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Characterization factors for material flow accounting (material footprint) for process-based LCA – Documentation for ecoinvent 3.7.1 and 3.8 in openLCA

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https://github.com/IndEcol/openLCA_ecoinvent_Material_Footprint_LCIA

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Characterization factors for material flow accounting (material footprint) for process-based LCA – Database for ecoinvent 3.7.1 and 3.8 in openLCA

April 2022

by Stefan Pauliuk

Content:

1. Additional background information
2. Documentation of the material footprint LCIA method
3. Exemplary Results and Discussion

References

List of frequent acronyms and abbreviations:

MB2019: Mostert and Bringezu (2019), the main reference for this work

CF: (LCIA) characterization factor

DMI: Direct material input

ei: ecoinvent life cycle inventory and process database

LCIA: Life cycle impact assessment

MFA: Material flow analysis

MRIO: Multi-regional input-output analysis

RME: Raw material equivalent

RMI: Raw material input

TMR: Total material requirement

1. Background information

Material flow accounting (MFA) (Fischer-Kowalski et al. 2011) is a method to systematically compile data on the total material use (input) and discards (output) of society/economy. Its system boundaries are consistent with the System of National Accounts and it is an established accounting methodology with a comprehensive database.[1] As an accounting scheme, MFA provides sector and country level data for *direct flows*, i.e., the material flows that directly flow into the economies and sectors for which they are reported. In supply chain assessment, direct flows are labelled *scope 1* indicators. MFA data are used to build environmental extension tables and calculate stressor matrices for input-output tables (Miller and Blair 2009). These derived data, in turn, are used for calculating the material footprint, a supply chain or scope 3 indicator with multi-regional input-output models (MRIO) (Wiedmann et al. 2015; Miller and Blair 2009).

In process-based LCA, commonly used for product-level supply chain studies, a corresponding impact assessment method to determine the material footprint of product systems was lacking for some time. Thanks to the work by Mostert and Bringezu (2019) (henceforth: MB2019), a list of 286 characterization factors for the material footprint of products and services, expressed as raw material equivalents (RME/RMI) and total material requirement (TMR), is now available for ecoinvent 3.1.

Here, an attempt to transfer and extend the material-specific MFA indicators (RMI and TMR) compiled by Mostert and Bringezu (2019) to process-based LCA in form of the databases ecoinvent 3.7.1 and 3.8 (Wernet et al. 2016) is described. The scope of the material flows covered here largely fits to the materials list used for the Mineral Resource Scarcity indicator of the ReCiPe life cycle impact assessment (LCIA) method (Huijbregts et al. 2016).

The rationale for creating such an LCIA method for material flow indicators is given by Mostert and Bringezu (2019). Its main advantage over price and scarcity-weighted material depletion indicators is that the total mass input to production is very easy to interpret. Next to using the aggregated indicator, LCA software allows for breaking down total impacts into individual materials, process contributions, and resource flows, which means that material footprint LCA indicators can be used to quickly identify the most relevant materials in a product's material footprint and where they occur. An in-depth impact assessment of the most relevant material flows regarding land transformation, eutrophication, or toxicity can then follow.

Here, we focus on documenting the technical aspects of making the characterization factors available for the openLCA distribution of ecoinvent 3.7.1 and 3.8.

[1] https://www.resourcepanel.org/global-material-flows-database

The system definition of MFA (Fig. 1) shows the main flows that are accounted for. A crucial step in MFA is to not only quantify industrial material commodities themselves but the total raw materials extracted and processed, as these flows can be much larger than the flows of useful materials and are major drivers of environmental impacts such as land use, GHG emissions, or toxicity impacts.

As explained by Eurostat:[2]

"The simple weight of traded goods provides an incomplete picture as it does not take into account the raw materials originally necessary to produce these traded goods. A more comprehensive picture on the 'material footprints' can be obtained by converting the traded goods into their raw material equivalents (RME), i.e. the amounts of raw materials required to provide the respective traded goods. Especially for finished and semi-finished products, imports and exports in RME are much higher than their corresponding physical weight.

Imports in RME are the amount of raw material required to produce the goods imported into the economy.

Exports in RME are the amount of raw material required to produce the goods exported from the economy.

Raw material input (RMI) is the amount of raw materials required to produce the goods, which are available for use in production and consumption activities of the economy.

Raw material consumption (RMC), measures the total amount of raw materials required to produce the goods used by the economy (also called 'material footprint').

Raw material input = Domestic extraction + Imports in RME

Raw material consumption = Domestic extraction + Imports in RME - Exports in RME = Raw material input - Exports in RME"

One can thus speak of the raw material equivalent (RME) as a *function* (the material footprint indicator calculation) that converts a given commodity flow into its raw material equivalent, i.e., all material that had to be processed to produce the material or commodity at hand.

[2] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Material_flow_indicators

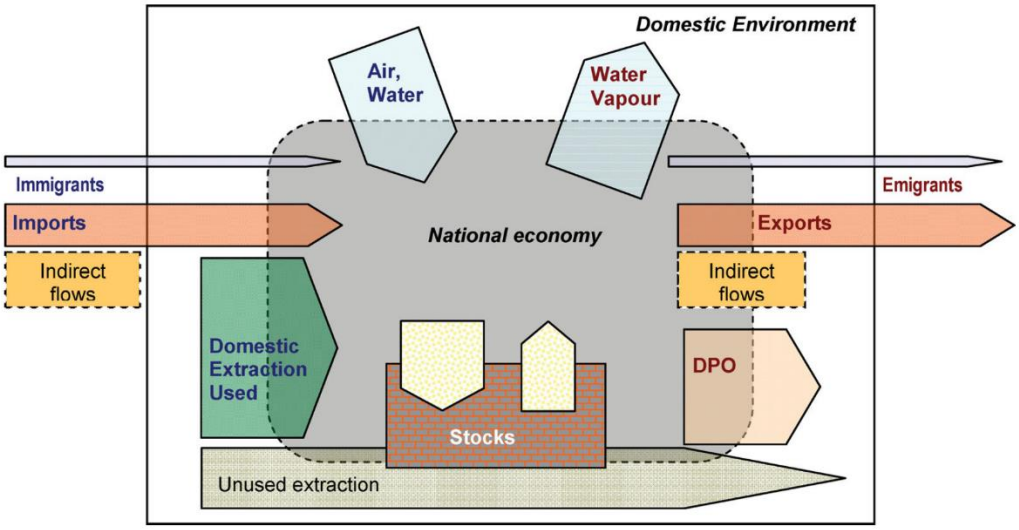
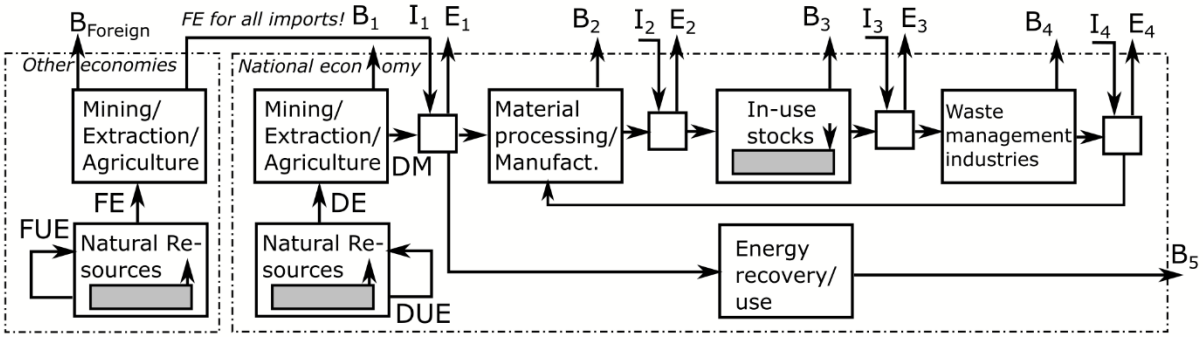


Figure 1 The economy-wide material balance model. Indirect (or embedded) material flows upstream of imports (and exports) can be expressed as raw material equivalents (RME). Definitions and interrelations between the indicators (as used in this figure and throughout the article): DE = domestic extraction used (amount of materials extracted from national territory for direct use); Imports = direct material input from trade (weight at border); Exports = material amounts exported (weight at border); DMI = direct material input = DE + Imports; DMC = domestic material consumption = DE + Imports – Exports; total material requirement (TMR) = DE + unused (domestic) extraction + Imports + unused extraction in country of origin; total material consumption (TMC) = TMR – exports – unused extraction of exports. DPO = domestic processed output, consisting of wastes, emissions, dissipatively used materials, and deliberate deposition (e.g., fertilizers); Balancing items = air and water contained in materials that evaporate during production processes respectively. that are drawn into commodities during production (e.g., oxygen in combustion); Immigrants and emigrants = flows of people who increase or decrease the population stock in this country.

Fig. 1: System definition of economy-wide material flow accounting. Source: Screenshot of Figure 1 in Fischer-Kowalski et al. (2011). Note that for the correct calculation of TMR and TMC, the trade flows need to be converted to their raw material equivalents (RME).

To show the different flows and their meaning more explicitly, the following system definition and indicator list is provided (Fig. 2).



Layers for flows in MFA system:

1: Total mass of a commodity
2: Dry mass of a commodity
3: Emissions/waste
4: Raw material equivalent of a commodity: input to processing (dry mass)
5: Total material requirement for a commodity: extraction from nature (dry mass)

Function:

RME: raw material equivalent: all raw materials needed for providing a given flow: 4

Flows (layer):

DM: Domestic material commodities entering the economy: 2 (not part of standard MFA)
DE: Domestic extraction of raw materials (enters industrial processing: 4) = RME(DM)
DUE: Domestic unused extraction: 5
FE: Foreign extraction of raw materials for import into focus region, = RME(sum(I_x)): 4
FUE: Foreign unused extraction associated with import into focus region: 5
UEE: Unused extraction (domestic and foreign) associated with exports (not shown): 5
B_x: Processed output (solid waste and emissions): 3
I_x: Imports at different stages of fabrication: 2
E_x: Exports at different stages of fabrication: 2
PTB: physical trade balance: sum(I_x)-sum(E_x): 2
Balancing flows (air, water, water vapour, ...) are not shown

Indicators:

DMI: Direct material input := DE + sum(I_x): 4/2 (not consistent across layers!)
DMC: Domestic material consumption := DE + sum(I_x) - sum(E_x) 4/2 (not consistent!)
RMI: raw material input: DE + RME(sum(I_x)): 4
RMC: raw material consumption: RMI - RME(sum(E_x)): 4, also 'material footprint', MF
TMR: Total material requirement:= DE + DUE + FE + FUE: 5
TMC: Total material consumption:= TMR - RME(sum(E_x)) - UEE: 5
DPO: Domestic processed output:= sum(B_x): 3

Fig. 2: Material flow accounting flows and indicators in a material flow analysis-type system definition. Five different layers are shown. They are needed to denote the different flow measures and indicators: total commodity mass (1), dry commodity mass (2), waste/emissions (3), raw material equivalent (RME) of dry commodity mass (4), and total material requirements (TMR) of dry commodity mass (5). The physical trade balance is defined in Schandl et al. (2017). Source: own drawing.

In the figure above, five layers, at which material flows can be quantified, are introduced and listed for each flow or indicator: total commodity mass (1), dry commodity mass (2), waste/emissions (3), raw material equivalent (RME) of dry commodity mass (4), and total material requirements (TMR) of dry commodity mass (5).

For LCA- and MRIO-type calculations, the two indicators RMI and RMC are the same and are commonly labelled as *material footprint* of a product or service. This is because a product system does not contain any exports of other products and commodities, all export flows are zero and therefore, the RMI indicator equals the material footprint.

Next to the RME, there is also the total material requirement of a commodity:

"*Total Material Requirement is a compound indicator reflecting all of the physical materials that are mobilized each year to support an economy, including "hidden", non-economic materials such as mineral overburden, processing waste and soil erosion. The TMR includes an aggregate indicator and disaggregated sub-indicators by resource sector.*"[3]

It also needs to be noted that DMI and DMC are not consistent across layers:

"*As part of the material flow accounts, Eurostat produces indicators among which is the indicator domestic material consumption (DMC). Those accounts, however, do not provide an entirely consistent picture of global material footprints because they record imports and exports in the actual weight of the traded goods when they cross country borders instead of the weight of materials extracted to produce them. As the former are lower than the latter, economy-wide material flow accounts (EW-MFA) and the derived DMC underestimate the material footprint. To adjust for this, the weight of processed goods traded internationally is converted into the corresponding raw material extractions they induce.*"[4]

This inconsistency across layers led to the definition of the raw material equivalent (RME) or material footprint. With RME as a function, we can write:

$$DE = RME(DM) \qquad (1)$$

$$FE = RME(sum(Ix)) \qquad (2)$$

With the help of MFA indicators, we can also establish the economy-wide material flow balance for a national economy:

$$DE + SUM(I_x) = SUM(E_x) + SUM(B_x) + \Delta S \qquad (3)$$

Here, ΔS denotes the stock change or net stock accumulation of goods and materials in the use phase (change of in-use stocks, not shown in Fig. 2)

[3] https://www.un.org/esa/sustdev/sdissues/consumption/cpp1224m9.htm

[4] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Material_flow_accounts_statistics_-_material_footprints

The following indicators are covered by this method:

(1) RMI = raw material input (material footprint), calculated (Fig. 2) as domestic extraction of materials (materials that enter any form of industrial processing) + the raw material equivalent (RME) of all imports (of material commodities) into the product system.

