect emissions) and not direct emissions (from households), which constitute a non-negligible share of the

[78] https://iiasa.ac.at/models-tools-data/ssp

total. Impacts on direct emissions from households were excluded, as they would require additional modelling efforts in order to characterise the mobility and housing stock in terms of their emission intensities and link them to the IOT framework.

In the next section, we provide the general mathematical formulation of the model's calculation and a more in depth explanation of the approach for each system, including the main formulas.

Mathematical formulation

General

The general mathematical formulation for modelling interventions within an IO framework is based on the work of Donati et al. (2020)[79] (refer to section Environmentally-Extended Input-Output Analysis for the notation related to the basic Leontief demand-driven model). Note that in the application the system used is multiregional. That is, each entry of an IO object identifies not only a row and/or column economic sector or final demand category but also a region.

In order to assess the environmental impact of an intervention we compare the impact that occurs in the baseline and a counterfactual scenario in which the corresponding changes have been implemented. This is expressed as $\Delta r = D_{cba}^{*} - D_{cba}$. A counterfactual scenario (an object adjoined with *) is constructed by adjusting particular elements in the objects that define the baseline EEIO system - namely S, A, Y and possibly G_e. 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 (where subscripts i and j represent two sector-region combinations) of an arbitrary M matrix object from the baseline to the counterfactual scenario, is performed as:

$$M_{ij}^{*} = M_{ij} * (1 - k_a)$$

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 effects, and of a *market penetration coefficient* (k_p) describing the size of the given market affected, $k_a = k_t * k_p$. The coefficients' value is always between 0 and 1. Furthermore, there might exist a substitution relation between edits in different entries. For example, a reduction in the volume of a particular material (e.g. steel) used in a production process may be compensated by an increase of another (e.g. aluminum). This type of relation is modelled as:

$$M_{ij}^{*} = M_{ij} + skw * (M_{mn}^{*} - M_{mn})$$

Here mn are the coordinates of the original change (e.g., reduction in steel) and ij are the coordinates of the substitution (e.g., increase in aluminum). skw is a substitution weighting factor accounting for differences in

[79] 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.

price and physical material properties between products, materials or services. In **Table 6** we summarised the main formulas and assumptions behind the development of k_t and k_p for each intervention blueprint.

Table 6. *Main formulas, variables and assumptions per intervention (note: Some interventions and their formulas are simplified for illustrative purposes). This is intended as a concise summary and not an exhaustive representation the each blueprint, its underlying data, formulation and assumptions*

Intervention	Technical change coefficient (k_t)	Market penetration coefficient (k_p)	Variables, assumptions and notes
Housing Underlying change[1]: $Sfut$ = residential building floor area (m²/pp), Pop = population Dimensions[2]: t (time)[2], α (building type), β (design), γ (energy service), δ (energy carrier), ϵ (climate change scenario), ϕ (material type)			
Occupancy increase	$kt_{stk} = 1 - (Sfut_{tn} * (1 - OR)\ / Sfut_{t0})$	$kp = GFCF_{res} * (IC_{tn} - IC_{t}$ [3,4]	OR = occupancy rate increase kt_{stk}= Technical change coefficient for stocks IC = degree of implementation in year t
Downsizing and lightweighting	$Mf_{tx,\alpha,\beta,\phi} = Sfut_{tx,\alpha} * Mc_{\alpha,\beta,\phi}$ $kt_{mat} = (1 - Mf_{tn}/Mf_{t0})$ $Ef_{tx,\alpha,\beta,\gamma,\delta,\epsilon} = Sfut_{tx,\alpha,\beta} * Ei_{\alpha,\beta,\gamma,\delta} * ECS_{tx,\gamma,\delta,\epsilon} * BEC_{tx,\gamma,\delta,\epsilon}$ $kt_{en} = (1 - Ef_{tn}/Ef_{t0})$		Mf = Material flow (ton) per building type α, design β and material type ϕ in year t Mc = Material composition (ton/m²) kt_{mat}= Technical change coefficient for material flows[5] Ef = Energy flow (J) per building type α, design β, energy service (γ), energy carrier (δ) and scenario (ϵ) in year t Ei = Energy intensity (J/m²) ECS = Energy carrier split BEC = building final-to-primary energy conversion kt_{en}= Technical change coefficient for energy flows[5] Assumption 1: intervention applies to the totality of the selected flows ($k_p = 1$)
Structural renovation	$kt_{stk} = 1 - (Sfut_{tn,\alpha} * (1 - LFT_{\alpha})$ $/ Sfut_{t0,\alpha})$	kp=Share of residential in total building's GFCF[3]	LFT = Lifetime extension coefficient, applies only to energy-efficient and ZEB building types, same across all building types. Assumption 1: Lifetime extension of buildings translates directly into the reduction in demand for new buildings.
Energy renovation	$Sren_{tx,\epsilon,\delta,a} = Sfut_{tx,\delta,a} * ICBR_{tx,\epsilon} * Ei_{\alpha,\beta,\gamma,\delta}$ $Ren\_Ef_{tx,\alpha,\beta,\gamma,\delta,\epsilon} = Sren_{tx,\delta,\epsilon,\alpha} * ESP$ $Ef_{tx,\alpha,\beta,\gamma,\delta,\epsilon} = Sfut_{tx,\alpha,\beta} * (1 - ICBR_{tx,\epsilon}) * Ei_{tx,\alpha,\beta,\gamma}$ $Tot\_Ef_{tx,\alpha,\beta,\gamma,\delta,\epsilon} = (Ren\_Ef_{tx,\alpha,\beta,\gamma,\delta,\epsilon} + Ef_{tx,\alpha,\beta,\gamma,\delta,\epsilon})$		$Sren$ = Portion of stock affected by renovation per building type α, energy carrier δ, and scenario ϵ, in year t $ICBR$ = Implementation curve of building renovation $RenEf$ = Energy flows (consumption) of the renovated part of the stock ESP = Energy saving potential

<table>
<tr><td></td><td>$* \ ECS_{tx,\gamma,\delta,\epsilon} * BEC_{tx,\gamma,\delta,\epsilon}$

$kt_{en} = (1 - Tot\_Ef_{tn}/Tot\_Ef_{t0})$</td><td>Assumption 1: intervention applies to the totality of the selected flows ($k_p = 1$)
Assumption 2: 0% renovation rate in year $t0$</td></tr>
<tr><td colspan="3">Mobility
Underlying change: Pkm = Person-kilometers travelled (pkm), , Pop = population
Dimensions[1]: t (time)[2], θ (powerdrive), ϑ (design)</td></tr>
<tr><td colspan="3">Baseline stock segmentation by ownership (starting point for all interventions):

$Sprv_{tx,\theta} = (((1 - CaS_{tx})/100) * ((1 - RiS_{tx})/100) * Pkm_{tx}/(OR_{tx} * Vkm_{tx})) * TS_{tx,\theta}$
$SCaS_{tx,\theta} = (((COS * CaS_{tx})/100) * ((1 - RiS_{tx})/100) * Pkm_{tx}/(OR_{tx} * Vkm_{tx})) * TS_{tx,\theta}$
$SRiS_{tx,\theta} = (((1 - CaS_{tx})/100) * (RiS_{tx}/100) * Pkm/(ORS_{tx} * OR_{tx} * Vkm_{tx})) * TS_{tx,\theta}$
$SCaS\_RiS_{tx,\theta} = (((COS * CaS_{tx})/100) * (RiS_{tx}/100) * Pkm_{tx}/(ORS_{tx} * OR_{tx} * Vkm_{tx})) * TS_{tx,\theta}$

$Stot = Sprv_{tx,\theta} + SCaS_{tx,\theta} + SRiS_{tx,\theta} + SCaS\_RiS_{tx,\theta}$

CaS = Share of Pkm delivered by shared cars , RiS = Share of Pkm delivered by shared rides, OR = Average vehicle occupancy rate, Vkm = Vehicle-kilometers per year, TS = Powerdrive type split, COS = Ratio of car ownership rate with vs. without participation in car-sharing,ORS = Ratio of car occupancy with vs. without participation in ride-sharing</td></tr>
<tr><td colspan="3">Average vehicle-kilometers depending on privately owned vs carsharing (starting point for all interventions):

$Vkm_{fut_{tx,\theta}} = (Sprv_{tx,\theta} + 1/COS * SCaS_{tx,\theta} + SRiS_{tx,\theta} + 1/COS * SCaS\_RiS_{tx,\theta}) * Vkm_{tx}/Stot_{tx,\theta}$
$Sprv$ = Mobility by privately-owned and not shared vehicle stock, $SCas$ =Mobility by car-shared but not ride-shared vehicle stock, $SRis$ = Mobility by ride-shared but not car-shared vehicle stock, $SCaS\_RiS$ = Mobility by car-shared and ride-shared vehicle stock</td></tr>
<tr><td>Occupancy increase</td><td>Stock segments and vkm are calculated as per the generalised formulas for target year tn under the following assumptions:

$CaS_{tn} = CaS_{t0}, RiS_{tn} = RiS_{t0}, COS_{tn} = COS_{t0}, Vkm_{tn} = Vkm_{0}, TS_{tn,\theta} = TS_{t0,\theta}$
Hence, only *OR* and *ORS* changes within time t_x

$kt_{stk} = 1 - (Stot_{tn}/Stot_{t0})$

$kt_{en} = 1 - (Vkm_{fut_{tn}}/(Vkm_{fut_{t0}})$</td><td>Assumption 1: intervention applies to the totality of the selected flows ($k_p = 1$)</td></tr>
<tr><td>Lifetime extension</td><td>Stock segments and vkm are calculated as per the generalised formulas for target year tn under the following assumptions:
$CaS_{tn} = CaS_{t0}, RiS_{tn} = RiS_{t0}, COS_{tn} = COS_{t0}, Vkm_{tn} = Vkm_{0},$
$ORS_{tn} = ORS_{t0}, OR_{tn} = OR_{t0}$
Hence, only *TS* changes within time t_x

$kt_{stk} = 1 - (Stot_{tn} * (1 - LFT_{\theta}) / Stot_{t0})$
$kt_{en} = 1 - (Vkm_{fut_{tn}}/(Vkm_{fut_{t0}})$</td><td>$LFT$ = Lifetime extension coefficient, applies only to PHEV, BEV and FCV.

Assumption 1: intervention applies to the totality of the selected flows ($k_p = 1$)

Assumption 2: Lifetime extension of vehicles translates directly into the reduction in demand for new vehicles.</td></tr>
<tr><td>Downsizing and lightweighting</td><td>Stock segments and vkm are calculated under the same assumptions as for the lifetime extension scenario and further disaggregated based on design ϑ, and (ex. for $Sprv$, applies to all segments):

$Sprv_{tx,\theta,\vartheta} = Sprv_{tx,\theta} * (1 - LWS_{tx,\theta,\vartheta}) * DWS_{tx,\theta,\vartheta}$</td><td>Assumption 1: kt_{mat} apply to the totality of the selected flows.

