The CIRCULARITY GAP REPORT Switzerland

Methodology Document

Circle Economy
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CIRCLE ECONOMY

Contents

List of abbreviations and acronyms

CE: Circular economy

CGR: Circularity Gap Report

CM: Circularity Metric

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

EW: Economy-wide

GDP: Gross domestic product

HSUT: Hybrid supply and use tables

IE: Industrial ecology

LCA: Life cycle assessment

MFA: Material flow analysis

MFAC: Material flow accounting

NSI: National statistical institute

PSUT: Physical supply and use tables

RME: Raw material equivalents

SEM: Socioeconomic metabolism

SEEA: System of Environmental-Economic Accounting

SNA: System of National Accounts

SNAC: Single national account consistent

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. [1]

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

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

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

Global warming potential (GWP) 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.[3]

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. [4]

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.[5]

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. [6]

Socioeconomic metabolism constitutes the self-reproduction and evolution of the biophysical structures of human society. It comprises the biophysical transformation processes, distribution processes and flows, that are controlled by humans for their purposes. Together, the biophysical structures of society ('in use stocks') and socioeconomic metabolism form the biophysical basis of society.[7]

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.

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

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

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

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

[7] 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

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.[8]

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.[9]

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).[10]

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

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

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

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

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 aligned with the classifications 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 analysis of the circular state of an economy, and its application for the *Circularity Gap Report Switzerland*. 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 include material flow accounting and analysis (MFA), life cycle assessment (LCA) and environmentally-extended input-output analysis (EE-IOA).

A theoretical cornerstone of IE is the concept of **socioeconomic metabolism (SEM),** the '*evolution of the biophysical structures of human society, including those biophysical transformation processes, distribution processes, and flows, which are controlled by humans for their purposes and that forms the biophysical basis of society*'.[11] [12] 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'*.[13]

SEM analysis is critical to the understanding of the current state of circularity across the key industrial value chains of an economy. It provides a systematic approach to the definition of systems and their boundaries, and enables us to pinpoint linear hotspots by tracing flows and stocks of materials and assessing their impacts. The aim of this 'diagnosis' is to 1) measure and monitor an economy's circularity across its industrial transition to a circular economy, 2) uncover where the main opportunities for circularity lie in key industrial value chains, and 3) set the ground for the development of circular economy roadmaps and strategies.

Circle Economy's SEM approach, which is visualised in **Figure one**, has been developed based on four key analytical elements. These also constitute the main components of traditional *Circularity Gap Reports* (CGRs), namely:

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[11] 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.

[12] Pauliuk, S., & Hertwich, E. G. (2015). *Socioeconomic metabolism as paradigm for studying the biophysical basis of human societies*. Ecological Economics, 119, 83-93.

[13] 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.

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)

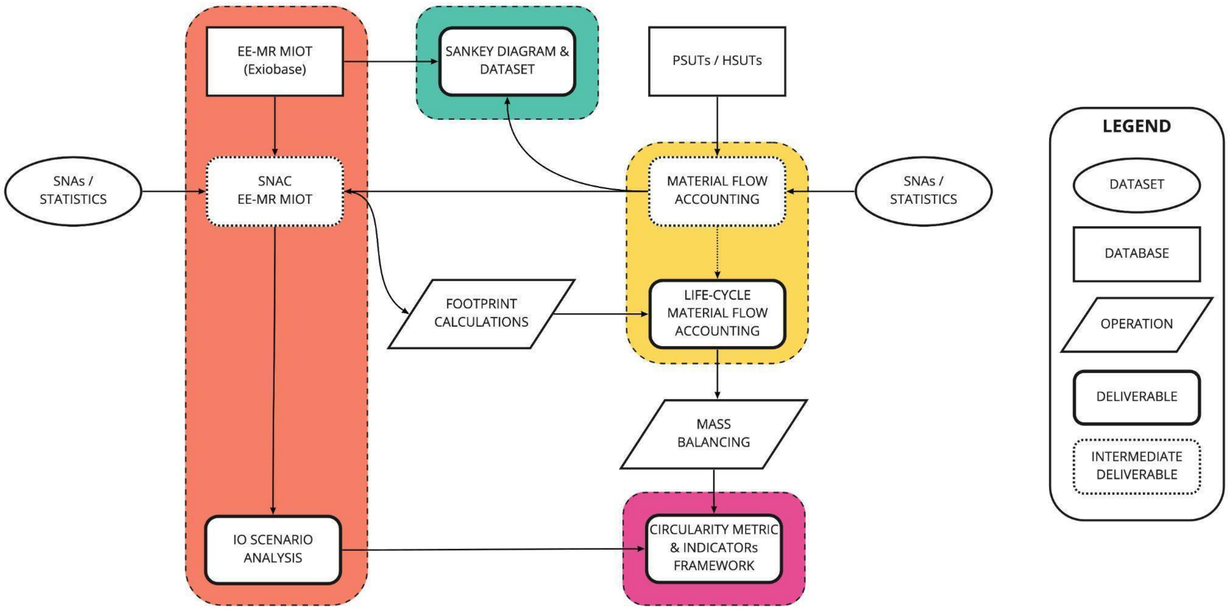

Figure one. Flowchart of data sources, operations and deliverables.

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

Statistics from NSIs and PSUTs are the preferred sources for physical input and output data used in the MFAc (for example, the extraction of resources, trade of physical commodities, waste, emissions, etcetera). Economy-wide MFA[14] (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

[14] CE's application of Material Flow Accounting is performed on the basis of the latest edition of Eurostat's Handbook of Material Flow Accounting which can be accessed at: Eurostat Handbook

for single countries, in an approach referred to as single-nation account consistent (SNAC) footprinting.[15] A similar approach is applied for sub-national regions, 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 the scenario analysis (ScenAn), which builds on a growing research stream that attempts to model circular economy interventions from a macroeconomic perspective.[16] [17] [18]

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.[19] Using Sankey diagrams to depict an IO database allows us to visually link any embodied environmental impact (such as resource extraction, greenhouse gas emissions, freshwater use, etcetera) to the production and consumption of products and services, thereby unravelling the global footprints (for materials, carbon, water, and so on) behind satisfying consumers' societal needs. Ultimately, this allows us to connect the ecological with the social—as well as the local with the global—side of the current environmental crisis and give insights into the challenges of creating an ecologically safe and socially just planet.

Disclaimer: Parts of the methodology refer to or make examples out of Eurostat datasets, accounting conventions and definitions, as this is the most important source of data within the EU. While not all dataset characteristics and accounting conventions are the same in other countries, it is assumed that most of the challenges and limitations are shared across statistical institutes.

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[15] 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

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

[17] 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. doi:10.1111/jiec.12702

[18] 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. doi:10.1016/j.ecolecon.2019.05.002

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

Methods and Frameworks

1. Material flow accounting

Economy-wide material flow accounts (EW-MFA) are a statistical accounting framework describing an economy's physical interaction with the natural environment, and with the rest of the world economy, in terms of material flows. They are a useful framework to derive a high-level overview and understanding of the socioeconomic metabolism (SEM) of the system being analysed. 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 materials originating from within a country's borders;
- Physical imports (all goods and materials) 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 materials in an economy in the form of, for example, buildings and infrastructure, machinery and durable goods. In EW-MFA, this material accumulation is called net additions to stock (NAS). **Table one** summarises the key variables and derived indicators of the EW-MFA framework.

Table one. Key EW-MFA variables and derived indicators.