Because a product system does not contain any exports of other products and commodities, all export flows are zero and therefore, in this situation, the RMI indicator equals the raw material consumption (RMC) and hence the material footprint.

The RMI indicators are divided into the following standard MFA categories: biomass, fossil fuels, metal ores, and non-metallic minerals; then abiotic materials (sum of the above except for biomass); then all materials (sum of the first four groups)

(2) TMR = total material requirement, defined (Fig. 2) as domestic extraction of materials (materials that enter any form of industrial processing) + RME(imports (of material commodities)) + unused (domestic) extraction (like overburden, that is extracted but not processed) + unused extraction in country of origin of imports = RMI + unused extraction domestically and in country of origin of imports.

The TMR indicators are divided into the same standard MFA categories as RMI.

(3) Ancillary method: Water footprint = direct input of water, NOT defined in Fig. 2 as water input is not part of material flow accounting. Still, it is easy to add, since ecoinvent contains eight different water inputs that can be mapped here with a characterization factor of $1 m^3/m^3$.

The water footprint is divided into the following categories: groundwater, freshwater (including groundwater), salt water, and all water.

How and why does this material footprint method work with ecoinvent?

The ecoinvent process database (Wernet et al. 2016) contains detailed information on material input because it is needed to establish the mass balance for the processes (like iron ore into iron ore pellet production) and because some of the established LCIA methods, like metal depletion, need those resource flows.

All implementations of LCIA methods in openLCA and all other LCA software I know are done via a simple matrix multiplication. Each elementary (resource or emission) flow is multiplied with its characterization factor for a given impact category, and then, all impacts in this category are summed up. This way, the extensive and process-

specific life cycle inventory is aggregated to 1-2 dozens of pressure (midpoints) and damage (endpoint) indicators. This matrix multiplication approach means that the same elementary flow attached to different processes are considered all the same.

For the update from ecoinvent 3.1 to 3.7.1 and 3.8, some substantial modification was necessary because the modelling of resource extraction has changed substantially.

Metal ores: Extensions and modifications compared to Mostert and Bringezu (2019)

A typical extraction process is shown in Fig. 3, where both the metal (here: iron) and the inert co-extraction (gangue) are listed. The raw material input to iron ore mining can be determined in two ways:

- First, by accounting for the iron flow and then adding to this flow the iron ore flow divided by the average ore grade given by Mostert and Bringezu
- Second, by accounting for the iron flow and then adding to this flow the value of the 'Gangue, in ground'

With the first approach, one would stay close to the global average estimates given by Mostert and Bringezu, and with the second approach, one would stick to the representative data of ecoinvent.

P Inputs/Outputs: iron ore mine operation, 63% Fe | iron ore, crude ore, 63% Fe | Cutoff, U

Inputs

Flow	Category	Amount	Unit	Costs/Reve...	Uncertainty
blasting	431:Demolition and site...	0.00023	kg		lognormal: ...
diesel, burned in building mac...	431:Demolition and site...	0.01608	MJ		lognormal: ...
electricity, medium voltage	351:Electric power gene...	0.00205	kWh		lognormal: ...
Gangue, in ground	Resource/in ground	0.49950	kg		lognormal: ...
Iron, in ground	Resource/in ground	0.63000	kg		lognormal: ...
mine infrastructure, iron	429:Construction of oth...	8.33330E-13	Item(s)		lognormal: ...
Occupation, mineral extraction...	Resource/land	0.00119	m2*a		lognormal: ...
recultivation, iron mine	390:Remediation activiti...	3.10000E-5	m2		lognormal: ...
Transformation, from forest	Resource/land	3.10000E-5	m2		lognormal: ...
Transformation, to mineral ext...	Resource/land	3.10000E-5	m2		lognormal: ...
Water, unspecified natural orig...	Resource/in water	8.23700E-5	m3		lognormal: ...

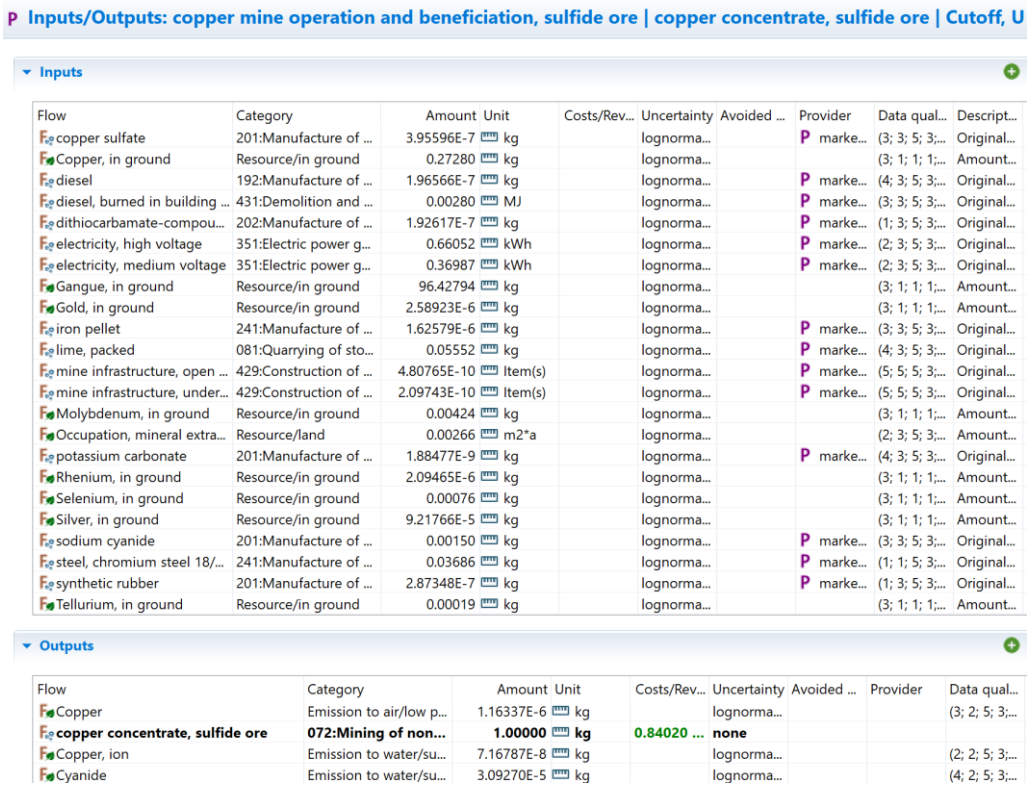
Outputs

Flow	Category	Amount	Unit	Costs/Reve...	Uncertainty
inert waste, for final disposal	382:Waste treatment an...	0.14950	kg		lognormal: ...
iron ore, crude ore, 63% Fe	**071:Mining of iron or...**	**1.00000**	**kg**	**0.04526 E...**	**none**
Particulates, < 2.5 um	Emission to air/low pop...	0.00014	kg		lognormal: ...

Fig. 3: Screenshot of iron ore extraction from ecoinvent 3.8 via openLCA. Only part of the process inventory is shown.

The simple extraction process picture in Fig. 3 often conflicts with reality, as some elementary flows are driven by the demand for a certain product, whereas others are co-extracted. For example, straw is co-extracted with grain. Moreover, the typical

mining output contains more than one metal. Extracted copper ore, for example, contains companion metals, including gold, silver, and tellurium (Fig. 4). The example of co-extraction shown in Figure 4, here for copper mining, is typical of the description of mining processes in ecoinvent and is therefore analysed and discussed in more detail below.



P Inputs/Outputs: copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U

Inputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided ...	Provider	Data qual...	Descript...
copper sulfate	201:Manufacture of ...	3.95596E-7	kg		lognorma...		P marke...	(3; 3; 5; 3;...	Original...
Copper, in ground	Resource/in ground	0.27280	kg		lognorma...			(3; 1; 1; 1;...	Amount...
diesel	192:Manufacture of ...	1.96566E-7	kg		lognorma...		P marke...	(4; 3; 5; 3;...	Original...
diesel, burned in building ...	431:Demolition and ...	0.00280	MJ		lognorma...		P marke...	(3; 3; 5; 3;...	Original...
dithiocarbamate-compou...	202:Manufacture of ...	1.92617E-7	kg		lognorma...		P marke...	(1; 3; 5; 3;...	Original...
electricity, high voltage	351:Electric power g...	0.66052	kWh		lognorma...		P marke...	(2; 3; 5; 3;...	Original...
electricity, medium voltage	351:Electric power g...	0.36987	kWh		lognorma...		P marke...	(2; 3; 5; 3;...	Original...
Gangue, in ground	Resource/in ground	96.42794	kg		lognorma...			(3; 1; 1; 1;...	Amount...
Gold, in ground	Resource/in ground	2.58923E-6	kg		lognorma...			(3; 1; 1; 1;...	Amount...
iron pellet	241:Manufacture of ...	1.62579E-6	kg		lognorma...		P marke...	(3; 3; 5; 3;...	Original...
lime, packed	081:Quarrying of sto...	0.05552	kg		lognorma...		P marke...	(4; 3; 5; 3;...	Original...
mine infrastructure, open ...	429:Construction of ...	4.80765E-10	Item(s)		lognorma...		P marke...	(5; 5; 5; 3;...	Original...
mine infrastructure, under...	429:Construction of ...	2.09743E-10	Item(s)		lognorma...		P marke...	(5; 5; 5; 3;...	Original...
Molybdenum, in ground	Resource/in ground	0.00424	kg		lognorma...			(3; 1; 1; 1;...	Amount...
Occupation, mineral extra...	Resource/land	0.00266	m2*a		lognorma...			(2; 3; 5; 3;...	Amount...
potassium carbonate	201:Manufacture of ...	1.88477E-9	kg		lognorma...		P marke...	(4; 3; 5; 3;...	Original...
Rhenium, in ground	Resource/in ground	2.09465E-6	kg		lognorma...			(3; 1; 1; 1;...	Amount...
Selenium, in ground	Resource/in ground	0.00076	kg		lognorma...			(3; 1; 1; 1;...	Amount...
Silver, in ground	Resource/in ground	9.21766E-5	kg		lognorma...			(3; 1; 1; 1;...	Amount...
sodium cyanide	201:Manufacture of ...	0.00150	kg		lognorma...		P marke...	(3; 3; 5; 3;...	Original...
steel, chromium steel 18/...	241:Manufacture of ...	0.03686	kg		lognorma...		P marke...	(1; 1; 5; 3;...	Original...
synthetic rubber	201:Manufacture of ...	2.87348E-7	kg		lognorma...		P marke...	(1; 3; 5; 3;...	Original...
Tellurium, in ground	Resource/in ground	0.00019	kg		lognorma...			(3; 1; 1; 1;...	Amount...

Outputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided ...	Provider	Data qual...
Copper	Emission to air/low p...	1.16337E-6	kg		lognorma...			(3; 2; 5; 3;...
copper concentrate, sulfide ore	**072:Mining of non...**	**1.00000**	**kg**	**0.84020 ...**	**none**			
Copper, ion	Emission to water/su...	7.16787E-8	kg		lognorma...			(2; 2; 5; 3;...
Cyanide	Emission to water/su...	3.09270E-5	kg		lognorma...			(4; 2; 5; 3;...

Fig. 4: Screenshot of copper ore (CuS) extraction from ecoinvent 3.8 via openLCA. Only part of the process inventory is shown.

From Figure 4, we can determine the RME of 1 kg of CuS concentrate according to the two accounting methods described above (Table 1). Here, all resource extraction elementary flows are considered.

Table 1: RME of 1 kg of CuS concentrate, ecoinvent process as partly shown in Fig. 4, two RME methods.