Assumption 2: $kt_{en}$is calculated for diesel, gasoline and electricity,</td></tr>
</table>

	$Mf_{tx,\theta,\vartheta} = Sprv_{tx,\theta,\vartheta} * MC_{tx,\theta,\vartheta}$ $kt_{stk} = 1 - (Stot_{tn}/Stot_{t0})$ $kt_{mat} = 1 - (\sum Mf_{tn}/\sum Mf_{t0})$ $kt_{en} = 1 - (Vkm_{fut_{tn}}/(Vkm_{fut_{t0}})$	depending on powerdrive θ . PHEV is assumed to use 50% gasoline, 50% electricity. For diesel and gasoline, kp applies to transport fuels only based on product shares from Exiobase ($k_p \neq 1$) LWS = Share of lightweight vehicles in ownership segment S, year t and powertrain θ DWS **=** Share of downsized vehicles
Car- and ride-sharing	Stock segments and vkm are calculated as per the generalised formulas for target year tn under the following assumptions: $OR_{tn} = OR_{t0}$, $Vkm_{tn} = Vkm_0$, $TS_{tn,\theta} = TS_{t0,\theta}$ Hence, CaS, RIS, and COS changes within time t_x $kt_{stk} = 1 - (Stot_{tn}/Stot_{t0})$ $kt_{en} = 1 - (Vkm_{fut_{tn}}/(Vkm_{fut_{t0}})$	Assumption 1: intervention applies to the totality of the selected flows ($k_p = 1$)
Nutrition Underlying change: CI = caloric intake (kcal/day/pp), Pop = population Dimensions[1]: t (time), food type (α), nutritional group (β), shift to vegetarian (c_{veget}), shift to vegan (c_{vegan}), shift to mediterranean (c_{med})		
Diet shift	$kcal_{base,\alpha,t0}$: kcal consumption in the base diet of the food type α $kcal_{base,\beta,t0}$: kcal consumption in the base diet of the nutritional group β $kcal_{\beta} = \sum_{\alpha} kcal_{\alpha}$ α ϵ β, can be extended to time dimension $kcal_{new,\alpha,t} = \sum_{i} kcal_{\alpha,t,i} * c_i \quad i \in dietary\ group$ $kcal_{\alpha,t,i} = kcal_{base,\alpha,t0,i} * (kcal_{new,\beta,t,i}/kcal_{base,\beta,t0,i})$ $kt_{\alpha} = 1 - kcal_{new,\alpha,t}/ kcal_{base,\alpha,t0}$	Vegetarian diet: no meat and fish nutritional groups. Kcal from these groups are allocated equally to grains, vegetables and fruits and dairy products. Vegan diet: no meat, fish and dairy nutritional groups. Kcal from these groups are allocated equally to grains and vegetables and fruits. Mediterranean diet: 50% reduction in meat nutritional group. Kcal from this group are allocated equally to the other groups.
Balanced diet	$kcal_{lim}$: kcal consumption of sufficiency levels $kcal_{\alpha,t} = kcal_{base,\alpha,t0} * ((1 - W_{\beta}) * kcal_{lim}/kcal_{base} + W_{\beta})$ $kt_{\alpha} = 1 - kcal_{\alpha,t}/ kcal_{base,\alpha,t0}$	Reduce calorific intake to sufficiency levels
Reduce avoidable food waste	$kcal_{\alpha,t} = kcal_{base,\alpha,t0} * (1 - W_{\beta} * elim_{waste,t})$ $kt_{\alpha} = 1 - kcal_{\alpha,t}/ kcal_{base,\alpha,t0}$	$elim_{waste,t}$**:** elimination of waste food potential
Sustainable agriculture	$kt_{transp} = x_{local}$ $kt_{energy} = x_{seasonal}$ $kt_{ferilizers} = x_{organic}$	Locally: Reduce transport needs of food industries by 50% (x_{local}). Seasonal: Reduce inputs of fuels and electricity to vegetable sector by 30% ($x_{seasonal}$) Organic: Reduce fertilizers, chemicals and medicines as inputs to food products by 100% ($x_{organic}$).
Manufacturing Underlying change: Pop = population		

R-strategies	$kt_{mat} = x_{\alpha,\beta,\gamma}$ $skw_{mat} = y_{\alpha,\beta,\gamma}$	$kp = z_{\alpha,\beta,\gamma} * (IC_{tn} - IC_{t0}) * pop_{tn}/pop_{t0}$	$x_{\alpha,\beta,\gamma}$ = Reduction potential in terms of lifetime extension of R-strategy α (remanufacturing, refurbishment, repair, upgrade, reuse) for product β (machinery, equipment) at demand level γ (intermediate, final) $y_{\alpha,\beta,\gamma}$ = Substitution effect in terms of depth of repair service $z_{\alpha,\beta,\gamma}$ = Market penetration in terms of assumptions, IC and pop IC = degree of implementation in year t pop = population in year t Assumption 1: Fixed sales assumption (remanufacturing and refurbishment): Fixed sales due to the redistribution of the same product (new life cycle). Displacement of new sales modelled as a net reduction in the inputs needed to produce the same volume of product output Assumption 2: Reduced sales assumption (repair, reuse, upgrade): Decrease in sales due to extended lifetime of the product (extended life cycle).Displacement of new sales modelled directly as a reduction in the product output
Fabrication yield improvements	$kt_{mat} = -\frac{\sum_{\beta\in\alpha}(x_{\alpha,i} * z_{i,\beta})}{\sum_{\beta=n} z_{i,\beta}}$ $skw_{mat} = -(\rho p_i/\rho s_i)$	$kp = (IC_{tn} - IC_{t0}) * pop_{tn}/pop_{t0}$	$x_{\alpha,i}$ = Reduction potential of material i for asset category α $z_{i,\beta}$ = Intermediate input of material i to sector β skw = Substitution factor for material i as the ratio of primary to secondary price of material i Note: The technical change coefficient for material i is the average of the reduction potentials x for different asset categories α weighted by the inputs of material i related to sector β relating to asset category α over the total input of material i into sector β Assumption 1: Reduction in the amount of selected materials going to recycling from their primary production and equal reduction to the use of the primary materials across sectors relating to the asset category
Fabrication scrap diversion	$kt_{mat} = x_{\alpha,i}$ $skw_{mat} = -(\rho p_i/\rho s_i)$	$kp = (IC_{tn} - IC_{t0}) * pop_{tn}/pop_{t0}$	$x_{\alpha,i}$ = Reduction potential of material i for asset category α skw = Substitution factor for material i as the ratio of primary to secondary price of material i Assumption 1: Reduction in the

			amount of metals going to recycling from manufacturing industries (scrap) and equal reduction to the use of the primary materials in the same sector relating to the asset category
Services (Lifestyles) Underlying change: Pop = population			
Textile	$kt_{mat} = x_{\alpha}$ $skw_{mat} = y_{\beta}$	$kp = pop_{tn}/pop_{t0}$	x_{α} = reduction potential in final consumption of product/service α y_{β} = Substitution factor for final consumption of product/service β Note: Lifestyle changes are modelled as reductions in the use of certain products/services, offset by an increase in the use of others. When substitution occurs across $n > 1$ product/services, a $1/n$ factor is applied to the kp to distribute the change equally
Media			
Household goods			
Market services			

[1] *Underlying change variables can be expressed either in absolute terms or normalised by population*

[2] *Subscripts define to which dimension the variable depends upon (e.g. no subscripts mean that the variable is a fixed value)* $tx = general\ year,\ t0 = baseline\ year,\ tn = target\ year$

[3] *$GFCF_{res}$: Share of Gross Fixed Capital Formation (GFCF) in residential buildings over total construction. This coefficient combines Net Additions to Stocks from the MISO2 model, average investment costs (€/m^2) and average material intensities (ton/m^2) of buildings and infrastructures to estimate total monetary investment in these two asset types and use this ratio to split GFCF into the fraction related to buildings versus infrastructure. This kp is only for A_CONS to I_GFCF.*

[4] *Kp applies for A_REAL to F_HOUS, F_NPSH, F_GOVE.*

[5] *Refer to the "Mapping" section for more information*

Table 7. *Main variables used to model kts*

Dimension	**Variables**
General	
Climate change scenario (ϵ)	• Baseline (unmitigated) • Representative Concentration Pathway 2.6 (RCP2.6)
Housing	
Building type[1]	• SFH_non-standard • SFH_standard • SFH_efficient • SFH_ZEB • MFH_non-standard • MFH_standard • MFH_efficient • MFH_ZEB • RT_non-standard • RT_standard • RT_efficient • RT_ZEB • informal_non-standard
Design	• Downsized

	• Lightweighted • Downsized and lightweighted
Energy Service	• Heating • Cooling • DHW
Energy carrier	• Coal, hard coal • Diesel • Natural gas • Electricity • Fuel wood
Material type	• Cement • Paper and cardboard • Wood and wood products • Concrete • Construction grade steel • Other
Mobility	
Power drive	• Internal Combustion Engine, gasoline (ICEG) • Internal Combustion Engine, diesel (ICED) • Hybrid Electric Vehicles (HEV) • Plugin Hybrid Electric Vehicles (PHEV) • Battery Electric Vehicles (BEV) • Fuel Cell Vehicles (FCV)
Design	• Microcar • Passenger car • Minivan_SUV • Light truck
Material type	• Automotive steel • Stainless steel • Cast iron • Wrought Al • Copper electric grade • Zinc • Plastics

[1]*SFH = single family house, MFH= multi-family house, RT = residential tower, ZEB = zero energy building*

Mapping

As shown in **Table 6**, the modelling parameters are dependent on a number of variables which typically define how the foreground system's input data from which the parameters are derived is mapped to the background macroeconomic system - Weavebase. Therefore, mapping is the process of coherently linking the parameters in their own format and classification to Weavebase's framework and classification. The linkage happens at both a conceptual and practical level. The conceptual linkage determines to which part of Weavebase's EE-MRIOT system the interventions and thus the parameters are applied to. This can be at the interindustry level (A matrix) for changes related to transactions between sectors, at the final demand level (Y matrix) for changes related to transactions between sectors and households, governments or capital investments or at the environmental extension level (S and G_e matrix) for changes related to environmental intensities of sectors. Once the concept is established, the practical linkage determines the actual correspondence between the input data and Weavebase classifications. Altogether, these elements form the coordinates that allow the coefficients to be applied to specific transactions in specific matrices of Weavebase's EE-MRIOT system. It should be noted that all variables are region-dependent and that the region of origin and destination of a flow is another key coordinate to be specified within a multi-regional system. For simplicity, subscripts related to regions were not included in the formulation. Finally, the time variable is not relevant in the mapping process since the background system is static and thus specified for a single year. **Table 7** summarises the main practical mappings for each system, distinguishing (for illustrative purposes) between three types of k_t as they relate to material/product/service flows, energy flows and asset stocks.