Code/Symbol	Label/Name	SEEA-CF type of flow	Formula for derived indicator
DE	Domestic extraction	Natural input	-
IMP	Imports	Product	-
EXP	Exports	Product	-
DPO	Domestic processed output	Residual	-
BI_in	Balancing items (input side)	Natural input	-
BI_out	Balancing items (output side)	Residual	-
DMC	Domestic material consumption	n.a.	*DMC = DE + IMP -EXP*
DMI	Domestic material input	n.a.	*DMI = DE + IMP*
PTB	Physical trade balance	n.a.	*PTB = IMP - EXP*
BI	Balancing items (input—output)	n.a.	*BI = BI_in - BI_out*
NAS	Net additions to stock	n.a.	*NAS = DMC + BI - DPO*

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

Domestically processed outputs (DPO). Consumption of materials by people in Switzerland and waste generated through the production and use of goods and services must be part of the material flows account, including:

- Direct emissions to air and water;
- Dissipative use of products (where materials are dispersed into the environment through their use), such as fertiliser application, and;
- Dissipative losses, such as emissions to air from automobile tyres; and brake wear and road abrasion.

The scale of water use is so significant that including its mass in MFAs obscures other resource use. For this reason, standard MFA practice is to only include the water mass contained in products: for example, 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 that all of the materials flowing into an economy in one year are accounted for. Balancing items on the input side mainly include oxygen requirements for combustion processes and respiration, nitrogen for the production of ammonia, and water requirements for the domestic production of exported beverages. Balancing items on the output side mainly include water vapour generated through 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 NAS). This includes materials that are retained within the economy in the form of buildings, infrastructure and longer life products (such as furniture or electronics). Landfilled waste is also considered to be a stock, as 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 one tonne of imported canned fish, the upstream raw material requirements are the fish, metal cans and the fossil fuel energy used to produce the canned fish. As these upstream raw material requirements are not exactly known, they are estimated based on input coefficients for different production processes, also known as Raw Material 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 Circle Economy's MFA). Examples of hidden flows are unused extraction from mining and quarrying (also known as overburden), discarded material from harvesting (such as wood harvesting losses), and soil and rock moved due to construction and dredging. Like indirect flows, these are also estimated using coefficients for biomass and minerals extraction processes.

2. Circle Economy's MFA approach

European Union Member States are required to annually report statistics on the production and trade of manufactured goods (known as ProdCom[20] and ComExt[21]). These detailed databases give consistency to MFAs for EU Member States, allowing high comparability. The EU-MFA Questionnaire[22] 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.

Circle Economy's MFA model is based on the EU-MFA approach,[23] which utilises the most reliable international data sources and allows for consistency and comparability between EU Member States. In a similar approach to that developed by Finland[24] and Denmark,[25] Circle Economy's model has extended the EU-MFA model. Indirect flows, stocks and net additions and subtractions are included, as well as some flows that were originally hidden that have been assessed in our analysis. However, estimating all hidden flows is not possible: in some areas, data is insufficient. To further assess these hidden flows, we rely on the Environmentally Extended Multi-Regional Input/Output (EE-MRIO) database Exiobase v3.8.2, and territory-specific datasets.

Material performance indicators are the building blocks needed to calculate the Circular Economy Indicators Framework (see Chapter five). In the context of CGRs, there are three 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 EU27 Member States, 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 **Switzerland,** 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 where only partial DE or trade data is available. Here, **Circle Economy's MFA model** needs to be used to develop the accounts from scratch and calculate the derived indicators.

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[20] Eurostat. (n.d.). Prodcom - Statistics by products - Overview. Retrieved from: ProdCom Overview
[21] Eurostat. (n.d.). Focus on Comext. Retrieved from: ComExt Overview
[22] Eurostat. (2013). Economy-wide material flow accounts. Retrieved from: MFA Questionnaire
[23] Eurostat. (2020). Material flows and resource productivity. Retrieved from: Eurostat EW-MFA
[24] Statistics Finland. (2018). Economy-wide material flow accounts. Retrieved from: Statistics Finland website
[25] Statistics Denmark. (2020). Economy-wide material flow accounts. Retrieved from: Statistics Denmark website

Circle Economy's MFA model was developed to be applied to 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[26]); and
5. **Balancing items on input and output sides** (which are needed to establish economy wide material balance, for example, 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 raw materials required to produce the traded materials are quantified. The former is known as **physical flows** and is measured by the MFA indicator **domestic material consumption (DMC)**. The latter is known as **raw material equivalents (RME)** and is measured by the indicator **raw material consumption (RMC)**. Circle Economy'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 of the economy (see **Table one** and **Figure two**).

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.

[26] 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; for example, fertiliser use, tyre abrasion

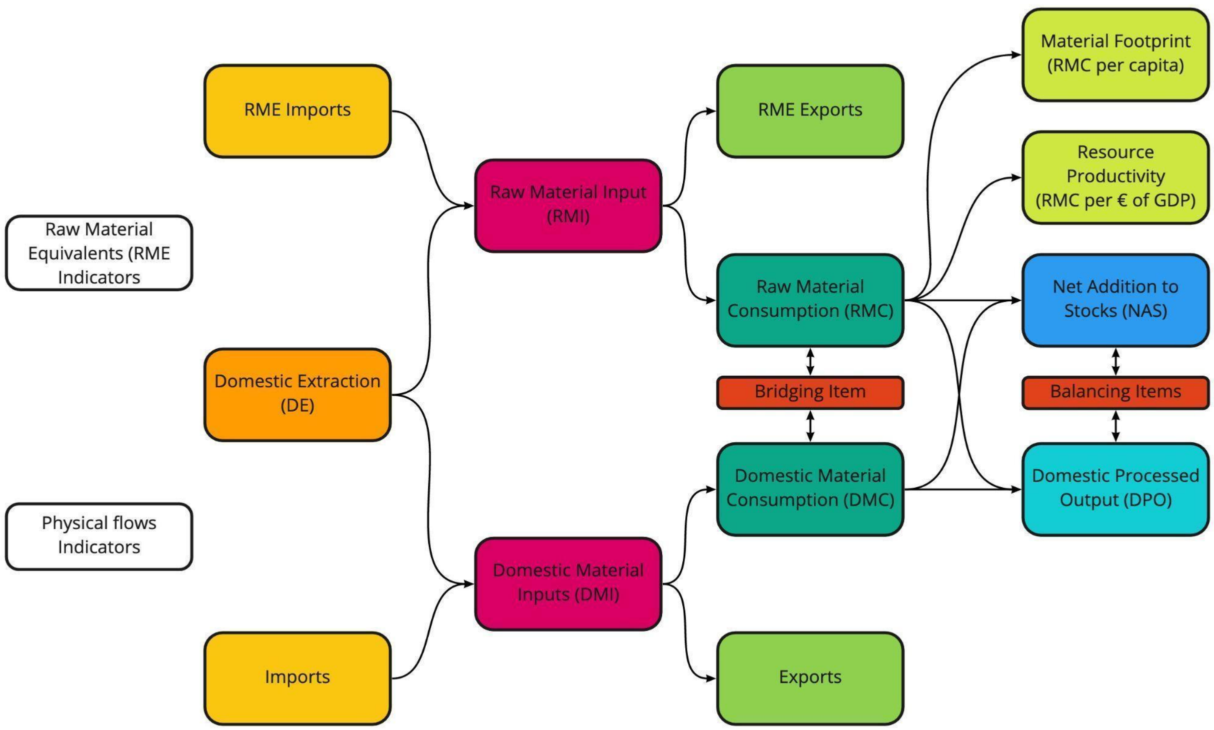

Figure two. Relationship between MFA indicators.

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 one. Key terms for Circle Economy's MFA Model

Decoupling**:** A trend where two variables which previously aligned, separate. The question of whether material consumption can decrease while GDP rises is of most interest for the Swiss MFA.

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 materials used in an economy, including imports and exports based on the physical mass of the materials traded. The mass of raw materials required to produce traded materials are not included.

Domestic material inputs (DMI)**:** The mass of materials that enter the economy including domestically extracted and imported materials.