Resource, all values in kg	**With RME via Mostert and Bringezu factors**	**With RME via Gangue, in ground**
Copper, in ground	39 (CF: 143 for different copper ores)	0,273 (CF: 1)
Gangue, in ground	0	96,4 (CF: 1)
Gold, in ground	2,45 (CF: 943610 for different gold deposits)	2,6E-6 (CF: 1)
Molybdenum, in ground	4,2	0,00424 (CF: 1)
Rhenium, in ground	2,09E-6 (CF: 1 for Re, crude ore, in ground)	2,09E-6 (CF: 1)
Selenium, in ground	0 (no CF for Se)	0,00076 (CF: 1)
Silver, in ground	0,97 (CF: 10561 for different silver ores)	9,2E-5 (CF: 1)
Tellurium, in ground	950 (CF: 5E6 for Te from silver ore)	0,00019 (CF: 1)
TOTAL (kg)	**997**	**96,7**

The value on the right side, with the RME mostly derived from 'Gangue in ground', roughly represents the expected value for a typical copper ore grade of below 1%. From this table, we see that simply using the ore-specific CFs (RMEs) compiled by MB2019 and using them as proxy for the "resource x, in ground" flows leads to a gross overestimation of the MF. Instead, for the "resource x, in ground" flows, the CF needs to be set to 1, as MB2019 already do for "Rhenium, in crude ore, in ground". The "resource x, in ground" flows are widely used in ei 3.7.1 and 3.8 but are not listed by MB2019 in the ei 3.1-compatible version of CFs.

Another example is the process for extracting molybdenite (MoS_2) from copper ore (Fig. 5):

P Inputs/Outputs: copper mine operation and beneficiation, sulfide ore | molybdenite | Cutoff, U

Inputs

Flow	Category	Amount	Unit	Costs/Reve...	Uncertainty	Avoided w...
copper sulfate	201:Manufacture of ba...	2.05328E-6	kg		lognormal:...	
Copper, in ground	Resource/in ground	1.52090	kg		lognormal:...	
diesel	192:Manufacture of ref...	1.02025E-6	kg		lognormal:...	
diesel, burned in building m...	431:Demolition and sit...	0.01452	MJ		lognormal:...	
dithiocarbamate-compound	202:Manufacture of ot...	6.81374E-7	kg		lognormal:...	
electricity, high voltage	351:Electric power gen...	2.33655	kWh		lognormal:...	
electricity, medium voltage	351:Electric power gen...	1.91975	kWh		lognormal:...	
Gangue, in ground	Resource/in ground	340.80804	kg		lognormal:...	
Gold, in ground	Resource/in ground	1.44183E-5	kg		lognormal:...	
iron pellet	241:Manufacture of ba...	8.43841E-6	kg		lognormal:...	
lime, packed	081:Quarrying of stone...	0.28817	kg		lognormal:...	
mine infrastructure, open cas...	429:Construction of ot...	1.70068E-9	Item(s)		lognormal:...	
mine infrastructure, undergr...	429:Construction of ot...	7.41955E-10	Item(s)		lognormal:...	
Molybdenum, in ground	Resource/in ground	0.14454	kg		lognormal:...	
Occupation, mineral extracti...	Resource/land	0.00942	m2*a		lognormal:...	
potassium carbonate	201:Manufacture of ba...	9.78261E-9	kg		lognormal:...	
Rhenium, in ground	Resource/in ground	2.56961E-6	kg		lognormal:...	
Selenium, in ground	Resource/in ground	0.00424	kg		lognormal:...	
Silver, in ground	Resource/in ground	0.00051	kg		lognormal:...	
sodium cyanide	201:Manufacture of ba...	0.00779	kg		lognormal:...	

Outputs

Flow	Category	Amount	Unit	Costs/Reve...	Uncertainty	Avoided pr...
Mercury	Emission to air/low po...	4.11537E-9	kg		lognormal:...	
Mercury	Emission to water/surf...	1.20562E-9	kg		lognormal:...	
molybdenite	**072:Mining of non-f...**	**1.00000**	**kg**	**5.84156 E...**	**none**	
Molybdenum	Emission to air/low po...	2.62265E-14	kg		lognormal:...	
Nickel	Emission to air/low po...	6.58460E-6	kg		lognormal:...	
Nickel, ion	Emission to water/surf...	7.79042E-7	kg		lognormal:...	
Nitrogen oxides	Emission to air/low po...	9.81502E-8	kg		lognormal:...	

Fig. 5: Screenshot of molybdenite (sulfidic ore) extraction from ecoinvent 3.8 via openLCA. Only part of the process inventory is shown.

As another example, Fig. 5 shows some of the different resource flows associated with molybdenite (MoS_2) extraction, whereas figure 6 shows a similar process, the operation of a molybdenite mine. One can see that there is only one main output but several metal resources involved (gold, copper, silver, …), which are co-extracted but only partially enter the main product. Moreover, the inventory in Fig. 5 lists 'gangue, in ground', whereas the inventory in Fig. 6 does not list any gangue. Gangue is the inert

material, which represents the additional material that needs to be processed to extract the ore. By definition, gangue thus belongs to the raw material equivalent of a metal.

P Inputs/Outputs: molybdenite mine operation | molybdenite | Cutoff, U

Inputs

Flow	Category	Amount	Unit	Costs/Reve...	Uncertainty
chemical, inorganic	201:Manufacture of ba...	0.16714	kg		lognormal:...
chemical, organic	192:Manufacture of ref...	0.04911	kg		lognormal:...
conveyor belt	281:Manufacture of ge...	1.64717E-5	m		lognormal:...
Copper, in ground	Resource/in ground	2.15586	kg		lognormal:...
diesel, burned in building m...	431:Demolition and sit...	0.01714	MJ		lognormal:...
electricity, high voltage	351:Electric power gen...	2.65849	kWh		lognormal:...
electricity, medium voltage	351:Electric power gen...	1.77434	kWh		lognormal:...
lime, packed	081:Quarrying of stone...	0.00218	kg		lognormal:...
lime, packed	081:Quarrying of stone...	0.17132	kg		lognormal:...
lime, packed	081:Quarrying of stone...	0.08569	kg		lognormal:...
mine infrastructure, open cas...	429:Construction of ot...	2.17403E-9	Item(s)		lognormal:...
mine infrastructure, undergr...	429:Construction of ot...	9.50758E-10	Item(s)		lognormal:...
Molybdenum, in ground	Resource/in ground	0.24586	kg		lognormal:...
Occupation, mineral extracti...	Resource/land	0.01132	m2*a		lognormal:...
sodium cyanide	201:Manufacture of ba...	0.00511	kg		lognormal:...
sodium cyanide	201:Manufacture of ba...	0.00252	kg		lognormal:...
steel, chromium steel 18/8, h...	241:Manufacture of ba...	0.16169	kg		lognormal:...
Transformation, from unkno...	Resource/land	0.00038	m2		lognormal:...
Transformation, to mineral e...	Resource/land	0.00038	m2		lognormal:...
Water, river	Resource/in water	0.21740	m3		lognormal:...

Outputs

Flow	Category	Amount	Unit	Costs/Reve...	Uncertainty
molybdenite	**072:Mining of non-f...**	**1.00000**	**kg**	**5.84156 E...**	**none**
Nickel	Emission to air/low po...	7.99363E-6	kg		lognormal:...
Nickel, ion	Emission to water/surf...	5.29275E-6	kg		lognormal:...
Nitrogen, organic bound	Emission to water/surf...	0.00495	kg		lognormal:...

Fig. 6: Screenshot of molybdenite mine operation from ecoinvent 3.8 via openLCA. Only part of the process inventory is shown.

Just by studying these two examples, one can see that there is a lack of consistency in the database when it comes to material input. If gangue, for example, had a characterization factor, it would count towards the material footprint in one process but not the other. Due to the simplicity of the matrix-based LCIA method implementation, a filtering or conditional application of the CFs is not possible. Only via defining more process-specific elementary flows, which greatly inflates the list of resources to be considered, can such a filtering or conditional application be achieved.

Two more examples include the mining of uranium (Fig. 7, without gangue), and bauxite (Fig. 8, with gangue). Also, for the different titanium production processes, gangue is inconsistently handled.

Problem: The listing of co-extracted metals and gangue is not consistent across the different ecoinvent processes. A fully consistent implementation of the material footprint with the matrix multiplication method and the existing process inventory is

not possible. Instead, a compromise has to be found that captures most of the relevant flows but does not grossly overestimate the resource input.

Inputs/Outputs: uranium mine operation, underground | uranium ore, as U | Cutoff, U

Inputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided ...
Transformation, from indu...	Resource/land	0.00500	m2		lognorma...	
Transformation, from unk...	Resource/land	0.00500	m2		lognorma...	
Transformation, to mineral...	Resource/land	0.00500	m2		lognorma...	
Transformation, to unkno...	Resource/land	0.00500	m2		lognorma...	
Uranium	Resource/in ground	1.05000	kg		lognorma...	
Water, unspecified natural...	Resource/in water	0.10000	m3		lognorma...	

Outputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided ...
Uranium alpha	Emission to water/su...	310.00000	kBq		lognorma...	
uranium ore, as U	**072:Mining of non...**	**1.00000**	**kg**	**20.9600...**	**none**	
Vanadium, ion	Emission to water/su...	0.00480	kg		lognorma...	
Water	Emission to air/unsp...	0.01500	m3		lognorma...	

Fig. 7: Screenshot of uranium mine operation from ecoinvent 3.8 via openLCA. Only part of the process inventory is shown.

Inputs/Outputs: bauxite mine operation | bauxite | Cutoff, U

Inputs

Flow	Category	Amount	Unit
Aluminium, in ground	Resource/in ground	0.21262	kg
blasting	431:Demolition and ...	0.00019	kg
electricity, medium voltage	351:Electric power g...	0.00150	kWh
Gallium, in ground	Resource/in ground	6.60000E-5	kg
Gangue, bauxite, in ground	Resource/in ground	2.25832	kg
heat, district or industrial, ...	351:Electric power g...	0.06488	MJ

Outputs

Flow	Category	Amount	Unit
bauxite	**072:Mining of non...**	**1.00000**	**kg**
inert waste	239:Manufacture of ...	1.53883E-7	kg
inert waste	239:Manufacture of ...	6.29791E-5	kg
inert waste	239:Manufacture of ...	1.78671E-5	kg
Particulates, < 2.5 um	Emission to air/unsp...	4.91545E-6	kg

Fig. 8: Screenshot of bauxite mine operation from ecoinvent 3.8 via openLCA. Only part of the process inventory is shown.

Next to the gangue-problem, the many different co-extracted materials, if all multiplied with their metal-ore-specific characterization factors, would greatly overestimate the RME of the goods and services studies. (see Table 1).

With these findings, the following choices were made:

(1) The resource "Gangue, in ground" is added to the list with CF = 1 kg/kg for both RMI and TMR. For bauxite gangue, the MB2019 ratio of TMR/RMI is kept.

(2) The major extraction processes for each metal are opened individually and checked whether gangue is included or not. If yes (e.g., Al, Cu, Fe, …) the CFs of the corresponding chemical elements ('resource x, in ground', mostly not present in the MB2019 dataset) are set to 1 kg/kg. If not (e.g., U, Sb, …), they are set to the MB2019 value for the ores of these metals or to values found by additional literature search. This choice captures the total processed material in most mining processes. See section 2 for details.

(3) Not the full list of ecoinvent resource flows is used, as there are many duplications and most flows only used once. Instead, only those resource flow that are already covered by the existing resource depletion indicators (like metal depletion in ReCiPe) are included. The resource flow list of the openLCA ecoinvent LCIA methods dataset is used as reference.

Biomass: Modifications compared to Mostert and Bringezu (2019)

The material footprint method documented here includes the harvested and processed biomass. There are different ways to include biomass into the footprint (Fig. 9). The three dark red circles in Fig. 9 mark the three different resource flows that can be used to estimate the harvested biomass. For each flow, a possible conversion to processed biomass exists.

