CIRCLE ECONOMY

The CIRCULARITY GAP REPORT **NORTHERN IRELAND**

Methodology document

Table of Contents

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).

Executive Summary

This methodology document provides the technical details behind the Circularity Gap Assessment - Circle Economy's (CE) analysis of the circular state of 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 **socio-economic 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 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, inform where the main opportunities for circularity lie in key industrial value chains and set the ground for the development of Circular Economy roadmaps and strategies.

CE's SEM approach is developed around 4 key analytical elements which also constitute the main deliverables of traditional Circularity Gap Reports (CGRs), namely:

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

Figure 1 shows the link between these four deliverables.

---

[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]

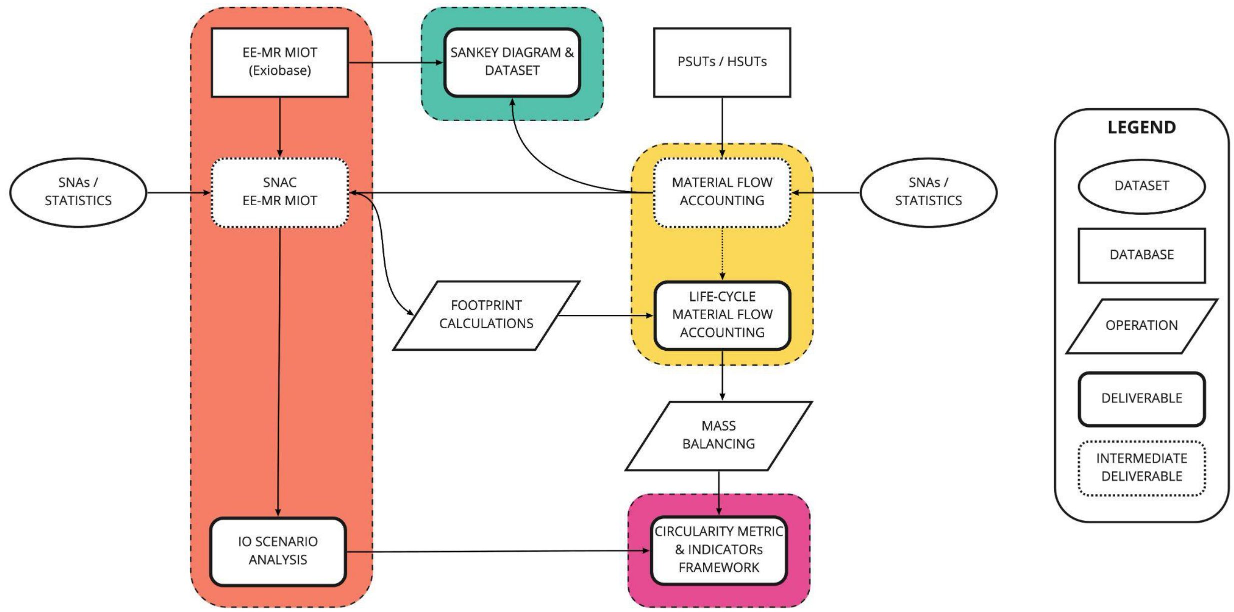

Figure 1. *Flowchart of data sources, operations and deliverables.*

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) (e.g. 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 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

---

[4] CE'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

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].

Finally, 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 to visually link any embodied environmental impact (e.g. resource extraction, greenhouse gas emissions, freshwater use, etc.) to the production and consumption of products and services, thereby unravelling the global footprints (e.g. material, carbon, water, etc.) behind satisfying societal needs of consumers. Ultimately, this allows 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.

Disclaimer: Parts of the methodology refers to or take as an example datasets, accounting conventions and definitions from Eurostat 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.

---

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 e.g. buildings and infrastructures, machinery and durable goods. In EW-MFA this material accumulation is called net additions to stock (NAS). **Table 1** summarises the key variables and derived indicators of EW-MFA framework.

Table 1 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	-

Code	Label	SEEA-CF type of flow	Formula for derived indicator
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 1. 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 Northern Ireland and waste generated through production and use of goods and services needs 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) e.g. fertiliser application; and
- Dissipative losses e.g. emissions to air from automobile tyre; 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 e.g. agricultural produce and imported beverages. Water for other consumptive uses (cleaning or irrigation) and in situ uses (such as hydroelectric power), sometimes known as bulk water in MFAs, will be excluded from these accounts.

Balancing Items and Material Accumulation. The input and output sides of the MFA are balanced to ensure all materials flowing into an economy in one year are accounted for. Balancing items on the input side mainly include oxygen requirements for combustion processes and respiration, nitrogen for 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 longer life products (e.g. furniture, 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 Materials Equivalent (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 of hidden flows are unused extraction from mining and quarrying (also known as overburden), discarded material from harvesting (e.g. wood harvesting losses), and soil and rock moved as a result of construction and dredging. Like indirect flows, these are also estimated using coefficients for biomass and minerals extraction processes.