***Inter-regional trade*:** Transaction of materials to and from a sub-national entity with the rest of the nation. This is embedded in Circle Economy'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. This is conceptually similar to the 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. This excludes the raw materials required to produce traded materials.

***Raw material inputs (RMI)*:** The mass of materials that enter the economy, including domestically extracted, imported material and the raw materials extracted to produce them. This represents 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. Circle Economy's MFA uses RME factors derived from the Multi-Regional Environmentally-Extended Input-Output (MR-EEIO) model Exiobase v3.8.1.

2.1 Extended MFA framework

While the EU-MFA approach provides a standardised 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 circular economy assessment developed by Mayer et al. (2019)[27] is '*a framework for a comprehensive and economy-wide biophysical assessment of a CE, utilising and systematically linking official statistics on resource extraction and use and waste flows in a mass-balanced approach*' (**Figure three**). Built upon the EU-MFA approach, it expands by integrating waste flows, recycling, and downcycled materials. Based on this framework, it is a comprehensive set of indicators that measure the scale and circularity of total material and waste flows and their socioeconomic and ecological loops.

The rationale for the application of this framework to the standard MFA data is to monitor progress towards a circular economy from an economy-wide perspective at the sub-national or national scale. In fact, it is only possible at these levels 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 this approach is the expansion of the EW-MFA boundaries by including flows of secondary materials and systematically mass-balancing material inputs with waste and secondary materials flows reported in the different statistical sources.[28]

[27] 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
[28] Waste generation and treatment (dataset 'env wastrt'), Material flow accounts (dataset 'env ac mfa'), International trade in goods statistics (ComExt)

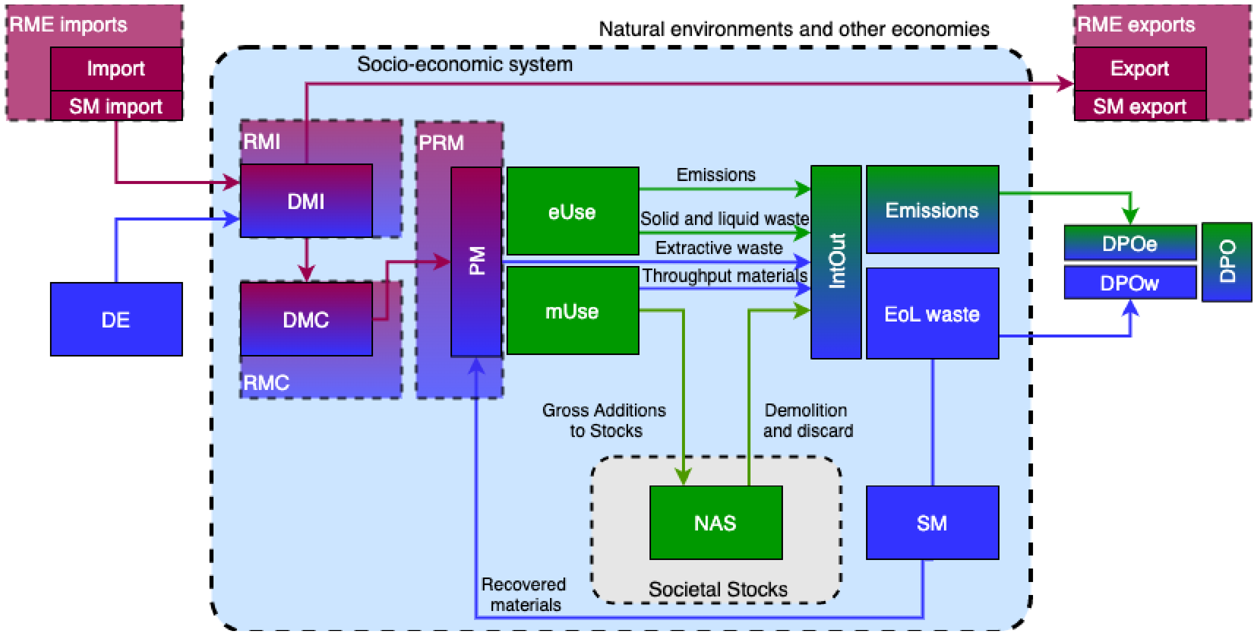

Figure three. Framework and throughput indicators for an economy-wide circular economy assessment. This framework applies individual materials (for example, DE of corn or iron) or aggregated material categories (for example, PM of biomass, fossil energy carriers) to the total material level (for example,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

Circle Economy's accounting framework traces materials in their main material groups from their extraction to major uses to their discard, and finally either material recovery or deposition to nature as waste or emissions. The main physical stages of the flow of materials through the entire system are marked by throughput indicators, represented as boxes. These include the source of material inputs (for example, domestic extraction, imports), major material transformation processing stages within the system (for example, processed materials, energetic and material use, in-use stocks of materials, waste treatment, EoL waste) and the destination of outflows (for example, exports, domestic processed output to the environment). Flows of materials are displayed as arrows between these boxes; the colours of 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 is split into extractive waste, materials used for stock building (i.e., gross additions to in-use stocks of materials [GAS]), and throughput materials. Extractive waste refers to waste material that occurs during early stages of the processing of domestically extracted ores and directly goes from PM to interim output (IntOut). Stock building materials comprise all materials that accumulate in buildings, infrastructure or durable goods with a lifetime of more than one year (for example, concrete, asphalt or steel). The share of stock-building materials in mUse was estimated based on information from industry and production statistics, results from material flow studies and various assumptions. Throughput materials comprise materials that do not accumulate in in-use stocks and can be split into two types of materials: first, materials used deliberately in a dissipative way such as salt or fertiliser minerals, and losses that occur during material processing (wastage, not reported in waste statistics); and second, short-lived products such as packaging or newspaper, manufacturing waste, and food waste (reported in waste statistics).

All materials that are neither added to stocks nor recycled are converted into gaseous, solid or liquid outputs within a 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 three**. IntOuts were split into emissions, comprising all gaseous emissions (for example, 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 (see the **Annex** for details). Emissions cannot be recycled and go straight into DPO. A fraction of total end-of-life (EoL) waste, reported as RCV B—(recovery other than energy recovery—backfilling) and RCV O (recovery other than energy recovery—except backfilling) in Eurostat waste statistics (env_wastrt), is reentering socioeconomic processes as secondary materials. The remaining EoL waste (after subtracting SM) is returned to the environment as DPO waste and either landfilled, incinerated, or deliberately applied (for example, manure, fertiliser). DPO emissions and DPO waste together form total DPO.

To close the material balance between input and output 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 (*Eq. one*) and mUse (*Eq. two*).

$$DPO\ emissions\ =\ eUse\ -\ solid\ and\ liquid\ wastes \qquad \text{(Eq. one)}$$

$$Demolition\ and\ discard\ =\ EoL\ waste\ from\ mUse\ -\ throughput\ materials\ in\ waste \qquad \text{(Eq. two)}$$

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 balancing items (oxygen uptake from air during combustion and water consumed by humans and livestock) were excluded. This means that all outflows from eUse include only the materials contained in actual inputs as composed in PM (for example, CO2 or SO2 in terms of C or S content; excrements at the average water content of food and feed intake). Closing the mass balance for eUse in this way implies that all inaccuracies in statistical data and assumptions that result in inconsistencies between input and output flows accrued in DPO emissions (DPOe). For the combustion of fossil energy carriers we cross-check the calculated 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 the 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 the 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 of less than one year) in mUse (for example, waste from packaging, paper, food waste, etcetera). In the third step, NAS were calculated as the difference between additions to stocks and discard and demolition. Closing the mass balance in this way implies that all inaccuracies in statistical data and assumptions that result in inconsistencies between input and output flows for mUse accrue in demolition and discard flows as residual flow category, and consequently in the value for NAS.

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[29] 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

[29] Regulation (EC) No 2150/2002. (2002). European Commission.

