CIRCLE ECONOMY

The CIRCULARITY GAP REPORT **SCOTLAND**

Methodology document

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Glossary

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

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

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). [Source]

Global Warming Potential (GWP) is a term that refers to 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]

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

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

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

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

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

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

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

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]

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

Sector describes 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 here—aligned with classifications as used in Exiobase V3. These relate closely to the European sector classification framework NACE Rev. 2.

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).

Acronym Cheatsheet

CM: Circularity metric
CMUr: Circular material use rate
CSC: Closing supply chains
DMC: Domestic material consumption
DPO: Domestically processed output
DPOe: DPO emissions
EE-IOA: Environmentally-extended input-output analysis
EE-MR MIOT: Environmentally-extended multi-regional monetary input-output tables
EE-MRIOD: Environmentally-extended multi-regional input-output database
EW-MFA: Economy-wide material flow analysis
GAS: Gross additions to in-use stocks of materials

HSUTs: Hybrid supply and use tables
IE: Industrial ecology
IECrp: Input ecological cycling rate potential
IF: Indicator framework
INCr: Input non-circularity rate
INRr: Input non-renewable material rate
IO-ScenAn: Input/Output-based scenario analysis
IOT: Input output table
ISCr: Input socioeconomic cycling rate
ITGS: International trade in goods statistics
LC-MFA: Life-cycle material flow accounting
LCA: Life cycle assessment
LULCC: Land use and land cover change
MFA: Material flow analysis
MFAc: Material flow accounting
NAS: Net additions to stock
NEA: Net extraction abroad
NSI: National statistical institutes
NSr: Net Stocking rate
OECrp: Output ecological cycling rate potential
ONRr: Output non-renewable material rate
PLE: Product lifetime extension
PM: Processed material
PRM: Processed raw material
PSUTs: Physical supply and use tables
RE: Resource efficiency
RMC: Raw material consumption
RME: Raw material equivalents
RWM: Residual waste management
SD: Sankey diagram
SEEA: System of environmental-economic accounting
SEM: Socioeconomic metabolism
SNA: System of national accounts
SNAC: Single-nation account consistent
SUT: Supply and use table
ScenAn: Scenario analysis

CIRCLE ECONOMY

Executive Summary

This methodology document provides the technical details behind the Circularity Gap Assessment—Circle Economy's (CE) analysis of the circular state of regional, national and global economies. The analytical approach is grounded in the field and methods of industrial ecology (IE) which is defined by some as the 'circular economy toolbox. Key IE tools and widely used investigation methods at CE include material flow accounting and analysis (MFA), life cycle assessment (LCA) and environmentally-extended input-output analysis (EE-IOA). A theoretical cornerstone of IE is the concept of **socioeconomic metabolism (SEM)**, the '*evolution of the biophysical structures of human society, including those biophysical transformation processes, distribution processes and flows, which are controlled by humans for their purposes and that forms the biophysical basis of society.'* [1,2] In practice, SEM analysis and thus also the Circularity Gap Assessment are operationalised in the **system of environmental-economic accounting (SEEA)**, a *'general framework that integrates economic and environmental data to provide a more comprehensive and multipurpose view of the interrelationships between the economy and the environment and the stocks and changes in stocks of environmental assets, as they bring benefits to humanity'.*[3]

SEM analysis is critical to understanding the current state of circularity across the key industrial value chains of an economy. It provides a systematic approach to the definition of systems and their boundaries and enables us to pinpoint linear hotspots by tracing flows and stocks of materials and assessing their impacts. The aim of this 'diagnosis' is to measure and monitor circularity in an economy's industrial transition to a circular economy, uncover the main opportunities for circularity in key industrial value chains and set the groundwork for the development of circular economy roadmaps and strategies.

CE's SEM approach is developed around four key analytical elements which also constitute the main deliverables of traditional *Circularity Gap Reports* (CGRs), namely:

1. Material flow accounting (MFAc)
2. Circularity Metric (CM) and indicator framework (CM-IF)
3. Input/Output-based scenario analysis (IO-ScenAn)
4. Sankey diagram (SD)

Figure one shows the link between these four deliverables.

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[1] Pauliuk, S., Majeau-Bettez, G., & Müller, D. B. (2015). A general system structure and accounting framework for socioeconomic metabolism. *Journal of Industrial Ecology, 19*(5), 728-741. doi:10.1111/jiec.12306

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

[3] European Commission, Food and Agricultural Organization of the United Nations, International Monetary Fund, Organization for Economic Co-operation, and Development; & World Bank. (2017). *System of Environmental-Economic Accounting 2012*. Washington, DC: International Monetary Fund. Retrieved from: Eurostat website

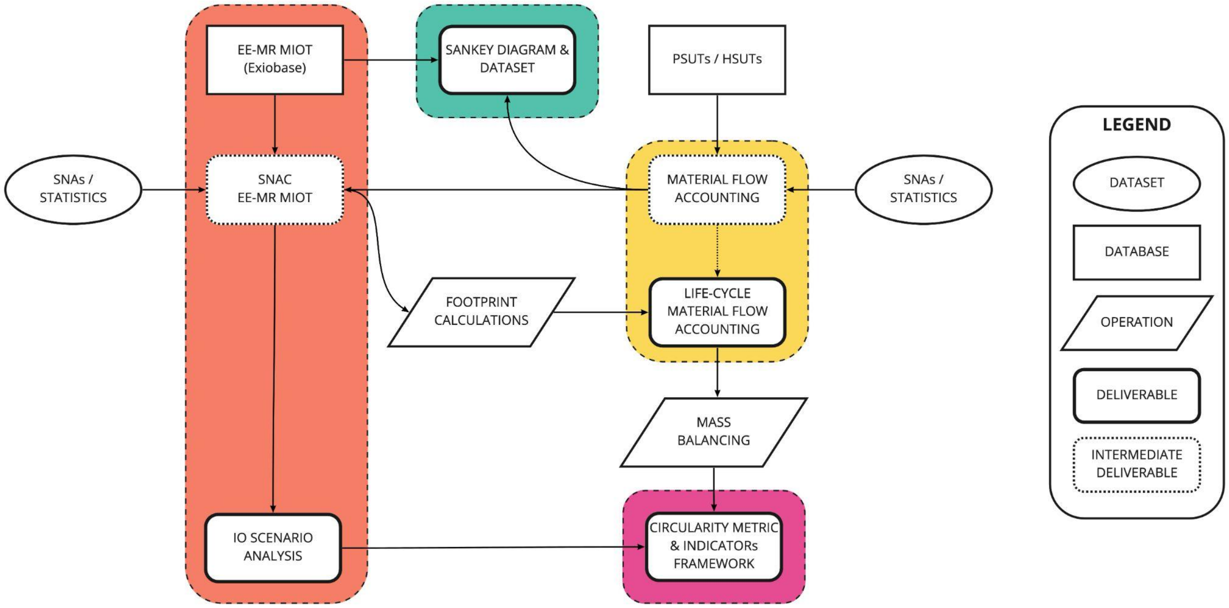

Figure one. *Flowchart of data sources, operations and deliverables.*
Notes: Dataset- SNAs/Statistics | Database EE-MR-MIOT (exiobase) | Intermediate Deliverable - SNAC EE MR MIOT | Deliverable - IO Scenario analysis | Database - Sankey Diagram and Dataset | Operation - Footprint calculations | Database PSUts/HSUTs | Intermediate Deliverable - Material Flow accounting | Deliverable - Life-cycle Material Flow accounting | Operation - Mass balancing | Deliverable - Circularity Metric and Indicators Framework.

The building blocks of SEM analysis are highlighted in colours, namely: *Accounting* in yellow, *Modelling* in red, *Measuring* in purple and *Mapping* in turquoise. The key data sources are the EE-MRIO database Exiobase, general statistics from national statistical institutes (NSI) and systems of national accounts (SNA) and, if available, physical or hybrid supply and use tables (PSUTs / HSUTs).