Circle Economy's MFA approach

European nation states are required to report statistics on the production and trade of manufactured goods annually (known as ProdCom[10] and ComExt[11]). These detailed databases give consistency to EU nation MFAs, allowing great comparability. The EU-MFA Questionnaire[12] and guidance is a fully functioning template for conducting MFAs. The EU-MFAs do not include indirect flows, hidden flows, stock and net additions and subtractions.

---

[10] Eurostat. (n.d.). Prodcom. Retrieved from: Eurostat website

[11] Eurostat. (n.d.). Comext. Retrieved from: Eurostat website

[12] Eurostat. (2013). Economy-wide material flow accounts (EW-MFA) - Questionnaire. Retrieved from: System of Environmental-Economic Accounting (SEEA) website

The CE's MFA model is based on the EU-MFA approach[13], utilising the most reliable international data sources and allowing consistency and comparability with EU nations. In a similar approach to that developed by Finland[14] and Denmark[15] the CE's model has extended the EU-MFA one. Indirect flows, stocks and net additions and subtractions are included (although, hidden flows were excluded at this time as data, thus far, remains insufficient). The Environmentally Extended Multi-Regional Input/Output (EE-MRIO) database Exiobase v3.8.1 and territory-specific datasets are used to do this.

Material performance indicators are the building blocks needed to calculate the Circular Economy Indicators Framework (see Chapter 5). In the context of CGRs, there are 3 possible cases under which the calculation of EW-MFA indicators may occur:

1. *All indicators already available at the required level of detail:* This is the case, for instance, of all EU28 nations for which Eurostat has already calculated the full indicator set until 2018. No further analytical effort is needed in this case;
2. *Some indicators available or available but not at the required level of detail:* This is the case of countries for which, for instance, DMC is available but DPO or NAS are not. Here, a *streamlined approach* can be taken whereby DPO and BIs only are estimated using the best available data in order to derive NAS;
3. *Most or no indicators available:* This is often the case in **sub-national** assessments - such as the one for **Northern Ireland** - where only partial DE or trade data is available. Here, **CE's Material Flow Accounts Model** needs to be used to develop the accounts from scratch and calculate the derived indicators.

CE's MFA model was developed to be applied at both national and sub-national levels and is based on the following flows:

1. **Domestic Extraction** (natural resources extracted from the nation/sub-national environment);
2. **Imports** (of raw materials, finished and semi-manufactured products and potentially waste);
3. **Exports** (of raw materials, finished and semi-manufactured products and potentially waste);
4. **Domestically Processed Outputs** (waste and emissions generated through production and consumption, as well as dissipative uses and losses[16]); and
5. **Balancing Items on Input and Output sides** (which are needed to establish economy wide material balance, e.g., oxygen used up and water vapour generated in combustion processes).

MFAs show material flows of traded materials in two ways. Either the mass of the materials traded are quantified or the mass of all raw material inputs required to produce traded materials are quantified. The former is known as **physical flows** and measured with the MFA indicator **Domestic**

[13] Eurostat. (2020). Material flows and resource productivity. Retrieved from: Eurostat website
[14] Statistics Finland. (2018). Economy-wide material flow accounts. Retrieved from: Statistics Finland website
[15] Denmark statistics Denmark. (2020). Economy-wide material flow accounts. Retrieved from: Statistics Denmark website
[16] Dissipative uses of products and dissipative losses are defined as materials which are dispersed into the environment as a deliberate or unavoidable consequence of product use e.g. fertiliser use, tyre abrasion.

Material Consumption (DMC). The latter is known as the **Raw Material Equivalents (RME)** and measured with the indicator **Raw Material Consumption (RMC)**. CE's MFA includes estimates of both physical flows and raw material equivalents as both are useful indicators for understanding a territory's material impacts. MFA results are also commonly presented as a set of six indicators that measure the resource burden for the economy (see **Table 1** and **Figure 2**).

These MFA indicators can be compared to other ones related to the economy, as well as to each other. For example, resource productivity is a measure of the total amount of materials used by an economy in relation to GDP. Trends in resource productivity can be shown once MFA indicators have been established.

Figure 2 shows the relationship between MFA indicators.