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 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, a manual iterative reconciliation process was performed. The objective of this optimisation is to minimise the difference between the two figures for the DMC, NAS and DPO indicators by adjusting the parameters of the extended MFA framework (for example, 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, although without a specified waste treatment route.

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

3. Environmentally extended 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 163 industries and/or 200 economic goods for 43 countries and five rest-of-the-world regions. Satellite accounts for resources and emissions are available for each sector and country. The original EXIOBASE 3 data series stops at year 2011, and nowcasting procedures have been applied for series after 2011, based on a range of auxiliary data, and largely, trade and macro-economic data which is available up to 2022, at which point the updated version began to include International Monetary Fund projections.[30]

As of EXIOBASE v3.8.2, 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, Circle Economy has developed its own version where material extraction is updated to the year 2017 on a country-by-country basis using the high resolution Global Material Flow Database, compiled using the Common Compilation Categories and provided—under request—by the IRP.[31] Industry allocations from 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 (for example, nowcasted monetary data from 2011 or industry allocation shares for material extraction). Accounts for later

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

[31] UN Environment Programme. (n.d.). Global material flows database. Retrieved from: UNEP website

years are based on nowcasted 2011 monetary data and material extraction data for the year 2017. It should be noted that material extraction data of the rest of the countries and regions is also a projection based on 2014 data.

For Switzerland, the multiregional model consisted of Switzerland plus 48 world regions and 163 industries each in the MRIOTs, where the Input-Output data used were EXIOBASE tables for 2019. The final demand matrix was updated with values from 2017 to deal with a bug in the Exiobase system for Switzerland in the years 2019 and 2018.

All calculations are performed using the open-source tool for analysing global EE-MIOTs, **pymrio**.[32] Production- and consumption-based accounts are calculated using a standard set of IO formulas as specified below and in **Table two.**

$D^{i}_{cba} = D^{i}_{pba} + D^{i}_{imp} - D^{i}_{exp}$ *(Eq. three)*

$D_{pba} = Fe + Ge$ *(Eq. four)*

$D_{imp} = MY_{t}$ *(Eq. five)*

$D_{exp} = M\hat{Y}_{t}e$ *(Eq. six)*

[32] Stadler, K., 2021. Pymrio – a python based Multi-Regional Input-Output Analysis Toolbox. *Journal of Open Research Software*, 9(1), 8. doi:10.5334/jors.251

Table two. Description of main pymrio variables.

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

Note: the ^ symbol represents the diagonalised vector, the e symbol represents a summation vector of ones.

4. Data

Developing a comprehensive MFA at the national level requires bringing together several separately developed data sources. Reliable primary data is used where available.

Table three provides a template for summarising the main data sources used.

4.1 Waste-system data

The data collected and evaluated includes elements such as waste generation, waste collection, waste treatment, and trade of waste of Switzerland. These waste flows are critical for the analysis of Switzerland's SEM and for the calculation of the indicators in the Circularity Metric framework for the *Circularity Gap Report Switzerland*.

The collection of waste data comprised more than 20 data sources including reports, scientific publications and online datasets. After scrutiny, data from these sources was extracted and converted for computational compatibility to complete the analysis. Only data for waste used for the waste-system analysis is included in this evaluation. The data sources in this evaluation include the Federal Office for the Environment, the Federal Office for Customs and Border Security FOCB, a journal article from ETH Zurich, the KAR model, and the Swiss Auto Recycling Association.

The evaluation indicates that most of the data is obtained from direct measurements on a yearly basis and some data is produced with assumptions and models. System boundaries and classifications are not consistent across data sources.

Table three. Data used for CGR Switzerland.

Flow	Headline values	Data (name and source)	Notes
Municipal and hazardous waste			
Municipal waste treated in Switzerland	Total municipal waste: 6'078,000 tonnes Municipal waste incinerated: 2'857,000 tonnes Municipal waste	Bundesamt für Umwelt BAFU. (2020). *ABFALLMENGEN UND RECYCLING 2019 IM ÜBERBLICK.* Source	Municipal incinerated waste includes hazardous waste, sewage sludge (dry), and imported waste

Flow	Headline values	Data (name and source)	Notes
	collected separately and recycled: 3’221,000 tonnes		
Exported hazardous waste	Exported: 432,927 tonnes	Bundesamt für Umwelt BAFU. (2020). *Sonderabfallstatistik 2019 Im Ausland behandelte Sonderabfälle aus der Schweiz (Export)*. Source	
Imported and treated hazardous waste	Imported: 114,952 tonnes	Bundesamt für Umwelt BAFU. (2020). *Sonderabfallstatistik 2019*. Source	
Domestic hazardous waste treated domestically	Treated: 1’441,661 tonnes	Bundesamt für Umwelt BAFU. (2020). *Sonderabfallstatistik 2019 Im Inland behandelte Abfälle aus der Schweiz*. Source	
Other wastes			
Exported waste in the classification: other wastes subject to reporting	Exported: 3’527,933 tonnes	Bundesamt für Umwelt BAFU. (2020). *Statistik der übrigen notifizierungspflichtigen Abfällen 2019*. Source	
Imported waste treated in Switzerland in the classification: other wastes subject to reporting	Imported: 504,834 tonnes	Bundesamt für Umwelt BAFU. (2020). *Statistik der übrigen notifizierungspflichtigen Abfällen 2019*. Source	
Construction and demolition waste			
Construction and demolition waste	11’200,000 tonnes recycled or reused 5’300,000 tonnes landfilled	Tinu Schneider Datenanalyse. (2020). *Kurzbericht: KAR-Modell Schweiz Modellierung der Materiallüsse von Kies, Aushub und Rückbaumaterial zum Bezugsjahr 2018*. Source	European and international economy-wide material flow accounting conventions indicate that movements of excavated soils are considered part of the environment and thus fall outside of the system boundaries of the analysis of the waste-system.

Flow	Headline values	Data (name and source)	Notes
Shredding and scrap			
RESH—shredding—scrap	61,428 tonnes processed in 2019 54,148 tonnes processed in 2020	Stiftung Auto Recycling Schweiz. (2020). *Jahrersbericht 2019*. source	Imports and exports of materials for shredding and imports and exports of scrap are recorded in the statistics of foreign trade
Trade of scrap	Imported 1'699,580 tonnes Exported 3'166,599 tonnes	Federal Office for Customs and Border Security FOCBS. (2022). *Trade of Waste Scrap CPA*. Source , Source	
Economic data			
Monetary flows of Swiss Input-Output Tables	n.a.	Source	
Monetary flows of Multiregional Input Output tables	n.a.	Stadler, K., Wood, R., Bulavskaya, T., Södersten, C. J., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Maerciai, S., Schmidt, J., Theurl, M., Plutzar, C., Kastner, T., Eisenmenger, N., Erd, K. H., Koning, A., & Tukker, A. (2020). EXIOBASE 3. doi:10.5281/zenodo.4277368	2019 reference year with updates in CHF from 2018
Materials and Emissions			
Domestic extraction, imports and exports	n.a.	Material flow accounts—Direct input flows and their aggregates. PxWeb (admin.ch). (2017–2019) Source	Material flow accounts
Energy accounts	n.a.	PEFA 2017-2019. Source	Energy accounts of economy and households
Air emissions accounts	n.a.	Air emissions accounts of the economy and households. 1990-2018. Source	GHG emissions accounts

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4.2 Data assessment

We performed an assessment of the collected data. We used the life cycle data Pedigree assessment framework by Weidema and Wesnaes (1996).[33] This framework consists of five data quality indicators that can obtain a score from 1 to 5 with 1 being the highest quality and 5 the lowest quality.

