Measuring and Mapping Circularity

Technical methodology document

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The need for measuring Circularity

Within the Circularity Gap Reporting initiative (CGRi) we strive to provide accurate measurement of the circular economy which is most prominently expressed in our Global and National Circularity Metrics. Their value lies in setting a benchmark measurement for the globe and nation states and to track progress over time. For the Global Circularity Metric (GCM), the ambition is to periodically report on its value and underlying fundamentals, for example every year, as it happens with the UN Emissions Gap report.[1]

The Ellen MacArthur Foundation, OECD, European Commission and other notable organizations have estimated that economies could greatly benefit from circular economy strategies on economic, social and environmental dimensions. However, a key challenge in implementing circular economy into government policy and business strategy is the lack of a consistent measurement framework. The value of using a single circularity metric for the global economy lies exactly there, the ability to track changes over time and measure progress in a consistent way.

The inspiration for our work, and the start of the collaboration between BOKU and Circle Economy, came from a paper published in July 2016, entitled "*How Circular is the Global Economy?*" by Willy Haas.[2] The aim of the paper was to quantify the material loops being closed as a share of the total material inputs in the world's economy, that is its degree of circular resource use. The study concluded that in 2005, 4 Gt out of 62 Gt of materials entering the global economy originated from a recycling stream resulting in a 7% global circularity rate. Comparable to Haas and colleagues, we therefore suggested that a meaningful circularity metric would measure the amount of recirculated materials as a fraction of the total material inputs into the global economy in a specific year.

This ambitious study inspired Circle Economy to further open the economic "black box" by quantifying and mapping the material throughput across global value chains to the final use by society to meet their functional needs. This effort was guided by one question: What does the material footprint behind satisfying key societal needs look like? Answering this question could create insights into the key levers needed to transition to a circular economy, whilst encouraging more targeted strategies and policies. In turn, the Global and National Circularity Metrics could represent a stepping stone and one of the high-level indicators for governments and institutions all over the world for tracking and reporting on the progress of such policies.

In this technical document, we present the theory, methods and sources behind our analysis and discuss the advantages and limitations of our approach.

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[1] Christiansen, Lars, Olivier Bois von Kursk, and James Arthur Haselip. "UN Environment Emissions Gap Report 2018." (2018).

[2] Haas, Willi, et al. "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 (2015)*: 765-777.

Theoretical Framework and System Definition

Multiregional Hybrid Supply-Use and Input-Output Tables (mr-HSUTs / mr-HIOTs)

The Circularity Gap modeling framework is founded in the System of Environmental-Economic Accounting (SEEA), a *"general framework that integrates economic and environmental data to provide a more comprehensive and multipurpose view of the interrelationships between the economy and the environment and the stocks and changes in stocks of environmental assets, as they bring benefits to humanity"*[3]. Constructed on SEEA principles, the EXIOBASE database contains one of the most comprehensive environmentally-extended mr-HSUTs and mr-HIOTs freely available. These tables were developed within the European Union FP7 project DESIRE[4] to accurately describe the way economic activities are interlinked to each other and the environment through physical and economic transactions. The tables have the following key characteristics:

- 43 nations plus 5 Rest-of-the-World (RoW) regions over the 2000-2011 period;
- 200 products and 164 industries;
- 39 resource and 66 emission categories (incl. avoided and unregistered);
- Supply and use of waste flows;
- Accumulation and depletion of stocks;
- Compiled in mixed units: mass (tonnes) for tangible good, energy (terajoules) for energy flows and monetary (million euro) for intangible services.

As such, 2011 represents the latest year for which comprehensive accounts (also named *extensions*) for key flows involved in the metric calculation are available. While this provides a useful data baseline and structure, it also reinforces the need for updating key figures to the most recent year for which data is available or can be estimated (see section *"Accounts Update Methodology"* section). To facilitate the process, we re-casted the supply and use framework into a system definition based on principles of Material Flow Analysis (MFA).