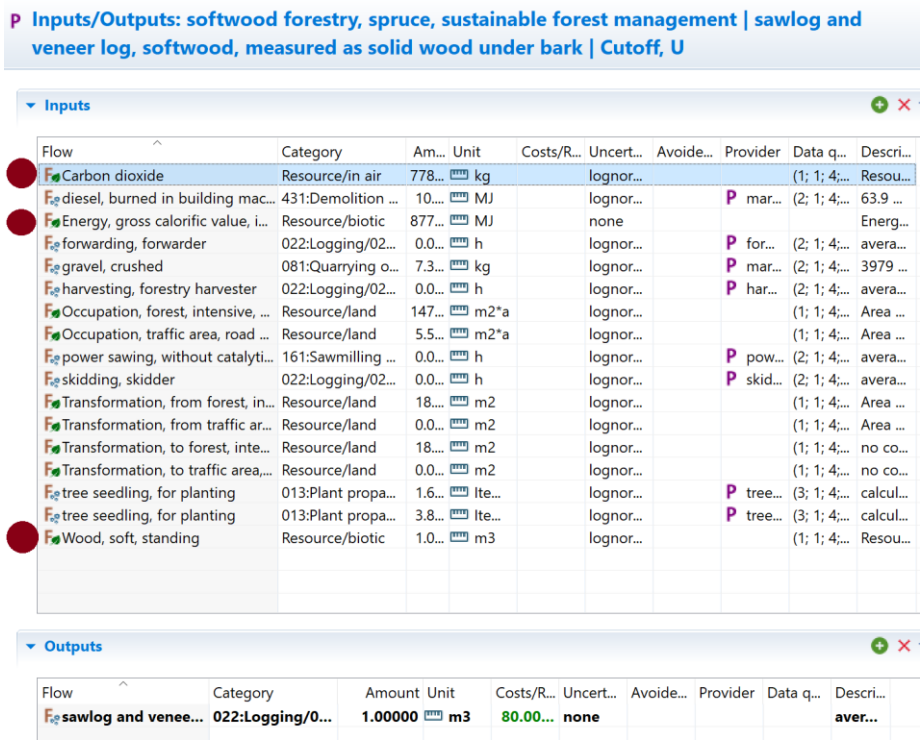
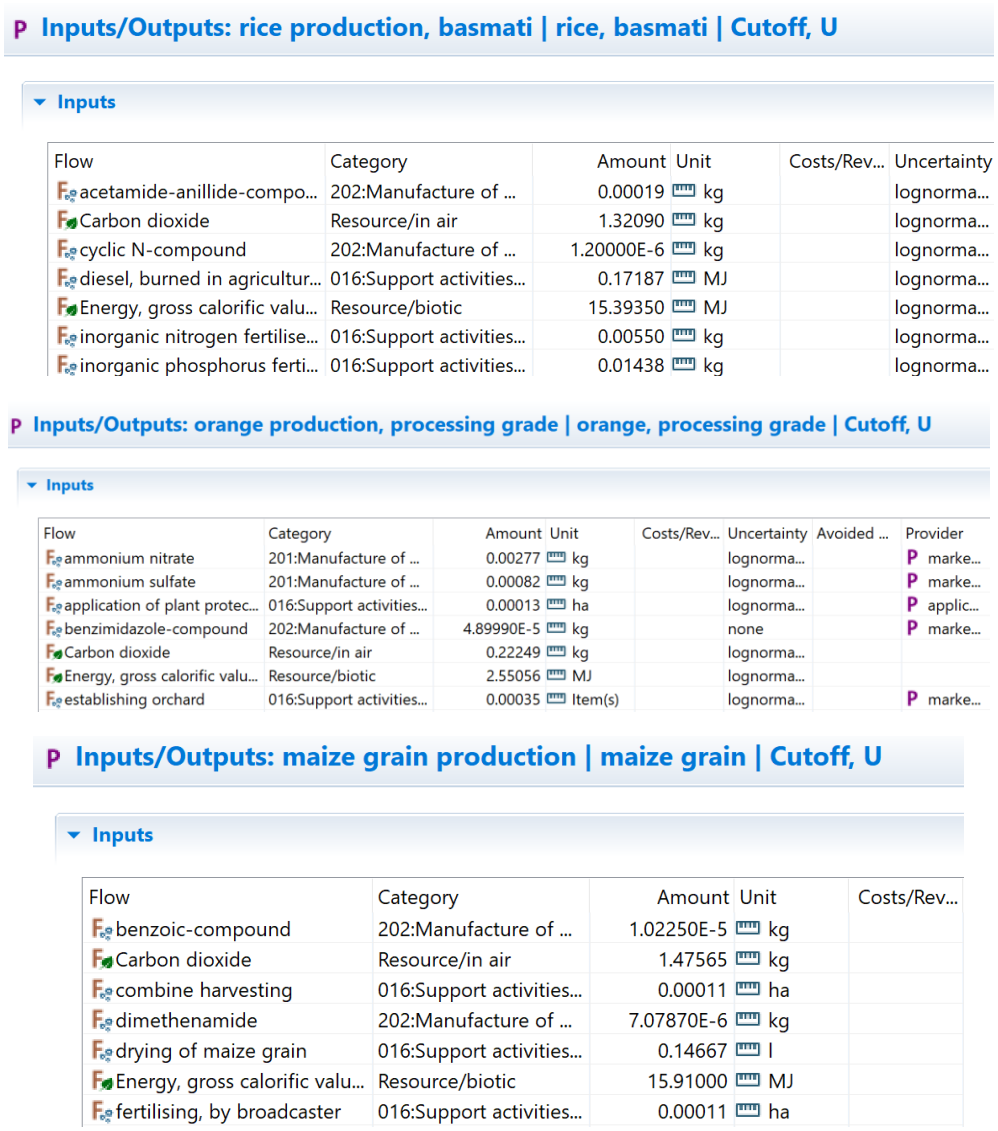


Fig. 9: Screenshot of spruce forestry from ecoinvent 3.8 via openLCA. Only part of the process inventory is shown. The three dark red circles mark the resource flows that can be used to estimate the harvested biomass.

First, from the carbon dioxide flow for photosynthesis, the harvested and processed biomass can be estimated by converting CO_2 to biomass (carbon content: roughly 50%) and then estimating the share of harvest residues. Second, the energy content of the biomass can be used to convert the reported energy flow to the processed mass. Third, the mass or volume flow of the biomass itself can be used by estimating and subtracting the water content and converting volume to mass with the density of the material.

While all forestry processes checked had the three flows included, the picture is different for agricultural processes (Fig. 10) as here, only the CO_2 uptake and the energy input is always present:



P Inputs/Outputs: rice production, basmati | rice, basmati | Cutoff, U

Inputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty
acetamide-anillide-compo...	202:Manufacture of ...	0.00019	kg		lognorma...
Carbon dioxide	Resource/in air	1.32090	kg		lognorma...
cyclic N-compound	202:Manufacture of ...	1.20000E-6	kg		lognorma...
diesel, burned in agricultur...	016:Support activities...	0.17187	MJ		lognorma...
Energy, gross calorific valu...	Resource/biotic	15.39350	MJ		lognorma...
inorganic nitrogen fertilise...	016:Support activities...	0.00550	kg		lognorma...
inorganic phosphorus ferti...	016:Support activities...	0.01438	kg		lognorma...

P Inputs/Outputs: orange production, processing grade | orange, processing grade | Cutoff, U

Inputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided ...	Provider
ammonium nitrate	201:Manufacture of ...	0.00277	kg		lognorma...		P marke...
ammonium sulfate	201:Manufacture of ...	0.00082	kg		lognorma...		P marke...
application of plant protec...	016:Support activities...	0.00013	ha		lognorma...		P applic...
benzimidazole-compound	202:Manufacture of ...	4.89990E-5	kg		none		P marke...
Carbon dioxide	Resource/in air	0.22249	kg		lognorma...		
Energy, gross calorific valu...	Resource/biotic	2.55056	MJ		lognorma...		
establishing orchard	016:Support activities...	0.00035	Item(s)		lognorma...		P marke...

P Inputs/Outputs: maize grain production | maize grain | Cutoff, U

Inputs

Flow	Category	Amount	Unit	Costs/Rev...
benzoic-compound	202:Manufacture of ...	1.02250E-5	kg	
Carbon dioxide	Resource/in air	1.47565	kg	
combine harvesting	016:Support activities...	0.00011	ha	
dimethenamide	202:Manufacture of ...	7.07870E-6	kg	
drying of maize grain	016:Support activities...	0.14667	l	
Energy, gross calorific valu...	Resource/biotic	15.91000	MJ	
fertilising, by broadcaster	016:Support activities...	0.00011	ha	

Fig. 10: Screenshot of different agricultural processes from ecoinvent 3.8 via openLCA. Only part of the process inventory is shown.

The CO_2 uptake flows, however, sometimes include flows that only represent the carbon contained in that biomass (example: softwood forestry, pine, sustainable forest management | pulpwood, softwood, measured as solid wood under bark | Cutoff, U, or sugarcane production | sugarcane | Cutoff, U) and sometimes also carbon that is released again trough respiration, decomposition, or burning of branches after harvest

(example: softwood forestry, paraná pine, sustainable forest management | sawlog and veneer log, paraná pine, measured as solid wood under bark | Cutoff, U, or hardwood forestry, azobe, sustainable forest management | sawlog and veneer log, azobe, measured as solid wood under bark | Cutoff, U).

With these findings, the following choices were made:

(1) **Because the actual biomass input is reported for forestry processed only and not for agriculture, it cannot be used as CF for biomass input with the simple matrix multiplication approach.**
(2) **Because CO_2 uptake in air for biomass production processes sometimes only includes carbon contained in that biomass and sometimes also carbon that is released again trough burning of residues or other decomposition processes, we cannot use this flow to simply apply a conversion factor from CO_2 to C (12/44) and from C to dry biomass (ca. factor of 2), though this would be easiest for the calculation.** The resource "Carbon dioxide, in air" is hence not added to the list of resource flows: The CF is set to 1 kg/kg but the flag for not including it in the CF list is set 'True'.
(3) **Instead, we convert energy to mass by using values for the average energy content of biomass. This is possible because the energy input is consistently included in ecoinvent because of the long-established calculation of cumulative energy demand (CED).** Details of the estimation are reported in the following section.

The choices above include all biomass flows and avoid the double-counting of biomass. For example, wood mass is covered both as energy equivalent and as volume. To avoid double-counting and to be complete also for agricultural products, the energy equivalent of the wood is included/converted to the material footprint, as energy equivalents are reported for all crops and forest products checked. The volume of harvested wood is excluded from the CF list.

The choices above, especially the inclusion of the gangue flows, represent a simplification compared to the extensive data collection by MB2019 to estimate average ore grades. This choice was necessary to be consistent with the way the different resource extraction flows are accounted for in ecoinvent 3.7.1 and 3.8.

As a consequence of these choices and simplifications, specific LCA results must always be checked in detail for plausibility, completeness, and regarding what specific materials are actually included! Manual correction can be applied to some components of the material footprint of a product system to increase its accuracy and completeness. For example, the RMI calculated with the gangue flow values can be replaced by the metal-specific and average ore grade-based CF values from MB2019 for specific resource extraction flows.

2. Technical documentation of the compilation material footprint LCIA method

Here, the data processing procedure is described that was implemented to convert and expand the Mostert and Bringezu (2019) assessment method for ecoinvent (ei) 3.1 (cut-off LCI) to ei 3.7 and ei 3.8. Table 2 lists the data sources and software tools used.

All code developed for this project is archived on GitHub under a permissive license via

https://github.com/IndEcol/openLCA_ecoinvent_Material_Footprint_LCIA

Table 2: Data sources and software tools used for the material footprint method update.

Data sources	Software tools (all part of GitHub repo)
[Data D1]: Supplementary material of Mostert and Bringezu (2019) that contains the original LCIA characterization factors and that was downloaded from the journal homepage on September 23, 2021: *resources-08-00061-s001.xml*	**[Software S1]:** Script *ei_LCIA_FlowsExtract.py* to export the elementary flows from an LCIA database in openLCA format.
[Data D2]: LCIA methods for ecoinvent 3.7.1 in openLCA, downloaded from the openLCA nexus on February 25, 2021: *ecoinvent_37_lcia_methods.zip*	**[Software S2]:** Script *ei_LCIA_MF_populate.py* to transfer the spreadsheet-coded LCIA methods to the openLCA JSON format.
[Data D3]: LCIA methods for ecoinvent 3.8 in openLCA, downloaded from the openLCA nexus on January 4, 2022: *ecoinvent_38_LCIA_methods_30112021.zip*	
[Data D4]: Additional literature values for natural resources not covered by Bringezu and Mostert (2019), documented in master data file *Material_Footprint_LCIA_Master_V1.xlsx*	

The following steps were taken to compile the update material footprint LCIA method for ecoinvent 3.7.1 and 3.8:

Step 1:

Excel-import the original xml file [Data D1], resources-08-00061-s001.xml, into Excel, using the xml import function on the data tab. Remove the generic description "generalComment", which is the same for all entries and which will be moved to the LCIA method definition. The remaining table with the characterization factors and the content of elementary_flows.xlsx are both copied to the main matching file:

[Masterfile]: Material_Footprint_LCIA_Master_V1.xlsx

Into the sheet 'ecoinvent_3_1_Mostert_xml'. The data in this sheet contain the characterization factors for both RMI and TMR, and are copied and split into the sheets

'Mostert_xml_RMI' and 'Mostert_xml_TMR' to simply the lookup for the updated LCIA method.