Data Quality Indicators:

I. Completeness

1 Complete dataset covering everything under study
2 Nearly complete dataset that contains representative data
3 Partially incomplete dataset missing important parts of data
4 Largely incomplete dataset not representative of the whole
5 Completeness unknown

II. Data specificity and classification

1 Data at the right specificity level and classification system in line with the study requirements
2 Data at the right specificity level but using a different yet compatible classification system
3 Data in the same classification system, but only available one level less specific
4 Data using a different but compatible classification system and not at the right specificity level; or more than one level less specific in the same classification system
5 Data using an incompatible classification system

III. Geographic correlation

1 Data from area under study
2 Data from a sub-unit within the area under study that is considered representative of the area under study
3 Data from a larger area that is considered representative of the area under study
4 Data from an overlapping area (smaller or larger) that is not considered representative of the area under study
5 No geographic correlation with the area under study

IV. Reliability

1 Verified data based on measurements
2 Verified data partly based on assumptions or non-verified data based on

[33] Weidema, B. P., & Wesnæs, M. S. (1996). Data quality management for life cycle inventories—an example of using data quality indicators. *Journal of Cleaner Production*, *4*(3–4), 167–174. doi:10.1016/S0959-6526(96)00043-1

measurements
3 Non-verified data partly based on assumptions
4 Qualified estimate (e.g. by industrial expert)
5 Non-qualified estimate or unknown reliability

V. Temporal correlation

1 Time period is equal to the period of study
2 Up to one year difference to year of study
3 Up to three years difference to year of study
4 Up to five years difference to year of study
5 Age of data unknown or more than five years difference

Table four. Data assessment.

Data (name and source)	Description	Completeness	Data specificity and classification	Geographic correlation	Reliability	Temporal correlation	Updated yearly
Bundesamt für Umwelt BAFU. (2020). *Sonderabfallstatistik 2019 - Importierte und in der Schweiz behandelte Sonderabfälle (Import)*. Retrieved from: BAFU website	Hazardous waste statistics 2019 Special waste imported and treated in Switzerland	3	2	1	1	1	yes
Bundesamt für Umwelt BAFU. (2020). *Sonderabfallstatistik 2019Im Ausland behandelte Sonderabfälle aus der Schweiz (Export)*. Retrieved from: BAFU website	Hazardous waste statistics 2019 Hazardous waste treated abroad from Switzerland (export)	3	2	1	1	1	yes
Bundesamt für Umwelt BAFU. (2020). *Sonderabfallstatistik 2019Im Inland behandelte Abfälle aus der Schweiz*. Retrieved from: BAFU website	Hazardous waste statistics 2019. Waste from Switzerland treated in Switzerland	3	2	1	1	1	yes

Data (name and source)	Description	Completeness	Data specificity and classification	Geographic correlation	Reliability	Temporal correlation	Updated yearly
Bundesamt für Umwelt BAFU. (2020). *Abfallmengen und recycling 2019im überlick*. Retrieved from: BAFU website	WASTE QUANTITIES AND RECYCLING 2019 AT A GLANCE. Includes lump sum of municipal waste, aluminium cans and tin, glass bottles, cardboard, and hazardous waste.	4	5	1	2	1	yes
Stiftung Auto Recycling Schweiz. (2020). *Jahrersbericht 2019*. Retrieved from: Stiftung website	2019 Year Report. Automotive Recycling Switzerland	3	5	1	2	1	unknown
Bundesamt für UmweltBAFU. (2020). *Verwertungvon Getränkeverpackungen 2019*. Retrieved from: BAFU website	Recycling of beverage packaging 2019	3	3	1	1	1	yes
Bundesamt für Umwelt BAFU. (2020). *Statistik der übrigen notifizierungspflichtigen Abfällen 2019*. Retrieved from: BAFU website	Statistics on other waste subject to notification 2019	2	2	1	1	1	yes
Tinu Schneider Datenanalyse. (2020). *Kurzbericht: KAR-Modell Schweiz Modellierung der Materiallüsse von Kies, Aushub und Rückbaumaterial zum Bezugsjahr 2018*. Retrieved from: KAR-Modell website	Short report: KAR model Switzerland modelling of the material flows of gravel, excavation and demolition material for the	2	4	1	2	1	unknown

Data (name and source)	Description	Completeness	Data specificity and classification	Geographic correlation	Reliability	Temporal correlation	Updated yearly
	reference year 2018						
Haupt, M., Vadenbo, C., & Hellweg, S. (2017). Do we have the right performance indicators for the circular economy?: insight into the Swiss waste management system. *Journal of Industrial Ecology*, *21*(3), 615–627. doi:10.1111/jiec.12506	Swiss Waste Management System	2	4	1	2	5	no
Federal Office for Customs and Border Security FOCBS. (2022). *Trade of waste scrap CPA*. Retrieved from: SwissImpex website , and Source	Trade of waste scrap	1	1	1	1	1	unknown
Federal Statistical Office. (2017). Swiss input-output table 2017. Retrieved from: BFS website	Monetary flows of Swiss Input-Output Tables	1	1	1	2	2	unknown
Stadler, K., Wood, R., Bulavskaya, T., Södersten, C. J., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Maerciai, S., Schmidt, J., Theurl, M., Plutzar, C., Kastner, T., Eisenmenger, N., Erd, K. H., Koning, A., & Tukker, A. (2020). EXIOBASE 3. doi:10.5281/zenodo.4277368	Monetary flows of Multiregional Input Output tables	1	1	1	2	1	no
Swiss Confederation. (2019). Material flow accounts—direct input flows and their aggregates 2017–2019. Retrieved from: Swiss Confederation website	Domestic extraction, imports and exports	1	1	1	1	1	no

Data (name and source)	Description	Completeness	Data specificity and classification	Geographic correlation	Reliability	Temporal correlation	Updated yearly
Swiss Confederation. (2019). Energy accounts of economy and households 2017–2019. Retrieved from: Swiss Confederation website	Energy accounts	1	1	1	1	1	unknown
Swiss Confederation (2018). Air emissions accounts of the economy and households 1990-2018. Retrieved from: Swiss Confederation website	GHG air emissions accounts	1	1	1	1	1	unknown

5. Circularity indicators framework

The indicators presented here are based on EW-MFA principles and are taken from the work of Mayer et al. (2019) and previous research,[34] [35] [36] and they are summarised in **Table five**. 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. Three pairs of indicators are used to measure the scale of material and waste flows:

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

2. In order to be able to capture displacement effects related to imports and exports, a consumption-based indicator was included in the form RMC, or material footprint;[37] a measure of global material use associated with domestic final consumption. No corresponding indicator on the output side is available at the moment of writing.

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

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[34] 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

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

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

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

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 (for example, recycled steel scrap from autobody manufacturing) is considered an industry internal flow and not accounted for as a secondary material. In this model of the physical economy secondary materials originate from discarded material stocks only. The outflows from the dissipative use of materials and combusted materials (energy use) can, by definition, not be recycled. This assumption may lead to a minor underestimation of downcycled materials, when solid wastes from the combustion of fossil materials are used in construction. Energy recovery (electricity, district heat) from the incineration of fossil or biomass waste is not considered 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. This ratio is then used to split the biomass flow in fresh-weight carbon-neutral and not-neutral on the input and output sides.

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 two**). The reason for this is that while the original indicator framework is calculated over PMs, in *Circularity Gap Reports* this is also done over PRMs. The latter has the advantage of taking a life-cycle perspective and reallocating raw material extraction to the point of final consumption; 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 (for example, gasoline, diesel, kerosene) that are being burned so the identification of their use is straightforward. However, the eUse fraction of fossil fuels in PRM accounts for the raw materials (for example, petroleum) across all kinds of products and applications, thus not necessarily related eUse. Therefore, we introduce a bridging item and refer to it as the **net extraction abroad rate (NEAr)**. When NEAr is negative, it means that the economy under study extracts more resources to satisfy final

demand abroad than those extracted abroad to satisfy domestic final demand. Another issue related to using RMEs rather than physical flows is that it is hard to track the fate of raw materials extracted abroad and that are not embedded into the traded commodity, but rather transformed into waste and emissions during processing.