Table 7.

Input data		Weavebase		
Coeff. type	**Object**	**Sector origin**[1]	**Sector substitution**[3]	**Sector destination**[2]
		Housing		
kt_{mat}	Cement and concrete	A_CMNT, A_BRIK, A_ONMM, A_STON, A_SDCL	-	A_CONS
	Steel and iron	A_STEL, A_STEW	-	A_CONS
	Paper	A_PAPE, A_PAPR	-	A_CONS
	Wood	A_WOOD	-	A_CONS
kt_{en}	Diesel	A_REFN	-	F_HOUS, F_NPSH, F_GOVE
	Wood fuel	A_WOOD	-	F_HOUS, F_NPSH, F_GOVE
	Coal	A_COAL, A_COKE	-	F_HOUS, F_NPSH, F_GOVE
	Natural gas	A_REFN	-	F_HOUS, F_NPSH, F_GOVE
	Electricity	A_POWC, A_POWG, A_POWN, A_POWH, A_POWW, A_POWP A_POWB, A_POWS, A_POWE, A_POWO, A_POWM, A_POWZ, A_POWT, A_POWD	-	F_HOUS, F_NPSH, F_GOVE
kt_{stk}	*[4]	A_CONS, A_REAL	-	F_HOUS, F_NPSH, F_GOVE, I_GFCF
		Mobility		
kt_{mat}	Steel and iron	A_STEL, A_STEW	-	A_MOTO
	Aluminum	A_ALUM, A_ALUW	-	A_MOTO
	Copper	A_COPP, A_COPW	-	A_MOTO
	Plastic	A_PLAS, A_RUBP	-	A_MOTO
kt_{en}	Gasoline and diesel	A_REFN, A_TDFU	-	F_HOUS, F_NPSH, F_GOVE

	Electricity	A_POWC, A_POWG, A_POWN, A_POWH, A_POWW, A_POWP A_POWB, A_POWS, A_POWE, A_POWO, A_POWM, A_POWZ, A_POWT, A_POWD	-	F_HOUS, F_NPSH, F_GOVE
kt_{stk}	*[4]	A_MOTO, A_TLND	-	F_HOUS, F_NPSH, F_GOVE, I_GFCF
Nutrition				
kt_{mat} [5]	Wheat, Barley, Maize, Rye, Oats, Millet, Sorghum, Cereals, Rice - (Cereals)	A_PARI, A_WHEA, A_OCER	-	-
	Potatoes, Cassava, Sweet potatoes, Roots, Other Yams - (Roots/Tubers)	A_OTCR	-	-
	Sugar (Raw Equivalent), Honey, Coffee, Cocoa Beans, Tea, Pepper, Pimento, Cloves, Spices, Wine, Beer, Beverages, Eggs, Sweeteners, Infant food, Miscellaneous, Sugar beet, Sugar cane - (Other)	A_SUGR, A_OANP, A_OTCR, A_BEVR, A_PLTR	-	-
	Beans, Peas, Pulses, Other and products (Oilseeds), Soyabeans, Groundnuts, Sunflower seed Coconuts, Sesame seed, Olives, Oilcrops - (Oilseeds and pulses)	A_OILS	-	-
	Nuts, Tomatoes, Onions Vegetables, Oranges, Mandarines, Lemons, Limes, Grapefruit, Citrus, Bananas, Plantains, Apples, Pineapples, Dates, Grapes, (excl wine) Other fruits - (Fruits and vegetables)	A_FVEG	-	-
	[Meat of] Bovine, Mutton & Goat, Pig, Poultry, Other, Offals, Edible, Fats - (Meat)	A_PCAT, A_PPIG, A_PPLT, A_POME	-	-
	Butter, Ghee Cream, Milk - Excluding Butter - (Milk)	A_DAIR	-	-
	[Fish] Freshwater, Demersal, Pelagic, Marine, Other, Crustaceans, Cephalopods, Molluscs, Aquatic Mammals Aquatic Animals, Aquatic Plants, Fish Body Oil, Fish	A_FISH, A_FSHP	-	-

	Liver Oil - (Fish and seafood)			
kt_{mat} [6]	Grains	A_PARI, A_WHEA, A_OCER, A_OILS, A_RICE	-	F_HOUS
	Vegetables, Fruit and Nuts	A_FVEG, A_OTCR	-	F_HOUS
	Meat	A_CATL, A_PIGS, A_PLTR, A_OMEA, A_OANP, A_PCAT, A_PPIG, A_PPLT, A_POME	-	F_HOUS
	Fish	A_FISH, A_FSHP	-	F_HOUS
	Dairy	A_MILK, A_DAIR	-	F_HOUS
	Other	A_SUGB, A_VOIL, A_SUGR, A_OFOD, A_BEVR	-	F_HOUS
Manufacturing				
kt_{mat}	Steel and Iron	A_STEL	A_STEW	Dependent on intervention
	Aluminum	A_ALUM	A_ALUW	
kt_{stk}	Vehicles	A_MOTO, A_OTRE	A_FURN, A_TDMO	
	Machinery	A_ELMA, A_MACH		
	Equipment / Other products	A_FABM, A_OFMA, A_RATV, A_MEIN		
Services (lifestyles)				
kt_{mat}	Textile	A_PLAS, A_RUBP, A_GARM, A_LETH	A_FIBR	Dependent on intervention
	Media	A_MDIA, A_OFMA, A_ELMA, A_RATV	A_ORGA	F_HOUS
	Household goods	A_CHMF, A_PAPE, A_NFER, A_PFER, A_RUBP, A_GLAS, A_CRMC, A_PREM, A_ALUM, A_FABM, A_FURN	A_MARE	F_HOUS
	Market services	A_HORE, A_TRAI, A_TWAS, A_TWAI, A_TAIR, A_TAUX	A_PTEL, A_ORGA, A_RECR	F_HOUS

[1] Sector of origin: Denotes the supplying sector in an IOT (rows)
[2] Sector of destination: Denotes the using sector/actor in an IOT (columns)
[3] Sector of substitution: Denotes the new supplying/using sector to which the whole or part of the original transaction is moving to
[4] Denotes a conceptual link
[5] FAOSTAT food balances - FAOSTAT waste (in brackets) - Exiobase sectors mapping
[6] Nutritional groups - Exiobase sectors mapping

CIRCLE ECONOMY

Annex B: Circular economy frameworks and indicators

This section first reviews two leading frameworks for monitoring circular economy, the UNECE/OECD Guidelines for Measuring Circular Economy and the ISO 59020 standard, and then elaborates the link between each of these with each other and the Circularity Indicator Set (CIS) used in Circularity Gap Reports (CGRs).

Summary of leading frameworks

UNECE/OECD: Guidelines for Measuring Circular Economy - Part A: Conceptual Framework, Indicators and Measurement Framework

To date, the document "*Guidelines for Measuring Circular Economy - Part A: Conceptual Framework, Indicators and Measurement Framework*" prepared jointly by the UNECE and OECD, represents one of the most comprehensive and authoritative publications on the topic of measuring circular economy progress at the national level.

Their *conceptual framework* combines the main features of CE[80,81] with the basic principles of environmental accounting and reporting[82,83,84] resulting in 4 main building blocks along which indicators are structured:

- Responses and actions: Focuses on policy tools and measures to promote circularity (policies, measures, conditions);
- Material life-cycle and value chain: Covers the flow of materials from extraction to disposal (production and consumption);
- Interactions with the environment: Examines the impact of material use on natural resources and environmental quality (environmental effectiveness, natural resource and environmental quality implications);
- Socio-economic opportunities: Addresses market developments, skills, and inclusivity in the transition to CE (economic efficiency and social equity);

The selection of indicators is in line with the criteria recommended under the Bellagio principles[85] of Relevance, Acceptance, Credibility, Ease to monitor and Robustness (RACER). The key components of the publications are the following:

- Provision of a headline definition which highlights the interrelated features of all circular economy definitions: "*The value of materials in the economy is maximised and maintained for as long as possible;*

[80] Potting, J., Hanemaaijer, A., Delahaye, R., Ganzevles, J., Hoekstra, R. & Lijzen, J. (2018): Circular Economy: What We Want to Know And Can Measure. Framework and Baseline Assessment for Monitoring The Progress of the Circular Economy in the Netherlands. The Hague: PBL Netherlands Environmental Assessment Agency. https://circulareconomy.europa.eu/platform/sites/default/files/pbl-2018-circular-economy-what-we-want-to-know-and-can-measure-3216.pdf

[81] 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.

[82] https://seea.un.org/sites/seea.un.org/files/seea_cf_final_en.pdf

[83] UNEP (2021). The use of natural resources in the economy: A Global Manual on Economy Wide Material Flow Accounting.Nairobi, Kenya.

[84] OECD, O. (1993). Core set of indicators for environmental performance reviews. Environmental Monograph, 83.