Statistics from NSI and PSUTs are the preferred sources for physical inputs and outputs data used in the material flow accounting (MFAc) (for example, extraction of resources, trade of physical commodities, waste, emissions, etc.). Economy-wide MFA[4] (EW-MFA) provides a standardised framework to quantify key flows in the socioeconomic metabolism of an economy and derive high level performance indicators. At the same time, it is also used in the compilation of the environmental extension (EE) part of the MRIO database. Additional nation-specific macroeconomic data can be integrated in the EE-MRIO database to calculate more recent and accurate footprints for single countries in an approach referred to as single-nation account consistent (SNAC) footprinting.[5] A similar approach is applied in cases of a sub-national scale to allow for the calculation of

[4] Circle Economy's application of Material Flow Accounting is performed on the basis of the latest edition of Eurostat's Handbook of Material Flow Accounting. Available here.
[5] 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

sub-national footprints. Material footprint results are then fed back to the MFA to form a life-cycle material flow accounting (LC-MFA) overview. LC-MFA constitutes the basis for the calculation of the Circularity Metric (CM) and the broader indicators framework (IF). The EE-MRIO database—or the SNAC version of it—also forms the basis for the scenario analysis (ScenAn) which builds on a growing research stream that attempts to model circular economy interventions from a macroeconomic perspective.[6,7,8]

For a more intuitive communication of the insights from SEM analysis, an infographic of material flows in the form of a Sankey diagram is produced.[9] Using Sankey diagrams to depict an IO database allows us to visually link any embodied environmental impact (for example, resource extraction, greenhouse gas emissions, freshwater use, etc.) to the production and consumption of products and services, thereby unravelling the global footprints (for example, material, carbon, water, etc.) behind satisfying consumers' societal needs of consumers. Ultimately, this allows us to connect the ecological with the social—as well as the local with the global—side of the current environmental crisis and give insights into the challenges of reaching an ecologically safe and socially just planet.

Finally, the socioeconomic metabolism analysis is complemented with a socioeconomic analysis. The latter addresses the enabling conditions for stimulating the desired circular strategies in the economy. A particular focus of this approach lies in the quantification of fiscal reform that can be applied to create circular investment potential, the allocation of this investment potential across different industries and circular strategies, as well as an estimation of the job creation potential associated with increased circular activity in the economy.

Disclaimer: Parts of this methodology document refers to or takes datasets, accounting conventions and definitions from Eurostat as an example, as this is the most important source of data within the EU. While not all dataset characteristics and accounting conventions will be exactly the same across other countries, it is assumed that most of the underlying issues are shared across statistical institutes.

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[6] 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.

[7] Wood, R., Moran, D., Stadler, K., Ivanova, D., Steen-Olsen, K., Tisserant, A., & Hertwich, E. G. (2018). Prioritizing consumption-based carbon policy based on the evaluation of mitigation potential using input-output methods. *Journal of Industrial Ecology, 22*(3), 540-552.

[8] Vita, G., Lundström, J. R., Hertwich, E. G., Quist, J., Ivanova, D., Stadler, K., & Wood, R. (2019). The environmental impact of green consumption and sufficiency lifestyles scenarios in Europe: connecting local sustainability visions to global consequences. *Ecological economics, 164*, 106322.

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

1. Material Flow Accounting

Economy-wide material flow accounts (EW-MFA) are a statistical accounting framework describing the physical interaction of the economy with the natural environment and with the rest of the world economy in terms of flows of materials. They represent a useful framework to derive a high-level overview and understanding of the socioeconomic metabolism of the system under analysis. EW-MFA records the throughput of materials (excluding bulk flows of water and air) at the input and output sides of the national economy. 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 input side

Material outputs from national economies include:

- Domestic Processed Output to the domestic environment;
- Physical Exports (all goods) to other economies;
- Balancing Items 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 buildings and infrastructures, machinery and durable goods, for example. In EW-MFA this material accumulation is called Net Additions to Stock (NAS). **Table one** summarises the key variables and derived indicators of EW-MFA framework.

Code	Label	SEEA-CF type of flow	Formula for derived indicator
DE	Domestic Extraction	Natural input	-
IMP	Imports	Product	-
EXP	Exports	Product	-
DPO	Domestic Processed Output	Residual	-
BI_in	Balancing Items (input side)	Natural Input	-
BI_out	Balancing Items (output side)	Residual	-

DMC	Domestic Material Consumption	n.a.	DMC = DE + IMP -EXP
DMI	Domestic Material Input	n.a.	DMI = DE + IMP
PTB	Physical Trade Balance	n.a.	PTB = IMP - EXP
BI	Balancing Items (input - output)	n.a.	BI = BI_in - BI_out
NAS	Net Additions to Stock	n.a.	NAS = DMC + BI - DPO

Table one shows key EW-MFA variables and derived indicators.

Domestic Extraction. This includes the extraction of natural resources from the domestic environment. 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 includes ferrous and non-ferrous metals;
3. Non-metallic minerals, which includes constructions aggregates, limestones and clays; and
4. Fossil energy materials/carriers, which comprises coal, natural gas and crude oil.

Imports and Exports. Both imports and exports include raw materials, as well as semi-manufactured and finished products and potentially wastes.

Domestically Processed Outputs (DPO). Consumption of materials by people in Scotland, and waste generated through the production and use of goods and services, need to be included in the material flows account. This includes:

- Direct emissions to air and water;
- Controlled and uncontrolled waste to landfill;
- Dissipative use of products (where materials are dispersed into the environment through their use), for example, fertiliser application; and
- Dissipative losses, for example emissions to air from automobile tyres; and brake wear and road abrasion, are also added to the DPO.

The scale of water use is so significant that including its mass in MFAs obscures other resource use. For this reason, standard MFA practice is to only include water mass contained in products: for example, agricultural products 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 and Material Accumulation. The input and output sides of the MFA are balanced to ensure that 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 the production of ammonia, 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 products with longer lifetimes like 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, and are needed to estimate the raw material requirements 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 Raw Material Equivalents (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 materials that remain unused are classified as hidden flows, which are not included in the CE's MFA. Examples include unused extraction from mining and quarrying (also known as overburden), discarded material from harvesting (such as wood harvesting losses), and soil and rock moved as a result of construction and dredging. Like indirect flows, these are also estimated using coefficients for biomass and minerals extraction processes.

At the time of this analysis, a Scottish Material Flow Account for the year 2018 was already developed and was therefore used as the starting point for the application of the extended MFA approach as outlined in the following section. For the methodological details behind the Scottish MFA refer to the Zero Waste Scotland website.[10]

Extended MFA framework

While the EU MFA approach provides a standardardised way to quantify key material flows, stocks and related indicators, it sometimes falls short in describing the link between all the datasets employed, and in reconciling them. The extended framework for an economy-wide CE assessment developed by Mayer et al. (2018)[11] 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*

[10] Zero Waste Scotland. (n.d.). Material flow accounts. Retrieved from: Zero Waste Scotland website
[11] 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

and waste flows in a mass-balanced approach' (**Figure two**). It builds on the EU MFA approach, expanding it by integrating waste flows, recycling, and downcycled materials (see **Chapter five**). Based on this framework, a comprehensive set of indicators that measure the scale and circularity of total material and waste flows and their socioeconomic and ecological loop closing has been developed.

The rationale for the application of this framework to the standard MFA data is to monitor progress towards a CE from an economy-wide perspective at the sub-national or higher 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.[12]

Figure two represents the framework and throughput indicators for an economy-wide CE assessment.