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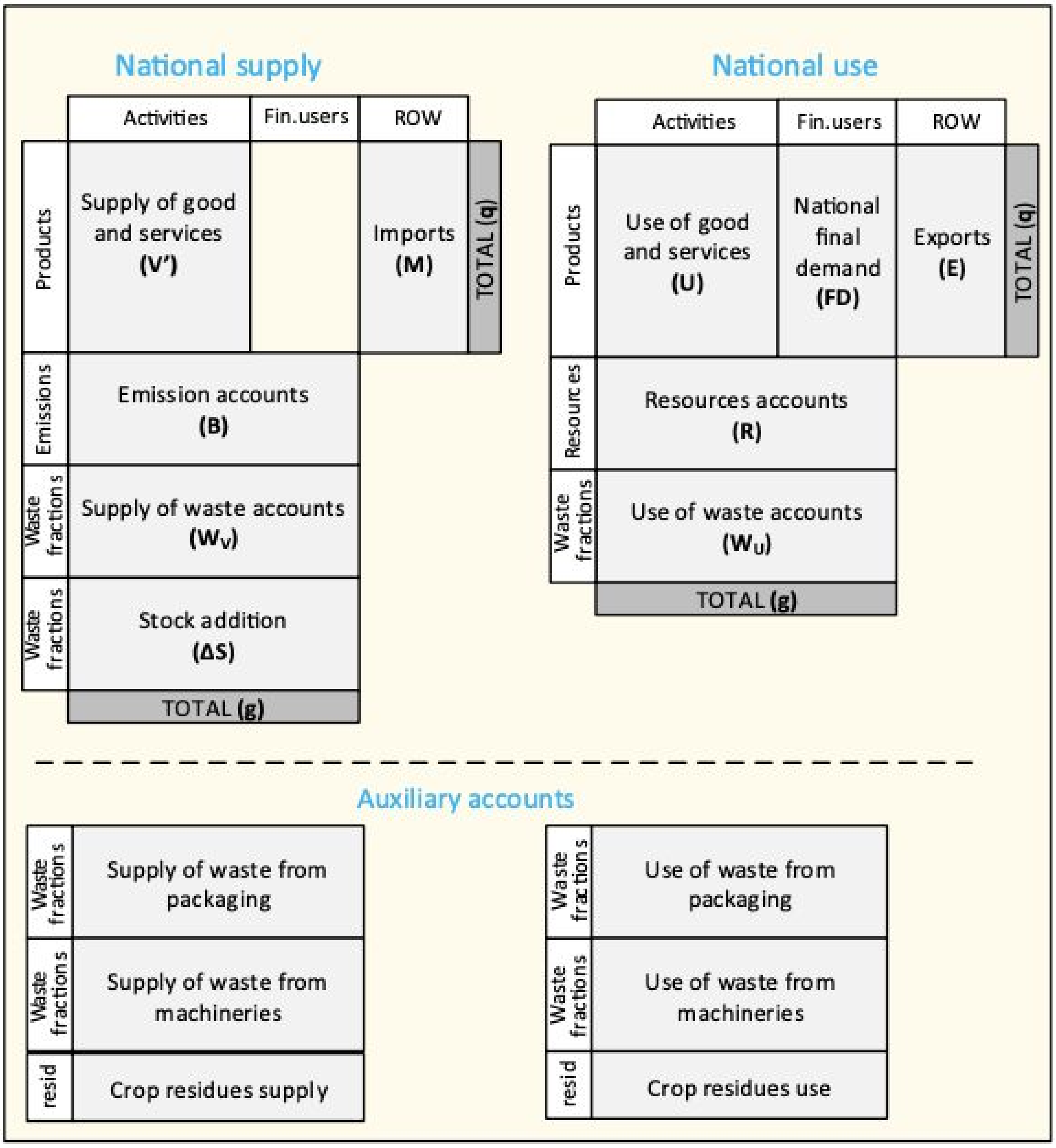
[3] European Commission; Food and Agricultural Organization of the United Nations; International Monetary Fund; Organization for Economic Co-operation and Development; World Bank. (2017). *System of Environmental-Economic Accounting 2012*. Washington, DC: International Monetary Fund.

[4] Merciai, S., & Schmidt, J. (2018). Methodology for the construction of global multi-regional hybrid supply and use tables for the EXIOBASE v3 database. *Journal of Industrial Ecology*, 22(3), 516-531.

The current version of the metric is calculated using EXIOBASE mr-HSUTS v3.3.17, of which Figure 1 shows a *simplified* tabular representation.

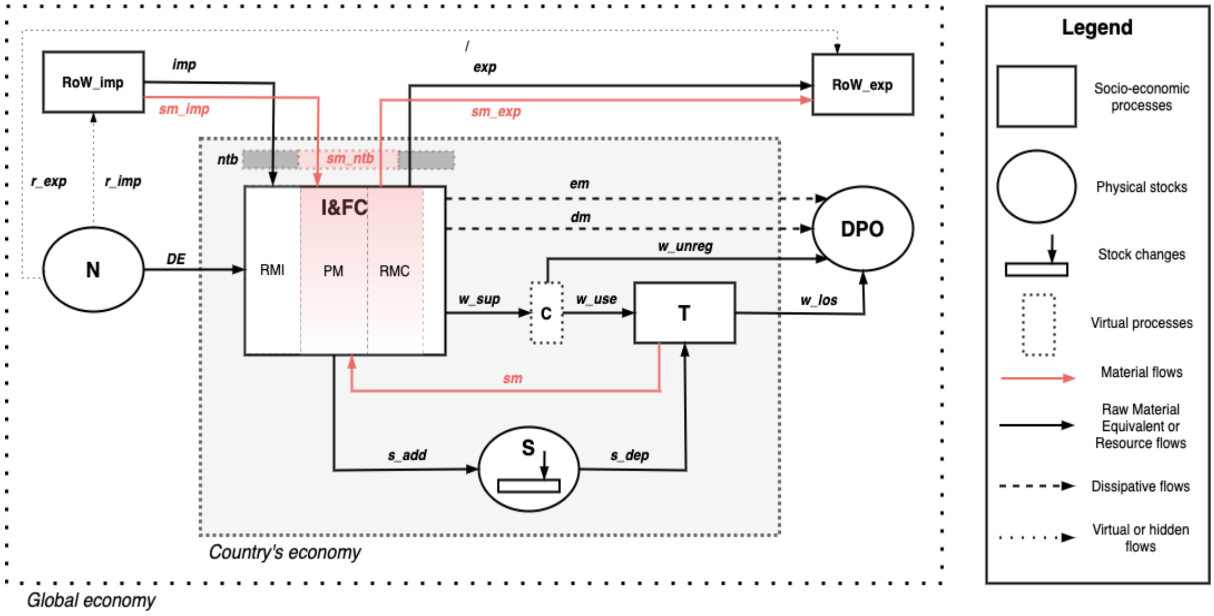
Figure 1. Simplified representation of the national hybrid supply and use framework, Merciai et al. (2019)



Economy-wide Material Flow Analysis (EW-MFA)

Building upon the work of Aguilar-Hernandez et al. (2019), the mr-HSUTs were rearranged in a novel system definition based on EW-MFA (Figure 2).