Step 2:

(a) The ecoinvent-openLCA LCIA method files [Data D2] and [Data D3] are each unzipped into a subfolder (one for each version). The resulting folder structure is shown in Fig. 11.

(b) All existing elementary flows from the ecoinvent LCIA methods are read and exported to xlsx, using the script ei_LCIA_FlowsExtract.py [Software S1], and the resulting file is automatically labelled as elementary_flows_ei_x_x.xlsx, (where x_x is the ecoinvent version number).

Note: This a crucial system boundary choice: Not the complete list of ei elementary resource flows is covered, but only those that are already used by the existing ei LCIA methods in their openLCA implementation. For background see section 1, and for further discussion, see section 3.

(c) The list of elementary flows exported under the previous step is copied to [Masterfile], new sheet 'ecoinvent_3_7_LCIA_import' or 'ecoinvent_3_8_LCIA_import.

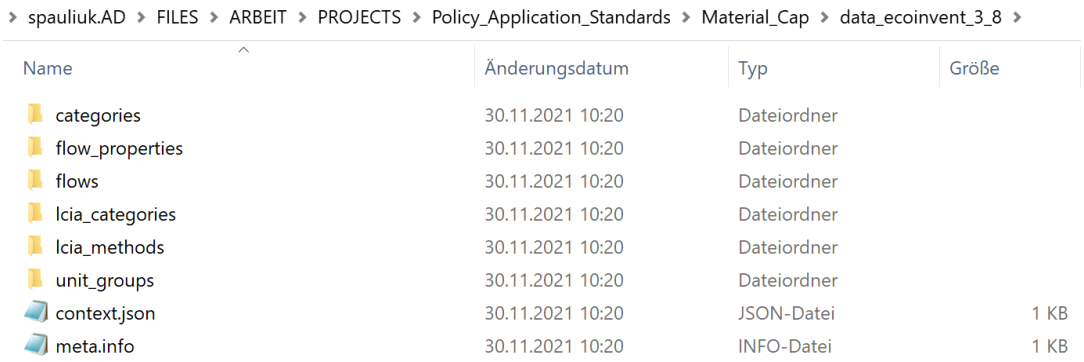


Fig. 11: Screenshot of the folder structure of an unzipped ecoinvent openLCA method. The python script [Software S2] saves the json files with the new characterization factors to the folder lcia_categories.

(d) From the copied list of all elementary flows, those flows where the 'category2' tag reads 'Resource' are copied to the new sheets 'ecoinvent_3_7_Match' or 'ecoinvent_3_8_Match'.

(e) In this sheet, the ei 3.7 (3.8) elementary flows are matched with the Mostert and Bringezu list wherever possible, by using the Excel lookup command "=VLOOKUP(B12;Mostert_xml_RMI!Q$2:U$144;5;0)"

(f) For those values where no automatic match was possible, the MB inventory [Data D1] were scanned for additional values in case the elementary flows got renamed or if proxy data can be used, e.g., 'Calcium carbonate, in ground' for 'Calcite, in ground'. Also, for a number of resource flows without specified concentration or ore grade, like 'Copper, in ground', a value from [Data D1] was used according to the choices made in section 1, and a comment on this proxy use was made in the matching

sheet. For all new substances and energy carriers not yet present in [Data D1], additional data were compiled from the literature according to the choices made in section 1, and these data and assumptions are documented in the sheet 'Additional_Data' in the [Masterfile] for each elementary flow.

These data include numerous publicly available reports, such as from USGS, BGS or source displayed on the Wikipedia (see sheet 'Additional_Data' in the [Masterfile] for each elementary flow), including a number of journal articles on specific metals and metal ores. (Han et al. 2021; Li et al. 2021; Wang et al. 2021; Liu et al. 2017; Höll et al. 2007; Rytuba 2003)

The new ore concentration and energy content of biomass values are documented on the sheet 'Additional_Data' in the [Masterfile]. For many metal ores, the CF is set to 1 kg/kg because the RME of the extraction of these metals is accounted for in the resource flow "Gangue, in ground" which was also added to the list with CF = 1 kg/kg.

(g) In columns X-AI of the matching sheet, the elementary flows are assigned to the different footprint indicators by assigning a 1 (True) if a given elementary flow (row) shall be added to a given material footprint indicator (column) with the characterization factor given in cols. P (RMI) and U (TMR). The list of indicators includes the following 16 categories, 6 RMI, 6 TMR, and 4 water footprint categories.

Raw material input (RMI), biomass

Raw material input (RMI), fossil fuels

Raw material input (RMI), metal ores

Raw material input (RMI), non-metallic minerals

Raw material input (RMI), abiotic materials (includes fossil fuels)

Raw material input (RMI), all materials

Total material requirement (TMR), biomass

Total material requirement (TMR), fossil fuels

Total material requirement (TMR), metal ores

Total material requirement (TMR), non-metallic minerals

Total material requirement (TMR), abiotic materials (includes fossil fuels)

Total material requirement (TMR), all materials

Ancillary indicator: Water footprint, groundwater

Ancillary indicator: Water footprint, freshwater

Ancillary indicator: Water footprint, saltwater

Ancillary indicator: Water footprint, all water

(h) A number of elementary flows are excluded from the database. These elementary flows are labelled as "Not relevant for material footprints" and flagged with a '1' in column K in the [Masterfile]. For example, wood mass is covered both as energy and as volume in ecoinvent. To avoid double-counting, the energy equivalent of the wood is included/converted to the material footprint, as energy equivalents are reported for all crops and forest products that were checked. Also, land use and land transformation are excluded from the method.

The result of this procedure is a complete dataset on the RMI, TMR, and water characterization factors in spreadsheet (Excel) format.

Step 3:

Transfer the spreadsheet data to JSON files into the directory three of the openLCA LCIA method.

(a) Create a list of all LCIA methods (here: material and water footprint) and all LCIA categories used under these method (here: 12 material and 4 water footprints). For each of these methods, a UUID and a corresponding UUID.json filename is needed. UUIDs can be generated in Python or here: https://www.uuidgenerator.net/. The list of definitions and UUIDs is contained in the [Masterfile], sheets 'LCIA_Define_ecoinvent_3_7' and 'LCIA_Define_ecoinvent_3_8'.

(b) In the sub-folder 'lcia_methods', manually create two new LCIA methods 'Material footprint' and 'Water footprint' in the folders created during step 2a (e.g., by creating two copies of an existing .json file and modifying its name and content according to the labels and UUIDs specified in step 3a). The script [Software S2] is programmed to read a method file with exactly 2 CFs included, delete them, and add the new ones. In these two new LCIA method files, the different new LCIA categories are listed (See [Masterfile] sheet 'LCIA_Define_ecoinvent_3_x'.

(c) In the sub-folder 'lcia_categories', manually create 16 new LCIA category JSON files in the folders created during step 2a (by creating 16 copies of an existing json file and modifying its name and content according to the labels and UUIDs specified in step 3a). In these 16 new LCIA category files, the different characterization factors need to be inserted from the spreadsheet.

(d) Run script ei_LCIA_MF_populate.py [Software S2] to populate the JSON files with the data from the spreadsheets 'ecoinvent_3_7_Match' or 'ecoinvent_3_8_Match' in the [Masterfile]. The script [Software S2] is programmed to read a method file with exactly 2 CFs included, delete them, and add the new ones.

Step 4:

Export to zip and import into openLCA.

Version a) zip the entire content of the folders created under Step 2a and import as complete set of LCIA methods (default ecoinvent-openLCA-LCIA methods plus the

material and water footprint methods) into the corresponding ecoinvent version in openLCA.

Version b) Zip only the new JSON files in their respective folders (2 files in lcia_methods and 16 in lcia_categories, see Fig. 12) and import the resulting zip file into the previously imported default ecoinvent-openLCA-LCIA methods. Since all UUIDS are consistent, openLCA will recognize and add the new methods and their characterization factors to the existing list of LCIA methods.

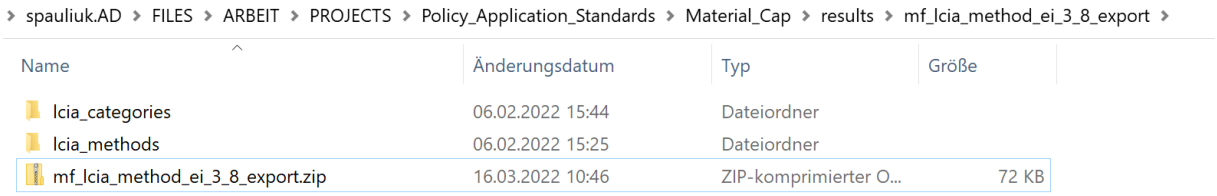


Fig. 12: Screenshot of the folder structure of the results folder. Here, the copies of the two new lcia methods and 16 new lcia categories files are archived and the two folders together are zipped for a small-sized archive for direct import into openLCA.

You will now be able to select the newly created LCIA methods when calculating the life cycle inventory and impacts of a product system.

Troubleshooting:

The import of the additional json files into openLCA runs smoothly. Please check the openLCA log file in case of problems with importing the new LCIA methods into openLCA. In case you get stuck, please post an issue on the GitHub repo:

https://github.com/IndEcol/openLCA_ecoinvent_Material_Footprint_LCIA

3. Exemplary Results and Discussion

The material and water footprint impact assessment methods presented here simply add up the raw material equivalent (RME, for RMI), the total material requirement/extraction (TMR), and the water input for all elementary resource input flows under a given resource category. The categories include biomass, fossil, metal ores, non-metallic minerals, abiotic, all for material footprint and groundwater, freshwater, saltwater, all water for the water footprint.

The material and water footprint indicators provide information on how much material or water enters or needs to be extracted for a given product system, without assessing any further impacts of this input/extraction, like toxicity, land use, etc. For these categories, the dedicated impact assessment methods like ReCiPe need to be used instead.

Comparison with ReCiPe LCIA indicators

Here, a comparison with the water depletion, fossil depletion, and metal depletion potentials in the ReCiPe LCIA method (Huijbregts et al. 2016) is offered. ReCiPe is widely used and can be seen as representative of the wide spectrum of LCIA methods regarding detailed characterization factors for resource-related impact categories.

Table 3: Comparison of resource related LCIA methods between the material and water footprint methods described here and the related ReCiPe methods. Page numbers are from the 2016 ReCiPe report (Huijbregts et al. 2016).

MFA-LCIA method	Related ReCiPe midpoint indicators	Description and comparison
Material footprint (RMI/ RME)	**mineral resource scarcity / fossil resource scarcity**	P87+88: "The primary extraction of a mineral resource (ME) will lead to an overall decrease in ore grade (OG), meaning the concentration of that resource in ores worldwide, which in turn will increase the ore [that needs to be] produced[/extracted] per kilogram of mineral resource extracted (OP). This, when combined with the expected future extraction of that mineral resource, leads to an average surplus ore potential (SOP) which is the midpoint indicator for this impact category. ", and "The midpoint characterization factor for mineral resource scarcity is Surplus Ore Potential (SOP). The SOP expresses the average extra amount of ore to be produced in the future due to the extraction of 1 kg of a mineral resource x, considering all future production (R) of that mineral resource relative to the average extra amount of ore produced in the future due to the extraction of 1 kg of copper (Cu), considering all future production of copper." → *The MFA-based material footprint answers a different question and is much simpler, as it simply converts and adds up all reported resource inputs into processed raw materials, using RME conversion factors, containing current average/typical ore grades.* Page 96: "The midpoint indicator for fossil resource use, determined as the Fossil Fuel Potential of fossil resource x (kg oil-eq/unit of resource), is defined as the ratio between the energy content of fossil resource x and the energy content of crude oil […]." → *The MFA-based fossil component of the material footprint answers the same question but is simpler in that it does not convert the different fossil fuels into a common energy-based equivalent but simply sums up the masses of the different fossil fuel elementary flows. It is thus a coarser indicator.*

Total material require-ment	None	→ *The MFA-based footprint for total material requirement answers a specific question regarding the total material extracted (and partly not processes, such as mining overburden or forest residues), for which there is no ReCiPe counterpart.*
Water footprints	**Water use**	Page 75: The characterization factor (CF) at midpoint level is m^3 of water *consumed* (water that the water source of origin is losing) per m^3 of water extracted from that water source. Flows that are already given as consumptive water flows, the midpoint indicator coincides with the inventory. For water flows that are reported simply as withdrawal or as extracted water, a factor needs to be applied to account for the water-use efficiency. Different data sources are used for this conversion for agriculture, industry or domestic use, partly country-specific data are available. → *The MFA-based water footprint answers a different question and is simpler, as it measures water use as input into the techno-sphere, i.e., all water inflows that are reported as a resource input to a process. The different water inputs are grouped into groundwater, freshwater, salt water, and all water, and are simply added up.*

Sample results

Figures 13-16 report typical material footprint results, where the contribution of selected processes is shown in detail.