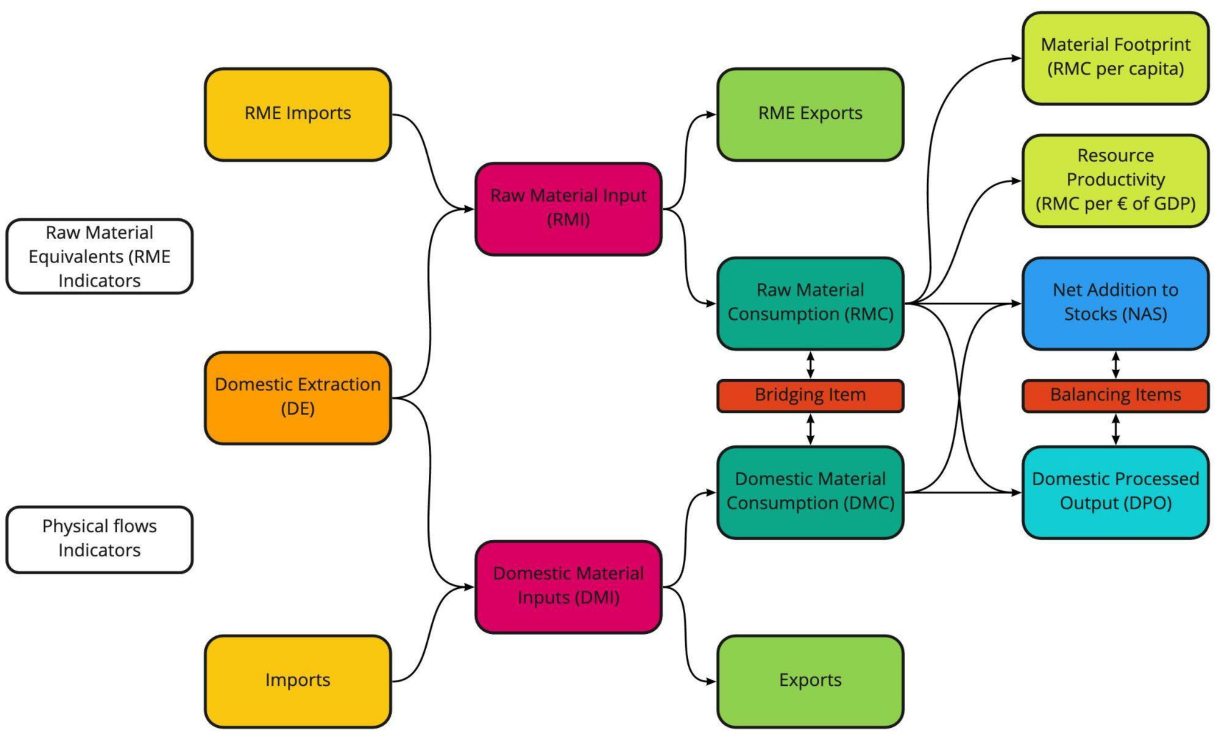

Figure 2. Relationship between MFA indicators.

If material consumption reduces compared to GDP, this is known as decoupling. Decoupling may indicate the possibility of environmental sustainability without economic loss. MFA indicators can be used to show whether decoupling is happening at a territorial scale.

Box 1. Key terms for CE's Material Flow Accounts Model

Decoupling A trend where two variables which previously aligned, separate. Of most interest for the Scottish MFA, is whether material consumption can decrease whilst GDP rises.

Domestic Extraction (DE) The raw materials from the national natural environment, such as fish, oil and stone, which are inputted into the same economy.

Domestic Material Consumption (DMC) The mass of material used in an economy including imports and exports based on the physical mass of the materials traded. The mass of raw material required to produce traded materials are not included.

Domestic Material Inputs (DMI) The mass of materials which enter the economy including domestically extracted and imported material.

Inter-regional trade Transaction of materials to and from a sub-national entity with the rest of the nation. This is embedded in the CE's MFA model separately from trade with the Rest of the World (RoW). As most of sub-national trade is with the rest of the country, this extra level of detail is required to ensure the accuracy of the model.

Material Footprint (MF) The average tonnes of materials, including raw material requirements for traded materials, used per person per year in an economy. This is the Raw Material Consumption (RMC) per capita. It is a similar concept to a carbon footprint for a nation, which shows greenhouse gas emissions per person.

Physical flows The mass of materials imported and exported to and from an economy based on the mass of the materials being traded. It excludes the raw materials required to produce traded materials.

Raw Material Inputs (RMI) The mass of materials which enter the economy including domestically extracted, imported material and the raw materials extracted to produce them. It represent the Total Material Requirement of an economy

Raw Material Consumption (RMC) The mass of material used in an economy to satisfy domestic consumption including imports and exports and the raw materials extracted to produce the traded materials. The asymmetry between domestic extraction and physical trade means a country could significantly reduce its DMC without reducing worldwide demand for material resources. RMC allows for a more complete measurement of material consumption.

Raw Material Equivalents (RME) Factors used to estimate the raw material extraction requirements for all traded materials and products. The CE's MFA uses RME factors derived from the Multi-Regional Environmentally-Extended Input-Output (MR-EEIO) model Exiobase v3.8.1.

Developing a comprehensive MFA at the sub-national level requires bringing together several separately developed data sources. Reliable primary data is used where available. Where source data is converted for use in CE's MFA model, this process is clearly documented. The choice to convert certain data is also justified, and assumptions made clear, with the output evaluated for quality through the Red-Amber-Green (RAG) status (**Table 2.1**). Remaining data gaps or uncertainties are clearly identified to allow continual improvement of the methodology in future. As with other MFAs, materials are grouped into four primary categories while maintaining a practical level of resolution. Final material flows are presented for the four primary categories and relevant sub-categories. **Table 2.2** provides a template for summarising the main data sources used.