Figure 2. System definition of national material flow inputs, outputs and stocks, own elaboration based on Aguilar-Hernandez et al. (2019)



<u>Flows</u> *- **DE**: Extraction of natural resources, **imp**: Imports, **exp:** Exports, **em**: Emissions, **md**: Dispersed and dissipated materials, **s_add**: Stock additions, **s_dep**: Stock depletions, **w_sup**: Supplied or generated waste, **w_use**: Treated waste **sm**: Secondary materials (recovered waste), **sm_imp**: secondary materials in imports, **sm_exp:** secondary materials in exports, **w_los**: Lost waste, **w_unreg**: Unregistered waste*

<u>Socio-economic processes</u> *– **RoW_imp:** Economies of import, **RoW_exp:** Economies of export, **I&FC:** Intermediate and final consumption, **T:** Waste treatment sectors*

<u>Virtual flows and processes</u> *- **r_imp**: Raw Materials Equivalents of imports, **r_exp**: Raw Materials Equivalents of exports, **ntb**: Net trade balance, **sm_ntb:** Net trade balance of secondary materials, **C:** Waste collection*

<u>Physical stocks</u> *– **N:** Natural stocks of resources, **S:** Socio-economic stocks of products, **DPO**: Domestic Processed Output*

At the **global level** the system is closed in terms of mass, since the presence of imports or exports would imply trade with alien species. The system balance is based on this set of <u>simplified</u>[5] equations:

$$DE = em + md + w_{unreg} + w_{los} + NAS$$

$$NAS = s_{add} - s_{dep}$$

$$w_{los} = w_{use} - sm$$

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[5] Note that this is still a simplified notation where all variables refers to both consumption by intermediate activities and by final demand categories.

$$w_{unreg} = w_{sup} - w_{use}$$

Where NAS represented the Net Stock Addition - that is the difference between the Gross Addition to Stocks and the Demolition and Depletion of Stock - for a specific year.

At the **nation level**, imports and exports of tangible products need to be taken into account and the balance can be re-written as follows:

$$DE^{reg} = em^{reg} + md^{reg} + w^{reg}_{unreg} + w^{reg}_{los} + NAS^{reg} + ntb^{reg}$$

$$ntb^{reg} = imp^{reg} - exp^{reg}$$

$$imp^{reg} = \sigma_{1xi} * \left(\hat{\alpha^{imp}} * Z^{RoW,reg}\right) * \sigma_{ix1}$$

$$exp^{reg} = \sigma_{1xi} * \left(\hat{\alpha^{exp}} * Z^{reg,RoW}\right) * \sigma_{ix1}$$

Where imp^{reg}, exp^{reg} and ntb^{reg} represent the imports, exports and net trade balance in terms of Raw Material Equivalent (RMEs) units respectively, σ_{1xi} is a summation vector, α is the vector of RME coefficients per product (kg resources per kg of product or € of service) and Z is the hybrid units intermediate consumption matrix. One key advantage of structuring hSUTs in this fashion is that each process (economic activity or physical stock) can be intuitively described by a system of linear balancing equations.

As reported by Eurostat, "*EW-MFA in RME account for the final use of products in terms of equivalents of 'domestic' extraction*". This means that the final use of products are expressed in terms of how much material was extracted from the environment, domestic or abroad, to produce the product for final use. MFA-RME are compiled using a modelling approach that allocates 'domestic' extraction of materials reported in EW-MFA to the final use of products by linking and re-attributing the natural inputs to economic activities producing the final goods. MFA-RME are also referred to as consumption-based accounts of material flows[6]. Eurostat reports imports (imported products) in RME, exports (exported products) in RME, while the two related headline indicators are the Raw Material Consumption (RMC), which represents the domestic final use of products in RME and the Raw Material Input (RMI) which is the total final use of products in RME.

All flows that are present in the extensions are classified into four key resource groups: biomass, fossil fuels, metal ores and non-metallic minerals. Oxygen and hydrogen are

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[6] The term 'consumption-based' captures the idea that the accounts take the viewpoint of the final products (i.e. products that have passed the final stage of production) that are demanded by final users. The term 'consumption' hence encompasses all final uses. Alternative terms used in the literature are demand-based accounting and footprints.

excluded from the mass balance. Mineral tailings or mining waste is included. From the waste use matrix w_{use}, waste recovered w_{rec} and w_{los} are derived by classifying the waste treatment sectors into four broad categories, namely: recycling and energy recovery (together "waste recovery"), landfilling and incineration (together "waste loss").

Table 1 provides further information on the rationale behind the classification and the relation between variables.

Table 1 Definition of waste-related variables

Variable code	***Variable name***	***Definition***
w_sup	*Waste supply*	*Total waste generated including unregistered waste*
w_use	*Waste use*	*Total waste treated by waste management activities*
sm	*Secondary materials (waste recovered)*	*Share of waste use that falls under R1-13 activities as of DIRECTIVE 2008/98/EC*
ws_rec	*Waste recovered from stock depletion*	*Share of w_rec that originated from stock depletions*
w_los	*Waste "lost"*	*Share of waste use that falls under D1-D15 activities as of DIRECTIVE 2008/98/EC*
ws_los	*Waste lost from stock depletion*	*Share of w_lost that originated from stock depletions*
s_unreg	*Share of unregistered waste*	w_unreg/w_sup
r_coll	*Collection rate*	$1 - s\_unreg$

The full categorization of extensions items into resource groups and of waste management activities as well as an extended equation set will be included in the Annex.

