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Measuring Product Material Footprint as New Life Cycle Impact Assessment Method: Indicators and Abiotic Characterization Factors

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Received: 20 February 2019; Accepted: 28 March 2019; Published: 2 April 2019

Abstract: The global economy is using growing amounts of natural resources such as raw materials, water, and land by making and using goods, services, and infrastructure. Aspirations on international, regional, and national levels e.g., the Sustainable Development Goals, the EU flagship initiative Roadmap to a Resource Efficient Europe or the German Program for Resource Efficiency are showing an urgent need to bring the global raw material use down to sustainable levels. An essential prerequisite to identify resource efficient options and to implement resource efficiency measures and solutions is the ability to compare different products or services regarding their raw material use. Until today, there is no internationally standardized approach defined and no software supported calculation method including the necessary data basis available to measure the raw material intensity of products. A new life cycle impact assessment (LCIA) method Product Material Footprint PMF is described. Two indicators are used to quantify the PMF: the Raw Material Input RMI and the Total Material Requirement TMR. The calculation of global median values for the characterization factors CF_{RMI} and CF_{TMR} of abiotic materials was done based on different databases. This article presents the methodological approach of the PMF, the calculation results for CF_{RMI} of 42 abiotic materials and CF_{TMR} of 36 abiotic materials, and the implementation of the LCIA method into the software openLCA for use with the ecoinvent database.

Keywords: product material footprint; new life cycle impact assessment method; abiotic materials; raw material input; total material requirement; characterization factors

1. Introduction

With the adoption of the United Nations 2030 Agenda for Sustainable Development, the Member States have agreed on 17 Sustainable Development Goals (SDGs) to promote activities of major importance for the planet [1]. For achieving the goals, an efficient and sustainable resource management is an essential prerequisite, since most of the SDGs have a direct or indirect relationship to the use of natural resources [2]. Of particular importance is target 12.2, which focuses on sustainable natural resource use measured by material productivity. Target 8.4, which addresses the need for continuous improvement of resource efficiency, is already on the international agenda: G20, OECD, or EU have developed or are developing strategies to increase the efficient use of resources to limit the negative environmental and health impacts such as emissions, waste, land use, and water pollution [3–5]. Nevertheless, the efficient use and fair distribution of natural resources requires a holistic vision for a transformation toward a sustainable society and new forms of economic activity [6].

Natural resources "are material and non-material assets occurring in nature that were, at some point in time, deemed useful for humans" [7]. The global use of materials underwent an unprecedented growth in recent decades driven by the industrialization of emerging countries and the continuous growth in production and consumption of developed countries [8]. In contrast to climate protection, there are, so far, no internationally binding goals for the sustainable use of natural resources. The current use of material resources is around 90 billion tons per year and expected to double until 2050, which also entails a loss of natural eco-systems and biodiversity [9]. If a global level of raw material use of 50 billion tons is taken as the Safe Operating Space (SOS) and a world population of 10 billion people is expected in 2050, then the global consumption should not exceed 5 tons per capita and year [10]. For Germany, this would mean that the raw material consumption must be reduced by more than 75% within the next 30 years.

Resource productivity is already increasing in Germany. Fewer resources are needed for one unit of economic output [11]. The German Federal Government committed itself to doubling abiotic material productivity by 2020 based on the 1990 values in its national sustainability strategy [12]. Increasing resource productivity is also part of the German Green Growth Strategy and pays off economically since the development and application of efficiency technologies are creating new jobs and opening up new markets. With the adoption of the German Resource Efficiency Program ProgRess, it was decided to report on progress in the development of resource efficiency every four years [13]. Against this background, ProgRess II was published for which, in addition to abiotic material productivity, total raw material productivity is mentioned for the first time as an indicator [14]. While abiotic material productivity is based on abiotic Direct Material Input (DMI), the total raw material productivity relates to Raw Material Input (RMI), which are indicators based on economy-wide material flow accounting [15–17].

The growing need to increase resource productivity of economies requires us to measure the life cycle wide use of natural material resources both at the country as well as at the product level. Driven by the growing demand for robust indicators to measure resource use, progress has been made in harmonizing the methods for measuring the economy-wide material use [18]. The RMI and the derived Raw Material Consumption (RMC) have been most widely applied and results are available for most countries in the world [11]. Due to data availability, the calculation of Total Material Requirement (TMR) has been limited to selected countries such as China [19] even though the meaning of the TMR in terms of environmental impact must be regarded higher than of the RMI, which is economically defined as the produce of the primary sectors [20]. In contrast to the methods for measuring the economy wide material use, the ability to measure the material intensity of products or services is still in its infancy as a standardized approach and a reliable data basis are still missing.

A product requires an input of raw materials in all phases of its life cycle and, therefore, the cumulated raw material input determines its material intensity, which can be a multiple of its own mass. The Material Input per Service unit (MIPS) was the first concept that accounted for the cumulated primary material requirements without further specification of the associated bundle of environmental impacts [21]. Saurat and Ritthoff provided an overview of methods and tools to determine the MIPS and demonstrated an advanced calculation method [22]. The life cycle wide primary raw material input for a product or service can be referred to as the material footprint [23] and its use as a sum parameter in LCA has already been proposed [24]. Its calculation, based on the Cumulated Raw Material Demand CRD, underwent a standardization process in Germany and is described in a recently published guideline [25]. For the abiotic components, the CRD and the RMI are identically defined.

Life cycle impact assessment (LCIA) methods were originally developed for measuring environmental impacts based on output-oriented indicators, which are calculated by Characterization Factors (CF) assigned to elementary flows. Most prominent is the carbon footprint, where the Global Warming Impact (GWI), which is often referred to as Global Warming Potential GWP, is calculated by the characterization factors (GWP) of greenhouse gases assigned to their mass flows. This article presents the Product Material Footprint (PMF) as a new LCIA method based on two input oriented indicators RMI and TMR. The indicators are calculated by assigning defined Characterization Factors Raw Material Input CF_{RMI} and Characterization Factors Total Material Requirement CF_{TMR} to the mass flows of the materials that are required as a life cycle wide input for the product or service. The calculation is done analogously to the Cumulated Energy Demand CED by adding different energy sources in terms of their energy equivalents [26,27]. Global median values for CF_{RMI} and CF_{TMR} were calculated for different abiotic materials with a focus on metals, non-metallic minerals, and fossil energetic materials using different databases. For the first time, these procedures were implemented into the software openLCA (version 1.7) for use with the ecoinvent database (version 3.1, cut-off LCI) as a new LCIA method and used for the software-supported calculation of the material intensity of products and services.