Status	RAG status classification
Green	Reliable data that is up-to-date - annually updated territorial data
Amber	Potential inaccuracies - national data scaled to regional level or territorial data not updated annually
Red	Likely inaccuracies - all other data

Table 2.1 RAG status classification.

Data requirement	Sources	RAG status
Domestic extraction, biomass: crops Domestic extraction, biomass: crop residues	Quantities of the main products in output: https://www.daera-ni.gov.uk/publications/quantities-main-products-output-1981-onward Statistics on crop production: https://www.daera-ni.gov.uk/publications/statistics-crop-production-form-1981 Crop and grass areas: https://www.daera-ni.gov.uk/publications/crop-and-grass-areas-1981-crops-2014	Green
Domestic extraction, biomass: wood	Wood Production: https://data.gov.uk/dataset/56f8153b-55b7-4112-87ec-e362561603da/wood-production-roundwood-removals-1976-to-2017-provisional	Green
Domestic extraction, biomass: Fish (incl. Feedstock requirements)	Fish landing tables: https://www.daera-ni.gov.uk/publications/fish-landings-northern-ireland Aquaculture production: https://www.seafish.org/document/?id=4382B7AA-FFCE-448B-850D-46A8F7959115	Green
Domestic extraction, biomass	Animal population: https://www.daera-	Green

Data requirement	Sources	RAG status
(grazed biomass and manure): live animals	ni.gov.uk/publications/farm-animal-population-data Farm animal populations: https://www.daera-ni.gov.uk/publications/farm-animal-population-data	
Domestic extraction, metal ores	D4E Annual Mineral Statements: https://www.economy-ni.gov.uk/publications/annual-minerals-statements Peat extraction: http://www.niassembly.gov.uk/globalassets/documents/raise/publications/2017-2022/2021/aera/3221.pdf	Amber
Domestic extraction, non-metallic minerals		
Domestic extraction, fossil fuels	Energy in Northern Ireland: https://www.economy-ni.gov.uk/sites/default/files/publications/economy/Energy-In-Northern-Ireland-2020.pdf	Amber
Imports and exports	*Method 1:* Primary data from local database (HMRC): https://www.uktradeinfo.com/trade-data/rts-custom-table/ *Method 2:* Downscaling from upper scale using proportions derived from monetary IOTs UK data from COMEXT: http://epp.eurostat.ec.europa.eu/newxtweb/ Northern Ireland's I-O Tables: https://www.nisra.gov.uk/statistics/economic-accounts-project/analytical-input-output-tables	Green
Raw material equivalents of imports and exports	Single National Account Consistent Exiobase v3.8.2	Green
Emissions to air	NAEI Air Emissions by Source: https://naei.beis.gov.uk/reports/reports?report_id=1010 NAEI GHG Inventory http://naei.beis.gov.uk/reports/reports?report_id=991	Green

Data requirement	Sources	RAG status
Emissions to water	E-PRTR Pollutant Release: https://prtr.eea.europa.eu/#/pollutantreleases	Green
Waste	Annual waste data from Northern Irish government on the amount and treatment routes of waste volumes	Amber
Dissipative use of products and dissipative losses	Various sources	Amber

Table 2.2 Summary of the main data and sources used in CE's MFA model (n.a. - not applicable).

Extended MFA framework

While the EU-MFA approach provides a standardardised way to quantify key material flows and stocks and related indicators, it sometimes falls short in describing the link between all the datasets employed and reconciling them. The extended framework for an economy-wide CE assessment developed by Mayer et al. (2018)[17] is "*a framework for a comprehensive and economy-wide biophysical assessment of a CE, utilizing and systematically linking official statistics on resource extraction and use and waste flows in a mass-balanced approach*" (**Figure 3**). Built upon the EU-MFA approach, it expands by integrating waste flows, recycling, and downcycled materials (see **Chapter 5**). Based on such a 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 is 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[18].

Figure 3 represents the framework and throughput indicators for an economy-wide CE assessment.