Global and National Circularity Metric

Based on the system definition described in Figure 2, our two key metrics can be calculated, namely: the **Global Circularity Metric (GCM)** and **National CIrcularity Metric (NCM)**. There are two sides to each metric: The index, which measures the degree of circularity of an economy, and its inverse – the gap – which measures the share of non-circular inputs to an economy. We named these the Global Circularity Index (GCI), Global Circularity Gap (GCG), National Circularity Index (NCI) and National Circularity Gap (NCG). Building upon the work by Haas and colleagues[7] and the framework and throughput indicators for an economy-wide Circular Economy (CE) assessment put forward by Mayer and colleagues[8], in its most generalized way the formula for calculating the Circularity Index is the following:

$$CI \;=\; \left(\frac{w_{rec} + sm_{ntb}}{RMC + w_{rec} + sm_{ntb}}\right) * 100$$

Where ntb_{rec} represents the *Net Trade Balance of cycled (or secondary) materials* while RMC is the *Raw Material Consumption*. As mentioned before, when taking a global perspective, imports, exports and thus also the net trade balance are null and therefore:

$$ntb \;= imp \;- exp \;= 0 \Leftrightarrow ntb \;=\; 0$$

$$RMC \;= de$$

$$GCI \;=\; \left(\frac{sm}{DE + sm}\right) * 100$$

Imports, exports, net trade balance and the concept of RMEs take prominent relevance when a national perspective is taken. In this respect, we argue that the NCI should be calculated as the share of cycled materials in the total raw material consumption of a country (including cycled materials) using the following formula:

$$NCI = \left(\frac{sm^{reg} + sm_{ntb}^{reg}}{RMC^{reg} + sm^{reg} + sm_{ntb}^{reg}}\right) * 100$$

$$sm_{ntb}^{reg} \;= (imp^{reg} \;* GCI) \;-\; (exp^{reg} * (\frac{w_{rec}^{reg}}{r^{reg} + w_{rec}^{reg}}))$$

$$RMC^{reg} \;=\; r^{reg} + ntb^{reg}$$

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[7] Haas, Willi, et al. "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 (2015): 765-777.

[8] Mayer, Andreas, et al. "Measuring progress towards a circular economy: a monitoring framework for economy-wide material loop closing in the EU28." *Journal of industrial ecology* 23.1 (2019): 62-76.

Note that in the absence of robust data on the amount of cycled (or secondary) material embedded in the imports and exports of the country, the former is estimated by applying the average GCI to the imports and a country-specific equivalent to the exports. A second – conceptually similar – way to calculate the NCI is the following:

$$NCI = \frac{smc^{reg}}{RMC + smc^{reg}}$$

$$smc^{reg} = \frac{RMC^{reg}}{RMI^{reg}} * sm^{reg} + imp^{reg} * CGI)$$

This second method avoids the use of the proxy domestic cycling rate $\frac{w_{rec}^{reg}}{r^{reg} + w_{rec}^{reg}}$ for estimating secondary materials in exports by instead applying the share of consumption over total input $\frac{RMC^{reg}}{RMI^{reg}}$ to both domestic and imported secondary materials to estimate the volume of secondary materials in consumption smc^{reg}. In this formula, imp^{reg} is not converted into RMEs as this would imply applying the same coefficients of normal products to secondary materails. Robust and updated reported figures are always used in place of this estimation whenever data is available. This workaround assumes that the amount of secondary materials ending up in domestic products and in products for export is equal and that the average recycling content of imports is the same for every country. Estimating the recycled content of imports and exports is an ongoing challenge, both in terms of data availability and because of different concepts in the measurement of traded products for statistical purposes (points of measurement). It is one of Circle Economies's core efforts to research the most robust and updated figures for this type of data as well as to contribute to the discussion and development of its underlying estimation methods. To conclude, the two complementary "gap" metrics are calculated as the simple inverse of their index.

$$GCG = 100 - GCI$$

$$NCG = 100 - NCI$$

Methodological challenges in measuring country-level circularity

Raw Material Equivalents of primary and secondary products. Raw Material Equivalents is an accounting concept introduced to improve the calculation of environmental pressure indicators at the national level. It allows practitioners to express the final use of products at different stages in the supply chain (e.g. raw materials, semi-manufactured products and services) into the amount of material extraction that was needed to produce them in the country of origin. Their rationale is to link material extractions in a given accounting period to the final use of products in the same accounting period to answer the question: how much material extraction was necessary to enable the final use of products of that period? As such, RMEs are a form of consumption-based accounting, sometimes referred to as “footprint”, and are usually calculated by linking resource accounts and MRIO models[9]. In many cases, RME coefficients are expressed in different units for tangible products (kg material per kg product) and intangible products or services (kg material per € service) and their application therefore relies on hybrid models such as Eurostat’s ADTA-IO.[10] Because of the complexity and the data-heavy nature of such models, there are inherent uncertainties in the estimation of RME coefficients mainly related to modeling assumptions and data quality. This is particularly true for the estimation of RMEs of secondary materials, which presents several challenges such as the inclusion of end-of-life product stocks from previous accounting periods and the inclusion of further inputs for processing[11]. Due to these limitations, our current method does not apply RMEs to any secondary material category and it is therefore not to fully reflect their substitution potential in terms of reduced material inputs and/or consumption.