2. Methodological Approach

2.1. LCIA Method and Characterization Model

The PMF is proposed as a new input oriented LCIA method that fulfills the requirements and necessary components described in ISO 14044 [28]. The method is applied for a software-supported calculation of RMI and TMR per Functional Unit (FU) based on the material input as the LCI result and the assigned CF_{RMI} and CF_{TMR}. The extraction of primary materials from the ecosphere and the transfer of raw materials like metal ores, non-metallic minerals, fossil energetic raw materials, and biomass into the technosphere is considered as the impact category and the natural environment as the area of protection (AoP). According to ISO 14044, a characterization model should be scientifically valid and based upon a distinct identifiable environmental mechanism [28]. The loss in life supporting services of the extracted materials and the environmental impacts of mining and beneficiation as well as the further processing in manufacturing during the use phase are quite diverse and vary according to local conditions, materials, and process technologies. Nevertheless, some basic causal relationships can be observed to characterize the type of impacts.

(A) The total extraction of primary materials usually leads to the loss of the in-situ life supporting functions and services of the extracted and translocated material and the affected landscapes, including cleared vegetation and changes in hydrology, consequently to a local to regional change and often to a damage of the natural environment as an endpoint around the location of the extraction. As a midpoint indicator, total extraction of primary materials associated with the life cycle of products and services is measured by the TMR.

(B) Furthermore, the extraction process determines the amount of raw materials that is further processed and used in production and consumption, the volume of final emissions and waste, and the associated bundle of environmental impacts on land, water, and air, which will subsequently—and additionally to (A)—occur at other places distant from the location of extraction. As a midpoint indicator, the RMI, measures the life-cycle wide cumulative amount of used extraction of raw materials.

Measuring the mass turnover of primary material extraction (A) and raw material extraction (B) accounts for basic determinants of environmental impact potentials. The method provides quantitative information on the sustainability of the product system in terms of efficient use of primary and raw materials as a proxy for the potential environmental damage to nature from the location of extraction to final disposal. The PMF and its indicators can be interpreted as measures of a generic environmental pressure associated with the life-cycle wide cumulative mass turnover of natural material extraction, translocation, and use [20].

Since every product system requires an input of material, energy, water, and land, all four footprints should be considered to get mostly sufficient information about the environmental impact potential [29] and to avoid trade-offs in the search for alternative solutions.

2.2. Calculation of Indicators

The characterization models for the carbon footprint based on the characterization factor GWP has been used in a great number of LCA and is widely accepted. The characterization model for the PMF, as an accounting for the material intensity of products or services, should consider the life-cycle wide input of raw materials as well as the total amount of primary material extracted. Therefore, two indicators are used to quantify the PMF: the Raw Material Input RMI and the Total Material Requirement TMR. The loss in supporting services of the extracted materials and the environmental impacts of mining and beneficiation are quite diverse and vary, according to materials and extraction processes. However, the mass of the material, which is used as an input into the product system, is always only a fraction of the extracted raw material. The lower the fraction, the higher the amount of extracted raw material is and the higher the loss in supporting functions and services is. Therefore, the RMI, measuring the total amount of raw materials that is extracted from nature and transferred into the technosphere, i.e., used extraction, is a proxy for the potential damage to the natural environment. The RMI per functional unit FU is calculated using the equation below.

$$\mathrm{RMI} = \sum_{i=1}^{n} m_{\mathrm{material}\ i} \times \mathrm{CF}_{\mathrm{RMI}_{\mathrm{material}\ i}} \quad (1)$$

The RMI is the raw material input measured in kg raw material per FU, $m_{\mathrm{material}\ i}$ is the mass of material i measured in kg per FU, n is the total number of different materials required for the provision of the FU, and the $\mathrm{CF}_{\mathrm{RMI}\ \mathrm{material}\ i}$ is the Characterization Factor Raw Material Input of material i measured in kg raw material per kg material.

The TMR is also used as an indicator, which measures the total amount of extracted primary material, so the material that is extracted to get access to the raw material remains in the ecosphere i.e., unused extraction. The TMR per FU is calculated using the equation below.

$$\mathrm{TMR} = \sum_{i=1}^{n} m_{\mathrm{material}\ i} \times \mathrm{CF}_{\mathrm{TMR}_{\mathrm{material}\ i}} \quad (2)$$

The TMR is the total material requirement measured in kg primary material per FU, $m_{\mathrm{material}\ i}$ is the mass of material i measured in kg per FU, n is the total number of different materials required for the provision of the FU, and the $\mathrm{CF}_{\mathrm{TMR}\ \mathrm{material}\ i}$ is the Characterization Factor Total Material Requirement of material i measured in kg primary material per kg material.

The RMI and the TMR are categorized by the material flows they are accounting for: the RMI accounts for used extractions from the environment, covering all raw materials that are sold by mining, agriculture, forestry, and fisheries. Therefore, the RMI is the sum of all abiotic and biotic raw materials, which represent an input into the product over its complete life cycle.

$$\mathrm{RMI} = \mathrm{RMI}_{\mathrm{abiotic}} + \mathrm{RMI}_{\mathrm{biotic}} \quad (3)$$

The TMR considers both used and unused extraction. The unused extraction includes all natural material that is moved and dumped to enable the extraction of the raw material. The TMR measures the total amount of abiotic and biotic primary material required over the complete life cycle of a product.

$$\mathrm{TMR} = \mathrm{TMR}_{\mathrm{abiotic}} + \mathrm{TMR}_{\mathrm{biotic}} \quad (4)$$

Thus, the TMR reflects the life cycle wide requirement of primary materials and the RMI of the life cycle wide input of raw materials for a product or service. The difference between the TMR and the RMI represents the unused extraction. The abiotic and biotic parts of both indicators should be calculated and reported separately because they are linked to different environmental impacts [10].

2.3. Calculation of Characterization Factors

The calculation of the $\mathrm{CF}_{\mathrm{RMI}}$ and $\mathrm{CF}_{\mathrm{TMR}}$ is based on the MIPS concept of Schmidt-Bleek and a further development of MIPS 2.0, which generates CF assigned to elementary flows of the ecoinvent database to calculate the input of natural resources as raw materials, water, and air [22,30]. The calculation of the raw material input in MIPS 2.0 has some methodological weaknesses and limitations: (1) It applies mass allocation instead of economic allocation for multi-metal ores. (2) It was developed for ecoinvent version 2.2 and has not been updated for ecoinvent version 3. (3) The data for calculation of the CF are solely based on information from the elementary flows "resource, in ground" of the ecoinvent database, which defines the flows of abiotic material from nature to the technosphere. However, these elementary flows were not developed for mass balanced calculation. Some flow descriptions contain information on the material concentration in the raw material. The update of LCI methods to account for different ore grades has been suggested [31], but, so far, the information are only available for a limited number of materials and mostly outdated e.g., ore grades for copper are based on data from the year 1994 [32]. The calculation and the use of updated world median values for the CF was proposed mainly to overcome further problems in the calculation using the ecoinvent database e.g., the limited number of elementary flows [33].