Table five. Summary of Circle Economy's Circularity Indicators Framework.

<table>
<tr><th colspan="6">Circularity Indicators Framework</th></tr>
<tr><td rowspan="2"></td><td rowspan="2">Dimension</td><td colspan="2">Input-side Indicator</td><td colspan="2">Output-side Indicator</td></tr>
<tr><td>Direct</td><td>Life-cycle</td><td>Direct</td><td>Life-cycle</td></tr>
<tr><td rowspan="2">Scale indicators (t)</td><td>In- and output flows</td><td>Domestic material consumption (DMC)</td><td>Raw material consumption (RMC) = DMC + NEA</td><td>Domestic Processed Output (DPO)</td><td>n.a.</td></tr>
<tr><td>Interim flows</td><td>Processed Materials (PM) = DMC + secondary materials</td><td>Processed Raw Materials (PRM) = RMC + secondary materials</td><td>Interim outputs (IntOut) = EoL waste + DPO emissions</td><td>n.a.</td></tr>
<tr><td rowspan="4">Metabolic rates (%)</td><td>Socioeconomic cycling (SC)</td><td>Input socioeconomic cycling rate (ISCr) = Share of secondary materials in PM</td><td>Input socioeconomic cycling rate (ISCr) = Share of secondary materials in PRM</td><td>Output socioeconomic cycling rate (OSCr) = Share of secondary materials in IntOut</td><td>n.a.</td></tr>
<tr><td>Ecological cycling potential (EC)</td><td colspan="2">Input ecological cycling rate potential (IECrp) = Share of DMC of primary biomass in PM</td><td>Output ecological cycling rate potential (OECrp) = Share of DPO biomass in IntOut</td><td>n.a.</td></tr>
<tr><td>Non-circularity (NC)</td><td colspan="2">Input non-circularity rate (INCr) = Share of eUse of fossil energy carriers in PM</td><td>Output non-circularity rate (ONCr) = Share of eUse of fossil energy carriers in IntOut</td><td>n.a.</td></tr>
<tr><td>Net additions to stocks (NAS)</td><td>Net stocking rate (NSr) = Share of NAS in</td><td>Net stocking rate (NSr) = Share of NAS in</td><td>Net stocking rate (NSr) = Share of NAS in</td><td>n.a.</td></tr>
</table>

		PM	PRM	IntOut	
		PM	PRM	IntOut	
	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.

Notes: Mass-based circular economy indicators measure the absolute size of input and output flows in mass units (e.g. tonnes) and circularity rates measure socioeconomic and ecological cycling relative to input and output flows in percentages.

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 Circle Economy'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).[38] Let's consider ISCr—the share of secondary materials in PRM—and re-write it in mathematical terms:

$ISCr \ = SM/PRM$ *(Eq. fourteen)*

Where:

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

$PRM \ = \ DMC \ + \ NEA + SM$ *(Eq. sixteen)*

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

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

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

then $ISCr$ can be rewritten as:

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

A higher ISCr rate value means that more secondary materials substitute for primary raw materials, thus reducing the environmental impacts of extracting virgin

[38] Eurostat. (2018). Circular material use rate: calculation method. Retrieved from: European Commission website

materials. The numerator and denominator of the equation above can be measured in different ways depending on considerations of analysis and data sources.

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

In this respect, it was decided that the ISCr rate measures a country's effort to deploy secondary materials. This perspective credits the country's effort to produce secondary material from recycled waste as opposed to gathering waste bound for recovery which indirectly contributes to the 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. Dataset on waste treatment (env_wastrt) are used (or compiled based on such regulation) for the calculation of the ISCr rate.
- **Economy-wide material flow accounts:** As already mentioned in Chapter one, EW-MFA describes the interaction of the domestic economy with the natural environment and the rest of the world economy in terms of flows of materials (excluding water and air). EW-MFA is a statistical framework conceptually embedded in environmental-economic accounts and fully compatible with concepts, principles, and classifications of national accounts—thus enabling a wide range of integrated analyses of environmental, energy and economic issues e.g. through environmental-economic modelling. The collection of EW-MFA data is based on Regulation (EU) 691/2011 and the dataset used (or compiled) is (or is based on) the env_ac_mfa data set.

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

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

5.1 Amount of waste recycled in domestic recovery plants

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

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

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

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

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

5.2 Adjusting circular use of material for net imports of waste

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

$$SM = SM_{dom} + SM_{imp} - SM_{exp} \qquad \text{(Eq. twenty-one)}$$

with:

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

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

Equation twenty-one describes the total recycled waste in treatment operations as 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 that 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.[39]

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

6. 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.[40] Underlying the Python library, a common data structure for flow data was defined, through which this method can be used to generate Sankey diagrams from different data sources such as material flow analyses, life-cycle inventories or directly measured data.[41]

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

For entries in the D^i_{pba} dataset, 'source' is always set to the environment as these are all inputs coming from domestic extraction 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

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

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

‘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[42] through a concordance matrix describing the assignment of EXIOBASE product sectors across consumption domains at the final demand level.

[42] 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

7. Scenario modelling

EEIOA can be applied to assess the economic and environmental implications of a transition towards a circular economy.[43] IOA, in its various forms, is a static structural model that provides a high resolution of sectors and structural economic composition, making it a useful tool for the impact assessment of supply-chains. As such, it is a suitable model for the creation of 'what-if' scenarios through the application of exogenous changes, which can also be named *nowcasting*. One of the advantages of this type of approach is the level of transparency in assumptions. This is especially important for circular economy impact assessment, as the variety of approaches makes it difficult to compare studies. Previous studies have tried to categorise types of interventions within a circular economy, their fundamental waste management models, and indicators. However, further and continuous development of assessment methods is still necessary to improve their application as policy tools.

As the first step, building on the work of Aguilar et al. (2018) and Donati et al. (2020) and integrating these with additional literature on circular strategies frameworks,[44] [45] [46] [47] a new comprehensive circular economy policy modelling framework was developed. We begin by asserting that the objective of a circular policy is always the implementation of the circular economy paradigm. In order to achieve this objective, different strategies exist. There are various categorisations of circular strategies such as ReSOLVE.[48] [49] However, in this study we integrate the the four-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).[50]

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[43] Aguilar-Hernandez, G. A., Sigüenza-Sanchez, C. P., Donati, F., Rodrigues, J. F., & Tukker, A. (2018). *Assessing circularity interventions: a review of EEIOA-based studies*. Journal of Economic Structures, 7(1), 1-24. doi:10.1186/s40008-018-0113-3
[44] 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
[45] Morseletto, P. (2020). *Targets for a circular economy*. Resources, Conservation and Recycling, 153, 104553. doi:10.1016/j.resconrec.2019.104553
[46] 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
[47] Donati, F., Aguilar-Hernandez, G. A., Sigüenza-Sánchez, C. P., de Koning, A., Rodrigues, J. F., & Tukker, A. (2020). *Modeling the circular economy in environmentally extended input-output tables: Methods, software and case study*. Resources, Conservation and Recycling, 152, 104508. doi:10.1016/j.resconrec.2019.104508
[48] McKinsey & Company (2016). The circular economy: Moving from theory to practice. Retrieved from: McKinsey website
[49] 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
[50] Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: measuring innovation in the product chain*. The Hague: PBL Publishers, 2544. Retrieved from: PBL Netherlands Environmental Assessment Agency

We define interventions as sets of strategies and improvement options (or simply interventions). For example, PLE can be achieved, among others, by reuse and remanufacturing, or 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 (for example, reuse and remanufacturing) is specialised when it refers to a specific product or application (for example, increased lifetime through reuse and remanufacturing in final consumers' vehicles). Interventions are modelled through sets of changes that affect the production and consumption systems. We further distinguish between primary and ancillary changes. For instance, if the intervention concerns increasing the life-time of vehicles the primary change would be a reduction of sales of vehicles resulting from 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 four**.