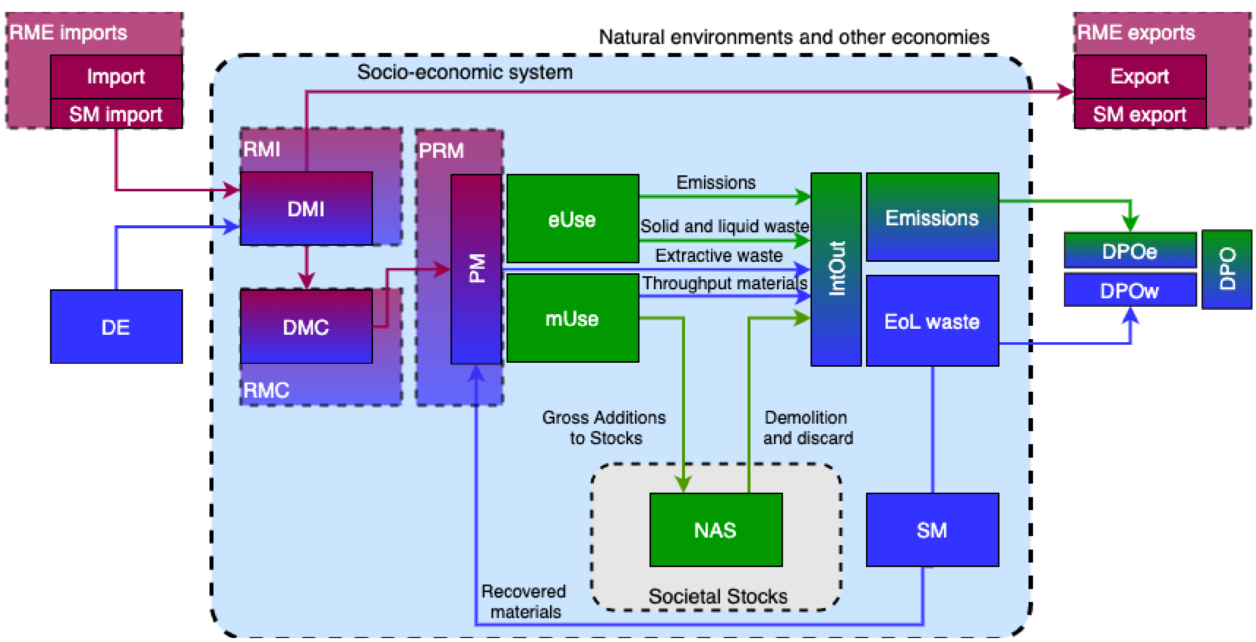

Figure two. *Framework and throughput indicators for an economy-wide CE assessment. This framework applies from individual materials (for example, DE of corn or iron) to aggregate material categories (for example, PM of biomass, fossil energy carriers) to the total material level (for example., total DE). Colours indicate the data sources used: purple = official trade statistics (ComExt), blue = official extraction, waste and emissions statistics (env_wastrt, env_ac_mfa), green = mass-balanced modelling. Please note that a shift from green to blue colour indicates a combination of statistical data and modelling. A description of this diagram is presented in the paragraphs below.*

The accounting framework shown in **Figure two** traces materials by main material groups from their extraction to major uses within the socioeconomic system, and eventually towards their disposal

[12] Waste generation and treatment (env wastrt), Material flow accounts (env ac mfa), International trade in goods statistics (ComExt).

and either material recovery or deposition into nature as waste and emissions. The main physical stages of the flow of materials through the entire system are marked by throughput indicators, represented as boxes. These include the source of material inputs (for example, domestic extraction, imports), major material transformation processing stages within the system (for example, processed materials, energetic and material use, in-use stocks of materials, waste treatment, end-of-life waste) and the destination of outflows (for example, exports, domestic processed output to the environment). Flows of materials are displayed as arrows between these boxes; the colours of flows indicate the type of data source. **Table S1** in the **Annex** provides a description of each indicator.

Processed materials (PMs) were defined as the sum total of DMC and secondary material (SM) inputs. PMs were allocated to either energetic or material use (see **Table S2** in the **Annex** for detailed allocation tables). Processed raw materials (PRMs), instead, were defined as the sum total of RMC and SM inputs. Energetic use (eUse) not only comprises materials used to provide technical energy (fuel wood and biofuels) but also feed and food, the primary energy sources for livestock and humans. Material use (mUse) was split into extractive waste, materials used for stock building (i.e., gross additions to in-use stocks of materials [GAS]), and throughput materials. Extractive waste refers to waste material that occurs during early stages of the processing of domestically extracted ores and directly goes from PM to interim output (IntOut). Stock building materials comprise all materials that accumulate in buildings, infrastructure or durable goods with a lifetime of more than one year (for example, concrete, asphalt or steel). The share of stock-building materials in mUse was estimated based on information from industry and production statistics, results from material flow studies and assumptions (see **Table S3** in the **Annex**). Throughput materials comprise materials that do not accumulate in in-use stocks, and can be split into two types of materials: first, materials used deliberately in a dissipative way such as salt or fertiliser minerals, and losses that occur during material processing (wastage, not reported in waste statistics); and second, short-lived products such as packaging or newspaper, manufacturing wastes, and food waste (reported in waste statistics).

All materials that are neither added to stocks nor recycled are converted into gaseous, solid or liquid outputs within the year of extraction. Together with demolition and discard 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 (for example, carbon dioxide [CO2], sulphur dioxide [SO2], methane [CH4]) including water vapour, and into end-of-life waste, including all solid (and liquid) outputs. Information on outflows was either sourced from Eurostat waste statistics or modelled and mass-balanced with input flows (see **Annex** for details). Emissions cannot be recycled and therefore go straight into Domestic Processed Output (DPO). A fraction of total end-of-life waste, reported as RCV B – (recovery other than energy recovery—backfilling) and RCV O (recovery other than energy recovery—except backfilling) in Eurostat waste statistics (env_wastrt), is re-entering socioeconomic processes as secondary materials. The remaining end-of-life waste (after subtracting SM) is returned to the environment as

DPO waste and is either landfilled, incinerated or deliberately applied to land (for example, manure, fertiliser). DPO emissions and DPO waste together form total DPO.

To close the material balance between input and output flows we combined 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 one) and mUse (equation two).

$$DPO\ emissions\ =\ eUse\ -\ solid\ and\ liquid\ wastes \quad 1)$$

$$Demolition\ and\ discard\ =\ EoL\ waste\ from\ mUse\ -\ throughput\ materials\ in\ waste \quad 2)$$

We assumed that all materials used to provide energy were converted into DPO emissions (including water vapour) and solid waste within a 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. DPO emissions were then calculated as the difference between eUse and the outflow of solid waste. 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 (for example, 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 DPOe with data from emission statistics (see **Table S4** in **Annex**).

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 end-of-life waste from mUse into waste flows resulting from discard, demolition and throughput materials was required. Total end-of-life waste from mUse was derived from waste statistics. While waste statistics report information on construction and demolition waste, this waste flow was not fully consistent with end-of-life waste from discard and demolition, which also contains waste flows from discarded long-living products such as furniture, cars or electric appliances. In the second step, we calculated the amount of discard and demolition as the difference between end-of-life waste from mUse reported in waste statistics and the fraction of throughput materials (i.e., materials with a life span less than one year) in mUse (for example, waste from packaging, paper, food waste, etc.). In the third step, NAS were calculated as the difference between GAS 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.

All flows and indicators were calculated for the four main material groups distinguished in EW-MFA. The calculation at the level of material groups was challenging because waste statistics of Eurostat[13] follow a classification that refers to economic sectors and activity (NACE classification), different collection systems, and/or hazard potential. Waste materials reported in one category typically comprise multiple material categories in EW-MFA, which requires an allocation of output to input flows. Waste flows reported in waste statistics needed adjustments to the system boundaries used in EW-MFA to ensure that input and output flows can be mass balanced (see **Table S5** in the **Annex** for detailed allocation tables).

The application of the extended MFA approach and in particular the harmonisation of systems boundaries across the EW-MFA and waste statistics generates a second set of indicator figures (and underlying variables) that deviate from the original estimates. In order to minimise this difference, a manual iterative reconciliation process is performed. The objective of the optimisation is to minimise the difference between the two figures for the DMC, NAS and DPO indicators by changing values of some key parameters of the extended MFA framework (for example, the share of mUse in PM and share of stock additions in mUse). Whenever the difference between indicators cannot be reconciled to satisfactory levels, an additional estimation of unreported waste is introduced.[14] The extended MFA calculations can be found in **Annex - MFA** (tab 'Circ_calc').

Imported and exported secondary materials (for example, scrap, waste paper) are distinguished from the trade flows and explicitly accounted for as secondary materials; they are therefore also reflected in circularity indicators (see Chapter five for more details).

[13] Regulation (EC) No 2150/2002; see European Commission and Eurostat (2013).
[14] It should be noted the treatment route of such unreported waste remains unspecified.

3. Input-Output Analysis

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

Of the available multiregional EEIO databases (EE-MRIOD), EXIOBASE stands out as a database compatible with the SEEA with 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 five rest-of-the-world regions. Satellite accounts for resources and emissions are available for each sector and country. The original EXIOBASE 3 data series ends 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.

As of v3.8.2,[15] the end years of real data points used are: 2011 monetary, 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 version where material extraction is updated to the year 2017 on a country-by-country basis using the high resolution Global Material Flow Database, compiled using the Common Compilation Categories and provided under request by the IRP.[16] Industry allocations of the baseline year 2011 were 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 2017, under a defined set of assumptions (for example, nowcasted monetary data from 2011 or industry allocation shares for material extraction). Accounts for later years will be based on nowcasted 2011 monetary data and material extraction data for the year 2017. It should be noted that material extraction data from IRP is itself a projection based on 2014 data.