The $CF_{RMI\ material\ i}$ can be defined as the ratio of the mass of the extracted raw material i.e., used extraction and the mass of the material i in the extracted raw material.

$$CF_{RMI_{material\ i}} = \frac{m_{extracted\ raw\ material}}{m_{material\ i\ in\ extracted\ raw\ material}} \quad (5)$$

The $CF_{RMI\ material\ i}$ can be also calculated by the concentration of the material i in the extracted raw material, e.g., the metal concentration in the extracted ore.

$$CF_{RMI_{material\ i}} = \frac{1}{c_{material\ i\ in\ extracted\ raw\ material}} \quad (6)$$

The $CF_{TMR\ material\ i}$ is calculated below.

$$CF_{TMR_{material\ i}} = CF_{RMI_{material\ i}} \times (1 + coeff_{extraction\ material\ i}) \quad (7)$$

The $coeff_{extraction\ material\ i}$ is the extraction coefficient of the material i calculated by the ratio of the mass of the unused extraction and the mass of the extracted primary material for production of the material measured in kg per kg.

$$coeff_{extraction\ material\ i} = \frac{m_{unused\ extraction}}{m_{extracted\ primary\ material\ for\ production\ of\ material\ i}} \quad (8)$$

For quantification of the $CF_{RMI\ material\ i}$, allocation has to be considered if the extracted raw material contains more than one material. For example, metallic minerals are extracted in mines with single-metal ores (SMO) but also with multiple-metal ores (MMO). For SMO, the total mass of the extracted mineral is attributed only to one metal and, therefore, the allocation factor $AF_{material\ i}$ is equal to one. For MMO, the total mass of the extracted minerals has to be distributed to all metals that are produced from the mine. In this case, the $AF_{material\ i}$ for each metal is greater than zero and less than one and the sum of all AF for a specific mine is equal to one. Economic allocation should be applied when the mineral is extracted and further processed with the aim to sell every single material according to the market value [34]. In particular, for metal mining, the value of extraction and the amount of metals produced may differ considerably depending on the price of the metal, which ultimately determines the purpose of the processes. The $AF_{material\ i}$ is calculated using the formula below.

$$AF_{material\ i} = \frac{c_{material\ i} \times AP_{material\ i}}{\sum_{j=1}^{m} c_{material_j} \times AP_{material_j}} \quad (9)$$

The $c_{material\ i}$ is the concentration of the material i in the extracted raw material, e.g., the ore, measured in percent, m is the total number of different materials in the extracted raw material, and $AP_{material\ j}$ is the average market price of the material j measured in monetary units. For economic allocation, a 10-year average market price should be considered [35].

2.4. Data Sources

Three different data sources were used to calculate the global median values for the CF_{RMI}. The results are applied in the described order due to higher global coverage and timeliness of the data. The data sources are: (1) the database of the former Raw Materials Group (RMG) [36], (2) a database taken from an IFEU report [34], and (3) the ecoinvent database (version 3.1).

The values for the CF_{RMI} of 10 metals were calculated using the RMG database, which provides information on the global mining sector and the associated data includes information on yearly production quantities of minerals and metal ore concentrations in each mine. From the mine specific allocation factor $AF_{\text{material i mine}}$ the $CF_{\text{RMI material i mine}}$ was calculated. The World Bank commodity price data were used to calculate the 10-year average market price of the materials [37]. The mines were sorted by the $CF_{\text{RMI material i mine}}$ and the allocated production volumes were cumulated to identify the mine with the median ton of global production. This mine represents the global median CF_{RMI} of material i. As an example, the values for the $CF_{\text{RMI copper mine}}$ over the allocated cumulative raw material production of 141 considered mines including the median value and the 25th and 75th percentile are shown in Figure 1.

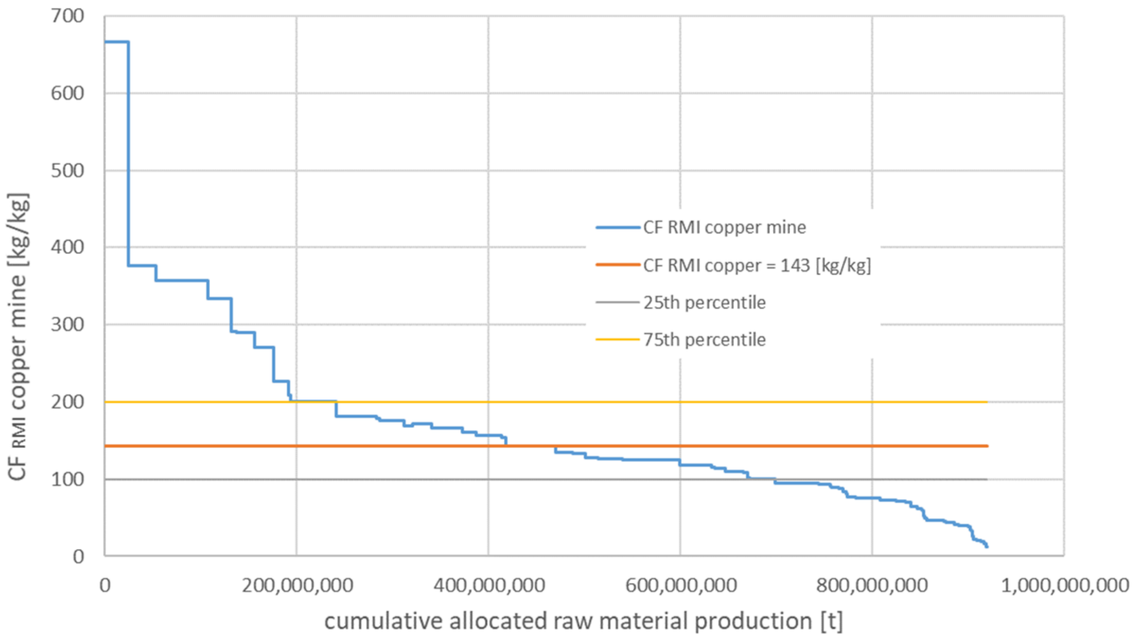

Figure 1. The values for the Characterization Factor Raw Material Input for copper per mine $CF_{\text{RMI copper mine}}$ and the median value as well as the 25th and 75th percentile over the cumulative allocated raw material production of 141 copper mines [36].

The global average values for the CF_{RMI} of 11 other metals were calculated from the database taken from the IFEU report. The report presents an approach for converting product flows into raw material equivalents RME and the underlying data [34]. The data refer to the year 2010 and are taken from annual reports of global mining companies and from the United States Geological Survey (USGS). The CF_{RMI} of 21 additional materials were calculated from the ecoinvent database. So far, LCA databases do not provide explicit data, which can be used to calculate the CF_{RMI} and CF_{TMR}. In the description of some elementary flows, in particular, "resource, in ground", the concentration of the material in the raw material is given, e.g., "Barite, 15% in crude ore, in ground." Using Equation (6) the $CF_{\text{RMI barite}}$ is resulting in 6.7 kg/kg. If a material is defined by elementary flows with different concentrations of the material in the raw material, the median value was applied.