Σ aluminium, ingot, primary, import from EU27 EFTA | aluminium, primary, ingot | Cutoff, U

Impact analysis: Material footprint

Subgroup by processes ☑ Don't show < 1 %

Name	Category	Inventory result	Impact factor	Impact result	Unit
Raw material input (RMI), abiotic materials				15.90243	kg
Raw material input (RMI), all materials				15.93573	kg
P bauxite mine operation | bauxite | Cutoff, U - GLO	072:Mining of non-ferrous met...			10.80554	kg
P gravel and sand quarry operation | gravel, round |	081:Quarrying of stone, sand an...			0.36448	kg
P gravel and sand quarry operation | gravel, round |	081:Quarrying of stone, sand an...			0.43210	kg
P hard coal mine operation, open cast, dragline | ha	051:Mining of hard coal / 0510:...			0.16222	kg
P lignite mine operation | lignite | Cutoff, U - RER	052:Mining of lignite / 0520:Mi...			1.23144	kg
P natural gas production | natural gas, high pressure	062:Extraction of natural gas / 0...			0.19825	kg
P petroleum and gas production, off-shore | natural	061:Extraction of crude petroleu...			0.20111	kg
P petroleum and gas production, on-shore | petrole	061:Extraction of crude petroleu...			0.16657	kg
Raw material input (RMI), biomass				0.03330	kg
Raw material input (RMI), fossil fuels				3.09833	kg
P hard coal mine operation and hard coal preparatic	051:Mining of hard coal / 0510:...			0.06005	kg
P hard coal mine operation and hard coal preparatic	051:Mining of hard coal / 0510:...			0.12604	kg
P hard coal mine operation and hard coal preparatic	051:Mining of hard coal / 0510:...			0.12585	kg
P hard coal mine operation and hard coal preparatic	051:Mining of hard coal / 0510:...			0.05654	kg
P hard coal mine operation and hard coal preparatic	051:Mining of hard coal / 0510:...			0.06638	kg
P hard coal mine operation and hard coal preparatic	051:Mining of hard coal / 0510:...			0.09266	kg
P hard coal mine operation | hard coal, run-of-mine	051:Mining of hard coal / 0510:...			0.03318	kg
P lignite mine operation | lignite | Cutoff, U - RER	052:Mining of lignite / 0520:Mi...			1.23144	kg
P natural gas production | natural gas, high pressure	062:Extraction of natural gas / 0...			0.07139	kg
P natural gas production | natural gas, high pressure	062:Extraction of natural gas / 0...			0.19825	kg
P petroleum and gas production, off-shore | natural	061:Extraction of crude petroleu...			0.03098	kg
P petroleum and gas production, off-shore | natural	061:Extraction of crude petroleu...			0.20111	kg
P petroleum and gas production, off-shore | petrole	061:Extraction of crude petroleu...			0.08279	kg
P petroleum and gas production, on-shore | natural	061:Extraction of crude petroleu...			0.05525	kg
P petroleum and gas production, on-shore | petrole	061:Extraction of crude petroleu...			0.16657	kg
P petroleum production, onshore | petroleum | Cutc	061:Extraction of crude petroleu...			0.15606	kg
P petroleum production, onshore | petroleum | Cutc	061:Extraction of crude petroleu...			0.06813	kg
Raw material input (RMI), metal ores				11.18448	kg
P bauxite mine operation | bauxite | Cutoff, U - GLO	072:Mining of non-ferrous met...			10.80554	kg
F Aluminium, in ground	Resource / in ground	0.92975 kg	1.00000 kg/kg	0.92975	kg
F Gangue, bauxite, in ground	Resource / in ground	9.87549 kg	1.00000 kg/kg	9.87549	kg
Raw material input (RMI), non-metallic minerals				1.61962	kg
Total material requirement (TMR), abiotic materials				28.20712	kg
Total material requirement (TMR), all materials				28.26348	kg
Total material requirement (TMR), biomass				0.05637	kg
Total material requirement (TMR), fossil fuels				3.71230	kg
Total material requirement (TMR), metal ores				22.78456	kg
Total material requirement (TMR), non-metallic mine				1.71026	kg

Fig. 13: Screenshot of the material footprint of 1 kg of aluminium, from ecoinvent 3.8 via openLCA. Only a part of the results is shown.

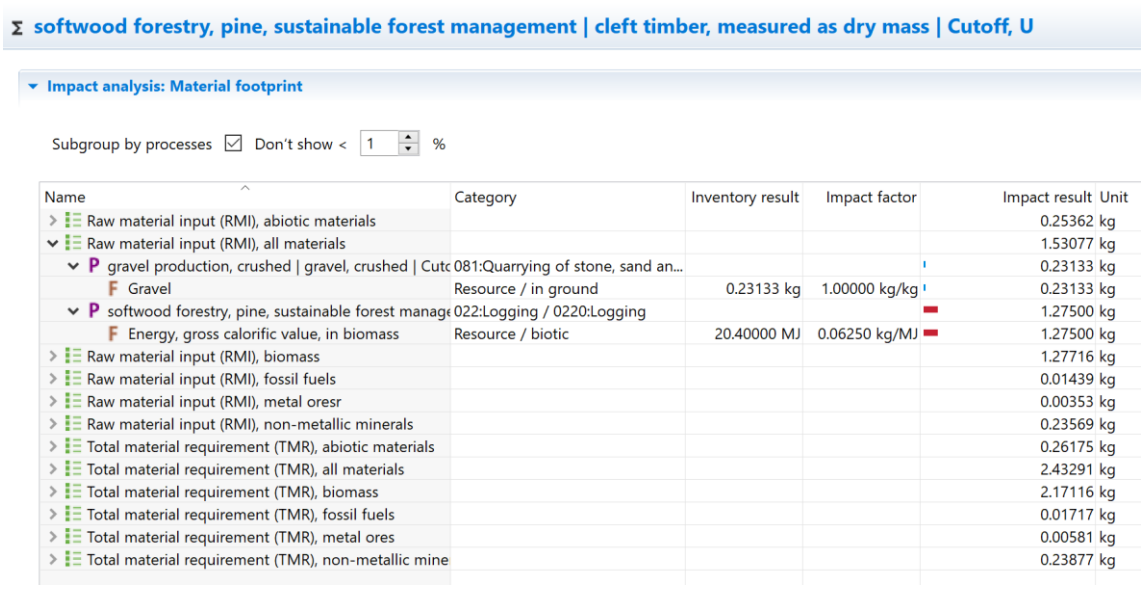
Σ market for copper, anode | copper, anode | Cutoff, U

Impact analysis: Material footprint

Subgroup by processes ☑ Don't show < 1 %

Name	Category	Inventory result	Impact factor	Impact result	Unit
Raw material input (RMI), abiotic materials				283.59737	kg
Raw material input (RMI), all materials				283.75159	kg
Raw material input (RMI), biomass				0.15423	kg
Raw material input (RMI), fossil fuels				2.72093	kg
Raw material input (RMI), metal ores				276.79351	kg
P copper mine operation and beneficiation, sulfide ore | coppe	072:Mining of non-ferrous met...			16.63079	kg
P copper mine operation and beneficiation, sulfide ore | coppe	072:Mining of non-ferrous met...			24.91670	kg
P copper mine operation and beneficiation, sulfide ore | coppe	072:Mining of non-ferrous met...			79.01081	kg
P copper mine operation and beneficiation, sulfide ore | coppe	072:Mining of non-ferrous met...			16.86336	kg
P copper mine operation and beneficiation, sulfide ore | coppe	072:Mining of non-ferrous met...			9.61896	kg
P copper mine operation and beneficiation, sulfide ore | coppe	072:Mining of non-ferrous met...			2.94743	kg
P copper mine operation and beneficiation, sulfide ore | coppe	072:Mining of non-ferrous met...			82.01959	kg
P copper mine operation and beneficiation, sulfide ore | coppe	072:Mining of non-ferrous met...			11.22161	kg
P copper mine operation and beneficiation, sulfide ore | coppe	072:Mining of non-ferrous met...			21.36471	kg
P copper mine operation and beneficiation, sulfide ore | coppe	072:Mining of non-ferrous met...			6.00687	kg
P zinc mine operation | copper concentrate, sulfide ore | Cutof	072:Mining of non-ferrous met...			3.09249	kg
Raw material input (RMI), non-metallic minerals				4.08292	kg
Total material requirement (TMR), abiotic materials				286.48263	kg
Total material requirement (TMR), all materials				286.74406	kg
Total material requirement (TMR), biomass				0.26144	kg
Total material requirement (TMR), fossil fuels				3.21793	kg
Total material requirement (TMR), metal ores				278.64862	kg
Total material requirement (TMR), non-metallic minerals				4.61607	kg

Fig. 14: Screenshot of the material footprint of 1 kg of copper from copper anodes, from ecoinvent 3.8 via openLCA. Only a part of the results is shown.



Name	Category	Inventory result	Impact factor	Impact result	Unit
Raw material input (RMI), abiotic materials				0.25362	kg
Raw material input (RMI), all materials				1.53077	kg
P gravel production, crushed | gravel, crushed | Cutc	081:Quarrying of stone, sand an...			0.23133	kg
F Gravel	Resource / in ground	0.23133 kg	1.00000 kg/kg	0.23133	kg
P softwood forestry, pine, sustainable forest manage	022:Logging / 0220:Logging			1.27500	kg
F Energy, gross calorific value, in biomass	Resource / biotic	20.40000 MJ	0.06250 kg/MJ	1.27500	kg
Raw material input (RMI), biomass				1.27716	kg
Raw material input (RMI), fossil fuels				0.01439	kg
Raw material input (RMI), metal oresr				0.00353	kg
Raw material input (RMI), non-metallic minerals				0.23569	kg
Total material requirement (TMR), abiotic materials				0.26175	kg
Total material requirement (TMR), all materials				2.43291	kg
Total material requirement (TMR), biomass				2.17116	kg
Total material requirement (TMR), fossil fuels				0.01717	kg
Total material requirement (TMR), metal ores				0.00581	kg
Total material requirement (TMR), non-metallic mine				0.23877	kg

Fig. 15: Screenshot of the material footprint of 1 kg of pine wood, from ecoinvent 3.8 via openLCA. Only a part of the results is shown.

The MF of aluminium is about 16 kg/kg, and it is clearly dominated by bauxite gangue, as expected (Fig. 13). Bauxite accounts for about 2/3 of the MF for aluminium, and large parts of the other third are attributed to fossil fuel extraction in the energy-intensive production chain for this material.

The MF of copper is much higher than for aluminium and overwhelmingly dominated by metal ore extraction (Fig. 14), as here, the average ore grade is below 1%. The contribution of about ten different mining processes reflects the mines from different world regions that contribute to the global copper ore supply mix.