All calculations are performed using the open source tool for analysing global EE-MIOTs, **pymrio.**[17] Production- and consumption-based accounts are calculated using a standard set of IO formulas as specified below and in **Table three.**

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[15] (2020). EXIOBASE 3. doi:10.5281/zenodo.4277368
[16] International Resource Panel. (n.d.). Global Material Flows Database. Retrieved from: International Resource Panel website
[17] Pymrio. (n.d.). pymrio - multi regional input output analysis in python. Retrieved from: pymrio website

$$D^{i}_{cba} = D^{i}_{pba} + D^{i}_{imp} - D^{i}_{exp}$$
$$D_{pba} = Fe + Ge$$
$$D_{imp} = MY_{t}$$
$$D_{exp} = M\hat{Y}_{t}e$$

Variable name	Symbol	Description
Consumption-based accounts	D^{i}_{cba}	Footprint of consumption
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	$L = (I - Z\hat{x}^{-1})^{-1}$	Total requirements matrix
Factor production coefficients	$S = F\hat{x}^{-1}$	–
Gross output	$x = Z_{e} + Y_{e}$	–
Transaction matrix	Z_{e}	Matrix of interindustry flows or intermediate transaction matrix
Final demand matrix	Y_{e}	–
Final demand matrix to satisfy factors of production abroad	$Y_{t} = Y - Y_{i,j} \mid i = j$	Final demand matrix with domestically satisfied final demand set to zero

Table three. Description of main pymrio variables.

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.[18] [19] [20] [21] [22] According to Tukker and colleagues,[23] [24] there are several approaches to the calculation of footprints. The one employed in this study can be regarded as a variation of Method six, the System of National Accounts Consistent (SNAC) method. The key differences lie in the fact that we do not perform the operations on SUTs but rather directly on IOTs and that the resulting database is **not rebalanced after the modifications**. This way, we guarantee full consistency of the single-country account with its SNA's data at the cost of not fully respecting the market balance. The relatively low influence of a non-fully balanced system in the production of results has already been recognised and documented in peer-reviewed literature.[25][26] For an exhaustive explanation of the SNAC procedure refer to Edens et al. (2015).[27]

The rationale behind the selection of a SNAC approach is expressed by Giljum and colleagues in the context of an expert workshop on 'Demand-based measures of materials flows' organised by the OECD, UNEP and its IRP:

'Countries that aim to take leadership in the process of establishing material footprint indicators could test "single-country national accounts consistent" or "SNAC models". Applying an international accounting approach using international data sources entails the risk of discrepancies with national statistical data. This problem can be overcome by replacing data for a specific country with data from official national trade and extraction statistics, thus building a single-country national accounts consistent (SNAC) footprint accounting model. This step is highly recommended when implementing a top-down trade and

[18] 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

[19] 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. doi:10.13140/RG.2.2.35017.95844

[20] 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

[21] 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

[22] 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

[23] 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

[24] Tukker, A., Giljum, S., & Wood, R. (2018). 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

[25] 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

[26] Wiedmann, T., Chen, G., Owen, A., Lenzen, M., Doust, M., Barrett, J., & Steele, K. (2020). Three-scope carbon emission inventories of Global Cities. *Journal of Industrial Ecology, 25*(3), 735-750. doi:10.1111/jiec.13063

[27] 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. doi:10.1080/09535314.2015.1048428

footprint model for monitoring or target setting purposes at the national level. SNAC models should improve the robustness of national calculations and remove uncertainties that originate from necessary manipulation of national data in the process of constructing an MRIO database.'"

The SNAC model is implemented in the form of a python script that is able to handle most IOT blocks (for example, Interindustry imports vectors as well as matrices) at different scales (national as well as sub-national) by means of custom concordance tables and standardised manipulation routines. There are five types of operations performed by the model (NB: only the first two have been implemented so far while the others are under development):

1. *Matching:* This term encompasses all operations of aggregation, proportioning and disaggregation of IOT blocks with the aim of re-casting an official SNA's IOT from its original format to Exiobase's format. This implies the compilation of concordance tables between Exiobase's ISIC rev.4 classification and those used by different NSIs. When possible, such concordance tables are sourced from Zenodo[28] and manually adapted to fit the specific case. Matching is carried out across the main IOT blocks: domestic intermediate transactions (Z_dom), intermediate imports (Z_imp), intermediate exports (Z_exp), domestic final demand (Y_dom), final demand for imports (Y_imp), final demand for exports (Y_exp) and the satellite account (F) of factor inputs and environmental extensions;

2. *Integration:* The process of nesting or substituting a vector/matrix into the MRIO database. Depending on the scale of the project, integration can be a simple substitution between the original Exiobase and the matched SNA blocks for a specific nation or—**in case of a sub-national entity not covered by Exiobase such as Scotland**—the nesting of a new 'cross-section' (the new region) within the MRIO database and the adjustment of the corresponding national blocks. In most cases this implies deducting sub-national blocks from the 'Rest of Nation' blocks;[29]

3. *Downscaling:* The process of using non-survey or partial non-survey methods such as location quotient methods to estimate new sub-national blocks from national ones. The downscaled blocks are then integrated within the MRIO database;

4. *Balancing:* The process of re-balancing total inputs and outputs (accounting identity) of the new two region 'cross-section' after nesting and adjusting the national intermediate transaction, final demand, imports and exports tables into components relating to the sub-national entities and the 'Rest of Nation'. Rebalancing is done through data reconciliation algorithms such as RAS;

5. *Nowcasting:* The process of updating the MRIO database, or a part of it, by assuming that only macroeconomic aggregates such as GDP or GVA change while the structure of their

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[28] Exiobase concordances

[29] Wiedmann, T., Chen, G., Owen, A., Lenzen, M., Doust, M., Barrett, J., & Steele, K. (2020). Three-scope carbon emission inventories of Global Cities. *Journal of Industrial Ecology, 25*(3), 735-750. doi:10.1111/jiec.13063

constituents remains the same. It is a simplified way to account for changes in volumes without the need of reflecting structural ones;

Matching and integration routines vary depending on the territorial scope and data availability. The latter is fully determined by the characteristics of import data, namely:

1. *Table format*: Whether the import data is provided as a vector of imported commodities or as a matrix of used commodities by importing industry. There can be situations in which monetary trade is completely missing: in the cases where non-survey or partial non-survey methods—such as location quotient methods—need to be used. While this is currently not implemented in the model, a *downscaling* step using location quotients is currently under development.

2. *Information on trading partners:* Whether import data are split by the region of origin.

3. *Information on inter-regional trade:* This only applies at the sub-national level and refers to whether import and export data between the sub-national entity and the 'Rest of Nation' are provided.

The combination of territorial scale and data characteristics generates a number of different cases with five possible outputs in terms content and size of the MRIO database (NB: case 2.4 is not yet implemented):

1. **National scale**: A 48 regions by 164 industries MRIOT, where the blocks of the nation under analysis contain values from the original SNA's tables, matched to the Exiobase classification and format.

2. **Sub-national scale**: In this case more options are possible:
   2.1. A 48 + 1 regions by 164 industries MRIOT where the blocks for the extra sub-national entity contain values from the original SNA's *sub-national* tables and where the original Exiobase national blocks have been re-calculated as the 'Rest of the Country' (for example, 'Rest of Canada' where the sub-national entity under analysis is a Canadian province, such as Quebec). This is the case of maximum available information: sub-national matrix of imports including interregional trade and with information on trading partners;
   2.2. A 3 regions by 164 industries MRIOT where the sub-national blocks contain values from the original SNA's *sub-national* tables, where the original Exiobase national blocks have been re-calculated as the 'Rest of the Country' and where all the other territories are aggregated into a single 'Rest of the World' region. This is the case of partial available information: sub-national IOT of imports including interregional trade and *without* information on trading partners. **This is the case for Scotland**;
   2.3. A 2 regions by 164 industries MRIOT where the sub-national blocks contain values from the original SNA's *sub-national* tables and all the other territories *including* the

original Exiobase national blocks are aggregated into a single 'Rest of the World' region. This is the case of minimum available information: sub-national IOT of imports *excluding* interregional trade and *without* information on trading partners;

2.4. A 2 regions by 164 industries MRIOT where the sub-national blocks contain *downscaled* values estimated using non-survey methods such as location quotients methods, where the original Exiobase national blocks have been re-calculated as the 'Rest of the Country' and added to the 'Rest of the World' region. This is the case when there is no information available.