For calculating the CF_{TMR}, the values of the $coeff_{\text{extraction material}}$ were taken from the Global Material Flows (GMF) database (version May 2016). This database provides data for the $coeff_{\text{extraction material}}$ on the basis of 45,726 data points from 38 different data sources, but is no longer updated [38]. The GMF database covers data on biomass, fossil fuels, minerals, and metals for 203 countries. From these data, the global median values for the $coeff_{extraction\ material}$ of 36 materials and, subsequently, the values for the CF_{TMR} were calculated (compare Equation (7)).

3. Results

3.1. Values for the Characterization Factor Raw Material Input CF_{RMI}

Table 1 shows the values for the CF_{RMI} of 10 metals calculated using data from the RMG database [36]: Chromium (Cr), Cobalt (Co), Copper (Cu), Gold (Ag), Iron (Fe), Lead (Pb), Molybdenum (Mo), Nickel (Ni), Silver (Ag), and Zinc (Zn).

Table 1. Values for the Characterization Factor Raw Material Input CF_{RMI} of 10 metals calculated with data from the RMG database [36].

Material	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Gold (Ag)	Iron (Fe)
CF_{RMI} [kg/kg]	2.7	115	143	943,610	2.7
Material	**Lead (Pb)**	**Molybdenum (Mo)**	**Nickel (Ni)**	**Silver (Ag)**	**Zinc (Zn)**
CF_{RMI} [kg/kg]	12	981	63	10,561	13

Table 2 shows the values for the CF_{RMI} of 11 metals calculated from the database of the IFEU report [34]: Aluminium (Al), Cadmium (Cd), Magnesium (Mg), Manganese (Mn), Palladium (Pd), Platinum (Pt), Rhodium (Rh), Tantalum (Ta), Tin (Sn), Titanium (Ti), and Zirconium (Zr).

Table 2. Values for the Characterization Factor Raw Material Input CF_{RMI} of 11 metals calculated with data from the database of the IFEU report [34].

Material	Aluminium (Al)	Cadmium (Cd)	Magnesium (Mg)	Manganese (Mn)	Palladium (Pd)	Platinum (Pt)
CF_{RMI} [kg/kg]	5.3	735	7.8	2.8	66,063	274,186
Material	**Rhodium (Rh)**	**Tantalum (Ta)**	**Tin (Sn)**	**Titanium (Ti)**	**Zirconium (Zr)**	
CF_{RMI} [kg/kg]	520,571	6105	415	61	53	

Table 3 shows the values for the CF_{RMI} of 21 materials calculated from data of the ecoinvent database (version 3.1, cut-off LCI): Barite (Ba), Cerium (Cer), Europium (Eu), Fluorine (F), Fluorspar (CaF_2), Gadolinium (Gd), Gallium (Ga), Indium (In), Kaolinite (Al_4), Kieserite ($Mg[SO_4]{\cdot}H_2O$), Lanthanum (La), Lithium (Li), Magnesite ($MgCO_3$), Neodymium (Nd), Phosphorus (P), Praseodymium (Pr), Samarium (Sm), Sylvite (KCl), Tellurium (Te), Titania (TiO_2), and Uranium (U).

Table 3. Values for the Characterization Factor Raw Material Input CF_{RMI} of 21 abiotic materials calculated from the ecoinvent database (version 3.1, cut-off LCI).

Material	**Barite (Ba)**	**Cerium (Cer)**	**Europium (Eu)**	**Fluorine (F)**	**Fluorspar (CaF_2)**	**Gadolinum (Gd)**	**Gallium (Ga)**
CF_{RMI} [kg/kg]	6.7	42	16,667	67	1.1	6667	7143
Material	**Indium (In)**	**Kaolinite (Al_4)**	**Kieserite ($Mg[SO_4]{\cdot}H_2O$)**	**Lanthanum (La)**	**Lithium (Li)**	**Magnesite ($MgCO_3$)**	**Neodymium (Nd)**
CF_{RMI} [kg/kg]	3334	4.2	4	139	667	1.7	250
Material	**Phosphorus (P)**	**Praseodymium (Pr)**	**Samarium (Sa)**	**Sylvite (KCl)**	**Tellurium (Te)**	**Titania (TiO_2)**	**Uranium (U)**
CF_{RMI} [kg/kg]	17	2381	3333	4	5,000,000	98	1000

3.2. *Values for the Characterization Factor Total Material Requirement CF_{TMR}*

Table 4 shows the values for the CF_{TMR} of 36 abiotic materials calculated using the GMF database [38]: Aluminium (Al), Anhydrite ($CaSO_4$), Barite (Ba), Basalt, Borax ($Na_2{\cdot}8H_2O$), Chromium (Cr), Clay, Coal, brown, Coal, hard, Copper (Cu), Diatomite (SiO_2), Dolomite, Feldspar, Fluorspar (CaF_2), Gold (Ag), Granite, Gravel, Gypsum ($CaSO_4{\cdot}2H_2O$), Iron (Fe), Kaolinite ($Al_4[OH]_8Si_4O_{10}$), Lead (Pb), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Oil, crude, Palladium (Pd), Phosphorus (P), Platinum (Pt), Rhodium (Rh), Silver (Ag), Steatite, Talc, Tin (Sn), Titania (TiO_2), Uranium (U), and Zinc (Zn).

Table 4. Values for the Characterization Factor Total Material Requirement CF_{TMR} of 36 abiotic materials calculated from the Global Material Flows (GMF) database [38].

Material	**Aluminium (Al)**	**Anhydrite ($CaSO_4$)**	**Barite (Ba)**	**Basalt**	**Borax ($Na_2{\cdot}8H_2O$)**	**Chromium (Cr)**
CF_{TMR} [kg/kg]	11	1.1	11	1.01	1.1	5.9
Material	**Clay**	**Coal, Brown**	**Coal, Hard**	**Copper (Cu)**	**Diatomite (SiO_2)**	**Dolomite**
CF_{TMR} [kg/kg]	2.3	1.3	1.2	157	1.1	1.01
Material	**Feldspar**	**Flourspar (CaF_2)**	**Gold (Au)**	**Granite**	**Gravel**	**Gypsum ($CaSO_4{\cdot}2H_2O$)**
CF_{TMR} [kg/kg]	1.1	1.4	2,906,319	1.01	1.01	1.04
Material	**Iron (Fe)**	**Kaolinite ($Al_4[OH]_8Si_4O_{10}$)**	**Lead (Pb)**	**Manganese (Mn)**	**Molybdenum (Mo)**	**Nickel (Ni)**
CF_{TMR} [kg/kg]	5.1	6.3	15	7.1	1854	101
Material	**Oil, Crude**	**Palladium (Pd)**	**Phosphorus (P)**	**Platinum (Pt)**	**Rhodium (Rh)**	**Silver (Ag)**
CF_{TMR} [kg/kg]	1.2	107,683	75	445,826	572,628	17,954
Material	**Steatite**	**Talc**	**Tin (Sn)**	**Titania (TiO_2)**	**Uranium (U)**	**Zinc (Zn)**
CF_{TMR} [kg/kg]	2	1.1	502	98	17,000	16

3.3. Software Implementation

The LCIA method PMF is implemented into the software openLCA (version 1.7) based on the calculated CF using the ecoinvent database (version 3.1, cut-off LCI). In this LCA software solution, new impact assessment methods can be created by adding new impact categories and impact factors and by assigning each elementary flow of the database to the impact factors with a CF [39]. The PMF was set up in openLCA by adding the impact categories Abiotic Raw Material Input and Abiotic Total Material Requirement and the impact factors $RMI_{abiotic}$ and $TMR_{abiotic}$.