---

[17] 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

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

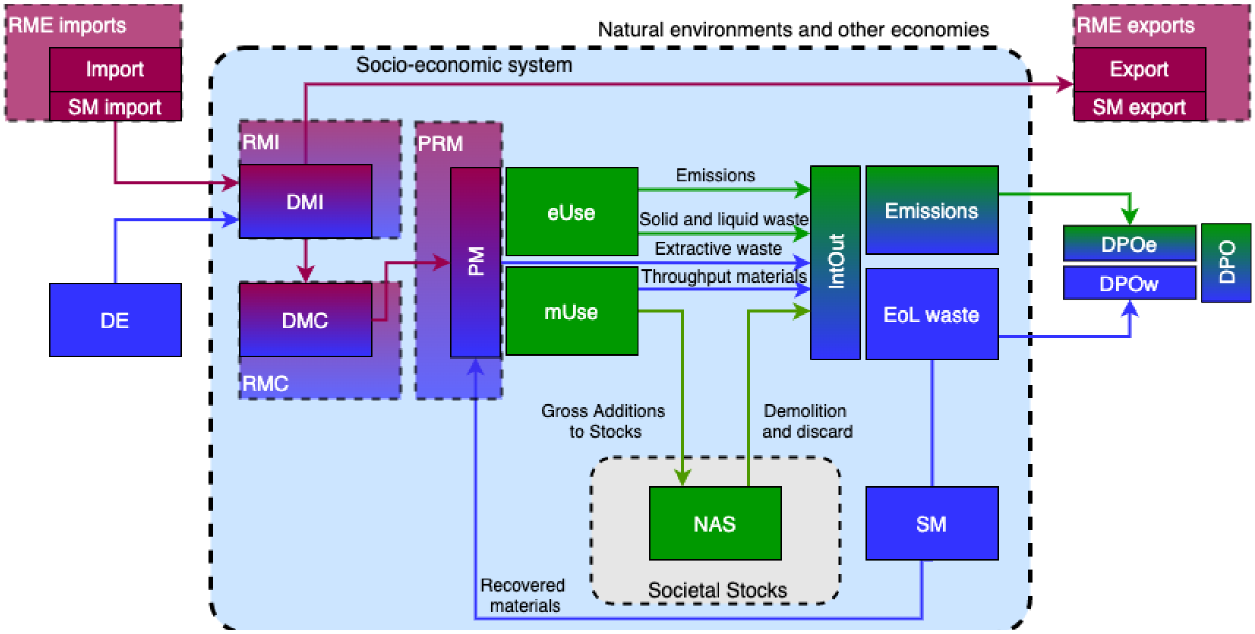

Figure 3. *Framework and throughput indicators for an economy-wide CE assessment. This framework applies from individual materials (e.g., DE of corn or iron) to aggregated material categories (e.g., PM of biomass, fossil energy carriers) to the total material level (e.g., total DE). Colours indicate data sources used: 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.*

The accounting framework shown in **Figure 3** traces materials by main material groups from their extraction to major uses within the socioeconomic system and towards discard and either material recovery or deposition to nature as wastes and emissions. The main physical stages of the flow of materials through the entire system are marked by throughput indicators, represented as boxes. These include the source of material inputs (e.g., domestic extraction, imports), major material transformation processing stages within the system (e.g. processed materials, energetic and material use, in-use stocks of materials, waste treatment, EoL waste) and the destination of outflows (e.g., exports, domestic processed output to the environment). Flows of materials are displayed as arrows between these boxes; the colours of flows indicate the type of data source.

Processed materials (PMs) were defined as the sum total of DMC and secondary material (SM) inputs. PMs were allocated to either energetic or material use. 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. mUse was split into extractive waste, materials used for stock building (i.e., gross additions to in-use stocks of materials [GAS]), and throughput materials. Extractive waste refers to waste material that occurs during early stages of the processing of domestically extracted ores and directly goes from PM to interim output (IntOut). Stock building materials comprise all materials that accumulate in buildings, infrastructures, or durable goods with a lifetime of more than one year (e.g., concrete, asphalt, or steel). The share of stock-building materials in mUse was estimated based on information from industry and production statistics, results from material flow studies and assumptions. 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 3**. IntOuts were split into emissions, comprising all gaseous emissions (e.g., carbon dioxide [CO2], sulphur dioxide [SO2], methane [CH4]) including water vapour and into EoL waste, including all solid (and liquid) outputs. Information on outflows was either sourced from Eurostat waste statistics or modelled and mass-balanced with input flows. Emissions cannot be recycled and go straight into domestic processed output (DPO). A fraction of total EoL waste, reported as RCV B – (recovery other than energy recovery—backfilling) and RCV O (recovery other than energy recovery—except backfilling) in Eurostat waste statistics (env_wastrt), is reentering socioeconomic processes as secondary materials. The remaining EoL waste (after subtracting SM) is returned to the environment as DPO waste and either landfilled, incinerated, or deliberately applied (e.g., 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 1) and mUse (equation 2).

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

We assumed that all materials used to provide energy were converted into DPO emissions (including water vapour) and solid waste within the year of extraction. We used data for solid waste from combustion reported in waste statistics and estimated the amount of solid waste from human and animal metabolism (excrements) by applying appropriate coefficients reflecting the non digestible fraction of food and feed intake. DPO emissions were then calculated as the difference between eUse and the outflow of solid waste. Note that so-called bal- ancing items (oxygen uptake from air during combustion and water consumed by humans and livestock) were excluded. This means that all outflows from eUse include only the materials contained in actual inputs as composed in PM (e.g., CO2 or SO2 in terms of C or S content; excrements at the average water content of food and feed intake). Closing the mass balance for eUse in this way implies that all inaccuracies in statistical data and assumptions that result in inconsistencies between input and output flows accrued in DPO emissions (DPOe). For the combustion of fossil energy carriers we cross-check the calculated DPO emissions with data from emission statistics.