Σ passenger car production, petrol/natural gas | passenger car, petrol/natural gas | Cutoff, U

Impact analysis: Material footprint

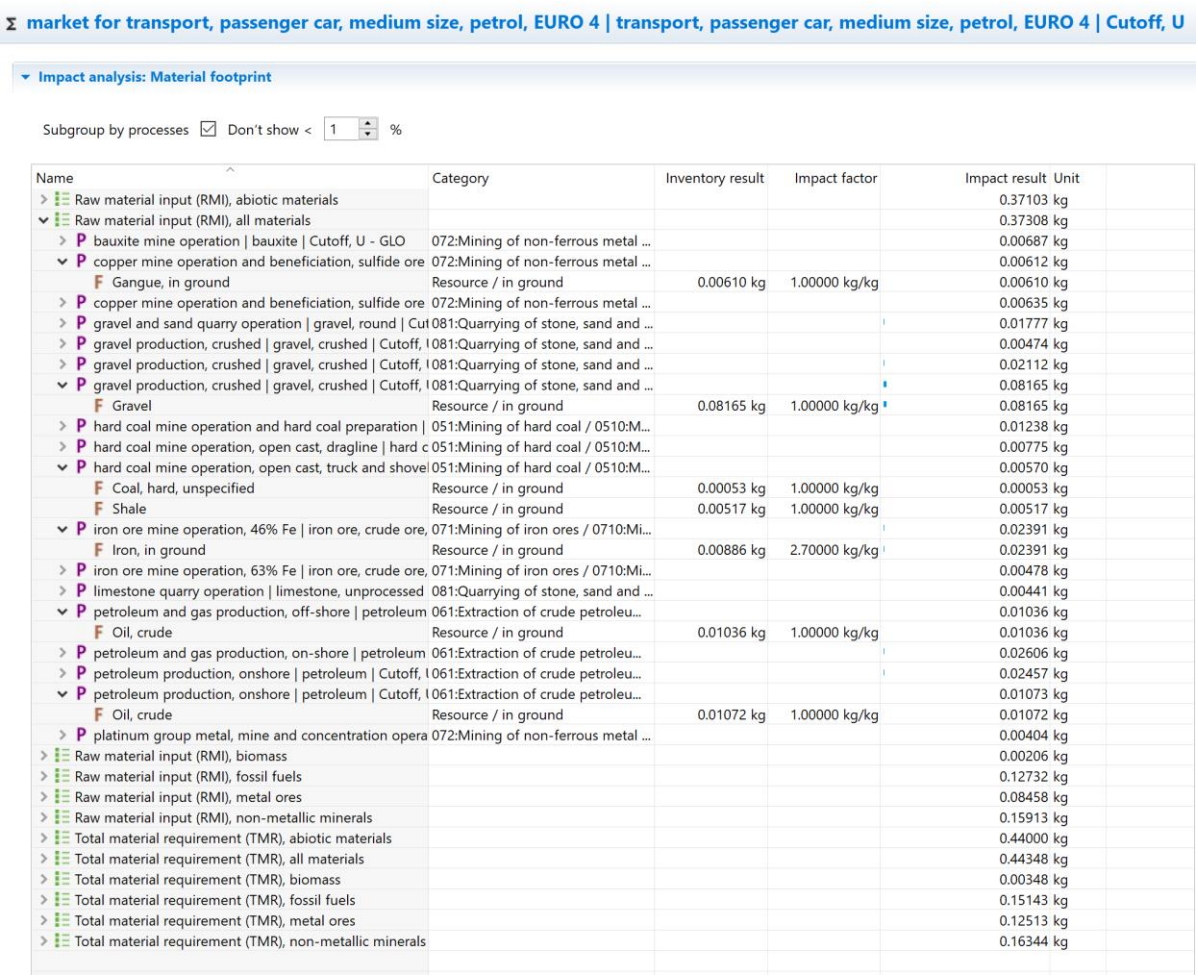
Subgroup by processes ☑ Don't show < 1 %

Name	Category	Inventory result	Impact factor	Impact result	Unit
Raw material input (RMI), abiotic materials				1.86738E4	kg
Raw material input (RMI), all materials				1.88843E4	kg
P bauxite mine operation | bauxite | Cutoff, U - GLO	072:Mining of non-ferrous metal or...			944.86164	kg
F Aluminium, in ground	Resource / in ground	81.29991 kg	1.00000 kg/kg	81.29991	kg
F Gangue, bauxite, in ground	Resource / in ground	863.53650 kg	1.00000 kg/kg	863.53650	kg
P copper mine operation and beneficiation, sulfide ore | copper concer	072:Mining of non-ferrous metal or...			248.63717	kg
P copper mine operation and beneficiation, sulfide ore | copper concer	072:Mining of non-ferrous metal or...			788.42791	kg
P copper mine operation and beneficiation, sulfide ore | copper concer	072:Mining of non-ferrous metal or...			818.45169	kg
F Gangue, in ground	Resource / in ground	815.79301 kg	1.00000 kg/kg	815.79301	kg
P copper mine operation and beneficiation, sulfide ore | copper concer	072:Mining of non-ferrous metal or...			213.19278	kg
P gold mine operation and gold production, unrefined | gold, unrefine	072:Mining of non-ferrous metal or...			449.72876	kg
P gravel and sand quarry operation | gravel, round | Cutoff, U - RoW	081:Quarrying of stone, sand and cl...			469.39816	kg
P gravel production, crushed | gravel, crushed | Cutoff, U - RoW	081:Quarrying of stone, sand and cl...			503.71380	kg
P hard coal mine operation and hard coal preparation | hard coal | Cutc	051:Mining of hard coal / 0510:Min...			203.59447	kg
P hard coal mine operation and hard coal preparation | hard coal | Cutc	051:Mining of hard coal / 0510:Min...			1308.57087	kg
F Coal, hard, unspecified	Resource / in ground	1296.72261 kg	1.00000 kg/kg	1296.72261	kg
P hard coal mine operation and hard coal preparation | hard coal | Cutc	051:Mining of hard coal / 0510:Min...			210.19019	kg
P hard coal mine operation | hard coal, run-of-mine | Cutoff, U - IN	051:Mining of hard coal / 0510:Min...			350.50957	kg
P hard coal mine operation, open cast, dragline | hard coal, run-of-min	051:Mining of hard coal / 0510:Min...			790.76526	kg
P hard coal mine operation, open cast, truck and shovel | hard coal, run	051:Mining of hard coal / 0510:Min...			581.70723	kg
P iron ore mine operation, 46% Fe | iron ore, crude ore, 46% Fe | Cutof	071:Mining of iron ores / 0710:Mini...			3016.07595	kg
F Iron, in ground	Resource / in ground	1117.06517 kg	2.70000 kg/kg	3016.07595	kg
P iron ore mine operation, 63% Fe | iron ore, crude ore, 63% Fe | Cutof	071:Mining of iron ores / 0710:Mini...			604.77699	kg
P lignite mine operation | lignite | Cutoff, U - RoW	052:Mining of lignite / 0520:Mining...			344.83636	kg
P limestone quarry operation | limestone, unprocessed | Cutoff, U - Ro\	081:Quarrying of stone, sand and cl...			446.83596	kg
P platinum group metal, mine and concentration operations | platinum	072:Mining of non-ferrous metal or...			494.87719	kg
P zinc mine operation | zinc concentrate | Cutoff, U - GLO	072:Mining of non-ferrous metal or...			313.59054	kg
Raw material input (RMI), biomass				210.44311	kg
Raw material input (RMI), fossil fuels				4694.12340	kg
Raw material input (RMI), metal oresr				1.01486E4	kg
Raw material input (RMI), non-metallic minerals				3831.12342	kg
Total material requirement (TMR), abiotic materials				2.45610E4	kg
Total material requirement (TMR), all materials				2.49171E4	kg
Total material requirement (TMR), biomass				356.05917	kg
Total material requirement (TMR), fossil fuels				5544.43788	kg
Total material requirement (TMR), metal ores				1.49367E4	kg
Total material requirement (TMR), non-metallic minerals				4079.84340	kg

Fig. 16: Screenshot of the material footprint of the production of a petrol car, 1500 kg, from ecoinvent 3.8 via openLCA. Only a part of the results is shown.

The MF of pine wood (Fig. 15), measured in dry mass only, is roughly 50% larger than the (wet) mass of the 1 kg of reference flow extracted. It largely consists of the biomass footprint of the harvested wood, estimated via the gross calorific value, and a smaller contribution of gravel for the forest roads, which are included in the product system.

The MF of an average petrol car (production phase only, weight: 1500 kg, Fig. 16), is about 19 tons, with clearly visible contributions from aluminium/bauxite, copper, gold, goal, iron ore, platinum group metals, gravel and sand (also the mineral source of silicon), limestone (for steel production), and zinc. With an annual world car production of about 100 million, this amounts to a total material footprint of almost 2 Gt just for producing passenger vehicles.



Σ market for transport, passenger car, medium size, petrol, EURO 4 | transport, passenger car, medium size, petrol, EURO 4 | Cutoff, U