[85] EEA (European Environment Agency) & ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) (2020): Bellagio Declaration. Circular Economy Monitoring Principles. https://epanet.eea.europa.eu/reports-letters/monitoring-progress-in-europes-circular-economy

the input of materials and their consumption is minimised; and the generation of waste is prevented and negative environmental impacts reduced throughout the life-cycle of materials";

- Introduction of a conceptual framework around four main components, with a clearly defined scope and definitions, covering all dimensions of a CE and the whole lifecycle of materials, products and services beyond just the physical aspects (see Figure 1);
- Establishment of a measurement framework translating the headline definition and the conceptual framework into statistical concepts, terms and definitions that operationalize the quantification;
- Provision of an initial set of indicators embedded in the conceptual and measurement frameworks, structured across 3 tiers (core, complementary and contextual) and evaluated by their relevance and measurability;

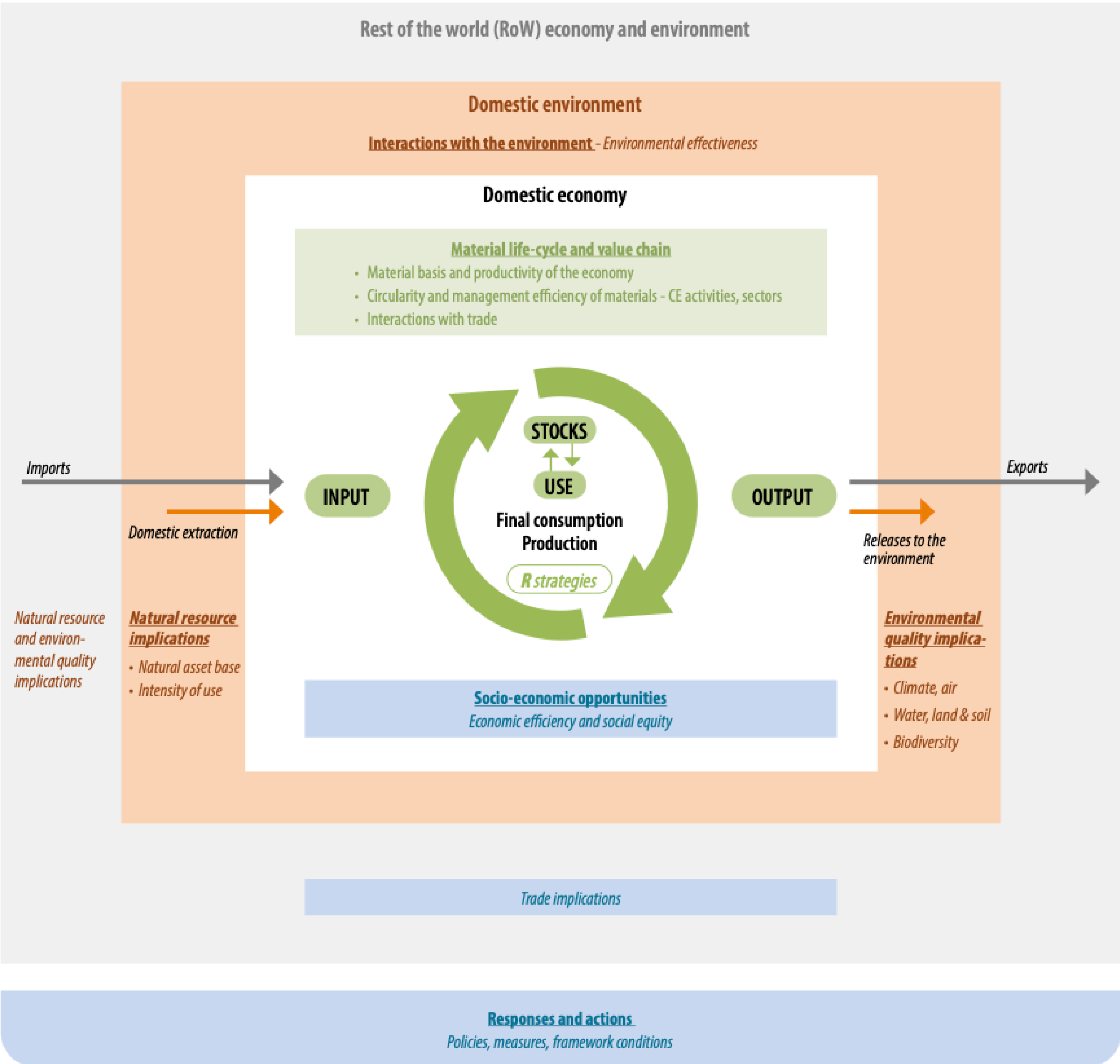

Figure 1. *Overview of the link between the conceptual framework building blocks and themes and the measurement framework*

The OECD/UNECE guidelines start with the definition of a broad conceptual framework covering all the relevant aspects of the CE, within which the measurement framework is embedded (see Figure 1). Most notably, the OECD/UNECE framework explicitly includes the interaction between the domestic economy (the system in focus) with other economies and their environments. In this definition, transboundary implications between socio-economic systems are accounted for, i.e. those related to trade, including their effects on natural assets and environmental quality within and outside the domestic environment. The “policy and responses” building block is presented outside of the environment-economy layers as they provide the framework conditions for the entire system to work. The “socio-economic opportunities” building block is usually measured on the level of the domestic economy and thus is presented within that layer although it also includes trade implications such as supply security of certain materials and goods.

The building block “material life-cycle and value chain”, which is at the heart of measuring a circular economy, is first translated into simple measurement concepts comparable to the ones of the ISO/DIS 59020 framework (inputs as extractions and imports, outputs as releases to the environment, short-term use, long-term stocks and R-strategies equivalent to ISO/DIS 59020’s “actions”). In a second step, the framework is expanded with a focus on the waste management system and its interactions with the production and consumption system as well as other more informal waste-related activities. Such an extended measurement framework - embedded in a broader conceptual frame of reference, rooted in statistical definitions and established primarily at the national/regional level - represents a comprehensive and organised system for the development of economy-wide circular economy indicators.

Based on such an underlying system, the OECD/UNECE guidelines put forward a set of stand-alone indicators organised by building blocks, themes and topics at an increasing level of detail. For instance, the “material life cycle and value chain” building block is divided into three themes. The first theme, “The material basis of the economy - Production, consumption, accumulation” is further divided into three topics, namely material inputs, material consumption and accumulation - each one characterised by a number of indicators. The full set is composed of 16 core (plus 5 placeholders), more than 70 complementary and 13 contextual indicators. Although core and complementary indicators are related to each other - for instance the “National recycling rate” indicator is related to the “Waste going to final disposal”, “circular material use rate” or “Ratio of products repaired or reused to new products sold” indicators, the link between them is underspecified. While they all fit nicely within the same conceptual and measurement framework, they still appear pretty much as stand-alone indicators of interdependent topics. In other words, the OECD/UNECE framework is ***comprehensive*** in that it covers all the important aspects related to the CE, however the lack of common denominators makes the final list of core indicators somewhat disjointed and less suited to act as cohesive set of headline indicators in typical EW-MFA fashion (limited to the “material life cycle and value chain” pillar).

ISO/DIS 59020:2023(E) Circular economy — Measuring and assessing circularity

The recently published “*ISO/DIS 59020:2023(E) Circular economy — Measuring and assessing circularity*” document is the first authoritative standardisation effort in respect to quantitative assessments of the circular economy. It is part of the larger 59000 series, which aims to provide a shared terminology, principles and guidelines for the implementation of the circular economy. It aims to provide organisations with guidance on how to effectively evaluate their circularity practices, ensuring sustainable resource management. While the ISO/DIS 59020 standard is mostly an *operational framework* focused on issues such as boundary setting, data acquisition, quality assurance, documentation and reporting, it also establishes a simple measurement framework and number of core circularity indicators. The scope and relationship of the operational and measurement frameworks are depicted in Figure 2. The salient features of the ISO/DIS 59020 core circularity indicators are:

- Multi-level perspective, including system (regional, organisational, product level), structure (subsystems, sub-regions, functional units, etc.) and actions (reuse, reduce, repair, etc.);
- Indicators set structured along 4 categories: resources (further split into inflows and outflows), energy, water and economic (value);
- Mutually exclusive nature of resource indicators, namely resource inflows/outflow according to four types of content (recycled, reused, virgin renewable and virgin non-renewable) and adding up to 100%;
- Provision to account for the "stock" element through a product lifetime perspective;

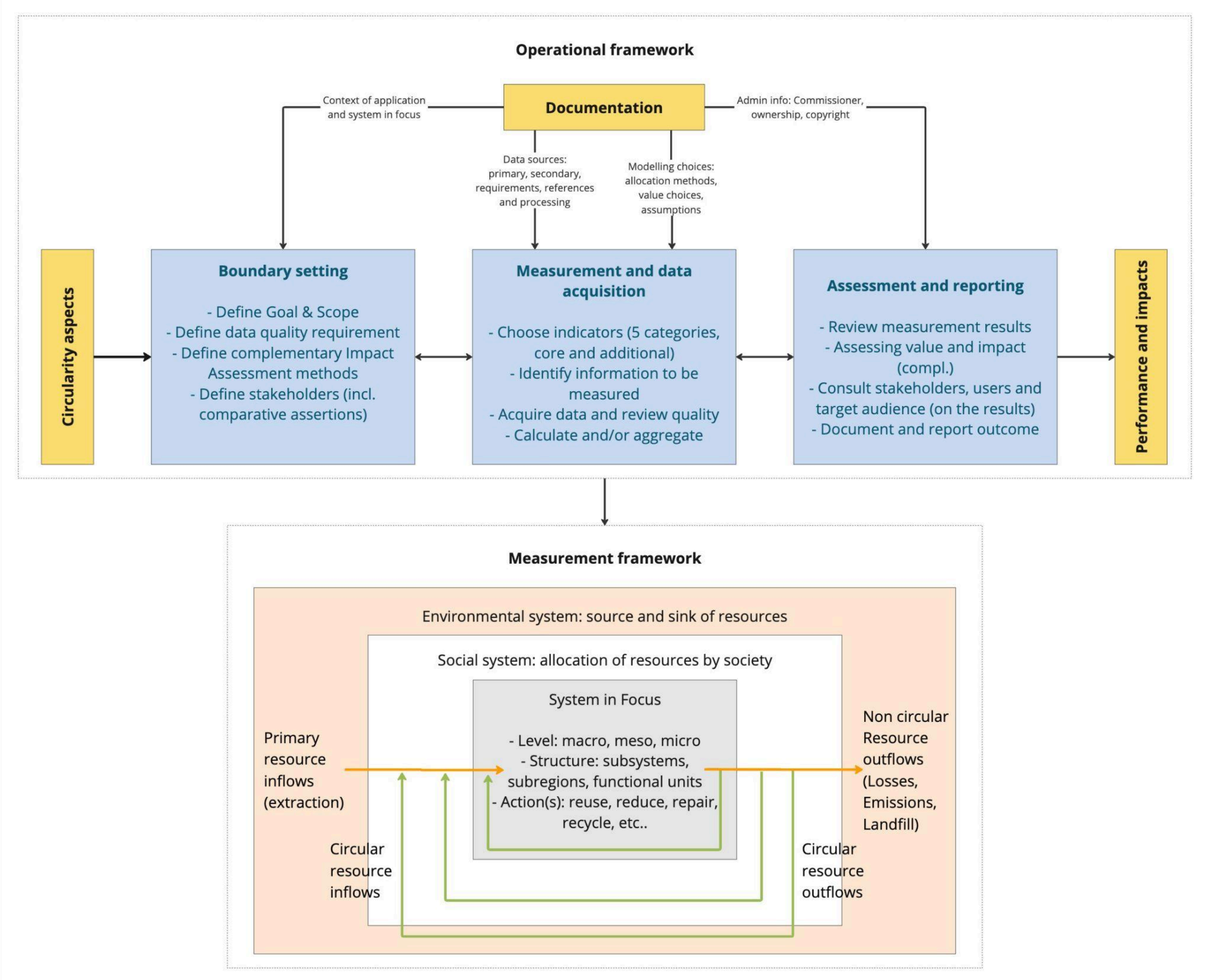

Figure 2. *Overview of the link between ISO/DIS 59020 operational and measurement framework*

The ISO/DIS 59020 measurement framework and indicators set are rather simple. The former emphasises the definition of the system in focus in terms of its level, structure and actions. The focus system is embedded into a social and an environmental one with few general flows describing their interactions: Primary resource inflows as the sourcing of materials from the environment, non circular resource outputs as the release of materials to the environment and different levels of circular inflows and outflows dependant on the system boundary they cross (see Figure 2). Circular flows can be internal to the system in focus (e.g. reprocessing of scrap), re-entering from the social system (e.g. recycling) or re-entering from the environmental system (e.g. composting). Trade flows and interactions with other systems/economies are not specified. This measurement framework supports a set of 14 core indicators, half of which are related to the “resource” category. The simplified nature of this system has the advantage of promoting the ***cohesiveness*** of the indicator set that is built on top, particularly concerning the resource inflows and outflows categories. The boundary of the system in focus is used as the point of measurement and common denominator of the indicators, which break down the resource inflow and outflow into four types of content, namely recycled, reused, virgin renewable and virgin non renewable. These indicators are therefore ***mutually exclusive*** and ***add up to 100%***.