Secondary materials embodied in trade. Next to the challenges connected with estimating the domestic extraction needed to enable the consumption of secondary materials, there are also practical limitations to the accounting of secondary materials embodied in trade. Physical transaction data is scarce or – whenever available – is quite outdated. Monetary transaction data is more abundant, but it is often too aggregated to be used or dubious due to accounting principles for the imputation of an economic value to a former waste flow. Due to a lack of specific information, the metric calculation applies the average GCI to the imports and a national-level equivalent for exports to estimate their respective amount of secondary materials.

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[9] Wiedmann, Thomas O., et al. "The material footprint of nations." *Proceedings of the national academy of sciences* 112.20 (2015): 6271-6276.

[10] Eurostat. “Handbook for estimating RME of imports and exports and RME-based indicators on the country-level - based on the EU RME model”, October 2019.

[11] EEEA/2018/01 Technical Note Eurostat. “Secondary materials in European material flow accounts in raw material equivalents”, November 2018.

Accounts Update Methodology

As mentioned in the previous section – while EXIOBASE provides global interlinked data on, among others, extracted resources and traded products – its reference year of 2011 makes for a quite outdated data source. Our general approach was, therefore, to use EXIOBASE to provide the structure and to resort to more recent sources to update the figures. This means that in our model, the size or magnitude of resource consumption refers to the most recent year for which data is available, yet the structure of consumption (i.e. which activities this consumption is attributed to) remains proportional to 2011 levels. Although it can slightly change from case to case, the implementation of updates is a 2-step process consisting of: (1) transformation of the original satellite matrix into coefficient matrices and (2) post-multiplication with the updated matrices. This can be expressed as:

$$A = Z * \widehat{x^{-1}}$$

$$Z^{new} = A * Z^{new}$$

With the updated matrices having always a higher aggregation level than the original ones, the multiplication of Z^{new} by the original coefficient matrix ensure that the updated values are proportionally re-distributed across regions and activities.

Resource accounts

Table 2 shows a comparison between resource extraction by resource group as estimated from EXIOBASE v3.3.17 hybrid accounts and the latest resource extraction data from the IRP[12].

Table 2. Comparison of resource extraction between EXIOBASE (2011) and IRP (2017)

Resource group	unit	v3.3.17 (2011) Baseline	IRP 2017 CGR 2020
Biomass	Gt	21.03	24.02
Fossil Fuels	Gt	14.14	15.04
Metals	Gt	1.48	1.75
Ores (mining waste)	Gt	6.22	7.37
Nonmetallic minerals	Gt	36.9	43.83
Total	**Gt**	**79.8**	**92.01**

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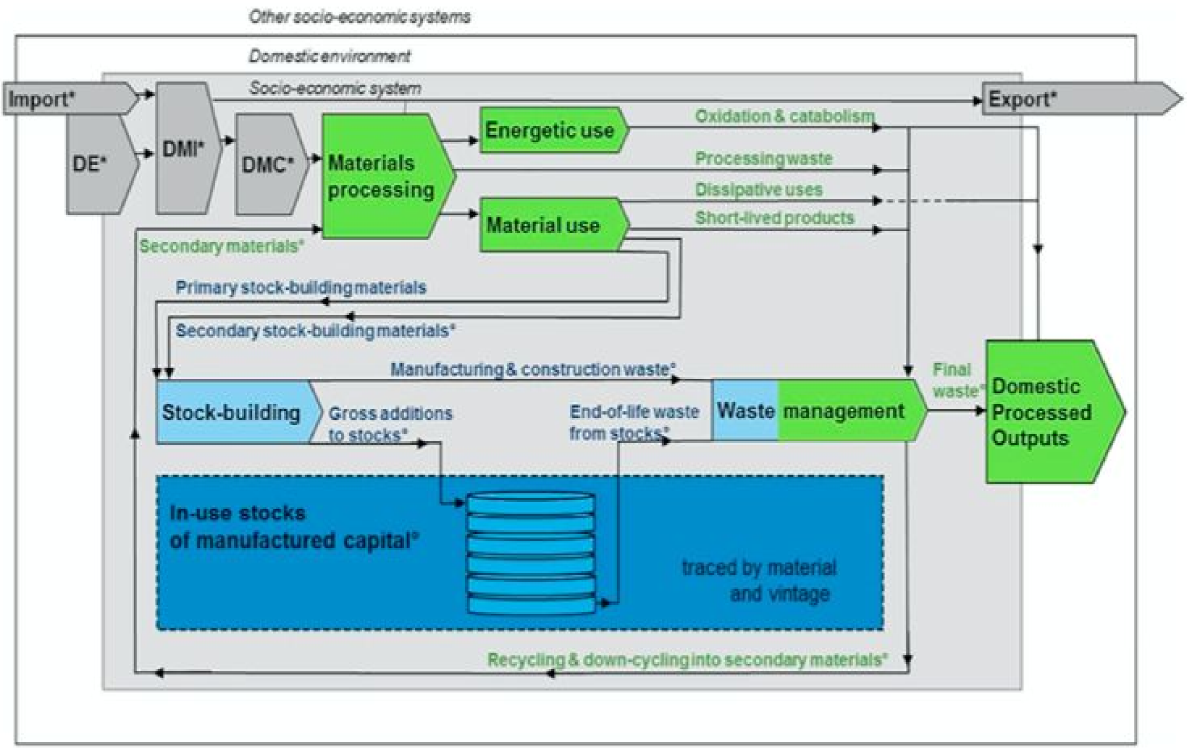
[12] Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., ... & Krausmann, F. (2018). Global material flows and resource productivity: forty years of evidence. *Journal of Industrial Ecology,* 22(4), 827-838.