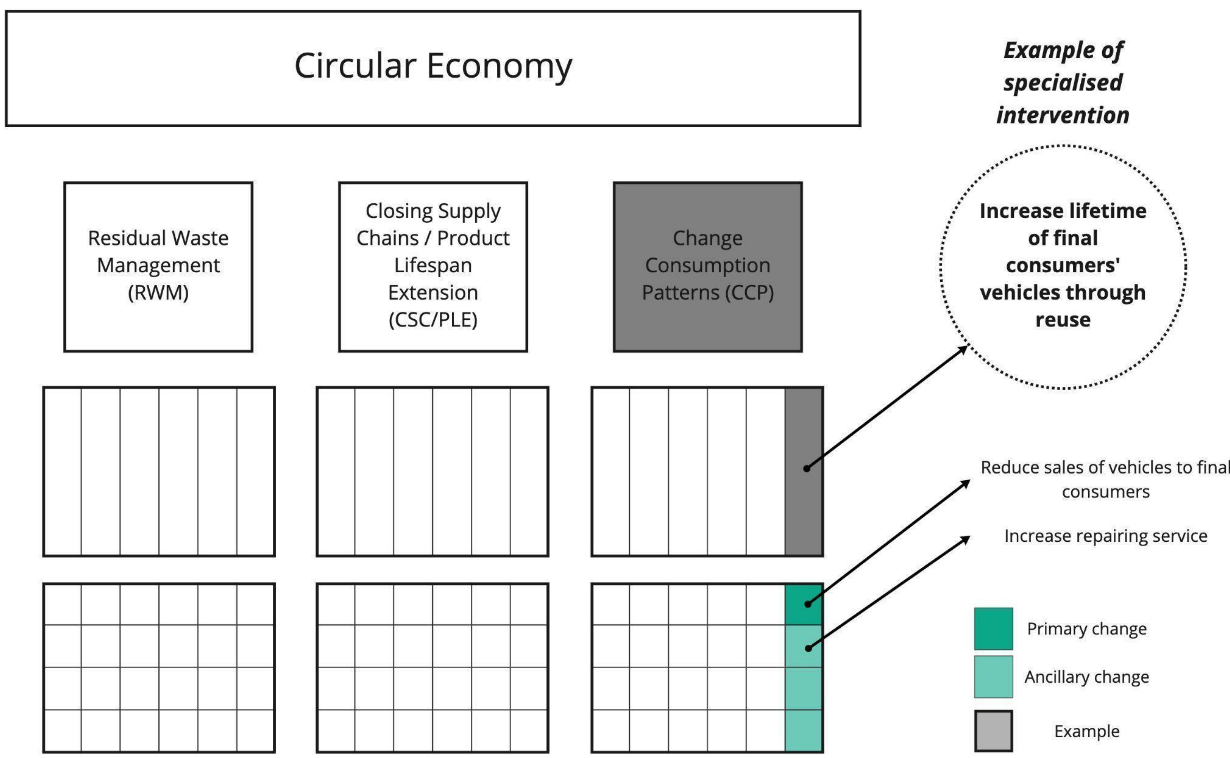

Figure four. Circular economy policy modelling framework (from Donati et al. 2020).

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

$D^{i}_{cba} = \hat{S}\,(I - A)^{-1} Y_{e}$ (Eq. twenty-two)

Note that (**Eq**. twenty-two) is another expression of D^{i}_{cba} in **Table two**, where D^{i}_{cba} is a resulting column vector of impacts occurring in each production sector (the response variable) and Y^{i}_{e} is the column vector of final demand of products delivered by each sector (the control variable). The parameters of the model are the column vector S^{i} of environmental intensities (environmental pressure per unit of economic output) and A is a matrix of technical coefficients (whose entry ij is the volume of inputs from sector i that are required to generate one unit of output of sector j). For some environmental pressures (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 this is the case it is necessary to include emissions from final demand to obtain total emissions, Ge.

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

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

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

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

If there are final consumption pressures, we can further define
$\Delta D_{cba,tot} = D^{*}_{cba,tot} - D_{cba,tot}$ where:
$D^{*}_{cba,tot} = (D^{*})'_{cba} e + Ge^{*}$ *(Eq. twenty-five)*

A counterfactual scenario (an object adjoined with *) is constructed by adjusting specific 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**[51] software as:

$M^{*}_{ij} = M_{ij}(1 - k_{a})$ *(Eq. twenty-six)*

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:

$k_{a} = k_{t}k_{p}$ *(Eq. twenty-seven)*

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

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

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

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

This modelling approach considers the impact of actions at the margin, if taken tomorrow, namely, counterfactual scenarios or 'what-if' scenarios. This approach is different than the concept of modelling the efficacy of the options if they are adopted gradually at different points in time which is far more complex, as the sequencing would create many different path-dependent trajectories, while some changes considered would affect the volume of a particular stock while others affect yearly flows, (for example, the carbon footprint of electric vehicles depends strongly on the carbon intensity of the electricity used to fuel them). With our counterfactual modelling techniques, we consider 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 considered.

7.1. Scenarios in the *Circularity Gap Report Switzerland*

In this section, we show the high-level drivers and assumptions behind the scenarios of the *Circularity Gap Report Switzerland*. These assumptions were used as guides to model fine-tuned changes as described in the previous section for each scenario. On average, each scenario can result in hundreds of changes along and across the 163 sectors in Circle Economy's model, and the same can be applied to at least two types of final demands, such as households and governments. In **Table six**, we list the main set of drivers used for modelling the scenarios.

Table six. High-level assumptions and drivers behind the modelling of the scenarios for the Circularity Gap Report Switzerland.

1. Embrace a circular lifestyle	
Interventions	**Strategies and assumptions**
1.1 Promote a material sufficiency lifestyle	● Minimise consumption of electronics, appliances, furniture and textiles ● Encourage product repairs ● Boost non-market and community services

	Finished products (textiles and wearing apparel) are reduced by between 17% and 45%. 20% of spending on textile materials (fibres and wool) and leather is substituted.[52] Consumption of fibres reduced by 20% due to increased recycling. Petroleum-based fabrics are substituted with natural ones. Use of furniture and home appliances is minimal. Furniture components are reused and redesigned. Desks and office chairs and domestic furniture (sofas and dining tables) are reused, refurbished and remanufactured. Product lifetimes are extended, resulting in a 53% reduction in the consumption of new products. Consumption of media, internet, telecommunications devices and computers is reduced. Use of commercial services is reduced by 26%, and consumers become highly dependent on inter-community exchange (e.g. time bank and Customer-to-Customer services). Passive and home-based activities and interests and consumption of media increase, while long-distance travel is decreased. Residents enjoy and engage with more local cultural activities and organisations.
2. Advance circular manufacturing	
Interventions	**Strategies and assumptions**
2.1 Implement resource-efficient/ symbiotic manufacturing	• Improve industrial processes to reduce virgin inputs for key manufacturing industries • Reduce yield losses • Divert scraps and cycle unavoidable waste Current demand for aluminium, steel, other metals, wood and chemicals by the manufacturing and metallurgical sectors in Switzerland is reduced by between 7% and 28%.
2.2 Employ R-strategies for manufactured goods	• Increase the lifetime of machinery, equipment, and vehicles through R-Strategies such as remanufacturing, refurbishment, repair and maintenance, upgrade, and reuse services

[52] Do-it-yourself here means that consumption of textiles is halved as a consequence of repairing, reusing, and recycling clothes. Of the remaining expenditure in new textile products, 20% are allocated to textiles made of natural fibres and leather.