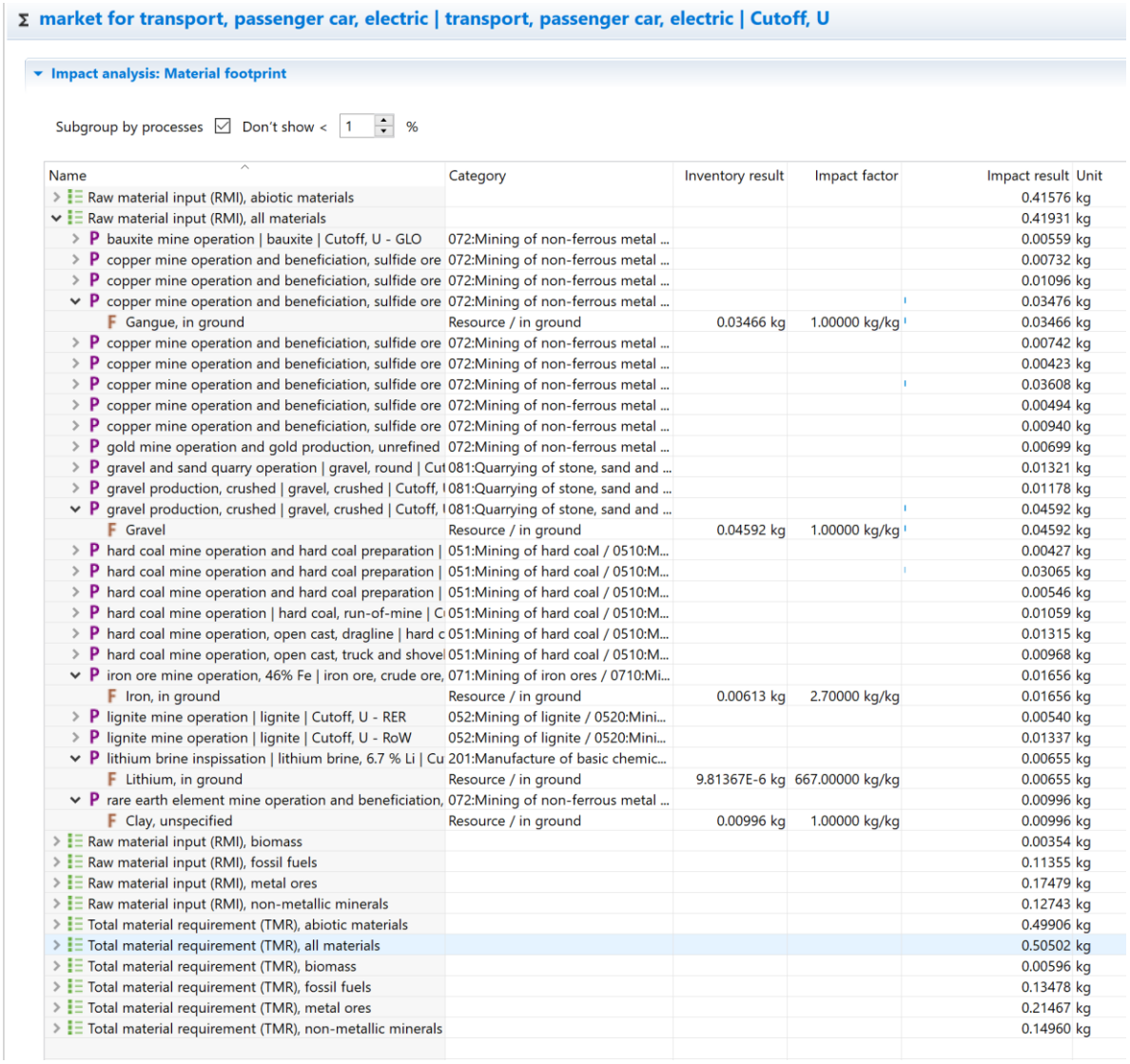
Impact analysis: Material footprint

Subgroup by processes ☑ Don't show < 1 %

Name	Category	Inventory result	Impact factor	Impact result	Unit
Raw material input (RMI), abiotic materials				0.37103	kg
Raw material input (RMI), all materials				0.37308	kg
P bauxite mine operation | bauxite | Cutoff, U - GLO	072:Mining of non-ferrous metal ...			0.00687	kg
P copper mine operation and beneficiation, sulfide ore	072:Mining of non-ferrous metal ...			0.00612	kg
F Gangue, in ground	Resource / in ground	0.00610 kg	1.00000 kg/kg	0.00610	kg
P copper mine operation and beneficiation, sulfide ore	072:Mining of non-ferrous metal ...			0.00635	kg
P gravel and sand quarry operation | gravel, round | Cut	081:Quarrying of stone, sand and ...			0.01777	kg
P gravel production, crushed | gravel, crushed | Cutoff, I	081:Quarrying of stone, sand and ...			0.00474	kg
P gravel production, crushed | gravel, crushed | Cutoff, I	081:Quarrying of stone, sand and ...			0.02112	kg
P gravel production, crushed | gravel, crushed | Cutoff, I	081:Quarrying of stone, sand and ...			0.08165	kg
F Gravel	Resource / in ground	0.08165 kg	1.00000 kg/kg	0.08165	kg
P hard coal mine operation and hard coal preparation |	051:Mining of hard coal / 0510:M...			0.01238	kg
P hard coal mine operation, open cast, dragline | hard c	051:Mining of hard coal / 0510:M...			0.00775	kg
P hard coal mine operation, open cast, truck and shovel	051:Mining of hard coal / 0510:M...			0.00570	kg
F Coal, hard, unspecified	Resource / in ground	0.00053 kg	1.00000 kg/kg	0.00053	kg
F Shale	Resource / in ground	0.00517 kg	1.00000 kg/kg	0.00517	kg
P iron ore mine operation, 46% Fe | iron ore, crude ore,	071:Mining of iron ores / 0710:Mi...			0.02391	kg
F Iron, in ground	Resource / in ground	0.00886 kg	2.70000 kg/kg	0.02391	kg
P iron ore mine operation, 63% Fe | iron ore, crude ore,	071:Mining of iron ores / 0710:Mi...			0.00478	kg
P limestone quarry operation | limestone, unprocessed	081:Quarrying of stone, sand and ...			0.00441	kg
P petroleum and gas production, off-shore | petroleum	061:Extraction of crude petroleu...			0.01036	kg
F Oil, crude	Resource / in ground	0.01036 kg	1.00000 kg/kg	0.01036	kg
P petroleum and gas production, on-shore | petroleum	061:Extraction of crude petroleu...			0.02606	kg
P petroleum production, onshore | petroleum | Cutoff, I	061:Extraction of crude petroleu...			0.02457	kg
P petroleum production, onshore | petroleum | Cutoff, I	061:Extraction of crude petroleu...			0.01073	kg
F Oil, crude	Resource / in ground	0.01072 kg	1.00000 kg/kg	0.01072	kg
P platinum group metal, mine and concentration opera	072:Mining of non-ferrous metal ...			0.00404	kg
Raw material input (RMI), biomass				0.00206	kg
Raw material input (RMI), fossil fuels				0.12732	kg
Raw material input (RMI), metal ores				0.08458	kg
Raw material input (RMI), non-metallic minerals				0.15913	kg
Total material requirement (TMR), abiotic materials				0.44000	kg
Total material requirement (TMR), all materials				0.44348	kg
Total material requirement (TMR), biomass				0.00348	kg
Total material requirement (TMR), fossil fuels				0.15143	kg
Total material requirement (TMR), metal ores				0.12513	kg
Total material requirement (TMR), non-metallic minerals				0.16344	kg

Fig. 17: Screenshot of the material footprint of the use (1 km driven) of a standard petrol passenger car, from ecoinvent 3.8 via openLCA. Only a part of the results is shown.

The MF of a kilometer driven with an average petrol car (all life cycle stages plus fuel supply and infrastructure, Fig. 17), is about 370 grams. It shows contributions from the main metals and materials used in the car (see Fig. 16), and also contributions from petroleum extraction. The fossil fuel footprint is about 130 g and the metal footprint about 85 g.



Σ market for transport, passenger car, electric | transport, passenger car, electric | Cutoff, U

Impact analysis: Material footprint

Subgroup by processes ☑ Don't show < 1 %

Name	Category	Inventory result	Impact factor	Impact result	Unit
Raw material input (RMI), abiotic materials				0.41576	kg
Raw material input (RMI), all materials				0.41931	kg
P bauxite mine operation | bauxite | Cutoff, U - GLO	072:Mining of non-ferrous metal ...			0.00559	kg
P copper mine operation and beneficiation, sulfide ore	072:Mining of non-ferrous metal ...			0.00732	kg
P copper mine operation and beneficiation, sulfide ore	072:Mining of non-ferrous metal ...			0.01096	kg
P copper mine operation and beneficiation, sulfide ore	072:Mining of non-ferrous metal ...			0.03476	kg
F Gangue, in ground	Resource / in ground	0.03466 kg	1.00000 kg/kg	0.03466	kg
P copper mine operation and beneficiation, sulfide ore	072:Mining of non-ferrous metal ...			0.00742	kg
P copper mine operation and beneficiation, sulfide ore	072:Mining of non-ferrous metal ...			0.00423	kg
P copper mine operation and beneficiation, sulfide ore	072:Mining of non-ferrous metal ...			0.03608	kg
P copper mine operation and beneficiation, sulfide ore	072:Mining of non-ferrous metal ...			0.00494	kg
P copper mine operation and beneficiation, sulfide ore	072:Mining of non-ferrous metal ...			0.00940	kg
P gold mine operation and gold production, unrefined	072:Mining of non-ferrous metal ...			0.00699	kg
P gravel and sand quarry operation | gravel, round | Cut	081:Quarrying of stone, sand and ...			0.01321	kg
P gravel production, crushed | gravel, crushed | Cutoff, I	081:Quarrying of stone, sand and ...			0.01178	kg
P gravel production, crushed | gravel, crushed | Cutoff, I	081:Quarrying of stone, sand and ...			0.04592	kg
F Gravel	Resource / in ground	0.04592 kg	1.00000 kg/kg	0.04592	kg
P hard coal mine operation and hard coal preparation |	051:Mining of hard coal / 0510:M...			0.00427	kg
P hard coal mine operation and hard coal preparation |	051:Mining of hard coal / 0510:M...			0.03065	kg
P hard coal mine operation and hard coal preparation |	051:Mining of hard coal / 0510:M...			0.00546	kg
P hard coal mine operation | hard coal, run-of-mine | C	051:Mining of hard coal / 0510:M...			0.01059	kg
P hard coal mine operation, open cast, dragline | hard c	051:Mining of hard coal / 0510:M...			0.01315	kg
P hard coal mine operation, open cast, truck and shovel	051:Mining of hard coal / 0510:M...			0.00968	kg
P iron ore mine operation, 46% Fe | iron ore, crude ore,	071:Mining of iron ores / 0710:Mi...			0.01656	kg
F Iron, in ground	Resource / in ground	0.00613 kg	2.70000 kg/kg	0.01656	kg
P lignite mine operation | lignite | Cutoff, U - RER	052:Mining of lignite / 0520:Mini...			0.00540	kg
P lignite mine operation | lignite | Cutoff, U - RoW	052:Mining of lignite / 0520:Mini...			0.01337	kg
P lithium brine inspissation | lithium brine, 6.7 % Li | Cu	201:Manufacture of basic chemic...			0.00655	kg
F Lithium, in ground	Resource / in ground	9.81367E-6 kg	667.00000 kg/kg	0.00655	kg
P rare earth element mine operation and beneficiation,	072:Mining of non-ferrous metal ...			0.00996	kg
F Clay, unspecified	Resource / in ground	0.00996 kg	1.00000 kg/kg	0.00996	kg
Raw material input (RMI), biomass				0.00354	kg
Raw material input (RMI), fossil fuels				0.11355	kg
Raw material input (RMI), metal ores				0.17479	kg
Raw material input (RMI), non-metallic minerals				0.12743	kg
Total material requirement (TMR), abiotic materials				0.49906	kg
Total material requirement (TMR), all materials				0.50502	kg
Total material requirement (TMR), biomass				0.00596	kg
Total material requirement (TMR), fossil fuels				0.13478	kg
Total material requirement (TMR), metal ores				0.21467	kg
Total material requirement (TMR), non-metallic minerals				0.14960	kg

Fig. 18: Screenshot of the material footprint of the use (1 km driven) of a standard electric passenger car, from ecoinvent 3.8 via openLCA. Only a part of the results is shown.

The MF of a kilometer driven with an average battery electric car (all life cycle stages plus fuel supply and infrastructure, Fig. 18), is about 420 grams. It shows contribution from the main metals and materials used in the car (see Fig. 16, but also lithium and rare earth elements mining is included/relevant now), and also contributions from coal mining, partly for production and partly for operation (via the electricity mix). The fossil fuel footprint is about 110 g and the metal footprint about 175 g.

Though the two product systems evaluated in Figs. 17 and 18 are used for demonstration only and were not carefully checked to be directly comparable regarding system boundary and functional unit, a clear trend in the MF can be seen and that require further analysis.

Compared to the MF of the standard petrol passenger car shown in Fig. 17, the fossil fuel footprint hardly declines, partly due to the remaining fossil energy in the use phase electricity mix and largely due to the very large (fossil) energy intensity of the manufacturing stage. The metal ore footprint roughly doubles.

Limitations and inaccuracies of the approach

The material footprint method documented here is a first attempt for supply a detailed (biomass, fossil fuels, metal ores, and non-metallic minerals) material footprint indicator for the latest ecoinvent versions 3.7.1. and 3.8. During the adaptation of the characterization factors from Mostert and Bringezu (2019), some observations led to a number of choices and simplifications.

First, the current ei process setup is comprehensive regarding metal extraction flows but not fully consistent when it comes to the coverage of gangue and overburden. A screening of the major metal ore extraction processes revealed the metals for which the RME is estimated via the reported gangue flows and for which the average ore grade needs to be used. This division of metals into RME estimation methods is not fully consistent, as the example of molybdenum in Figs. 5 and 6 shows. Moreover, the choices above, especially the inclusion of the gangue flow values, represent a simplification compared to the extensive data collection by MB2019 to estimate average ore grades. This choice was necessary to be consistent with the way the different resource extraction flows are accounted for in ecoinvent. Thus, this approach makes the best use of the information currently present in ecoinvent. A further refinement of the method would require a systematic overhaul of ecoinvent regarding the reporting of all extracted and all processed material flows other than the actual metal flows. Also, the metal ore-specific scale-up from RMI to TMR is not possible for the generic gangue flow, but it is included for bauxite gangue.

Second, a crucial system boundary choice was made: Not the complete list of ei elementary resource flows is covered, but only those that are already used by the existing ei LCIA methods in their openLCA implementation. The main reason is to ensure consistency with these metal depletion methods in the coverage of resources.

Third, for estimating biomass inputs and extraction, reported CO_2 and biomass inputs are ignored. Rather, the energy equivalent of biomass is used, because this is the only info that is consistently available across process and the only one that allows for simple matrix-based calculations (and not some if-then restrictions). The energy content is only rough approximation for the biomass weight, especially for 'wet' products, like fruits and vegetables. Fish (dry weight) is not included as no caloric value equivalent for fish is reported in ecoinvent.

Fourth, for more accurate calculations of the material footprint, many extraction processed require mass balance and data quality checking and a re-evaluation of the representativeness of the material extraction data for the regions for which they are reported.

Fifth, the water use figures are very preliminary and need proper checking. Due to the choice of scope, the flow list is consistent with the water depletion potential (WDP) of ReCiPe, as it includes the same elementary flows (including cooling water) and some not (including water flowing through turbines).

As a consequence of these limitations, specific LCA results must always be checked in detail for plausibility, completeness, and regarding what specific materials are actually included! Manual correction can be applied to some components of the material footprint of a product system to increase its accuracy and completeness.

Open issues and outlook

The current resource flow list was extracted from the openLCA LCIA methods for ecoinvent 3.7.1 and 3.8. This list comprises the 414 most commonly used resource flows for ei 3.7.1 and 419 flows for ei 3.8. With that list, the scope of this material footprint method is compatible with that of the openLCA LCIE methods, including ReCiPe.

Still, more discussion and future refinement on the list of flows to include is needed between ecoinvent and material flow accounting experts. For example, many elementary flows of ecoinvent are not included in the openLCA LCIA method. Vice versa, the openLCA LCIA methods include CFs for resources flows that do not appear in the flow directory of that method file. E.g. 'Zirconia, Resource/Unspecified', UUID: 312615c8-af6f-34dc-9dc0-6c4652fe01ab, for which a CF for the Crustal Scarcity Indicator is given but that does not appear in the flow directory of the LCIA method data file. Also, more information about the assignment of resource flows to compartments in ecoinvent is needed, e.g., what is the reason for grouping a resource into the 'unspecified' category.

For future updates of the material footprint LCIA method, the use of the complete ei resource flow list needs to be investigated, i.e., the inclusion of those flows that are currently not linked to the openLCA LCIA methods. For ei 3.8, this group includes 5622 flows. However, the majority of these flows are land transformation and occupation as well as water flows. This issue links to a broader discussion on the consistent application of LCIA methods across software implementations (Speck et al. 2015). Technically, the list of these flows can be easily exported from openLCA (via export to JSON-LD) and parsed into table form by a Python script for matching to existing characterization factors.

Overall, for future updates of the material footprint LCIA method, we need a broader understanding of the elementary flow lists in ecoinvent. More information is needed regarding the reasons behind the broad differentiation and creation of the many different EFs for individual elements and their matching to the different LCIA method files. A consensus is needed on which proxy (energy, gangue) to use for the material footprint and which (additional) elementary flows therefore need to be routinely monitored and included in the life cycle databases. This refinement should be part of a large, concerted effort of making life cycle impact assessment more consistent across LCA software and the underlying process and sector databases.

Specific LCA results must always be checked in detail for plausibility, completeness, and regarding what specific materials are actually included! Manual correction can be applied to some components of the material footprint of a product system to increase its accuracy and completeness.

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