The values of the CF_{RMI} and CF_{TMR} are assigned to the 143 elementary flows "resource, in ground" of the ecoinvent database. The elementary flows refer to 78 different materials since some materials are described by different elementary flows, e.g., copper by 12 elementary flows. The CF_{RMI} calculated from the RMG database are assigned to 59 elementary flows, calculated from the IFEU database to 11 elementary flows, and calculated from the ecoinvent database to 26 elementary flows. For 36 materials or 42 elementary flows, no values for the CF_{RMI} could be calculated. For these materials, the CF_{RMI} is set to one, considering the own mass. In total, five elementary flows "resources, in ground" of the ecoinvent database are identified as not being flows of abiotic material. For these elementary flows, the CF_{RMI} is set to zero. Figure 2 shows the share of elementary flows "resource, in ground" of the ecoinvent database (version 3.1, cut-off LCI) for which the values of the Characterization Factor Raw Material Input CF_{RMI} are assigned according to data sources and assumptions.

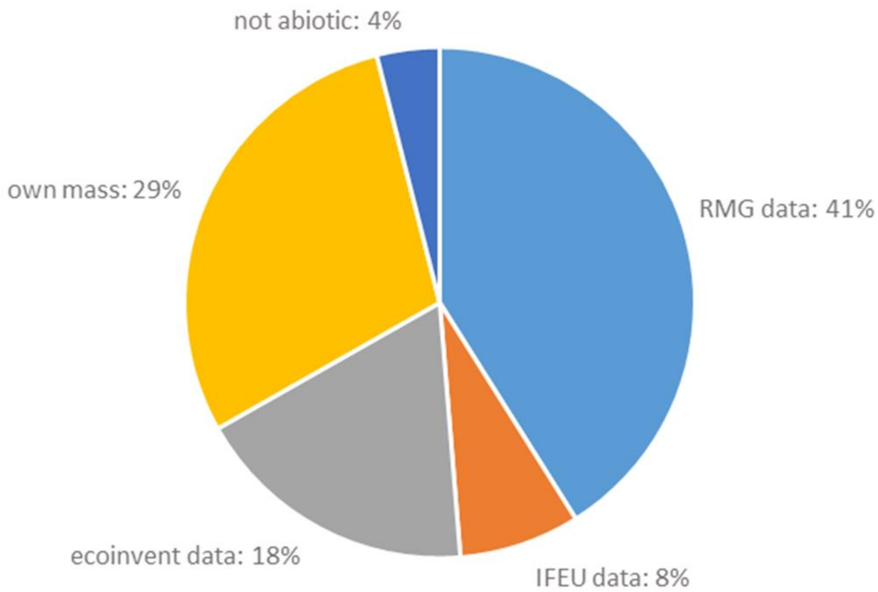

Figure 2. Share of elementary flows "resource, in ground" of the ecoinvent database (version 3.1, cut-off LCI) for which the values of the Characterization Factor Raw Material Input CF_{RMI} are assigned according to data sources and assumptions.

The flow property of most elementary flows is mass and, therefore, the values of the CF_{RMI} are calculated in the unit kg/kg. The flow property of the elementary flows "Gas, mine, off-gas, process, coal mining" and "Gas, natural, in ground" is volume and, therefore, the values of the CF_{RMI} are calculated in the unit kg/m^3.

The complete list of the 143 elementary flows "resource, in ground" of the ecoinvent database and the assigned values for the CF_{RMI} can be found in Table A1 and the values for the CF_{TMR} in Table A2 in the Appendix A. An EcoSpold file in XML-Format to import the LCIA method PMF into the software openLCA (version 1.7) for use with the ecoinvent database (version 3.1, cut-off LCI) is provided in the Supplementary Materials.

4. Discussion

Resource efficiency is high on the political agenda and there is a wide consensus that economic performance should be decoupled from natural resource use. At present, the measurement of the life cycle wide use of raw materials on a product level is still in its initial stage, mainly due to the absence of defined standards, reliable data, and adequate software solutions. A new LCIA method including the global median data for the CF has been developed to measure the material intensity of products and services. The PMF can easily be applied by LCA practitioners for automated calculation of the two material input indicators RMI and TMR, which has been shown using the open source software openLCA with the ecoinvent database. Since there is no internationally agreed standard on how to measure the PMF, both indicators should be used to provide two-fold information on the cumulative raw material use and on the total primary material requirement. While the latter can be regarded as a midpoint indicator of the environmental pressure at the locations of extraction, the former is a midpoint indicator for the environmental impact potential along the production chain up to a final disposal. Thus, both indicators convey complementary information. The PMF has been applied in recent case studies measuring the material intensity of chemical products, building structures, and electrical energy storage technologies [40–43].

Several LCIA methods and indicators focusing on resource use and depletion have been developed in recent years [44]. The most prominent is the Abiotic Depletion Potential (ADP). The indicator has been proposed to assess the relative scarcity of abiotic resources [45]. The characterization model has been controversially discussed and the underlying data for calculating the impact indicator covering 42 materials have not been updated since 2009 [46]. Since the ADP assesses resource depletion related to the natural resource availability, it is not an impact indicator related to the natural environment [47]. The PMF is following a different approach by quantifying the used and processed material as well as the total extraction of primary material from nature. With the extraction process, the support and service functions of the moved and used material are disturbed or lost, e.g., sand dredging in coastal areas leading to land erosion, ecosystem damages, and increased risk of flooding [48]. Neither RMI nor TMR can measure substance-specific environmental impacts such as eco-toxicity. For these impacts, other indicators must be used. Raw material extraction is an input-oriented intervention according to the LCA framework and, therefore, a good basis for measuring resource efficiency [49]. As the PMF is calculated per FU, the inverse is a measure for the life cycle wide material efficiency.