	Product lifetimes are extended, mainly through repair and maintenance, which leads to reduced consumption of selected finished products for households, and machinery and equipment for industries. The net reductions modelled in the consumption of durable products range from 2.5% to 12.5% for motorised vehicles, and between 2.5% and 45% for all other machinery and equipment consumed by industries.
3. Rethink transport and mobility	
Interventions	**Strategies and assumptions**
3.1 Reduce reliance on private vehicles	• Reduce the need for private car ownership and use Shopping trips by car by households are eliminated. We assume that private car travel is substituted by bikes, scooters, and car sharing. In the medium term, this intervention is assumed to reduce the need for private transportation vehicles while potentially using the land previously used for parking with bicycle infrastructure. The modelling of this intervention was informed by data on passenger kilometres by modality.[53] Passenger kilometres from private motorised transport topped 85.2 billion. In contrast, public road transport (bus, trolley, tram) represented only 3.4 billion passenger kilometres, with railways and cable cars claiming 14.3 billion. Human-powered mobility—walking and cycling—represented 8.4 billion kilometres. The average passenger car occupancy rate in 2015 was 1.56,[54] and households owned an average of 1.16 cars as of the same year.[55] In 2021, there was an average of 541 passenger cars per 1,000 inhabitants in Switzerland.[56]
3.2 Embrace flex work	• Continue to work from home where possible, to lower commuting needs and thus demand on transport Trips are reduced by increased work from home, especially for hires living far from work. In modelling this intervention, we assume that flex work increases by 50%, matched by a 20% reduction in commuter transport by car, bus and train. We also assume that demand for

[53] Federal Statistical Office. (2021). Passenger transport performance. Retrieved from: BFS website
[54] Federal Statistical Office & Federal Office for Spatial Development. (2017). *Population's travel behaviour 2015.* Retrieved from: BFS website
[55] Federal Statistical Office. (2017). Possession de véhicules, de permis et d'abonnements des TP. Retrieved from: BFS website
[56] Federal Statistical Office. (2023). Road vehicles - Stock, level of motorisation. Retrieved from: BFS website

	commercial real estate will drop as more workers stay at home. We do not assume an energy rebound because the consumption is occurring at home rather than at the office, whereas the costs of ICT equipment are assumed to stay with the employer.
3.3 Pursue a modal shift for transport	• Increase the number of journeys taken by public transport Teleworking rose sharply from the onset of the covid-19 pandemic: 39.6% of employed people (nearly 1.8 million people) teleworked, at least occasionally, in 2021.[57] This coincided with a drop in seat occupancy in trains, which decreased from 28.9% in 2019 to 18% in 2021.[58] To model this intervention, the population was divided into segments and their demand for mobility was shifted towards other options. The main options represented in the model are buses and railways, representing a relevant share of urban and extra-urban public transport. The shift towards walking and biking was represented by a reduction of passenger kilometres. This can be realistically modelled together with intervention 3.1, by considering the actual potential for a shift of passenger kilometres from private to public transport.
3.4 Improve vehicle design	• Use lightweight vehicles to reduce metal input and increase fuel efficiency Lightweighting of vehicles results in a reduction in material demand of between 17% and 50% (mainly aluminium, copper and steel, but also refinery products) for cars and public transport vehicles.
3.5 Reduce air travel	• Reduce the need for air travel We assume a reduction in air traffic in congested regions with specified limits. Households' demand for air mobility services is reduced by capping the number of trips per capita per year from 3 to 1.5 for a net reduction of 50%. Also, a reduction of the average passenger kilometres per capita to 2,000 implies a reduction of demand for fuel from the air mobility sector. No reduction in tourism-related activity is modelled (e.g. Hotels and Restaurants) as

[57] This category includes three different subgroups of teleworkers based on the proportion of time that they work from home. First, people who telecommute from home on a regular basis, i.e. for more than 50% of their activity, remain few in number. They represent less than 1% of employed working people in 2001, 3% in 2019 and 4.3% in 2020. Secondly, we can distinguish working people who regularly telecommute from home, but for less than half of their working time. They represent 10.6% of the employed working population in 2019 and 12.8% in 2020. Finally, the third category, that of people who only occasionally telework at home, shows the greatest increase between 2019 and 2020. It goes from 11% to 17.1% of the employed working population (767,000 people). Based on the source.
[58] SBB. (n.d.). Verkehr. Retrieved from: SBB website

	this is assumed to be offset through a rebound in spending on local tourism activities. There were around 1.2 million civil aircraft movements in 2021, and 900 thousand in 2019.[59]
Build a circular built environment	
Interventions	**Strategies and assumptions**
4.1 Optimise housing stock expansion & increase occupancy rates	• Cycle construction and demolition waste • Utilise idle/unused commercial buildings • Decrease virgin material use for construction • Enforce incentives for co-housing and multifunctional spaces • Increase occupancy by taxing unoccupied spaces New residential buildings built with virgin materials are capped, leading to a maximum increase in the reuse of sustainable construction materials. Taxation on second homes, Airbnb apartments and unoccupied spaces is increased to increase overall residential occupancy rates. To model this intervention, we used an occupant density of 0.59 people per room, as of 2021. The average number of rooms per person was 1.8, compared to the EU average of 1.6.[60]
4.2 Shape an energy-efficient building stock	• Improve the existing building stock through deep retrofits • Use secondary and regenerative materials for retrofitting • Make use of smart metres The renovation of residential and commercial buildings is carried out up to passive house standards. Overall energy demand for heating and cooling is reduced by 20% to 30%,[61] [62] [63] and oil boilers are replaced by heat pumps.
4.3 Scale resource-efficient building practices	• Use lightweight building materials • Increase lifetimes of bearing elements • Improve construction processes through modularisation and off-site construction • Keep the supply chain as local as possible

[59] Swiss Confederation. (n.d.). Mouvements aériens (décollages et atterrissages) dans le trafic de ligne et charter. Retrieved from: BFS website
[60] Eurostat. (2021). Size of housing. Retrieved from: Europa website
[61] The Federal Council. (2021). Energy renovation: First sort, then refurbish. Retrieved from: Swiss Confederation website
[62] Moran, D., Wood, R., Hertwich, E., Mattson, K., Rodriguez, J.F.D., Schanes, K., & Barrett, J. (2018). Quantifying the potential for consumer oriented policy to reduce European and foreign carbon emissions. *Climate Policy*. doi:10.1080/14693062.2018.1551186
[63] Issuu. (2022). *Energy efficiency in Switzerland - a mainstay of the energy transition*. Retrieved from: Issuu website

	• Limit energy use in homes through energy-efficient appliances Lightweighting of bearing elements was modelled based on a mix of assumptions from Donati et al., (2020) 'Lightweighting' and Vita et al., "Natural Construction.' Up to 18% of cement and refinery products are substituted by bricks, stone, wood, and alternative construction products. Transport fuels used by the construction sector are reduced by 50% as an effect of sourcing local construction materials.
5. Nurture a circular food system	
Interventions	**Strategies and assumptions**
5.1 Shift to more sustainable food production	• Prioritise local, seasonal and organic food production Locally-produced food is prioritised in households and in the HORECA sector with a policy focus on national food self-sufficiency. The need for chemical fertilisers and pesticides is eliminated through organic food production, as is the hot-housing of fruit and vegetables due to shifting consumer preference towards seasonal produce.
5.2 Reduce food waste	• Cut household-level organic waste • Cycle unavoidable food waste • Reduce caloric intake The purchases of certain food products by households is decreased as a consequence of a balanced diet. Reductions range between 3.8% for dairy products and 57% for sugary beverages. We assume that a reduction in caloric intake corresponds to a reduction in post-consumer waste. Our modelling activity assumes 2.426 million tonnes of avoidable food waste in Switzerland,[64] out of a total of 13.65 million tonnes of food waste.[65] Most avoidable food waste takes place in processing (963,000 tonnes) and households (778,000 tonnes).

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