In all sub-national cases in which only one or more vectors of imports are provided, for example, vectors of imported commodities by trading partners, the Exiobase intermediate imports transaction matrix of the corresponding parent nation is used to determine the input shares into industries. This operation is carried out under the assumption that the way imports are used by national and sub-national industries is the same or similar. Since transaction matrices for exports are not produced by NSIs, the original Exiobase intermediate exports transaction matrix is always used to disaggregate the sub-national exports vector.

Scenario Analysis

EE-IOA can be applied to assess the economic and environmental implications of a transition towards a circular economy.[30] IOA, in its various forms, is a static structural model that provides a high resolution of sectors and structural 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 through the application of exogenous changes. One of the advantages of this type of approach is the level of transparency in assumptions. This is especially important for circular impact assessment as the variety of approaches makes it difficult to compare studies. Previous studies have tried to categorise types of interventions within the circular economy, their fundamental waste management models and indicators. However, there is still a need for current circular economy assessment methods to become more comparable and robust in order to serve as policy tools.

As a first step, building on the work of Aguilar et al. (2018) and Donati et al. (2020) and integrating it with additional literature on circular strategies frameworks,[31] [32] [33] a new comprehensive circular economy policy modelling framework was developed. We began by asserting that the objective of a

[30] 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

[31] Blomsma, F., Pieroni, M., Kravchenko, M., Pigosso, D. C., Hildenbrand, J., Kristinsdottir, A. R., . . . McAloone, T. C. (2019). Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. *Journal of Cleaner Production, 241*, 118271. doi:10.1016/j.jclepro.2019.118271

[32] Morseletto, P. (2020). Targets for a circular economy. Resources, Conservation and Recycling, 153, 104553.

[33] Reike, D., Vermeulen, W. J., & Witjes, S. (2018). The Circular Economy: New or refurbished as CE 3.0? — exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling, 135*, 246-264. doi:10.1016/j.resconrec.2017.08.027

circular policy is always the implementation of the circular economy paradigm. In order to achieve this objective different strategies exist. There are various categorisations of circular economy strategies such as ReSOLVE.[34] [35] However, in this study we integrate the the 4-strategy classification of Aguilar-Hernandez et al. (2018)—which consists of: Product Lifetime Extension (PLE); Resource Efficiency (RE); Closing Supply Chains (CSC); Residual Waste Management (RWM)—with a variation of the 10Rs framework developed by Potting et al. (2017).[36]

We define strategies as sets of policy interventions and improvement options (or simply interventions). For example, PLE can be achieved, among others, by reuse and remanufacturing, or delaying products' replacement (Allwood and Cullen, 2015). In other words, while these two interventions aim at the same objective—the extension of a product's life—the way they are implemented is different. We further distinguish between a general description of interventions and specialised interventions. An intervention (for example, reuse and remanufacturing) is specialised when it refers to a specific product or application (for example, increase lifetime through reuse and remanufacturing forin 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 of sales of vehicles resulting from fewer consumers needing to replace their vehicles. A corresponding ancillary change would be the potential increase in repair services caused by a higher utilisation of the good. We show this conceptual approach in **Figure four**. A more detailed overview and description of the framework's elements is provided in **Annex—Scenarios** (tab 'CE Policy Frame').

[34] MacArthur, E. (2013). Towards the circular economy. Journal of Industrial Ecology, 2, 23-44.
[35] Bocken, N. M., De Pauw, I., Bakker, C., & Van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering, 33*(5), 308-320. doi:10.1080/21681015.2016.1172124
[36] Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: measuring innovation in the product chain*. Retrieved from: PBL website

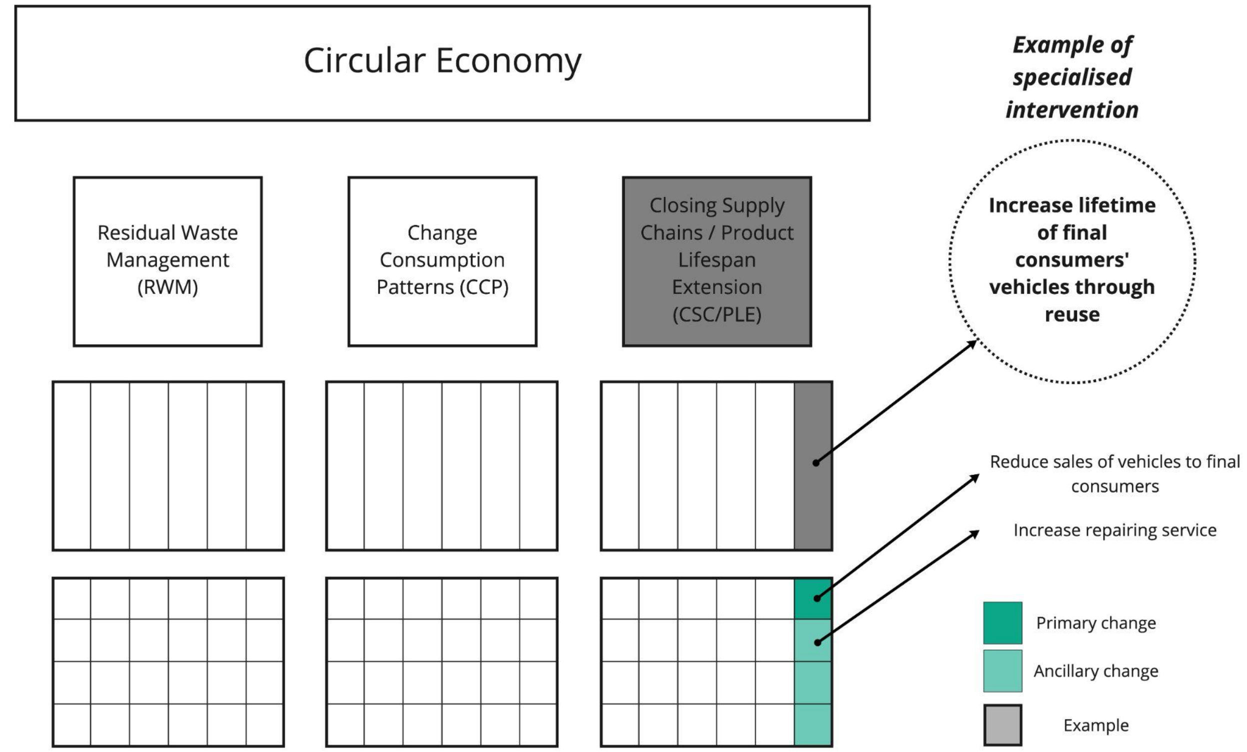

Figure four. Circular Economy policy modelling framework.
Notes: Circular Economy —Residual Waste Management; Change Consumption Patterns (CCP); Closing Supply Chains/Product Lifespan Extension (CSC/PLE) | Example of; Specialised intervention—Increase lifetime of final consumers' vehicles through reuse; Primary change—Reduce sales of vehicles to final consumers; Ancillary change—Increase repairing service.

Hereby, we present systematic methods to build complex circular economy counterfactual (what-if) scenarios with EEIOTs. The basic Leontief demand-driven model can be framed such that a stimulus vector of final demand leads to a set of impacts occurring in each production sector as:

$$D_{cba} = \widehat{S}\,(I - A)^{-1} Y_e$$

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

$$D_{cba,\,tot} = D_{cba}^{'}e + Ge$$

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

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

$$\widehat{S^{*}}\,(I - A^{*})^{-1}\,Y_{e}^{*}$$

If there are final consumption pressures, we can further define $\Delta D_{cba,tot} = D_{cba,tot}^{*} - D_{cba,tot}$ where:

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

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

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

The edit of a particular entry ij of an arbitrary T matrix object from the baseline to the counterfactual scenario, is performed by the **pycirk**[37] software 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

[37] Pycirk. (n.d.). Pycirk. Retrieved from: pycirk website

maximum potential effect, and of a market penetration coefficient (k_p) describing the size of the given market affected so that:

$$k_a = k_t k_p$$

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

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

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

This model considers the impact of actions at the margin, if taken tomorrow (so-called 'what-if' scenarios). Modelling the efficacy of the options if they are adopted at different points in time becomes far more complex, as the sequencing creates many different path-dependent trajectories (for example, the carbon footprint of electric vehicles depends strongly on the carbon intensity of the electricity used to fuel them). Some of the behaviour changes considered affect the volume of a particular stock while others affect yearly flows. We considered the impact of a particular behaviour change as the yearly impact in a future year in which the relevant stock has been fully replaced. For example, the impact of improving building insulation is the comparison between the status quo and a situation where a given fraction of existing buildings and the same fraction of new construction has improved insulation. In other words, we compare the baseline scenario against a future steady-state situation in which the relevant stock has been replaced following the change. Rebound effects due to re-spending are not taken into account. The file with the original scenario parameters together with the results (tab 'S_Results') can be found in **Annex—Scenarios**.