The ISO/DIS 59004 standard *“Circular Economy - Terminology, Principles and Guidance for implementation”* lays out terms and definitions, transitioning principles, general aspects and practical actions to delineate and move towards a circular economy. However, while this is useful for “organisations to understand and contribute to a circular economy and contributing to sustainable development”, it does not systematically and structurally organise thoughts for the indicators proposed in the standard. For instance, the five core indicators categories (resource inflows, resource outflows, energy, water and value) are not directly addressed in the document, which rather focuses on general principles organisations should align with (e.g. system thinking, value creation, value sharing, etc..) and actions (e.g. design for circularity, recycling, repair, etc.) they should strive to implement. Furthermore, while the embedded nature of the economic, social and environmental systems is acknowledged throughout the standard and the selection of complementary methods for impact measurements and assessment recommended, this falls short on presenting a comprehensive, organised and interlinked framework of key measurement themes and topics for the circular economy. Important aspects such as impacts on the environment, effects on employment, security of supply or policy and regulations are mentioned (e.g. in Annex C and D), but not included. For this reason, the ISO 59000 series can arguably represent a conceptual framework for identifying and structuring a comprehensive set of indicators.

Relationship between UNECE and ISO

Figure 3 summarises the relationship between different frameworks and their coverage by the ISO/DIS 59020 standard and UNECE/OECD guidelines.

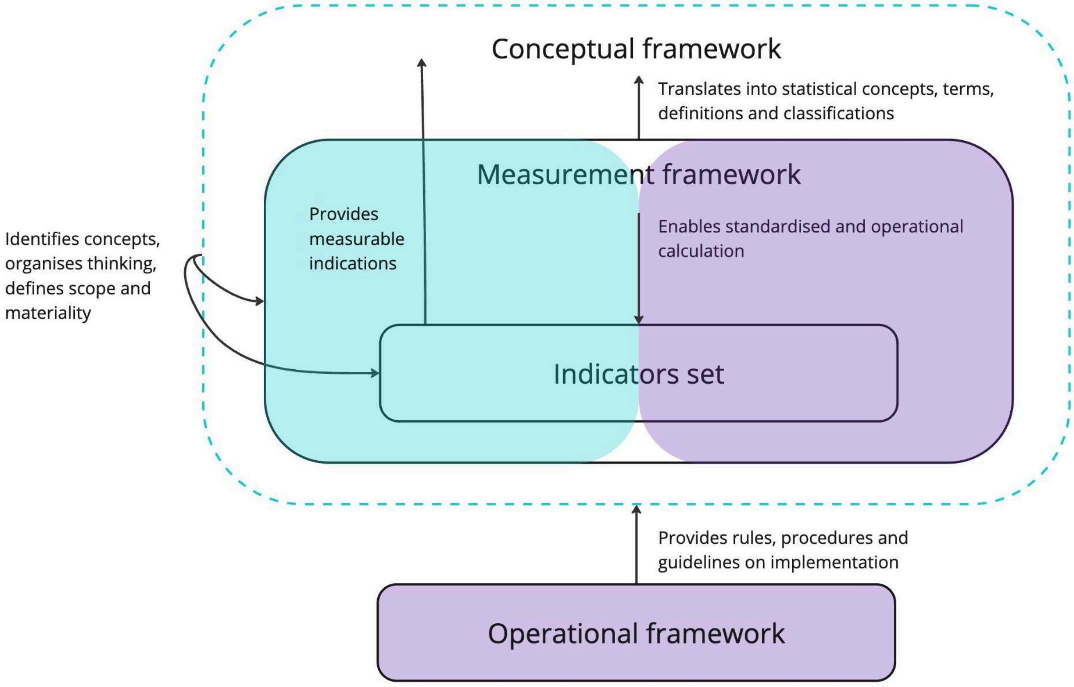

Figure 3. *Relationship between frameworks and coverage by UNECE/OECD guidelines (blue) and ISO/DIS 59020 standard (purple).*

Definitions:

- A *conceptual framework* organises thinking about indicators to identify relevant metrics and to ensure that nothing important gets overlooked. It reflects the integrated and cross-cutting nature of a CE while organising the indicators in a way useful to decision-makers and the public;
- A *measurement and monitoring framework* helps to structure and combine underlying data, link CE concepts and definitions to the terms and definitions used in official statistics, and ensure coherence among data sets. Policymakers benefit from consistent, comparable and comprehensive data and indicators when an integrated accounting approach is used;
- An *operational framework* focuses on the processes underlying the development and deployment of metrics and indicators by providing rules, procedure and guidelines. Practitioners benefit from generalised guidance for the implementation of measurement efforts and standardised results are useful for comparability and replicability.

Circularity Indicator Set and leading frameworks - Alignment and integration

While an *embedded conceptual and measurement framework measured by tiered indicators* like by the OECD/UNECE guidelines brings *structure and comprehensiveness,* the ISO/DIS 59020 approach of *mutually exclusive indicators sharing a common denominator* provides *cohesiveness and ensures a more unified vision of the indicator set.* Integrating these two features would result in an indicators set that is both comprehensive in its coverage of CE-relevant themes and topics and cohesive in its presentation of a unified set of headline measurements. It should be noted that in the ISO/DIS 59020 standard, only the “resource inflows” and “resource outflows” categories follow this approach; whereas the “Energy”, “Water” and “Value” categories are still measured by stand-alone and overlapping indicators. In principle, the formulation of mutually exclusive indicators could be applied to any of those categories although, in practice, some lend themselves better than others to this approach. For instance, energy inputs could easily be divided into a renewable (circular) and non-renewable (non-circular) share on the input side and recorded in energy units to allow for the inclusion of renewables without physical energy inputs such as wind and solar. On the output side, the division could be between emissions from non renewable (i.e. non biogenic) and renewable (i.e. biogenic, under certain conditions) energy carriers. For "Water" and "Value", the definition of circular and non-circular flows is less straightforward and would need to take a number of category-specific issues such as water stress and quality or circular investment taxonomies into account. Some themes such as those related to "interactions with the environment" cover a broad range of impacts-related topics from climate change to resource depletion and, while they can be conceptually linked to resource flows, they can hardly be unified in a mutually exclusive way. In this case, other approaches such as the creation of composite indices by means of weighting can be used for the creation of an aggregated headline indicator. Simplifying indicator results by either relating them average situations (i.e. normalisation[86]) or converging them into a single score (i.e. weighting[87]) is a common yet debated practice in Life-Cycle Impact Assessments (LCIA) and comes with its own pros and cons. For instance, the "consumption footprint"[88] indicator of Eurostat's circular economy monitoring framework is the combination of 16 LCA-based metrics aggregated in a single score using global impacts and planetary boundaries as normalisation/weighting factors. The advantage of providing a single and clear benchmark for the aggregate pressure of several impact categories comes at the cost of more uncertainty and arbitrariness inherent to the aggregation process. Regardless of the approach, alignment of the indicators sets and underlying frameworks is a prerequisite to integration.

Alignment between Circularity Indicator Set and ISO Standard

Table 1 looks at the compatibility between the ISO/DIS 59020:2023(E) standard for measuring and assessing circularity and the CGR methodology by evaluating the coverage and alignment of some key elements.

Table 1. *Summary of the key elements of the ISO/DIS 59020:2023(E) standard and their alignment to the CGR methodology*

Element	Coverage / Alignment	Notes
Measurement dimensions and levels of application	Partial	"*The framework is applicable to multiple levels of an economic system, ranging from regional, inter-organisational, organisational to the product level*". While the ISO standard is focused on the organisational (micro) level, the CGR methodology is focused on the regional, national and supranational (meso and macro) level
3-steps operational framework entailing: *Boundary setting, circularity measurement and data acquisition and circularity assessment and reporting*	Partial	While *Boundary setting* is inherently covered (ensuring appropriate boundaries and meaningful outcome), certain elements of the circularity measurement, data acquisition, assessment and reporting are not. For instance, "*appropriate indicators of value with careful consideration of its retention, recovering or addition to resource value or restoration (e.g. regeneration of ecosystems*" is not covered. Specific goals for data

[86] https://pre-sustainability.com/articles/the-normalisation-step-in-lcia/
[87] https://pre-sustainability.com/articles/weighting-applying-a-value-judgement-to-lca-results/
[88] https://ec.europa.eu/eurostat/cache/metadata/en/cei_gsr010_esmsip2.htm

		quality requirements are not formulated or explicit provision for public disclosure of comparative assertions are not made.
Circular goals, aspects and actions	Partial	*Goals* can be set in scenario modelling in the form of normative targets to explore their broader environmental (and social) implications. *Actions* (e.g. 9R strategies, composting, energy recovery) are included in the CGR scope by the *circular strategies* and reflected in the scenario modelling framework. *Aspects* (e.g. durability, recyclability, repairability) relate to qualitative characteristics of flows which are typically not considered in either baseline nor scenario assessments.
Circular measurement taxonomy	Partial	The *Resource flow measurement* principle defined as "resource inflows and outflows crossing boundaries of the system in focus (including losses and emissions) " is aligned with the EW-MFA economy-environmental boundary definition. *Circular categories and related indicators* are only fully covered for resource inflows and outflow, however energy, water and economic ones are only partially aligned with the standard.
Measuring and assessing sustainability impacts	-	Are not covered by the standard itself, but a reference to other standards is made. The CGR methodology and models allow to quantitatively address elements of the *social, environmental and economic impact & value*, however they are currently not reported (except for carbon footprint)
Resource inflows and outflows	Partial	"Sorting and processing losses" in the recycling process as the difference between inputs and output to the recycling operation are not quantified in CGR methodology. Inputs to the recycling plant are considered a proxy for the output from recycling plants in the current CGR methodology. This doesn't allow for a proper distinction between recyclable (output) and recycled (input) content. For stock additions (lifespan >1 year) indicators of time such as average lifetimes are not covered by the CGR methodology (static approach).