Due to a lack of knowledge of actual in-use stocks, we used the following approach to close the material balance: In a first step, a consistent split of total EoL waste from mUse into waste flows resulting from discard and demolition and throughput materials was required. Total EoL waste from mUse was derived from waste statistics. While waste statistics report information on construction and demolition waste, this waste flow was not fully consistent with EoL waste from discard and demolition, which also contains waste flows from discarded long-living products such as furniture, cars, or electric appliances. In a second step, we calculated the amount of discard and demolition as the difference between EoL waste from mUse reported in waste statistics and the fraction of throughput materials (i.e., materials with a life span < 1 year) in mUse (e.g., waste from packaging, paper, food waste, etc.). In a 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[19] 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.

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 control variables) that deviate from the original estimates. In order to minimise this difference, an 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 (e.g. 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[20].

Imported and exported secondary materials (e.g. 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 5 for more details).

[19] Regulation (EC) No 2150/2002; see European Commission and Eurostat (2013).

[20] It should be noted the treatment route of such unreported waste remains unspecified.

3. Input-Output Analysis

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

Of the available multiregional EEIO databases (EE-MRIO), EXIOBASE stands out as a database compatible with the SEEA with a high industrial detail matched with multiple social and environmental satellite accounts. EXIOBASE represents the production and consumption of 164 industries and/or 200 economic goods for 43 countries and 5 rest-of-the-world 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[21], 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 materials extraction are 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[22]. Industry allocations of the baseline year 2011 have been applied under the assumption that the structure of the extractive industries has not radically changed in the last decade. This operation allows us to calculate reasonably robust material footprint accounts up until the year 2017, under a defined set of assumptions (e.g. 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 is also a projection based on 2014 data.

All calculations are performed using the open source tool for analysing global EE-MIOTs, **pymrio**[23]. Production- and consumption-based accounts are calculated using a standard set of IO formulas as specified below and in **Table 3.**

$$D^i_{cba} = D^i_{pba} + D^i_{imp} - D^i_{exp}$$
$$D_{pba} = Fe + Ge$$

[21] (2020). EXIOBASE 3. doi:10.5281/zenodo.4277368

[22] International Resource Panel. (n.d.). Global Material Flows Database. Retrieved from: International Resource Panel website

[23] Pymrio. (n.d.). pymrio - multi regional input output analysis in python. Retrieved from: pymrio website

$$D_{imp} = MY_t$$
$$D_{exp} = \widehat{MY_t e}$$

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	$L = (I - Z\widehat{x}^{-1})^{-1}$	Total requirements matrix
Factor production coefficients	$S = F\widehat{x}^{-1}$	–
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	$Y_t = Y - Y_{i,j} \| i = j$	Final demand matrix with domestically satisfied final demand set to zero

Table 3. Description of main pymrio variables

Note: the $\widehat{\ }$ 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[24] [25] [26] [27] [28]. According to Tukker and colleagues[29] [30], there are several approaches to the calculation of footprints and the one employed in this study can be regarded as a variation of method 6, 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[31] [32]. For an exhaustive explanation of the SNAC procedure refer to Edens et al. (2015)[33].

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

---

24 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

25 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.

26 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

27 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

28 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

29 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

30 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

31 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

32 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

33 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

accounting model. This step is highly recommended when implementing a top-down trade and 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 (e.g. Interindustry imports vectors as well as matrices) at different scales (e.g. 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[34] 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 Northern Ireland** - 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[35];

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 2 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;

---

34 Source

35 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

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 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 which cases 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" (e.g. "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 Northern Ireland**;

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 of no available information.

In all sub-national cases in which only one or more vectors of imports are provided, e.g. vectors of imported commodities by trading partners, the original 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

EEIOA can be applied to assess the economic and environmental implications of a transition towards a circular economy[36]. IOA, in its various forms, is a static structural model which provides a high resolution of sectors and structural economic composition and makes it a useful tool for the impact assessment of supply-chains. As such, it is a suitable model for the creation of "what-if" scenarios through the application of exogenous changes. One of the advantages of this type of approach is the level of transparency in assumptions. This is especially important for CE impact assessment as the variety of approaches makes it difficult to compare studies. Previous studies have tried to categorize types of interventions within CE, their fundamental waste management models and indicators. However, there is still a need for current CE assessment methods to become more comparable and robust in order to serve as policy tools.

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

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[37] [38] [39], a new comprehensive CE policy modelling framework is developed. We begin by asserting that the objective of a CE policy is always the implementation of the circular economy paradigm. In order to achieve this objective different strategies exist. There are various categorizations of CE strategies such as ReSOLVE[40] [41]. 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)[42].