Stock accounts

Static models struggle to properly capture stock-flow dynamics and, although HSUTs development aims at bridging this gap, they are still falling short compared to dynamic stock models. Therefore, the key source used to update stock-related flows and changes is the MISO (Material Inputs, Stocks and Outputs) model developed by BOKU[13]. Figure 3 depicts the system definition of the model, while the table below shows the correspondence between variables from the GCM and the MISO models. The latest dataset available contains a time-series (2015-2050) based on global convergence of trends to industrial levels for primary stock-building materials and secondary stock-building materials (together Gross additions to stocks), EoL waste from stocks and final waste.

Figure 3. System definition of national material flow inputs, outputs and stocks (Wiedenhofer et al. 2019)



MISO variable name	GCM variable
Imports	imp^{reg}
Exports	exp^{reg}
Domestic extraction	$de\ (or\ de^{reg})$
Domestic Material Input (DMI)	$de^{reg} + imp^{reg}$

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[13] Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W., & Krausmann, F. (2019). Integrating material stock dynamics into economy-wide material flow accounting: concepts, modelling, and global application for 1900–2050. *Ecological economics*, 156, 121-133.

Domestic Material Consumption (DMC)	$de^{reg} + imp^{reg} - exp^{reg}$
Oxidation and catabolism	em
Dissipative uses	dm
Short-lived products and processing waste	w_{sup}
Gross addition to stocks	s_{add}
End-of-life waste from stock	s_{dep}
Recycling and down-cycling secondary materials	$sm + ws_{rec}$
Final waste	$w_{unreg} + w_{los} + ws_{los}$

This allows us to estimate – at the global level – *s_add* and *s_dep,* as well as the fraction of waste from stock being recycled *ws_rec* or lost *ws_los*. The latter are estimated by applying 2014 global average recycling rates for 14 broad product categories as presented in the supporting information of Wiedenhofer and colleagues and by assuming that what is not recycled is either landfilled or incinerated.[14] We further so as the shares of landfilled versus incinerated. Table 3 gives an overview of some estimated figures by year and source.

Table 3. Comparison of selected stock-related variables across CGR reports

Resource group	**unit**	**v3.3.17 (2011) Baseline**		**Krausmann et al. (2018) - 2015 CGR 2018/2019**		**Wiedenhofer et al. (2019) - 2017 CGR 2020**		
		s_add	s_dep	s_add	s_dep	s_add	s_dep	s_dep to w_rec
Biomass	Gt	0.6	0.32	-	-	1.3	1.08	0.21
Fossil Fuels	Gt	0.5	0.09	-	-	0.33	0.18	0.04
Metals	Gt	1.7	1.32	-	-	1.59	0.55	0.42
Nonmetallic minerals	Gt	26.8	0.63	-	-	44.8	13.4	5.7
Total	**Gt**	**29.6**	**2.36**	**36**	**14.5**	**48.05***	**12.2***	**6.34**

* Based on "Global convergence scenario"

It is clear that, for both *s_add* and *s_dep,* there is a considerable difference between the baseline value from EXIOBASE and those from the MISO model as well as for the shares of waste fractions. There is still no explanation for this large underestimation of C&DW in the hSUTs.

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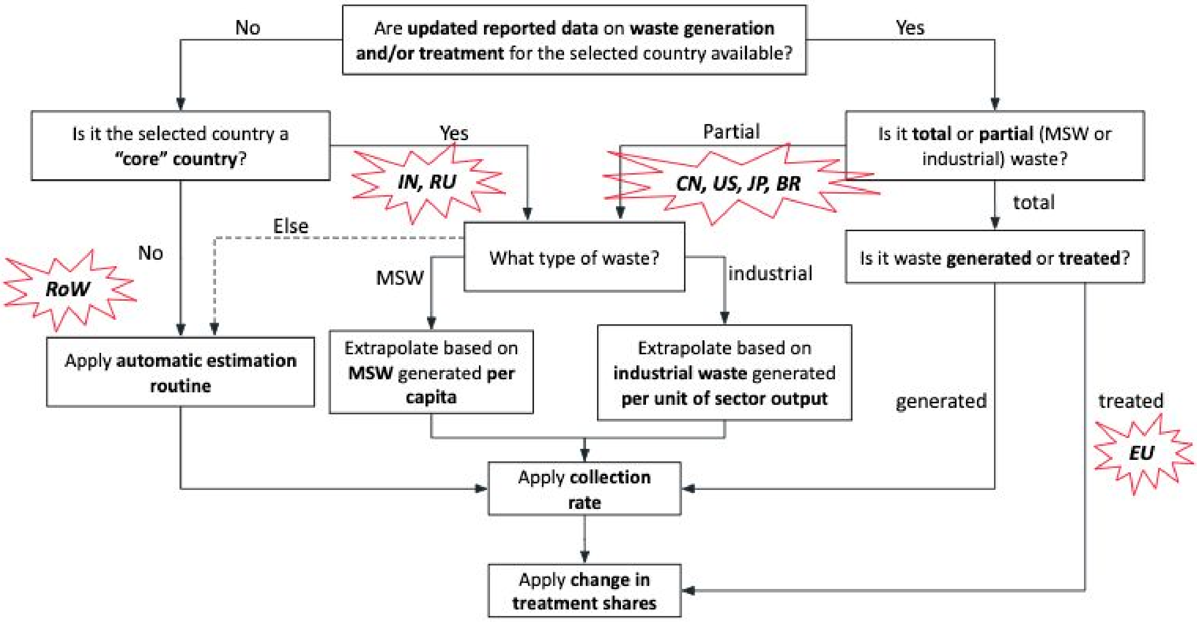
[14] Wiedenhofer, Dominik, et al. "Integrating material stock dynamics into economy-wide material flow accounting: concepts, modelling, and global application for 1900–2050." *Ecological economics* 156 (2019): 121-133.