Alignment between Circularity Indicator Set and UNECE Guidelines

Table 2 looks at the compatibility between the OECD/UNECE guidelines for measuring the circular economy and the CGR methodology by evaluating the coverage and alignment of some key elements.

Table 2. *Summary of the key elements of the OECD/UNECE framework and their alignment to the CGR methodology*

Element	Coverage /	Notes

	Alignment	
Aligned with *SNA* and *SEEA* frameworks	Full	*EW-MFAs, AEAs, IOTs* and the other building blocks of the CGR methodology are subsets of the SNA and SEEA framework and therefore highly aligned
Four building blocks based on accounting and Bellagio principles and the pressure-state-response (PSR) model	Partial	Only the *Material life-cycle and value chain* and elements of the *Socio-economic opportunities* component are currently included. The methodology and models allow to quantitatively address elements of the *Interactions with the environment* component, however they are currently not reported (except for climate). The *Responses and actions component* is mostly addressed qualitatively
Material life-cycle and value chain Theme 1 - *Interactions with trade and globalisation*	Full	Indicators on the level and characteristics of materials supply and their use in the economy or in industries, particularly material inputs, consumption and accumulation as well as indicators relating material use to GDP, value-added or other socio-economic output variables through intensity or productivity ratios - are widely covered
Material life-cycle and value chain Theme 2 - *Management efficiency of materials and waste, and the circularity of material flows*	Full	Indicators on waste generation, recycling rates, circular use rates, shares of secondary raw materials in material inputs or consumption; renewable content of material used in production processes, products diverted from the waste stream (repaired, remanufactured, reused), materials leaving the economic cycle, i.e. waste going to final disposal - are widely covered
Material life-cycle and value chain Theme 3 - *Interactions with trade and globalisation*	Full	Indicators on exports and imports of materials, second-hand goods, end-of-life products and waste, the physical trade balance and the material intensity of trade - are widely covered
OECD environmental indicators 3-Tier structure based on relevance, measurability and usefulness	Full	CIS can be organised in a 3-Tier structure where UNECE/OECD's core and complementary indicators (Tier 1 and 2) are both considered complementary (Tier 2) and contextual are the same
Measurement dimensions and levels of application	Partial	The framework needs to be scalable to the interrelated levels the circular economy operates on: Micro (e.g. products and companies), meso (e.g. sectors, industries, cities, sub-national governments) and macro level (i.e. national or supranational economies). While the CGR framework lends well to be applied to the macro and partially to the meso level, it is not particularly suited to the micro level
Expanded versus traditional scope of waste statistics	Partial	The CGR measurement framework covers all the elements of the UNECE proposed extended scope of waste statistics. However, due to their exclusion from

		traditional waste statistics, the coverage is usually quite limited.

Integration of Circularity Indicator Set and the leading frameworks - challenges and rationale

At present, the CGR effort is focused on the integration of the OECD/UNECE guidelines and ISO/DIS 59020 standard measurement frameworks in respect to the "material life cycle and value chain" and "Interactions with the environment" themes of the former and the "resource inputs" and "resource output" categories of the latter. The remaining themes and categories are touched upon, but not addressed; and their systematic integration will be covered in future work together with the implementation of the ISO/DIS 59020 operational framework into the delivery of CGR reports. The main barrier to a full integration of these two work streams lies in some fundamental differences between them in terms of goals, scope and definitions:

- The ISO/DIS 59020 standard, with its product and process-oriented focus, offers a detailed and standardised framework focused on technical precision which is most suitable for organisations aiming for specific circularity assessments. In contrast, the UNECE/OECD Guidelines provide a broader, more flexible framework that covers systemic issues and emphasises monitoring at different governance levels, making it suitable for regional and national-level circular economy initiatives;
- In the UNECE/OECD framework, water resources and energy (beyond energy carriers) are covered to the extent that they are part of an integrated approach to the entire resource cycle and the associated environmental impacts. Differently from the ISO standard, which includes a "water" category, bulk water flows and circular use of water resources are not within scope. This underpins the "accounting" nature of the UNECE/OECD framework which, in line with EW-MFA accounts, excludes water abstractions from natural water bodies due to their high quantities. However, even if bulk water flows are excluded from the EW-MFA measurement, sustainable use of freshwater resources is conceptually part of a circular economy. Similarly, no explicit indicator on energy consumption or share of renewables in the energy mix is included and the energy aspect is considered only in relation to physical energy carriers or environmental impacts;
- In the ISO/DIS 59020 standard the term "resource" is quite broad and encompasses "raw materials", "feedstocks", "material" or "components". Conversely, the UNECE/OECD framework applies more statistical definitions distinguishing, for instance, between "natural resources", primary "raw materials", "secondary raw materials", "residuals", etc. This difference can create confusion when, for instance, inputs from the environment versus inputs from the economy need to be distinguished. Generally speaking, the terminology between the standard and guidelines are vastly aligned but not fully overlapping. While the former is focused on the integration of its glossary with other ISO standards to ensure consistency and interoperability, the latter is focused on coherence with the concepts and classifications of the System of Environmental and Economic Accounts (SEEA) that facilitates the integration of physical and monetary statistics. One of the drawbacks of the accounting structure is that it is designed to measure interactions between the economy and the environment at the macro- and meso-level and thus not very suitable for obtaining information on specific products or production processes such as product lifespans, material compositions or specifications (e.g. secondhand, bio-based);
- [...]

Despite these differences, the CIS lends itself well to integration with the ISO/DIS 59020 standard and the UNECE/OECD guidelines in the form of *compliance* and *superimposition*, respectively. The CIS applies the same "mutually exclusive" logic of the ISO's resource inflows and outflows indicators to the national level (corresponding to the UNECE/OECD's "material life-cycle and value chain" building block), thereby creating a *cohesive set of input- and output-side EW-MFA-based headline indicators.* Because one of the main objectives of the ISO 59020 standard is to ensure consistency and facilitate benchmarking and comparisons across different levels of application, it provides precise definitions and standardised methodologies for calculating each indicator. In order to fully *comply* with the standard, a number of specifications and modifications to the CIS are introduced:

- *Differentiation between recycled/reused and recyclable/reusable technical materials:* The ISO/DIS 59020 standard requires recycling and reuse to be measured at both the input and the output side. The former represents the fraction of input resources that is confirmed as recycled content, including pre-consumer and post-consumer materials, but excluding reutilisation within an industrial process. Reuse is intended strictly as remanufacturing since all aspects associated with the durability of the product including reliability, maintenance, update, upgrade, repair, reuse and refurbishment do not qualify as reused content. The latter, instead, is a calculation of the average fraction of content from the resource outflow that was (or realistically will be) recovered and recycled into secondary material for use as a resource inflow to the same or another system in focus or, alternatively, for reuse in the production, maintenance or repair of other products. From an economy-wide perspective, the distinction between recycled content of the inflow and recycled content derived from the outflow (i.e. recyclable content) translates into the ability to distinguish between waste collected for recycling and secondary materials[89]. While waste collected for recycling is measured at the recycling plant gate, secondary materials are measured at their point of deployment into the market. Therefore, any sorting and processing losses in recycling operations will determine a difference between waste collected for recycling (recyclable) and waste recycled (secondary material). Under this distinction, Eurostat's assumption that "the input to recovery plants is an acceptable proxy for the output from recovery plants"[90] cannot anymore be adopted and sorting and processing losses in recovery operations needs to be quantified. The distinction between reused and reusable content is more difficult to cover as statistics on this topic are still lacking and no methodology has been developed yet;
- *Definition and quantification of "sustainably produced renewable content" and "recirculation - safe return to the biosphere":* The ISO/DIS 59020 standard provides a general definition of this, stating that "Renewable material is biomass that is replenishable at a rate equal to or greater than the rate of depletion and [...] a bio-based inflow is only considered circular if it is regenerative, at a minimum sustainably grown or managed". On the output side, the "percent actual recirculation of outflow in the biological cycle" indicator represents the fraction of outflow content (e.g. biomass or nutrients) that is recirculated at end of life for safe return to the biosphere (biodegradation), and meets the qualifying conditions for recirculation (e.g. composting or anaerobic digestion). These definitions and the concepts behind them are in line with those related to the input and output ecological cycling potential rate (see "The renewable biomass issue" section in Annex A). Therefore, while more feasible methodologies for the systematic estimation of the sustainability of biomass-related substance and nutrient flows and cycles becomes available, the economy-wide carbon cycle approach by Haas et al. (2020) can be considered an initial proxy for the estimation of renewable biomass inputs and safe recirculation of outflows related to the biological cycle;

[89] "Requires a common definition of "recyclable" materials. "Recyclability" is challenging to define. Technical and economic factors play a role" (UNECE/OCED commentary for the "Proportion of recyclable raw materials in DMC" indicator)

[90] https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/ks-gq-18-013

- *Alignment with the lifetime perspective on long-term products and materials (stock additions)*: The issue of the relationship between physical stocks, lifetime extension, durability and value retention is a known and complex issue to measure in the circular economy context. In EW-MFA fashion, the CIS only measures stock additions in relation to their mass and uses a static mass balance approach that doesn't take technical lifetimes into account. The resulting stocking rate (%) is considered as one of the mutually exclusive indicators that make up the inflow. In this context, the effect of CE strategies like extending product lifetimes, renovation or sharing could be observed indirectly as an increase of the service lifetime of in-use stocks and potentially a stabilisation of in-use stock growth, as indicated by the NAS. The ISO/DIS 59020 standard, on the other hand, "measures the (useful) expected lifetime of a product or material as represented by its durability and determined using a technical assessment method that takes into consideration the reliability of the product or material and lifetime extensions from performing maintenance, repair, updates, upgrades, and refurbishment". This underpins a fundamental difference between the "mutually exclusive" logics of the CIS and the ISO/DIS 59020 standard. While the former designates inflows (and outflows) shares based on their destination, the latter does so based on the idea of content. "Stocked" is not considered a type of flow content as "virgin non-renewable" or "recycled" are, and thus is measured under a different concept. In the CIS, "stocking" is considered a flow destination in the same way as "technical cycling" or "non-circular use" are. In this particular case, compliance with the ISO/DIS 59020 standard requires the adoption of a new indicator - the "average lifetime of stock relative to global average" - next to the standard "stocking rate". This can be considered as a sub-indicator e and used to provide a more nuanced and comprehensive measure of the material accumulation theme under the same concept applied with the UNECE/OECD core indicators, as exampled below ;

Following this logic, the UNECE/OECD's "material life-cycle and value chain" building block and all of its underlying topics can be measured by the CIS - *a set of mutually exclusive input- and output-side EW-MFA-based headline indicators compliant with the ISO/DIS 59020 standard (limited to the resource inflows and outflows categories).* However, while some CIS indicators provide a direct measure of a particular topic (for instance ITCr and OTCr provide a direct measure of topics "2.2 Circularity of material flows" and "2.4 Materials diverted from final disposal through recycling or recovery", respectively), others do so in a less direct and clear way. As an example, while INRr and ONRr do account for the amount of potentially recyclable materials that are instead disposed, they can be used to measure topic "2.5 Materials leaving the economic cycle"; however they are not suited to capture topic "2.4 Waste generation (materials ending up as waste)". Moreover, many of the UNECE/OECD indicators such as "total waste generation" or "material consumption and productivity" include variations looking at intensities (normalised indicators), trends and mixes (material composition breakdowns) that provide considerable additional information compared to a more one-dimensional indicator set. Some of these core and complementary indicators are not directly exposed by the CIS headlines indicators, but they are a prerequisite for their calculation. For instance, the calculation of the ITCs requires data on "Demand-based raw material consumption (RMC)", "National recycling rates" for both MSW and special waste and "Trade in waste, secondary materials, secondary raw materials, second-hand goods". The IECPr requires data on "Proportion of materials from renewable natural stocks in DMC" and "emissions and removals from land use, land use change and forestry".