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 the product's life, the way they are implemented is different. We further distinguish between a general description of interventions and specialised interventions. An intervention (e.g. reuse and remanufacturing) is specialized when it refers to a specific product or application (e.g. increase lifetime through reuse and remanufacturing in final consumers' vehicles). Interventions are modelled through sets of changes that affect the production and consumption systems. We further distinguish between primary and ancillary changes. For instance, if the intervention concerns increasing the life-time of vehicles the primary change would be a reduction of sales of vehicles resulting from less consumers needing to replace their vehicles. A corresponding ancillary change would be the potential increase in repairing services caused by a higher utilisation of the good. We show this conceptual approach in **Figure 4**.

[37] 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

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

[39] 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

[40] MacArthur, E. (2013). Towards the circular economy. Journal of Industrial Ecology, 2, 23-44.

[41] 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

[42] Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: measuring innovation in the product chain*. Retrieved from: PBL website

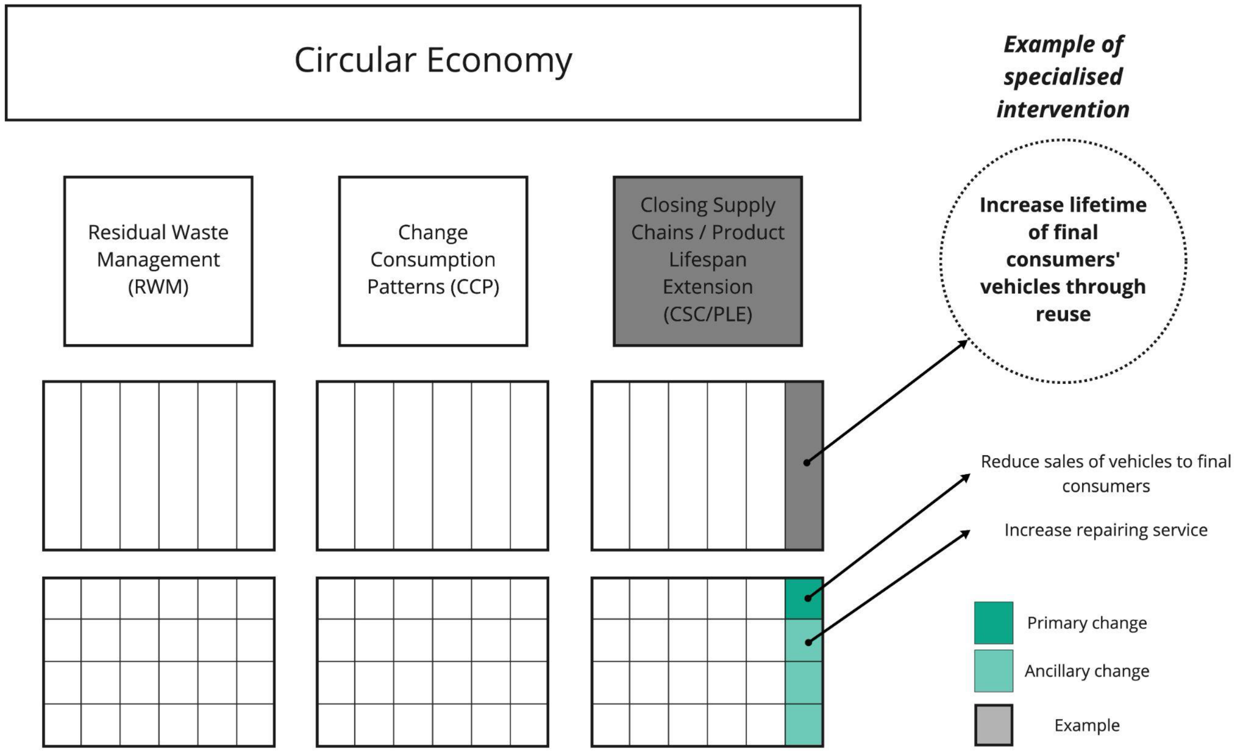

Figure 4. Circular Economy policy modelling framework.

Hereby, we present systematic methods to build complex CE 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 3** where D_{cba}^{i} is the column vector of impacts occurring in each production sector (the response variable) and Y_e^i 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 (e.g., global warming) there are direct emissions resulting from final consumption activities (e.g., 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 transpose. If more information is available, the intensity of final consumption environmental pressures 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 (e.g., EU or Rest of the World).

In order to assess the environmental or socio-economic impact of implementing a CE 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 CE intervention and strategy have been implemented. More formally, the impact of the CE 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**[43] 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 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 (e.g. steel) used in a production process might be compensated by an increase of another (e.g. aluminium). This type of relation is modelled as:

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

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

Here mn are the coordinates of the original change (e.g., reduction in steel) and ij are the coordinates of the substitution (e.g., increase in 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 (e.g. 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.