4. Circularity Indicators Framework

The indicators presented here are based on EW-MFA principles and are taken from the work of Mayer et al. (2018)[38] and previous research.[39] [40] [41] This work distinguishes between scale indicators, which provide measures for the overall size of the socioeconomic metabolism, and metabolic rates, which measure socioeconomic and ecological cycling relative to input and output flows. Providing independent measures for flows on both the input and output sides is necessary because of the delaying effect that in-use stocks of materials have on output flows.

1. Three pairs of indicators are used to measure the scale of material and waste flows: DMC measures all materials directly used in a national production system and is regarded as a proxy for the aggregated pressure the economy exerts on the environment. DPO measures the total amount of outflow of wastes and emissions from a national economy.

2. In order to be able to capture displacement effects related to imports and exports, a consumption-based life-cycle indicator was included in the form of raw material consumption (RMC), or material footprint;[42] a measure of global material use associated with domestic final consumption. No corresponding indicator on the output side is available at the moment of writing.

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

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[38] 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

[39] 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

[40] 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

[41] European Commission, Joint Research Centre, Nita, V., Haas, W., Blengini, G. (2017). Development of a Sankey diagram of material flows in the EU economy based on Eurostat data : monitoring of non-energy & non-food material flows in the EU-28 for the EC Raw Materials Information System (RMIS). Retrieved from: Publications Office of the European Union website

[42] 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

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

1. The socioeconomic cycling rates measure the contribution of secondary materials to PM and PRM (**input socioeconomic cycling rate [ISCr]**)—when calculated based on DMC and RMC respectively—and the share of IntOut that is diverted to be used as secondary materials (**output socioeconomic cycling rate [OSCr]**). Recycled waste from material processing and manufacturing (for example, 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 under-estimation of downcycled materials, as solid waste from the combustion of fossil materials are used in construction, for example. Energy recovery (electricity, district heat) from the incineration of fossil or biomass waste is not considered recycling as it does not generate secondary materials.

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

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

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

5. The difference between 100% and the sum total of the four metabolic rates serve as a measure for the unexploited potential for socioeconomic cycling and represents the input and output of non-renewable materials available for cycling; namely the **input non-renewable material rate (INRr)** and **output non-renewable material rate (ONRr)**.

6. Finally, the difference between RMC and DMC is used as a bridging item rather than an actual indicator. The reason for this is that while the original indicator framework is calculated over PMs, for our Circularity Gap Reports this is also done over PRMs. The latter has the advantage of taking a life-cycle perspective and reallocating raw material extraction to the point of final consumption, at the disadvantage of introducing an overlap in system boundaries which is not straightforward to deal with. Calculating indicators on RME-based flows in the same way as one would do on direct physical flows, would imply extending assumptions that are valid only within the economy under analysis to all the other economies. As an example, let's consider the estimation of the non circular flows: the fossil fuels fraction in PM is made of the actual products (for example, gasoline, kerosene, plastic) that are being used within the country under analysis so the identification of their use, in this case fossil fuel products for energy purposes, is straightforward. However, the fossil fuel fraction in PRM accounts for the raw materials (for example, petroleum, natural gas) extracted anywhere in the world and embodied in all kinds of products and applications, making it difficult to trace back their original use. Therefore, we introduce a **bridging item** and refer to it as **net extraction abroad (NEA)**. When it 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. Another issue related to using RMEs rather than physical flows is that it is hard to track the fate of raw materials extracted abroad and that are not embedded into the traded commodity, but rather transformed into waste and emissions during processing.

	Dimension	Input-side Indicator		Output-side Indicator	
		Direct	Life-cycle	Direct	Life-cycle

Scale indicators (t)	In- and output flows	Domestic material consumption (**DMC**)	Raw material consumption (**RMC**) = DMC + NEA	Domestic Processed Output (**DPO**)	n.a.
	Interim flows	Processed Materials (**PM**) = DMC + secondary materials	Processed Raw Materials (**PRM**) = RMC + secondary materials	Interim outputs (**IntOut**) = EoL waste + DPO emissions	n.a
Metabolic rates (%)	Socioeconomic cycling (SC)	Input socioeconomic cycling rate (**ISCr**) = Share of secondary materials in PM	Input socioeconomic cycling rate (**ISCr**) = Share of secondary materials in PRM	Output socioeconomic cycling rate (**OSCr**) = Share of secondary materials in IntOut	n.a
	Ecological cycling potential (EC)	Input ecological cycling rate potential (**IECrp**) = Share of DMC of primary biomass in PM		Output ecological cycling rate potential (**OECrp**) = Share of DPO biomass in IntOut	n.a
	Non-circularity (NC)	Input non-circularity rate (**INCr**) = Share of eUse of fossil energy carriers in PM		Output non-circularity rate (**ONCr**) = Share of eUse of fossil energy carriers in IntOut	n.a
	Net additions to stocks (NAS)	Net stocking rate (**NSr**) = Share of NAS in PM	Net stocking rate (**NSr**) = Share of NAS in PRM	Net stocking rate (**NSr**) = Share of NAS in IntOut	n.a
	Net Extraction Abroad (NEA)	n.a.	Net extraction abroad rate (**NEAr**) = share of NEA in PRM		n.a
	Non-renewable input (NR)	Non-renewable input rate (**NRIr**) = 100 - (ISCr + IECrp + INCr + NSr)	Non-renewable input rate (**NRIr**) = 100 - (ISCr + IECrp + INCr + NSr + NEAr)	Non-renewable output rate (**NROr**) = 100 - (OSCr + OECrp + ONCr + NSr)	n.a

Table four. Mass-based circular economy indicators, where scale indicators measure the absolute size of input and output flows in tons and metabolic rates measure cycling and other uses relative to input and output flows in percentage (n.a. = not applicable).

It should be noted that for simplicity, so far we have considered the net amount of traded secondary materials as part of DMC despite these flows being explicitly quantified and treated in CE's MFA model. The estimation of imported and exported secondary materials is based on the methodology developed by Eurostat and used in the calculation of the circular material use rate (CMUr).[43] Let's consider ISCr—the share of secondary materials in PRM—and re-write it in mathematical terms:

$$ISCr = SM/PRM$$

Where:

$$DMC = DE + IMP - EXP$$

$$PRM = DMC + NEA + SM$$

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

then $ISCr$ can be rewritten as:

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

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

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

In this respect, it was decided that the ISCr rate measures a country's effort to deploy secondary materials. This perspective credits the country's effort to produce secondary material from recycled waste as opposed to gathering waste bound for recovery which indirectly contributes to the

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

worldwide supply of secondary materials and hence avoidance of primary material extractions. Remarkably, this is the opposite perspective than the one taken by the Eurostat's CMUr.

The ISCr rate indicator is based on official statistics 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 ISCr rate.

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

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

Amount of waste recycled in domestic recovery plants

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

- Residual material legally declared as waste which is recovered and fed back to the economy after treatment (material flowing through the legally demarcated waste management system).

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

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

Hence, SM_{dom} is approximated using waste statistics collected or presented based on European waste statistics. While waste statistics measures the input of waste into recovery operations and not the amount of secondary raw materials that result from these operations; an analysis by Eurostat concluded that the input to recovery plants is an acceptable proxy for the output from recovery plants. On the basis of the treatment operations defined in the Waste Framework Directive 75/442/EEC, a distinction is made in treatment types, namely:

- Recovery—energy recovery (RCV_E). Operation R1 corresponds with the treated amount of waste used principally as fuel or other means to generate energy.
- Recovery—recycling and backfilling (RCV_R_B). RCV_R_B breaks down in RCV_R (Recovery—recycling) and RCV_B (Recovery—backfilling). RCV_R is the waste recycled in domestic recovery plants and it comprises the recovery operations R2 to R11—as defined in the Waste Framework Directive 75/442/EEC.