Therefore, on the one hand, some UNECE/OECD's core indicators are underlying the CIS ones as they represent a prerequisite for their calculation. On the other, their broader and more faceted coverage provides more operationality, context and nuance to the measurement. This two-fold situation offers an ideal opportunity to *superimpose* the CIS headline to the UNECE/OECD core and complementary indicators. In this configuration, the CIS would sit on top of the UNECE/OECD one providing the higher-level cohesive set of headline indicators. Leveraging their underlying and/or complementary nature, UNECE/OECD ones would then act as sub-indicators to support, enrich and expand the headline measurement.

Table 3 summarises the integration between the CIS and the leading frameworks for CE measuring and monitoring, highlighting its relationships with key elements of the UNECE/OECD guidelines (themes, topics, tiered indicators) and the ISO/DIS 59020 standard (category, content, principle).

Table 3. CIS framework and its relationship with key elements of the UNECE/OECD guidelines (theme, topics, tiered indicators) and the ISO/DIS 59020 standard (category, content, principle)

<table>
<tr><td rowspan="4">UNECE/OECD</td><td>Themes</td><td colspan="11">1) Material life cycle, value chain –> production and consumption
2) interactions with the environment –> environmental effectiveness</td></tr>
<tr><td rowspan="3">Topics</td><td colspan="6">1.1) Material basis of the economy - Production, consumption and accumulation
1.3) Interactions with trade</td><td colspan="5"></td></tr>
<tr><td colspan="6">1.2) Circularity of material flows</td><td colspan="5">1.2) management efficiency of materials & waste</td></tr>
<tr><td colspan="6">2.1) Natural resource implications</td><td colspan="5">2.2) Environmental quality implications</td></tr>
<tr><td rowspan="3">ISO</td><td>Category</td><td colspan="5">Resource Inflows (I)</td><td>Accumulation</td><td colspan="5">Resource Outflows (O)</td></tr>
<tr><td>Content</td><td>Recycled & Reused</td><td>Virgin Renewable</td><td colspan="3">Virgin Non-renewable**</td><td>Accumulation</td><td>Recycling & Reuse</td><td>Recirculation</td><td colspan="3">Non-Recovered**</td></tr>
<tr><td>Principle</td><td colspan="6">∑ = 100%</td><td colspan="5">∑ = 100%</td></tr>
<tr><td rowspan="2">CE</td><td>Headlines</td><td colspan="2">Circularity</td><td colspan="3">Circularity Gap (Linearity)</td><td>Circularity Lag</td><td colspan="2">Circularity</td><td colspan="3">Circularity Gap (Linearity)</td></tr>
<tr><td>Tier 1</td><td>(I)TCr</td><td>(I)ECPr</td><td>(I)NRBr</td><td>(I)NCr</td><td>(I)NRr</td><td>NSr</td><td>(O)TCr</td><td>(O)ECPr</td><td>(O)NRBr</td><td>(O)NCr</td><td>(O)NRr</td></tr>
<tr><td>UNECE/OECD</td><td>Examples of Tier 2 [91,92,93]</td><td>- DMC/I (ton)
- Physical NTB
- RMC/I (ton)
- RME NTB (ton)
- SMC/I (ton)
- Secondary materials NTB (ton)
- CMUR</td><td colspan="2">- DMC biomass
- RMC biomass
- Reclamation rate of organic substances
- Afforestation rate
- Land protection rate
- Water stress level
- Ecological overshoot</td><td>- Electricity in total energy mix
- Renewable energy in total final energy consumption
- Energy intensity (MJ/€)
-Energy efficiency (MJ/-)
- Fossil subsidies (-)</td><td>- Material self-sufficiency
- Material import dependency</td><td>- Urbanisation rate
- Average lifetimes of products (?)</td><td>- National recycling rate
- Waste collection rate</td><td colspan="2">- LULUCF emissions cba (ton)
- Safely treated domestic wastewater flows</td><td>- GHG emissions pba, cba, territorial (ton)</td><td>- Total waste generation (ton)
- National controlled/ uncontrolled disposal rate
- DPO (ton)</td></tr>
</table>

[91] Units are in % unless otherwise specified
[92] Includes only indicators that can be quantified. Where possible and applicable - trends, mix and intensities - are included as per OECD/UNECE's guidelines recommendations
[93] Indicators marked in **bold** correspond to the OECD/UNECE **core indicators** (or proxies thereof)

	Tier 3[94]	- Changes in natural stocks of mineral resources - % of population with access to waste management services: basic waste collection; separate collection - Sectoral drivers (e.g. floor space per capita, passenger kilometres) - Population growth and households size - GDP growth and structure (trends, value added by sector, per capita) - Income inequality (Gini index) - Human development index (HDI) - Final consumption expenditure: government, household, capital

*Blue: Technical Cycle, Green: Biological cycle

** Includes both potentially circular and inherently non-circular materials that are non-renewable and non-recoverable

[94] Correspond to contextual indicators

Annex C: Supporting information for the Circular Jobs Analysis

Table 1: Overview of sectors of [fully] circular economy activity, identified in ISIC

Sectors of circular economy activities	ISIC (1-4 digit)	R strategies	Rationale for inclusion	Known issues / challenges	Corresponds with CEA
Renting and leasing of motor vehicles; personal and household goods; other machinery, equipment and tangible goods (N)	771 772 773	Rethink Reduce	Shared access, and the shift from product to service can reduce production needs. Can create incentives for extended product lifespans.	Rebound effects[95] (e.g. increased affordability of new, luxury goods). Circularity depends on product longevity, usage patterns and business models.	No
Library and archives activities (R)	9101		Shared access improves product utilization. Reduces demand for new goods.	Need to be accessible to avoid idle time. Digital alternatives may be more resource efficient.	No
Urban and suburban passenger land transport (H)	4921	Rethink Reduce	Shared access, and the shift from product to service can reduce production needs. Reduces demand for new extraction and private car usage.	Extent of circular strategies like repair, remanufacturing and recycling within public transport are not captured. Public transport in many countries still largely relies on fossil fuels.	No
Retail sale of second-hand goods (G)	4774	Reuse	Extends product lifespans. Reduces demand for new goods.	Rebound effects (e.g. increased affordability of new, luxury goods that retain resale value). Circularity depends on product longevity and usage patterns.	No
Repair of fabricated metal products, machinery and equipment	331	Repair Refurbish	Extends product lifespans. Reduces the need for new production.	Often requires new manufactured parts rather than refurbished / reused equipment. Some specialized repairs may be	No

[95] "Circular economy rebound occurs when circular economy activities, which have lower per-unit-production impacts, also cause increased levels of production, reducing their benefit." (Zlnk and Geyer, 2017).

(C)				energy and resource intensive.	
Maintenance and repair of motor vehicles (G)	452				No
Repair of computers and personal household goods (S)	95				No
Washing and (dry-) cleaning of textile and fur products (S)	9601		Extends the lifetime of products. Can also carry out repairs and alterations.	It sometimes requires intensive use of chemicals, water and energy.	No
Sewerage (E)	37	Recycle Recover	Wastewater treatment enables recycling and reuse, and the recovery of nutrients.	Wastewater is not always treated. Treated water is often discharged instead of recycled.	Yes
Waste collection (E)	381		Extracts valuable materials from waste streams. Enables recycling and materials recovery.	Waste collection does not ensure recycling. Downcycling limits full recovery potential. Losses during recovery, sorting and processing.	Yes
Materials recovery (E)	383				Yes
Remediation activities and other waste management services (E)	39				Yes
Wholesale of waste and scrap and other products n.e.c. (G)	4669		Extracts value from waste streams. Reduces demand for new extraction.	Should exclude wholesale of industrial chemicals ('other products n.e.c.').	No

Table 2: Overview of sectors of partially-circular economy activity, identified in ISIC

Sector of partially circular economy activities	Sectors of circular economy activities	ISIC 4-digit	Approach to determining circularity