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)[44] and previous research.[45] [46] [47] It 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[48]; 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;

---

[44] 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

[45] 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

[46] 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

[47] 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

[48] 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 and IntOut:

1. The socioeconomic cycling rates measure the contribution of secondary materials to PM (**input socioeconomic cycling rate [ISCr]**) - *calculated based on both DMC and RMC* - and the share of IntOut that is diverted to be used as secondary materials (**output socioeconomic cycling rate [OSCr]**). Recycled waste from material processing and manufacturing (e.g. recycled steel scrap from autobody manufacturing) is considered an industry internal flow and not accounted for as secondary material. In this model of the physical economy secondary materials originate from discarded material stocks only. The outflows from the dissipative use of materials and combusted materials (energy use) can, by definition, not be recycled. This assumption may lead to a minor under-estimation of downcycled materials, when solid wastes from the combustion of fossil materials are used in construction. Energy recovery (electricity, district heat) from the incineration of fossil or biomass waste is not considered as recycling since it does not generate secondary materials;

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

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

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

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

6. Finally, the difference between RMC and DMC is referred to as net extraction abroad (NEA) and it is used as a bridging item rather than an actual indicator (see **Figure 2**). The reason for this is that while the original indicator framework is calculated over PMs, in CGRs this is also done over PRMs. The latter has the advantage of taking a life-cycle perspective and reallocating raw material extraction to the point of final consumption; however it has the disadvantage of introducing an overlap in the system boundary definition which is not straightforward to reconcile. Calculating indicators on PRM the same way as on PM, would imply extending assumptions that are supposedly valid only within the system boundary definition (the economy under analysis), outside of it (all the other economies). As an example, let's consider the estimation of the non circular flows: The eUse fraction of fossil fuels in PM is made of the actual fuels (e.g. gasoline, diesel, kerosene) that are being burned so the identification of their use is straightforward. However, the eUse fraction of fossil fuels in PRM accounts for the raw materials (e.g. petroleum) across all kinds of products and applications, thus not necessarily related eUse. Therefore, we introduce a bridging item and refer to it as the **net extraction abroad rate (NEAr)**. When NEAr is negative, it means that the economy under study extracts more resources to satisfy final demand abroad than those extracted abroad to satisfy domestic final demand. Another issue related to using RMEs rather than physical flows is that it is hard to track the fate of raw materials extracted abroad and that are not embedded into the traded commodity, but rather transformed into waste and emissions during processing.

	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 4. Mass-based circular economy indicators where scale indicators measure the absolute size of input and output flows in tons and circularity rates measure socioeconomic and ecological cycling relative to input and output flows in percentage (n.a. = not applicable).

It should be noted that for simplicity, so far we have considered net the amount of traded secondary materials as part of DMC despite these flows being explicitly quantified and treated in CE's MFA model. The estimation of imported and exported secondary materials is based on the methodology developed by Eurostat and used in the calculation of the circular material use rate (CMUr)[49]. Let's consider ISCr - the share of secondary materials in PRM - and re-write it in mathematical terms:

$$ISCr = SM/PRM$$

Where:

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

$$PRM = DMC + NEA + SM$$

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

To avoid double counting we rewrite DMC in its normal form

$$DMC = DE + IMP - EXP$$

then $ISCr$ can be rewritten as:

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

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

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

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

In this respect, it was decided that the ISCr rate measures a country's effort to deploy secondary materials. This perspective credits the country's effort to produce secondary material from recycled waste as opposed to gathering waste bound for recovery which indirectly contributes to the worldwide supply of secondary materials and hence avoidance of primary material extractions. Remarkably, this is the opposite perspective than the one taken by the Eurostat's CMUr.

The ISCr rate indicator is based on 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 1, 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 after treatment fed back to the economy (material flowing through the legally demarcated waste management system);
- Residual material, outside the legal waste coverage (outside the waste management system), generated e.g. as by-product during certain production processes, and fed back into the economy. This category can further be distinguished into:
    - Residual material subject to economic transactions between establishments;
    - Intra-establishment flows

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

Hence, SM_{dom} is approximated using waste statistics collected or presented based on 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 produce secondary materials, including waste collected in another country and later imported for domestic deployment. Consequently, the total amount of recycled waste in treatment operations is adjusted as follows:

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

with:

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

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

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

In order to calculate the amounts of imported waste (SM_{imp}) and exported waste (SM_{exp}), Eurostat has identified the CN-codes which can be considered trade in waste[50].

[50] 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. Since 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[51]. Underlying the Python library, a common data structure for flow data is defined, through which this method can be used to generate Sankey diagrams from different data sources such as material flow analysis, life-cycle inventories, or directly measured data[52].

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” are 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. 2017[53] through a concordance matrix describing the assignment of EXIOBASE product sectors across consumption domains at the final demand level.

---

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

52 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

53 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