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

Adjusting circular use of material for net imports of waste

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

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

with:

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

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

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

In order to calculate the amounts of imported waste (SM_{imp}) and exported waste (SM_{exp}), Eurostat has identified the CN-codes which can be considered trade in waste.[44]

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

5. System visualisation

Sankey diagrams are used to visualise flows of materials and energy in many applications, to aid understanding of losses and inefficiencies, to map out production processes, and to give a sense of scale across a system. As available data and models become increasingly complex and detailed, new types of visualisation may be needed. This is because there is more than one way to visualise a dataset as a Sankey diagram, and different ways are appropriate in different situations. A systematic method was adopted for generating different hybrid Sankey diagrams from a dataset, with an accompanying open-source Python implementation called Floweaver.[45] Underlying the Python library, a common data structure for flow data was defined. Through this method it is possible to generate Sankey diagrams from different data sources, such as material flow analysis, life-cycle inventories or directly measured data.[46]

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

For entries in the D^i_{pba} dataset, 'source' is always set to the environment as these are all inputs coming from domestic extraction while the ''target' is the extractive industries. For entries in the Zm dataset, both 'source' and 'target' are domestic industries, as this matrix represents the resources embodied in domestic inter-industry transactions. For entries in the D^i_{imp} dataset, 'source' is always set to the exporting foreign region while the 'target' is the importing domestic industry. For entries in the D^i_{exp} dataset, 'source' is always the domestic exporting industry while 'target' is the importing foreign region. Finally, for entries in the D^i_{cba} dataset, the 'source' is the domestic industry whereas the 'target' is the societal need under which the material footprint was categorised. The categorisation of the material footprint by societal need follows the approach used by Ivanova et al.

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

[46] Lupton, R., & Allwood, J. (2017). Hybrid Sankey Diagrams: Visual Analysis of multidimensional data for Understanding Resource Use. *Resources, Conservation and Recycling, 124*, 141-151. doi:10.1016/j.resconrec.2017.05.002

2017[47] through a concordance matrix describing the assignment of EXIOBASE product sectors across consumption domains at the final demand level (**Annex—Societal Needs**).

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

6. Socioeconomic analysis

The previous sections outlined the methodology used to analyse Scotland's material metabolism, under both baseline conditions and 'what-if' counterfactual circular interventions. This section examines the approach taken to determine which socioeconomic conditions can enable these interventions. The socioeconomic conditions covered by this analysis include 1) a quantification of the fiscal reform required to generate public funds, labelled as 'circular investment potential', 2) the allocation of these funds to facilitate different circular strategies across four key industries, as well as 3) a quantification of the job creation potential needed to realise circular activities.

Few approaches have been taken to quantitatively analyse the macro-scale socioeconomic and environmental impact of circular economy interventions. The three most notable methods are macro-economic models such as Computational General Equilibrium (CGE) models and Integrated Assessment Models (IAMs), as well as structural models such as Environmentally Extended Input Output Analysis (EE-IOA). IAMs and CGE are advantageous because they are dynamic methods. The former can account for the interactions and feedbacks between socioeconomic and ecological cycles, while the latter can account for non-linear effects in the macro-economic system, such as price elasticity and rebound effects. Despite these advantages, these approaches are usually limited by their high spatial and temporal resolution and high complexity. This makes them suitable for analysing long-term trends. Structural models provide a static snapshot of the economy. The linear foundation of these models lacks an endogenous accounting of price changes or induced effects. However, these models can trace, at high sectoral resolution, economy-wide changes along the supply chain within and between countries. Moreover, Input-Output models are consistent with the System of National Accounts, and thus are able to capture impacts on employment and value creation relatively easily. Accordingly, these models are suited to trace the socioeconomic impacts of circular interventions in the economy.[48] In this analysis, we build on the use of Environmentally Extended Multi-Regional Input-Output Analysis for circular economy scenarios.

As noted, the approach can be summarised in three steps, namely:

1) Quantifying the circular investment potential,
2) Allocating the circular investments to the industries through a participatory process, and
3) Calculating the job creation potential associated with the increased circular activity.

These steps are described below in more detail, followed by a discussion on the limitations of this approach. Finally, this section includes a summary of the Circular Jobs Methodology, which has been mentioned in the main report and applied in a previous study to provide a baseline estimation of the circular activity in the Scottish labour market.[49]

[48] Glenn A. Aguilar-Hernandez, João F. Dias Rodrigues, Arnold Tukker, Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies, Journal of Cleaner Production, Volume 278, 2021, 123421, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.123421.

[49] Zero Waste Scotland & Circle Economy. (2020). *The future of work: baseline employment analysis and skills pathways for the circular economy in Scotland.* Retrieved from: Circle Economy website

Step one: Quantifying the circular investment potential

The application of the 'what-if' scenarios, as explained in Section three, presents reductions in both the physical and monetary output of the economy. This theoretical reduction in monetary output can be attributed to the static nature of the underlying input-output modelling framework. This fails to capture dynamics such as price elasticity and behavioural changes in consumption. Accordingly, circular interventions create imbalances in the input-output model, which we address through exogenous assumptions. To do so, the first step is quantifying these imbalances. For each of the 'what-if' scenarios, the imbalance is quantified as the difference between the economic output in the counterfactual scenario and the state of the economy under baseline conditions.

After quantifying the imbalances, we apply an exogenous procedure to rebalance the economy, assuming that the Gross Domestic Product (GDP) remains constant, and following analytical practices of similar scope.[50][51] In our analysis, monetary imbalances are redistributed to the matrix of the factor inputs (tax instead subsidies on product, compensation of employees). The rationale behind this procedure is to capture which socioeconomic conditions enable the circular interventions. In this sense, we quantify the fiscal reform required to *balance* the socioeconomic outcomes of the circular scenarios. In other words, we consider how the theoretical decrease in monetary output could be offset by revenue flowing in from environmental taxation. We also consider how this additional revenue could be used to stimulate more circular activities in the economy: government spending in the form of subsidies, grants and investment in infrastructure, for example. We label this flow of tax revenue to circular activities 'circular investment potential'.

To this end, this approach outlines the components of a fiscal regime where taxation is based on the material footprints of industries—and accordingly, larger subsidies are given to the activities and the employment that work towards mitigating this footprint. An example of this experimental policy approach has been demonstrated in the Ex'tax Project,[52] which revealed how fiscal reform in EU countries can shift the tax burden from labour to resource use and pollution, enabling a more circular, sustainable economy that supports environmental protection.

Step two: Allocating the circular investments to the industries through a participatory process

Circular investment potential is then distributed across economic sectors based on the four circular flows of Bocken's framework, namely: *Narrow*, *Slow*, *Cycle* and *Regenerate*, as shown in the table below.

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[50] Kirsten S. Wiebe, Marek Harsdorff, Guillermo Montt, Moana S. Simas, and Richard Wood. Environmental Science & Technology 2019 53 (11), 6362-6373. DOI: 10.1021/acs.est.9b01208
[51] Cooper, S., Skelton, A. C., Owen, A., Densley-Tingley, D., & Allwood, J. M. (2016). A multi-method approach for analysing the potential employment impacts of material efficiency. Resources, Conservation and Recycling, 109, 54-66.
[52] Ex'tax project. (2016). *New era. New plan. Europe. A fiscal strategy for an inclusive, circular economy.* Retrieved from: New Era New Plan website

Circular strategy	Type of fiscal reform	Targeted value-added element	Rationale
Narrow	Tax on type and amount of raw material inputs	Taxes less subsidies	Disincentivising overconsumption and reducing the demand for products with high environmental footprint
Slow	Tax relief/break on labour, subsidies to process adjustment and re-skilling of employees		
Cycle	Subsidies for jobs creation in waste collection, treatment, and re-processing sectors	Compensation of employees	Enabling the additional workforce expected to meet the increasing demand for circular products
Regenerate	Subsidies to jobs creation in research and development of regenerative materials and renewable energy production		

Mathematically, the allocation of circular investment potential mentioned in Step one and Step two can be summarised by the following equations:

$$delta\_out(S0 - SX) = y(N) + x(S) + z(C) + w(R)$$
$$x + y + z + w = 1$$

Where:

S0 and **SX** represent the output of the economy under baseline conditions and subject to circular scenario interventions, respectively.

N, **S**, **C** and **R** represent the 'circular investment potential', from tax revenues, destined to *Narrow*, *Slow*, *Cycle* and *Regenerate* circular strategies, respectively.