Agriculture	Growing of cereals (except rice), leguminous crops, and oil seeds	0111	Agriculture secondary model
	Growing of rice	0112	Agriculture secondary model
	Growing of vegetables and melons, roots and tubers	0113	Agriculture secondary model
	Growing of sugar cane	0114	Agriculture secondary model
	Growing of tobacco	0115	Agriculture secondary model
	Growing of fibre crops	0116	Agriculture secondary model
	Growing of other non-perennial crops	0119	Agriculture secondary model
	Growing of grapes	0121	Agriculture secondary model
	Growing of tropical and subtropical fruits	0122	Agriculture secondary model
	Growing of citrus fruits	0123	Agriculture secondary model
	Growing of pome fruits and stone fruits	0124	Agriculture secondary model
	Growing of other tree and bush fruits and nuts	0125	Agriculture secondary model
	Growing of oleaginous fruits	0126	Agriculture secondary model
	Growing of beverage crops	0127	Agriculture secondary model
	Growing of spices, aromatic, drug and pharmaceutical crops	0128	Agriculture secondary model
	Growing of other perennial crops	0129	Agriculture secondary model
	Support activities for crop production	0161	Agriculture secondary model
Mining and quarrying	Quarrying of stone, sand and clay	0810	Economic circularity
	Support activities for other mining and quarrying	0990	Economic circularity
Manufacturing	Processing and preserving of meat	1010	Average of economic circularity and material circularity
	Processing and preserving of fish, crustaceans and molluscs	1020	Average of economic circularity and material circularity
	Processing and preserving of fruit and vegetables	1030	Average of economic circularity and material circularity
	Manufacture of vegetable and animal oils and	1040	Average of economic circularity and

	fats		material circularity
	Manufacture of dairy products	1050	Average of economic circularity and material circularity
	Manufacture of grain mill products	1061	Average of economic circularity and material circularity
	Manufacture of starches and starch products	1062	Average of economic circularity and material circularity
	Manufacture of bakery products	1071	Average of economic circularity and material circularity
	Manufacture of sugar	1072	Average of economic circularity and material circularity
	Manufacture of cocoa, chocolate and sugar confectionery	1073	Average of economic circularity and material circularity
	Manufacture of macaroni, noodles, couscous and similar farinaceous products	1074	Average of economic circularity and material circularity
	Manufacture of prepared meals and dishes	1075	Average of economic circularity and material circularity
	Manufacture of other food products n.e.c.	1079	Average of economic circularity and material circularity
	Manufacture of prepared animal feeds	1080	Average of economic circularity and material circularity
	Distilling, rectifying and blending of spirits	1101	Average of economic circularity and material circularity
	Manufacture of wines	1102	Average of economic circularity and material circularity
	Manufacture of malt liquors and malt	1103	Average of economic circularity and material circularity
	Manufacture of soft drinks; production of mineral waters and other bottled waters	1104	Average of economic circularity and material circularity
	Manufacture of tobacco products	1200	Average of economic circularity and material circularity
	Preparation and spinning of textile fibres	1311	Average of economic circularity and material circularity
	Weaving of textiles	1312	Average of economic circularity and material circularity
	Finishing of textiles	1313	Average of economic circularity and material circularity
	Manufacture of other textiles	1391	Average of economic circularity and material circularity

	Manufacture of knitted and crocheted fabrics	1392	Average of economic circularity and material circularity
	Manufacture of made-up textile articles, except apparel	1393	Average of economic circularity and material circularity
	Manufacture of carpets and rugs	1394	Average of economic circularity and material circularity
	Manufacture of cordage, rope, twine and netting	1399	Average of economic circularity and material circularity
	Manufacture of wearing apparel, except fur apparel	1410	Average of economic circularity and material circularity
	Manufacture of articles of fur	1420	Average of economic circularity and material circularity
	Manufacture of knitted and crocheted apparel	1430	Average of economic circularity and material circularity
	Tanning and dressing of leather; manufacture of luggage, handbags, saddlery and harness	1511	Average of economic circularity and material circularity
	Manufacture of footwear	1520	Average of economic circularity and material circularity
	Sawmilling and planing of wood	1610	Average of economic circularity and material circularity
	Manufacture of veneer sheets; manufacture of plywood, laminboard, particle board and other panels	1621	Average of economic circularity and material circularity
	Manufacture of builders' carpentry and joinery	1622	Average of economic circularity and material circularity
	Manufacture of wooden containers	1623	Average of economic circularity and material circularity
	Manufacture of other products of wood; manufacture of articles of cork, straw and plaiting materials	1629	Average of economic circularity and material circularity
	Manufacture of pulp, paper and paperboard	1701	Average of economic circularity and material circularity
	Manufacture of corrugated paper and paperboard and of containers of paper and paperboard	1702	Average of economic circularity and material circularity
	Manufacture of other articles of paper and paperboard	1709	Average of economic circularity and material circularity
	Printing	1811	Average of economic circularity and material circularity

	Service activities related to printing	1812	Average of economic circularity and material circularity
	Reproduction of recorded media	1820	Average of economic circularity and material circularity
	Manufacture of coke oven products	1910	Average of economic circularity and material circularity
	Manufacture of refined petroleum products	1920	Average of economic circularity and material circularity
	Manufacture of basic chemicals	2011	Average of economic circularity and material circularity
	Manufacture of fertilizers and nitrogen compounds	2012	Average of economic circularity and material circularity
	Manufacture of plastics and synthetic rubber in primary forms	2013	Average of economic circularity and material circularity
	Manufacture of pesticides and other agrochemical products	2021	Average of economic circularity and material circularity
	Manufacture of paints, varnishes and similar coatings, printing ink and mastics	2022	Average of economic circularity and material circularity
	Manufacture of soap and detergents, cleaning and polishing preparations, perfumes and toilet preparations	2023	Average of economic circularity and material circularity
	Manufacture of other chemical products n.e.c.	2029	Average of economic circularity and material circularity
	Manufacture of man-made fibres	2030	Average of economic circularity and material circularity
	Manufacture of pharmaceuticals, medicinal chemical and botanical products	2100	Average of economic circularity and material circularity
	Manufacture of rubber products	2211	Average of economic circularity and material circularity
	Manufacture of plastics products	2220	Average of economic circularity and material circularity
	Manufacture of glass and glass products	2310	Average of economic circularity and material circularity
	Manufacture of refractory products	2391	Average of economic circularity and material circularity
	Manufacture of clay building materials	2392	Average of economic circularity and material circularity
	Manufacture of other porcelain and ceramic products	2393	Average of economic circularity and material circularity

	Manufacture of cement, lime and plaster	2394	Average of economic circularity and material circularity
	Manufacture of articles of concrete, cement and plaster	2395	Average of economic circularity and material circularity
	Cutting, shaping and finishing of stone	2396	Average of economic circularity and material circularity
	Manufacture of other non-metallic mineral products n.e.c.	2399	Average of economic circularity and material circularity
	Manufacture of basic iron and steel	2410	Average of economic circularity and material circularity
	Manufacture of basic precious and other non-ferrous metals	2420	Average of economic circularity and material circularity
	Casting of metals	2431	Average of economic circularity and material circularity
	Manufacture of structural metal products	2511	Average of economic circularity and material circularity
	Manufacture of tanks, reservoirs and containers of metal	2512	Average of economic circularity and material circularity
	Manufacture of steam generators, except central heating hot water boilers	2513	Average of economic circularity and material circularity
	Manufacture of weapons and ammunition	2520	Average of economic circularity and material circularity
	Manufacture of fabricated metal products, except machinery and equipment n.e.c.	2591	Average of economic circularity and material circularity
	Manufacture of cutlery, hand tools and general hardware	2592	Average of economic circularity and material circularity
	Manufacture of other fabricated metal products n.e.c.	2599	Average of economic circularity and material circularity
	Manufacture of electronic components and boards	2610	Average of economic circularity and material circularity
	Manufacture of computers and peripheral equipment	2620	Average of economic circularity and material circularity
	Manufacture of communication equipment	2630	Average of economic circularity and material circularity
	Manufacture of consumer electronics	2640	Average of economic circularity and material circularity
	Manufacture of measuring, testing, navigating and control equipment	2651	Average of economic circularity and material circularity
	Manufacture of watches and clocks	2652	Average of economic circularity and

			material circularity
	Manufacture of irradiation, electromedical and electrotherapeutic equipment	2660	Average of economic circularity and material circularity
	Manufacture of optical instruments and photographic equipment	2670	Average of economic circularity and material circularity
	Manufacture of magnetic and optical media	2680	Average of economic circularity and material circularity
	Manufacture of electric motors, generators, transformers and electricity distribution apparatus	2710	Average of economic circularity and material circularity
	Manufacture of batteries and accumulators	2720	Average of economic circularity and material circularity
	Manufacture of wiring and wiring devices	2731	Average of economic circularity and material circularity
	Manufacture of electric lighting equipment	2740	Average of economic circularity and material circularity
	Manufacture of domestic appliances	2750	Average of economic circularity and material circularity
	Manufacture of other electrical equipment	2790	Average of economic circularity and material circularity
	Manufacture of general-purpose machinery	2811	Average of economic circularity and material circularity
	Manufacture of pumps, compressors, taps and valves	2813	Average of economic circularity and material circularity
	Manufacture of lifting and handling equipment	2816	Average of economic circularity and material circularity
	Manufacture of other general-purpose machinery	2819	Average of economic circularity and material circularity
	Manufacture of special-purpose machinery	2821	Average of economic circularity and material circularity
	Manufacture of metal-forming machinery and machine tools	2822	Average of economic circularity and material circularity
	Manufacture of machinery for metallurgy	2823	Average of economic circularity and material circularity
	Manufacture of machinery for mining, quarrying and construction	2824	Average of economic circularity and material circularity
	Manufacture of other special-purpose machinery	2829	Average of economic circularity and material circularity
	Manufacture of motor vehicles	2910	Average of economic circularity and

			material circularity
	Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers and semi-trailers	2920	Average of economic circularity and material circularity
	Manufacture of parts and accessories for motor vehicles	2930	Average of economic circularity and material circularity
	Building of ships and boats	3010	Average of economic circularity and material circularity
	Manufacture of railway locomotives and rolling stock	3020	Average of economic circularity and material circularity
	Manufacture of air and spacecraft and related machinery	3030	Average of economic circularity and material circularity
	Manufacture of military fighting vehicles	3040	Average of economic circularity and material circularity
	Manufacture of transport equipment n.e.c.	3090	Average of economic circularity and material circularity
	Manufacture of furniture	3100	Average of economic circularity and material circularity
	Manufacture of jewelry and related articles	3211	Average of economic circularity and material circularity
	Manufacture of musical instruments	3212	Average of economic circularity and material circularity
	Manufacture of sports goods	3230	Average of economic circularity and material circularity
	Manufacture of games and toys	3240	Average of economic circularity and material circularity
	Manufacture of medical and dental instruments and supplies	3250	Average of economic circularity and material circularity
	Manufacture of brooms and brushes	3290	Average of economic circularity and material circularity
	Repair of fabricated metal products, machinery and equipment	3311	Average of economic circularity and material circularity
	Installation of industrial machinery and equipment	3320	Average of economic circularity and material circularity
Construction	Construction of buildings	4100	Average of economic circularity and material circularity
	Construction of roads and railways	4210	Average of economic circularity and material circularity
	Construction of utility projects	4220	Average of economic circularity and material circularity

	Construction of other civil engineering projects	4290	Average of economic circularity and material circularity
	Demolition	4311	Average of economic circularity and material circularity
	Site preparation	4312	Average of economic circularity and material circularity
	Electrical installation	4321	Average of economic circularity and material circularity
	Plumbing, heat and air-conditioning installation	4322	Average of economic circularity and material circularity
	Other construction installation	4329	Average of economic circularity and material circularity
	Building completion and finishing	4330	Average of economic circularity and material circularity
	Other specialized construction activities	4390	Average of economic circularity and material circularity