5. Outlook

As a first step, the global median values for 42 CF_{RMI} and for 36 CF_{TMR} out of 78 abiotic materials in the ecoinvent database are provided. Nevertheless, there is still a considerable need for further research to improve the data basis and to overcome limitations of the approach. (1) The data for calculation of the CF for the remaining abiotic materials have to be collected and a database for a regular update has to be set up. (2) The uncertainties in the CF have to be quantified. For the first estimation, the value of the $CF_{RMI\ copper}$ calculated from the RMG database—143 kg raw material per kg copper—has been compared with the results from the IFEU report and the ecoinvent database. The ecoinvent elementary flow, which is related to the global median copper production, gives a concentration of 0.36% copper in crude ore. This would result in 278 kg raw material per kg copper. Whereas the primary data source shows a concentration of 0.99% copper in crude ore [32] resulting in 101 kg raw material per kg copper. This result is close to 99.5 kg raw material per kg copper calculated from the IFEU report [34]. (3) At present, the calculation of the CF_{RMI} is based only on the content of the material in the raw material. In the future, the losses during further processing and, thus, the overall process efficiency of mining, beneficiation, and smelting, which is, e.g., for the global copper production around 80% [32], should be considered. (4) The provided values for the CF are global median values that take international markets and supply chains for raw materials into account. The calculation of the CF_{RMI} using the RMG database has shown that the local conditions of the raw material extraction, in the case of metals and the ore grade of the specific mine, has a significant impact on the results. Therefore, it is advisable to adjust the values in the impact category, if the exact origin and concentration of the material in the raw material is known. In the future, the calculation method of PMF for RMI_{biotic} and TMR_{biotic} and the values for CF_{RMI} and CF_{TMR} of biotic materials will be provided.

Supplementary Materials: The following are available online at http://www.mdpi.com/2079-9276/8/2/61/s1, LCIA method PMF as EcoSpold file in XML-Format for openLCA (version 1.7) and ecoinvent database (version 3.1, cut-off LCI) (see page 9).

Author Contributions: C.M. prepared the article including research, assessment, and writing. S.B. provided support across all phases and edited the article.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Nomenclature

c	concentration
$coeff_{extraction}$	extraction coefficient
m	mass
ADP	Abiotic Depletion Potential
AF	Allocation Factor
AP	Average Market Price
CF	Characterization Factor
CF_{RMI}	Characterization Factor Raw Material Input
CF_{TMR}	Characterization Factor Total Material Requirement
CED	Cumulative Energy Demand
CRD	Cumulated Raw Material Demand
DMI	Direct Material Input
FU	Functional Unit
GWI	Global Warming Impact
GWP	Global Warming Potential
PMF	Product Material Footprint
RMC	Raw Material Consumption
RME	Raw Material Equivalents
RMI	Raw Material Input
$RMI_{abiotic}$	Abiotic Raw Material Input
RMI_{biotic}	Biotic Raw Material Input
TMR	Total Material Requirement
$TMR_{abiotic}$	Abiotic Total Material Requirement
TMR_{biotic}	Biotic Total Material Requirement

Acronyms

AoP	Area of Protection
EU	European Union
IFEU	Institut für Energie- und Umweltforschung, Heidelberg
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MIPS	Material Input Per Service Unit
MMO	Multiple Metal Ore
RMG	Raw Materials Group
SDGs	Sustainable Development Goals
SMO	Single Metal Ore
SOS	Safe Operating Space
USGS	United States Geological Survey
XML	Extended Markup Language

Appendix A

Table A1. Values for Characterization Factor Raw Material Input CF $_{RMI}$ assigned to the elementary flows "resource, in ground" of the ecoinvent database (version 3.1, cut-off LCI).

No.	Elementary Flow "Resource, in Ground"	CF_{RMI} [kg/kg]
1	Aluminum, 24% in bauxite, 11% in crude ore, in ground	5.3
2	Aluminum, in ground	5.3
3	Anhydrite, in ground	1.0
4	Barite, 15% in crude ore, in ground	6.7
5	Basalt, in ground	1.0
6	Borax, in ground	1.0
7	Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground	735.0
8	Calcium carbonate, in ground	1.0
9	Carbon, in organic matter, in soil	1.0
10	Cerium, 24% in bastnasite, 2.4% in crude ore, in ground	42.0
11	Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	2.7
12	Chrysotile, in ground	1.0
13	Cinnabar, in ground	1.0
14	Clay, bentonite, in ground	1.0
15	Clay, unspecified, in ground	1.0
16	Coal, brown, in ground	1.0
17	Coal, hard, unspecified, in ground	1.0
18	Cobalt, in ground	115.0
19	Colemanite, in ground	1.0
20	Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore, in ground	143.0
21	Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore, in ground	143.0
22	Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore, in ground	143.0
23	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	143.0
24	Copper, 1.13% in sulfide, Cu 0.76% and Ni 0.76% in crude ore, in ground	143.0
25	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	143.0
26	Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	143.0
27	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	143.0
28	Copper, Cu 0.2%, in mixed ore, in ground	143.0
29	Copper, Cu 0.38%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Pb 0.014%, in ore, in ground	143.0
30	Cu, Cu 3.2E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0% in ore, in ground	143.0
31	Cu, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore, in ground	143.0
32	Diatomite, in ground	1.0
33	Dolomite, in ground	1.0
34	Energy, geothermal, converted	0.0
35	Europium, 0.06% in bastnasite, 0.006% in crude ore, in ground	16,667.0
36	Feldspar, in ground	1.0
37	Fluorine, 4.5% in apatite, 1% in crude ore, in ground	67.0
38	Fluorine, 4.5% in apatite, 3% in crude ore, in ground	67.0
39	Fluorspar, 92%, in ground	1.1
40	Gadolinium, 0.15% in bastnasite, 0.015% in crude ore, in ground	6667.0
41	Gallium, 0.014% in bauxite, in ground	7143.0
42	Gallium, in ground	7143.0
43	Gangue, bauxite, in ground	1.0
44	Gas, mine, off-gas, process, coal mining *	0.8
45	Gas, natural, in ground *	0.8
46	Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore, in ground	943,610.0
47	Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore, in ground	943,610.0
48	Gold, Au 1.4E-4%, in ore, in ground	943,610.0
49	Gold, Au 1.8E-4%, in mixed ore, in ground	943,610.0
50	Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore, in ground	943,610.0
51	Gold, Au 4.3E-4%, in ore, in ground	943,610.0
52	Gold, Au 4.9E-5%, in ore, in ground	943,610.0
53	Gold, Au 5.4E-4%, Ag 1.5E-5%, in ore, in ground	943,610.0
54	Gold, Au 6.7E-4%, in ore, in ground	943,610.0
55	Gold, Au 6.8E-4%, Ag 1.5E-4%, in ore, in ground	943,610.0
56	Gold, Au 7.1E-4%, in ore, in ground	943,610.0