The parameters x, y, z and w are four scalars representing the allocation weights to *S*, *N*, *C* and *R* strategies, respectively. In particular, the allocation weights are linked to each sector as follows:

x reduce footprint by extending the life-time service of products and resources (slow)
y reduce footprint through the substitution of 'greener' products
z increase in waste collection and recycling activities (cycle)
w increase use of regenerative resources and spending in related R&D (regenerate)

The economic sectors in the input-output tables are classified into four key industries, namely:

1. **Agrifood**, including all agriculture, food supply chains, packaging and associated waste generation and treatment;
2. **Mobility**, meaning the use of transportation services and the supply chain of vehicles and energy carriers;
3. **Construction**, with a special focus on residential buildings, which also share common aspects with commercial buildings and infrastructure planning—for example, the policy landscape, material intensity and the prioritisation of preservation over new construction;
4. **Consumables**, encompassing a wide range of manufactured product categories like electronics and textiles, for which the volumes of production and consumption (waste) can be reduced through servitisation and the adoption of a minimalist lifestyle.

The table below shows the mapping between the circular strategies and the industries in question.

		Circular flows of Bocken's framework			
Industry	**Interventions**	**Regenerate**	**Cycle/Use waste**	**Slow/Preserve**	**Narrow**
Agrifood	Plant-based diet Balanced diet Advanced biorefinery Local, organic, seasonal food cooperatives	Reducing input of chemical and intensive food production reduces the land degradation	Investment in bio-refinery and other (local) energy recovery facilities	Food distribution before expiry	Reduce excess consumption and avoidable food waste. Reduce distance in supply chain
Mobility	Flex work Car-free lifestyle Modal shift Fleet electrification Durable vehicles	Cleaner energy powering transportation system	Recycling of metallic parts and production of cars with secondary materials	Repair, maintenance, refurbishing, and second-hand	Reduce vehicle ownership and demand for travel, especially with private vehicles
Construction	Cap stock expansion Increase occupancy rates Deep renovation Co-Housing , Multi-functional space District heating	Cleaner energy on the production and consumption side. Prioritise easy materials to recycle.	Demolition and recycling into secondary materials for the construction sector	Renovation and repurposing	Limit the amount of new buildings and increase occupancy rates
Consumables	Durable consumables Material sufficiency	Make cleaner and more recyclable consumables	Collection of hard-to-recycle consumables	Longer life-time service of garments (upcycling, downcycling),	Reduce demand for product with low/limited utility

				electronics, furniture, etc.	
Cross-cutting	Industrial symbiosis electronic waste recycling programme Advanced waste to energy	Make cleaner	Cascading and industrial cooperation on waste management	Rental of machinery for industrial production	Reduce energy consumption

To sufficiently allocate investment to each industry, we need measures of the waste generation volumes, recyclability metrics and other indicators that describe the capacity of the country to handle secondary materials. In this analysis, the allocation of circular investments was based on a participatory process involving local experts, rounded out by our in-house knowledge.

The allocation process is guided by a stakeholders survey aimed at tailoring the approach to the local context. Through the survey, local stakeholders from different sectors and areas of expertise could provide quantitative ranking of the relevance of different circular strategies per industry. Initially, a set of default weights was defined building on our experience with circular strategies. Then, the scores from stakeholders' input were used to calibrate the allocation weights accordingly. For the calibration, the weights were normalised according to the equation below. Note that within this normalisation technique, the sum of all normalised values is zero. The normalised values are then added to the default weights. However, these values were rectified by a scaling factor to avoid negative values in the allocation weights. The value of the factor was determined iteratively, starting from no scaling and reduced gradually until negative values were resolved at a factor of 0.2.

$$cf = \frac{w_{s,i} - \overline{w}_{s,i}}{max(w_{s,i}) - min\,(w_{s,i})}$$

Where :

cf: calibration factor for the allocation weights.

$w_{s,i}$: average allocation weight from local stakeholders' responses per circular strategy per industry.

Step three: Calculating the job creation potential associated with the increased circular activity

In this step, job creation potential is calculated based on the circular investment potential allocated to the *Regenerate* and *Cycle* strategies, where additional workforce is expected to meet the increasing demand for circular products. Mathematically, the circular investment is channelled into compensation for employees, and hence the job creation potential follows the equation below:

$$JCP_{s,i} = CIP_{s,i} \times EM_i$$

Where:

JCP: Job creation potential per industrial sector per circular strategy.

CIP: Circular investment potential per industry per circular strategy (i.e. **N**, **S**, **C** and **R**).

EM: Employment multipliers per industrial sector.

LIMITATIONS OF THE SOCIOECONOMIC ANALYSIS APPROACH

Step one: Quantifying the circular investment potential. This analysis is based on environmentally extended input-output scenario modelling, and hence is limited by the common shortcomings of this method as described in literature.[53] An apparent decrease in economic output is projected by the application of counterfactual scenarios. However, in truth we do not (and cannot) have full clarity on what that change may look like in a future reality. For example, new circular business models may introduce new actors into the value chain, with new services that are not captured by the model. The assumption that the additional tax revenues are equal to the monetary reduction of the output is based on the linearity of the input-output system, but the elasticity of demand is different for every sector. This simplification, however, aims to provide a monetary input to the allocation process rather than estimating the additional monetary resources. The approach does not advocate for harsher tax regimes, but rather a targeted destination of tax revenues to environmental causes and gradual replacement of arbitrary taxation with environmental taxation.

Step two: Allocating the circular investments to the industries through a participatory process. The participatory approach needs to be balanced in terms of sector representation and stakeholder classes (academic experts, authorities and business representatives, for example) to achieve an objective outcome and a fair distribution of resources.

Step three: Calculating the job creation potential associated with the increased circular activity. A limitation of this approach is the focus on additional job creation potential associated with circular activities, without detailed quantification of systemic shifts in the labour market. In this regard, existing jobs need to be protected by law making sure that, as long as the output reduction

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

of sectors does not exceed the operating surplus and hence the capacity of the businesses to compensate their employees, job losses will be prevented. Despite the fact that fiscal reform might cause short-term unemployment in the sectors that are most penalised by taxation, an efficient allocation of investments to re-skilling and to the creation of new jobs in circular sectors can compensate for the expected layoffs. Thus, we believe that a shift in employment will occur in response to the different fiscal regime from the linear to the circular activities. This can either occur within the same sector (such as from production to disassembly of the same product category) or between sectors (such as from extractive sectors to recycling sectors).

THE CIRCULAR JOBS METRIC EXPLAINED

The transition to circularity will inevitably result in changes to the labour market, while changes in the labour market will inevitably determine how effective and quick the transition will be. Our Circular Jobs Metric can help policymakers and other stakeholders tap into the employment potential of the circular economy by showing how jobs contribute to realising various circular strategies—and in which sectors these jobs occur.

In 2020, Circle Economy and Zero Waste Scotland produced a first baseline for employment related to circular activity and explored the implications of the transition to a circular economy for the Scottish labour market.[54] It presented a baseline measurement of the number and geographical distribution of jobs related to the circular economy in Scotland and explored the types of circular jobs, roles and skills associated with opportunity areas across three value chains: construction, bioeconomy and capital equipment. This was based on 2016 data and used the Circular Jobs Methodology, which was developed by Circle Economy in collaboration with Erasmus University Rotterdam.

To estimate circular jobs in that study, we utilised input-output tables, employment data and imported material data to determine how much circular activity is occurring within each economic sector. The Circular Jobs Methodology helps to calculate the share of economic activities, out of the entire sector's transactions, that serve to close material loops, extend product lifetimes and prioritise regenerative resources. The methodology also considers the relationship between enabling and indirectly 'circular' sectors with core 'circular' activities to calculate the share of indirectly circular activities. This helps determine the proportion of employment that takes part in circular activities across the whole economy: eventually translated into a number of circular jobs.

In that methodology, a circular job refers to any occupation that directly involves or indirectly supports one of the strategies of the circular economy. We differentiated between three types of circular jobs: core, enabling and indirectly circular jobs.

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- Core circular jobs are all jobs that ensure the closure of raw material cycles, including jobs in repair, renewable energy, waste and resource management. They form the core of the circular economy.
- Enabling circular jobs are jobs that remove barriers for and enable the acceleration and upscaling of core circular activities, including jobs that arise in leasing, education, design and digital technology. They form the supporting shell of the circular economy.
- Indirect circular jobs are jobs that indirectly uphold the circular economy. These jobs occur in other sectors that do not play a direct role in furthering the transition to the circular economy but can still adopt circular strategies. They include jobs that provide services to core circular strategies, including jobs in information services, logistics and the public sector.

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