Waste accounts

Waste accounts represents the core effort of the updating procedure, but also the most uncertain due to renowned data limitations on both waste generation and treatment. Figure 4 depicts the decision tree developed to guide the updating process. For practical purposes, we distinguish between "core countries" or groups of and the Rest of the World (RoW). "Core countries" (CN, US, IN, RU, BR, JP, EU) are those that together represent 77.5% and 71% of the registered and total waste generated respectively. Please note that, at the moment of publication of the new CGR 2020, the procedure described below was fully completed only for the EU, partially completed for CN, US, JP and BR (preliminary data collection) and not complete for IN, RU and RoW.

Figure 4. Decision tree for updating waste accounts



For the EU, the dataset used presents waste treated by country and resource group for the year 2016 (*env_wassd*). The total figure for solid waste treated goes up from 1.2 Gt to 1.9Gt with average waste recovered up by 11%. For "core" countries, some reported data is available through the UNSD, OECD and What-a-waste 2.0 (World Bank) datasets, however many data gaps still need to be filled, especially as far as industrial waste is concerned. When this is the case, extrapolation based on per capita (for MSW) and per unit of industry output (for industrial waste) is performed. For the former, we refer to the UN medium variant population dataset while, for the latter, we refer to EXIOBASE v3.4. By coupling waste data with the mrMIOTs, industry-specific unit volumes of waste generated (ton/M€) are calculated. Updated figures for sectoral output (Meuro) are then gathered from different sources and used to estimate the new waste volumes (sectoral output is expressed 2011 constant prices to isolate the effect of inflation).

Finally, for all those countries for which there is no data availability at all, an "automated estimation routine" has been developed. This routine considers that emission data are much more easily and readily available than waste data. Therefore, emissions are updated using data from the EDGAR database.[15] The following constraint is then introduced in the model:

$$\frac{md_n}{r_n + sm_n} = \mu$$

This means that the ratio between total material input $r + w_{rec}$ and material dispersed md (balancing item) is constant over time. This way, the model can endogenously estimate the new waste supply by applying an iterative procedure to downscale dispersed materials, while upscaling waste generation so that the condition holds true. While this straightforward procedure allows us to get a rough estimate of waste supply in any year n, the modeling assumption behind it is clearly a simplification of reality in which efficiency improvements are supposed to reduce this ratio over time. However, given the heterogeneous nature of the dispersed material category (also referred to as dissipative uses and losses in MFA terminology) it is challenging to estimate an efficiency improvement rate. Even in that case, we argue that since the projection is on a rather short term (2011 to 2017), the inclusion of such rate would have minimal effect.

Overall, the main obstacle in updating waste satellite accounts is the availability of reliable recycling, energy recovery, landfilling and incineration shares of waste treatment for recent years. To increase the amount of data points we can use, we are in the process of generating a more detailed waste treatment matrix by waste fraction and supplying sector that would allow us to rely on MSW- and industrial-specific treatment share rather than average ones.[16] Table 4 lists a comparison of aggregated data for most of the waste-related flows.

Table 4. Comparison of selected waste-related variables across CGR reports

Resource group	**unit**	**v3.3.14 (2011) CGR2018/19**			**v3.3.17 (2011) CGR2020**				**v3.3.17 (2011)**	**Eurostat 2016**
		w_use	w_rec	w_los + w_unreg	w_use	w_rec	ws_rec	w_los + w_unreg	Recovery rate (EU)	Recovery rate
Biomass	Gt	7.87	7.13	2.81	2.74	0.41	0.21	3.53	44.9%	78.1%
of which manure	Gt	1.54	1.54		1.52	(1.52) Not incl.		3.15	Not incl	Not incl.
of which sewage / WWT	Gt	5.06	5.06		0.52	WWT not incl.		0	Not incl	Not incl.
Fossil Fuels	Gt	0.45	0.04	0.4	0.15	0.076	0.04	0.26	11.3%	66.6%
Metals	Gt	0.6	0.52	0.7	0.95	0.48	0.42	0.82	42.8%	91%
Nonmetallic minerals	Gt	0.78	0.67	2.24	1.27	1.18	5.7	2.14	51.7%	52.7%
Total	**Gt**	**9.7**	**8.37**	**5.53**	**5.11**	**2.16**	**6.34**	**6.74**	**47%**	**58.5%**

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[15] Olivier, Jos GJ, K. M. Schure, and J. A. H. W. Peters. "Trends in global CO2 and total greenhouse gas emissions." *PBL Netherlands Environmental Assessment Agency 5* (2017).

[16] Tisserant, Alexandre, et al. "Solid waste and the circular economy: a global analysis of waste treatment and waste footprints." *Journal of Industrial Ecology* 21.3 (2017): 628-640.