Table A1. *Cont.*

No.	Elementary Flow "Resource, in Ground"	CF_{RMI} [kg/kg]
57	Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	943,610.0
58	Gold, Au 9.7E-5%, Ag 7.6E-5%, in ore, in ground	943,610.0
59	Granite, in ground	1.0
60	Gravel, in ground	1.0
61	Gypsum, in ground	1.0
62	Helium, 0.08% in natural gas, in ground	1.0
63	Indium, 0.005% in sulfide, In 0.003%, Pb, Zn, Ag, Cd, in ground	3334.0
64	Iron, 46% in ore, 25% in crude ore, in ground	2.7
65	Iron, 72% in magnetite, 14% in crude ore, in ground	2.7
66	Kaolinite, 24% in crude ore, in ground	4.2
67	Kieserite, 25% in crude ore, in ground	4.0
68	Lanthanum, 7.2% in bastnasite, 0.72% in crude ore, in ground	139.0
69	Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground	12.0
70	Lead, Pb 0.014%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, in ore, in ground	12.0
71	Lead, Pb 3.6E-1%, in mixed ore, in ground	12.0
72	Lithium, 0.15% in brine, in ground	667.0
73	Magnesite, 60% in crude ore, in ground	1.7
74	Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	2.8
75	Metamorphous rock, graphite containing, in ground	1.0
76	Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	981.0
77	Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	981.0
78	Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore, in ground	981.0
79	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.22% in crude ore, in ground	981.0
80	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	981.0
81	Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	981.0
82	Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	981.0
83	Neodymium, 4% in bastnasite, 0.4% in crude ore, in ground	250.0
84	Ni, Ni 2.3E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Cu 3.2E+0% in ore, in ground	63.0
85	Ni, Ni 3.7E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Cu 5.2E-2% in ore, in ground	63.0
86	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	63.0
87	Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	63.3
88	Oil, crude, in ground	1.0
89	Olivine, in ground	1.0
90	Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	66,063.0
91	Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	66,063.0
92	Perlite, in ground	1.0
93	Phosphorus, 18% in apatite, 12% in crude ore, in ground	17.0
94	Phosphorus, 18% in apatite, 4% in crude ore, in ground	17.0
95	Praseodymium, 0.42% in bastnasite, 0.042% in crude ore, in ground	2381.0
96	Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	274,186.0
97	Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	274,186.0
98	Pumice, in ground	1.0
99	Pyrite, in ground	1.0
100	Pyrolusite, in ground	1.0
101	Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	520,571.0
102	Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	520,571.0
103	Rhenium, in crude ore, in ground	1.0
104	Samarium, 0.3% in bastnasite, 0.03% in crude ore, in ground	3333.0
105	Sand, unspecified, in ground	1.0
106	Shale, in ground	1.0
107	Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In, in ground	10,561.0
108	Silver, 0.01% in crude ore, in ground	10,561.0
109	Silver, 3.2 ppm in sulfide, Ag 1.2 ppm, Cu and Te, in crude ore, in ground	10,561.0
110	Silver, Ag 1.5E-4%, Au 6.8E-4%, in ore, in ground	10,561.0
111	Silver, Ag 1.5E-5%, Au 5.4E-4%, in ore, in ground	10,561.0
112	Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore, in ground	10,561.0
113	Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore, in ground	10,561.0
114	Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore, in ground	10,561.0
115	Silver, Ag 5.4E-3%, in mixed ore, in ground	10,561.0
116	Silver, Ag 7.6E-5%, Au 9.7E-5%, in ore, in ground	10,561.0

Table A1. *Cont.*

No.	Elementary Flow "Resource, in Ground"	CF_{RMI} [kg/kg]
117	Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	10,561.0
118	Sodium chloride, in ground	1.0
119	Sodium nitrate, in ground	1.0
120	Sodium sulphate, various forms, in ground	1.0
121	Spodumene, in ground	1.0
122	Steatite, in ground	1.0
123	Stibnite, in ground	1.0
124	Sulfur, in ground	1.0
125	Sylvite, 25% in sylvinite, in ground	4.0
126	Talc, in ground	1.0
127	Tantalum, 81.9% in tantalite, 1.6E-4% in crude ore, in ground	6105.0
128	Tellurium, 0.5ppm in sulfide, Te 0.2ppm, Cu and Ag, in crude ore, in ground	5,000,000.0
129	Tin, 79% in cassiterite, 0.1% in crude ore, in ground	415.0
130	TiO_2, 54% in ilmenite, 18% in crude ore, in ground	98.0
131	TiO_2, 54% in ilmenite, 2.6% in crude ore, in ground	98.0
132	TiO_2, 95% in rutile, 0.40% in crude ore, in ground	98.0
133	Ulexite, in ground	1.0
134	Uranium, in ground	1000.0
135	Vermiculite, in ground	1.0
136	Volume occupied, final repository for low-active radioactive waste	0.0
137	Volume occupied, final repository for radioactive waste	0.0
138	Volume occupied, underground deposit	0.0
139	Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	13.0
140	Zinc, Zn 0.63%, Au 9.7E-4%, Ag 9.7E-4%, Cu 0.38%, Pb 0.014%, in ore, in ground	13.0
141	Zinc, Zn 3.1%, in mixed ore, in ground	13.0
142	Zirconia, as baddeleyite, in ground	1.0
143	Zirconium, 50% in zircon, 0.39% in crude ore, in ground	53.0

* in [kg/MJ].

Table A2. Values for the Characterization Factors Total Material Requirement CF $_{TMR}$ assigned to the elementary flows "resource, in ground" of ecoinvent database (version 3.1, cut-off LCI).

No.	Elementary Flow "Resource, in Ground"	CF_{TMR} [kg/kg]
1	Aluminum, 24% in bauxite, 11% in crude ore, in ground	11.0
2	Aluminum, in ground	11.0
3	Anhydrite, in ground	1.1
4	Barite, 15% in crude ore, in ground	11.0
5	Basalt, in ground	1.01
6	Borax, in ground	1.1
7	Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground	735.0
8	Calcium carbonate, in ground	1.0
9	Carbon, in organic matter, in soil	1.0
10	Cerium, 24% in bastnasite, 2.4% in crude ore, in ground	42.0
11	Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	5.9
12	Chrysotile, in ground	1.0
13	Cinnabar, in ground	1.0
14	Clay, bentonite, in ground	2.3
15	Clay, unspecified, in ground	2.3
16	Coal, brown, in ground	1.3
17	Coal, hard, unspecified, in ground	1.2
18	Cobalt, in ground	115.0
19	Colemanite, in ground	1.0
20	Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore, in ground	157.0
21	Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore, in ground	157.0
22	Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore, in ground	157.0
23	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	157.0
24	Copper, 1.13% in sulfide, Cu 0.76% and Ni 0.76% in crude ore, in ground	157.0
25	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	157.0

Table A2. *Cont.*

No.	Elementary Flow "Resource, in Ground"	CF_{TMR} [kg/kg]
26	Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	157.0
27	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	157.0
28	Copper, Cu 0.2%, in mixed ore, in ground	157.0
29	Copper, Cu 0.38%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Pb 0.014%, in ore, in ground	157.0
30	Cu, Cu 3.2E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0% in ore, in ground	157.0
31	Cu, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore, in ground	157.0
32	Diatomite, in ground	1.1
33	Dolomite, in ground	1.01
34	Energy, geothermal, converted	0.0
35	Europium, 0.06% in bastnasite, 0.006% in crude ore, in ground	16,667.0
36	Feldspar, in ground	1.1
37	Fluorine, 4.5% in apatite, 1% in crude ore, in ground	67.0
38	Fluorine, 4.5% in apatite, 3% in crude ore, in ground	67.0
39	Fluorspar, 92%, in ground	1.4
40	Gadolinium, 0.15% in bastnasite, 0.015% in crude ore, in ground	6667.0
41	Gallium, 0.014% in bauxite, in ground	7143.0
42	Gallium, in ground	7143.0
43	Gangue, bauxite, in ground	1.0
44	Gas, mine, off-gas, process, coal mining *	0.8
45	Gas, natural, in ground *	0.8
46	Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore, in ground	2,906,319.0
47	Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore, in ground	2,906,319.0
48	Gold, Au 1.4E-4%, in ore, in ground	2,906,319.0
49	Gold, Au 1.8E-4%, in mixed ore, in ground	2,906,319.0
50	Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore, in ground	2,906,319.0
51	Gold, Au 4.3E-4%, in ore, in ground	2,906,319.0
52	Gold, Au 4.9E-5%, in ore, in ground	2,906,319.0
53	Gold, Au 5.4E-4%, Ag 1.5E-5%, in ore, in ground	2,906,319.0
54	Gold, Au 6.7E-4%, in ore, in ground	2,906,319.0
55	Gold, Au 6.8E-4%, Ag 1.5E-4%, in ore, in ground	2,906,319.0
56	Gold, Au 7.1E-4%, in ore, in ground	2,906,319.0
57	Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	2,906,319.0
58	Gold, Au 9.7E-5%, Ag 7.6E-5%, in ore, in ground	2,906,319.0
59	Granite, in ground	1.01
60	Gravel, in ground	1.01
61	Gypsum, in ground	1.04
62	Helium, 0.08% in natural gas, in ground	1.0
63	Indium, 0.005% in sulfide, In 0.003%, Pb, Zn, Ag, Cd, in ground	3334.0
64	Iron, 46% in ore, 25% in crude ore, in ground	5.1
65	Iron, 72% in magnetite, 14% in crude ore, in ground	5.1
66	Kaolinite, 24% in crude ore, in ground	6.3
67	Kieserite, 25% in crude ore, in ground	4.0
68	Lanthanum, 7.2% in bastnasite, 0.72% in crude ore, in ground	139.0
69	Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground	15.0
70	Lead, Pb 0.014%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, in ore, in ground	15.0
71	Lead, Pb 3.6E-1%, in mixed ore, in ground	15.0
72	Lithium, 0.15% in brine, in ground	667.0
73	Magnesite, 60% in crude ore, in ground	1.7
74	Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	7.1
75	Metamorphous rock, graphite containing, in ground	1.0
76	Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	1854.0
77	Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	1854.0
78	Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore, in ground	1854.0
79	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.22% in crude ore, in ground	1854.0
80	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	1854.0
81	Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	1854.0
82	Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	1854.0
83	Neodymium, 4% in bastnasite, 0.4% in crude ore, in ground	250.0
84	Ni, Ni 2.3E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Cu 3.2E+0% in ore, in ground	101.0
85	Ni, Ni 3.7E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Cu 5.2E-2% in ore, in ground	101.0

Table A2. *Cont.*

No.	Elementary Flow "Resource, in Ground"	CF_{TMR} [kg/kg]
86	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	101.0
87	Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	101.0
88	Oil, crude, in ground	1.2
89	Olivine, in ground	1.0
90	Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	107,683.0
91	Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	107,683.0
92	Perlite, in ground	1.0
93	Phosphorus, 18% in apatite, 12% in crude ore, in ground	75.0
94	Phosphorus, 18% in apatite, 4% in crude ore, in ground	75.0
95	Praseodymium, 0.42% in bastnasite, 0.042% in crude ore, in ground	2381.0
96	Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	445,826.0
97	Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	445,826.0
98	Pumice, in ground	1.0
99	Pyrite, in ground	1.0
100	Pyrolusite, in ground	1.0
101	Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	572,628.0
102	Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	572,628.0
103	Rhenium, in crude ore, in ground	1.0
104	Samarium, 0.3% in bastnasite, 0.03% in crude ore, in ground	3333.0
105	Sand, unspecified, in ground	1.0
106	Shale, in ground	1.0
107	Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In, in ground	17,954.0
108	Silver, 0.01% in crude ore, in ground	17,954.0
109	Silver, 3.2 ppm in sulfide, Ag 1.2 ppm, Cu and Te, in crude ore, in ground	17,954.0
110	Silver, Ag 1.5E-4%, Au 6.8E-4%, in ore, in ground	17,954.0
111	Silver, Ag 1.5E-5%, Au 5.4E-4%, in ore, in ground	17,954.0
112	Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore, in ground	17,954.0
113	Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore, in ground	17,954.0
114	Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore, in ground	17,954.0
115	Silver, Ag 5.4E-3%, in mixed ore, in ground	17,954.0
116	Silver, Ag 7.6E-5%, Au 9.7E-5%, in ore, in ground	17,954.0
117	Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	17,954.0
118	Sodium chloride, in ground	1.0
119	Sodium nitrate, in ground	1.0
120	Sodium sulphate, various forms, in ground	1.0
121	Spodumene, in ground	1.0
122	Steatite, in ground	2.0
123	Stibnite, in ground	1.0
124	Sulfur, in ground	1.0
125	Sylvite, 25% in sylvinite, in ground	4.0
126	Talc, in ground	1.1
127	Tantalum, 81.9% in tantalite, 1.6E-4% in crude ore, in ground	6105.0
128	Tellurium, 0.5ppm in sulfide, Te 0.2ppm, Cu and Ag, in crude ore, in ground	5,000,000.0
129	Tin, 79% in cassiterite, 0.1% in crude ore, in ground	502.0
130	TiO_2, 54% in ilmenite, 18% in crude ore, in ground	98.0
131	TiO_2, 54% in ilmenite, 2.6% in crude ore, in ground	98.0
132	TiO_2, 95% in rutile, 0.40% in crude ore, in ground	98.0
133	Ulexite, in ground	1.0
134	Uranium, in ground	17,000.0
135	Vermiculite, in ground	1.0
136	Volume occupied, final repository for low-active radioactive waste	0.0
137	Volume occupied, final repository for radioactive waste	0.0
138	Volume occupied, underground deposit	0.0
139	Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	16.0
140	Zinc, Zn 0.63%, Au 9.7E-4%, Ag 9.7E-4%, Cu 0.38%, Pb 0.014%, in ore, in ground	16.0
141	Zinc, Zn 3.1%, in mixed ore, in ground	16.0
142	Zirconia, as baddeleyite, in ground	1.0
143	Zirconium, 50% in zircon, 0.39% in crude ore, in ground	53.0

* in [kg/m^3].

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