As it can be seen highlighted in red, there are also considerable differences in this case. To begin with, between v3.3.14 and v3.3.17 of EXIOBASE, there is a 4.5Gt difference in sewage generation. This will greatly affect the metric, especially considering that in this update we are excluding the ambiguous activity “Wastewater treatment” from the list of recovery activities as well as “Manure, storage and land application”. This is partly because the recovery rates, as presented in the *env_wassd* dataset by Eurostat, do not account for liquid waste fractions such as sludges and manure and, therefore, they cannot be applied to such flows. On a more general level, the ambiguous definition of treatment techniques such as “land spreading” and the issue of storage in statistic accounting adds to the problem underlined above. Nevertheless, we recognize the exclusion of liquid waste from the metric as one of the main limitations of this methodology and one of the most urgent to be addressed. Secondly, since new data on stock depletion and resulting recycled waste has become available, the composition of the recovered flow changed and it better aligned with current literature and common knowledge which sees nonmetallic minerals as the predominant mass flow in almost any recycling stream. This change is linked to the issue about C&DW raised in the previous section.

Sankey Diagram Methodology

To develop the Sankey of global resource flows, we used the updated datasets to map how extracted resources undergo transformation through various industries to meet societal needs. The data manipulations needed to construct such visual representation are detailed in the sections below.

First, the 200 products, 164 industries and 48 country codes in EXIOBASE, were aggregated into 40 products and 20 industries for the whole world. Next, each of the products were assigned to one of 7 societal needs:

- Nutrition
- Housing
- Consumables
- Mobility
- Communication
- Healthcare and Education
- Services

The products and industries were also categorised into the various phases of the linear economy:

- *Take* = extraction of resources
- *Process* = processing of primary resources for use in production
- *Produce* = production of products for use by society
- *Provide* = services that use products to meet societal needs
- *Waste* = services that treat waste material

The products in the *Take* phase were also categorised by their main resource group:

- Biomass
- Fossil
- Metal Ores
- Minerals.

All of these categorisations can be found in the Annex. The categorised industries and products were structured into specific linear flows that reflect the transformation of extracted resources into products produced for societal consumption. We assume that no products can be extracted and immediately meet societal needs. Even food products are assumed to require some processing before they are consumed by society.

Some products require some processing from industries before meeting societal needs:

Take → Process → Functional Need

Example: Forestry supplying Wood → Wood and Paper Processing supplying Paper → Communications Functional Need

Some products require some processing into semi-finished products as well as production into final products before meeting societal needs:

Take → Produce → Functional Need
Example: Forestry supplying Wood → Manufacturing Wood into dashboards and parts for vehicles → Mobility Functional Need

Take → Process → Produce → Functional Need
Example: Fossil Fuels Extraction supplying Petroleum → Fuel and Chemical Processing creating Plastics → Manufacturing Plastics into parts for vehicles → Mobility Functional Need

Lastly, some products are processed, produced into final products, and utilised in the provision of services that meet societal needs:

Take → Provide → Functional Need
Example: Forestry supplying Wood → Construction using Wood for houses → Housing Functional Need

Take → Process → Provide → Functional Need
Example: Mining of Minerals → Fuel and Chemical Processing into Paint → Retail of Paints → Consumables Functional Need

Take → Produce → Provide → Functional Need
Example: Extraction of Natural Gas → Electricity and Heat Production → Financial Exchanges using Electricity → Services Functional Need

Take → Process → Produce → Provide → Functional Need
Example: Mining of Metal Ore → Metal Processing → Manufacturing of Heavy Machines → Construction Services → Housing Functional Need

One caveat is that this means that certain flows are not captured if they don’t fit the linear process. For example, Tractor production is required for Agriculture, but since Tractors are in the Produce phase, while Agriculture is in the Take phase, these “feedback loops” are not considered. This was done to simplify the global resource flows, as it is a challenge to accurately represent the global economy in a structured manner.

Data conversion and scaling

The data in EXIOBASE was constructed using monetary data from national input output tables and statistics. This data was transformed to create hybrid tables that are in both physical units (in tonnes, terajoules) and monetary units (in euros) using a variety of statistical techniques and models. However, In order to construct the Sankey diagram, all global resource flows needed to be in a single standard unit. Therefore, all the EXIOBASE data, both physical and monetary, needed to be converted to a unit of measure in tonnes. To conduct this conversion, for all products that were not recorded in tonnes, we calculated their material intensity by summing up all physical inputs and dividing them by the total output in monetary or energy units according to the formula below:

$$c_{fct} = \frac{\sum_{i=ton} u_{i,j}}{\sum_{i \neq ton} v_{i,j}}$$

While this only captures the direct inputs in tonnes per unit of output, this allowed us to calculate a proxy conversion factor to transform all physical and monetary data into physical units in tons. These conversation factors are outlined in Table 3 in the Annex.

After these transformations, namely the cutting of feedback loops and conversion based on proxy factors, the magnitude and scale of resource extraction and use by society no longer reflected the amount of resources extracted as updated from the IRP. In order for the Sankey to reflect the actual mass of extracted resources, the flows calculated from EXIOBASE were scaled using scaling factors.

The portion of the Sankey highlighting the end-of-use of resources after they meet societal needs was constructed using the updated data from the waste and stock accounts. Waste data in EXIOBASE provides information on the amount of waste in tonnes generated by the various industries and the amount of waste in tonnes used by various industries. As already mentioned in chapter 2, the industries that use waste were categorised based on the type of waste treatment they engage in – landfill, incineration, recycling, etc. The full categorisation of the industries and their waste treatment methods can be seen in the Annex.

The creation of the Sankey Diagram can be seen as an explorative and creative way to open up the "black box" of the economy – that is the "**I&C"** (Intermediate and final consumption) process of Figure 2 – to shed more light into its inner workings. The actual data for inputs, outputs and stock changes are taken from the model and used to "recalibrate" the left (inputs) and right (output) side of the Sankey and match the precise figures.