Concise description of application fields for different MFA approaches and indicators

Deliverable D3.2

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MinFuture partner institutions

CSIRO	Commonwealth Scientific and Industrial Research Organization
CUNI	Univerzita Karlova v Praze
DELOITTE	BIO Intelligence Service
ECOLOGIC	Ecologic Institute
IFEU	Institut für Energie und Umweltforschung Heidelberg
IGSMIE PAN	Polska Akademia Nauk Instytut Gospodarki Surowcami Mineralnymi i Energia
MinPol	Guenter Tiess - Agency for International Minerals Policy
MIT	Massachusetts Institute of Technology MIT Corporation
NERC	Natural Environment Research Council – British Geological Survey
NGU	Geological Survey of Norway
NTNU	Norges teknisk-naturvitenskapelige universitet
RU	The Ritsumeikan trust academic juridical person
SDU	Syddansk Universitet
TU Wien	Technische Universitaet Wien
UAB	Universitat Autònoma de Barcelona
UCAM	The Chancellor, Masters, and Scholars of the University of Cambridge

1 Executive Summary

MinFuture is a collaborative project funded by the Horizon 2020 framework, aiming to identify, integrate, and develop expertise for global material flow analysis and scenario modelling. In order for material flow analysis to be comprehensive, integrative and systemic in its approach, MinFuture analyses the material cycles across four dimensions: 1) life cycle stages, including all processing steps from mining to waste disposal, 2) trade flows through the global economy, 3) the interactions or "linkages" that occur during the material cycle, such as compositional change, energy content, and monetary value, 4) and a time dimension to calibration and future scenario modelling. To this end, one of the first tasks of MinFuture is to have a comprehensive understanding of existing modelling approaches and indicators of resource accounting to the field of mineral raw materials management. This deliverable entitled "Concise description of application fields for different MFA approaches and indicators" summarizes the results of this task.

The deliverable describes the various methods of material flow analysis (MFA) applied to raw materials, and analyses existing indicators in terms of a characterization scheme that was developed by the MinFuture partners (chapter 4). Chapter 5 gives various case studies illustrating MFA methods and indicators, and chapter 6 identifies some recommendations.

In addition to the four dimensions (stages, trade, linkages, time), we also identified some additional "transversal" factors that are important to consider when evaluating MFAs. Some of these transversal factors are data related, such as how is data visualized or how is data uncertainty handled, whereas some other factors to consider are more general or difficult to categorize, such as how the analysis contributes to decision making. Table 10 in Chapter 6 summarizes the assessment of all the MFA methods.

Indicators for efficient and effective raw materials use are used to define problems, to formulate policies, and to implement policies. The aim of the policies informed by raw materials indicators is always to change certain aspects of the socio-economic metabolism. Since the different parts of the socio-economic metabolism are all linked with each other, we can also say that the aim is to transform the socio-economic metabolism in a desired direction. This is a complex task, because (i) the socio-economic metabolism is highly complex (dynamic, multi-layer, international supply chains); (ii) the socio-economic metabolism is still poorly understood; (iii) indicators are drastic simplifications of the socio-economic metabolism; (iv) the desired direction is often not clearly defined; and (v) there are many, often diverging, interests of different stakeholders.

There are three main recommendations in regards to indicators used to measure raw materials in the EU: 1) raw material indicators used in policy should consider the physical quality and criticality of the materials, 2) researchers and analysts should provide complete traceability and repeatability of the data provided in their studies, so as to promote raw material data in a centralized database, 3) indicators should be used to complement consistent monitoring of the socio-economic metabolism by government authorities.

2 Introduction

Global demand for minerals is growing rapidly, driven by rapid population growth, urbanization and an increasingly diverse range of technical applications. Global material supply chains linking the extraction, transport and processing stages of raw materials have become increasingly complex and today involve multiple players and product components. The project MinFuture aims to provide transparency about existing approaches and identify information gaps concerning global material flows in order to maintain competitiveness in (and of) the European economy.

MinFuture brings together 16 international partners from across universities, public organisations and companies, to deliver new insight, strategic intelligence and a clear roadmap for enabling effective access to global material information.

In order to accomplish this goal, MinFuture analyses the material cycles across four dimensions: 1) life cycle stages, including all processing steps from mining to waste disposal, 2) trade flows through the global economy, 3) the interactions or "linkages" that occur during the material cycle, such as compositional change, energy content, and monetary value, 4) and a time dimension to calibration and future scenario modelling. These four dimensions will be integrated into one common methodology that will be developed by 6 Work Packages (WP). WP 2 and 3 will build the integrated methodology based on clear understanding of challenges, systems, data, models and indicators, and visualization requirements. WP4 will apply the methodology to study the critical raw materials (CRM) required for wind energy systems. Lastly, WP5 and WP6 will facilitate a roadmap of recommendations and a web platform, respectively. For a full description of the WPs, please see http://www.minfuture.eu/.

This report compiles the findings of the first task (3.1) of WP3, which is to have a comprehensive understanding of existing modelling approaches and indicators of resource accounting to the field of mineral raw materials management. The different Material Flow Analysis approaches such as bulk-MFA, physical and economical input/output based MFA, static and dynamic MFA, (multi-) regional and/or materials-based MFA are systematically analysed based on a characterization scheme. Components of such a scheme are the field of employment, data requirements, handling of data uncertainty, contribution to decision-making, shortcomings, potentials and challenges for the integration with non-material models, e.g., econometric models. The scheme itself draws substantially from the results of WP2, where challenges and requirements for modelling tools are elaborated. In a second step, existing and alternative indicators for efficient and/or effective raw materials use are compiled and analysed with respect to target accuracy, definition requirements, and robustness.

The resulting assessment of existing MFA approaches and indicators will serve to determine what are the limitations and the advantages of such methods. Task 3.1 will also help identify key attributes that should be included in the integrated methodology proposed by MinFuture. To summarize, task 3.1 has the following objectives:

- To assess existing resource modelling approaches.
- To perform a systematic characterization existing MFA approaches for resource accounting.
- To describe the application fields for different MFA approaches.
- To assess indicators presently used to quantitatively assess raw materials in the EU.
- To compile and assess existing and alternative indicators for efficient and/or effective raw materials.

The present report will provide a concise description of application fields for different MFA approaches including deficit analysis for the implementation to the global level. Assessment of individual approaches' potential to contribute to a common methodology will be qualified to track global mineral raw material flows including a list of efficiency indicators together with their definitions.

The report is organized in the following manner:

- Chapter 3 is dedicated to describing MFA methods in the context of raw materials in terms of processes, spatial coverage, layers, time, data, and other criteria
- Chapter 4 focuses on the indicators, determined by MFA and other methods, which have been used in the context of raw materials, highlighting advantages and disadvantages
- Chapter 5 presents several case studies that make use of the MFA methods and indicators presented in this report to analyse raw materials
- Chapter 6 presents conclusions and recommendations based on the analysis presented.

3 Material Flow Analysis

3.1 MFA Introduction

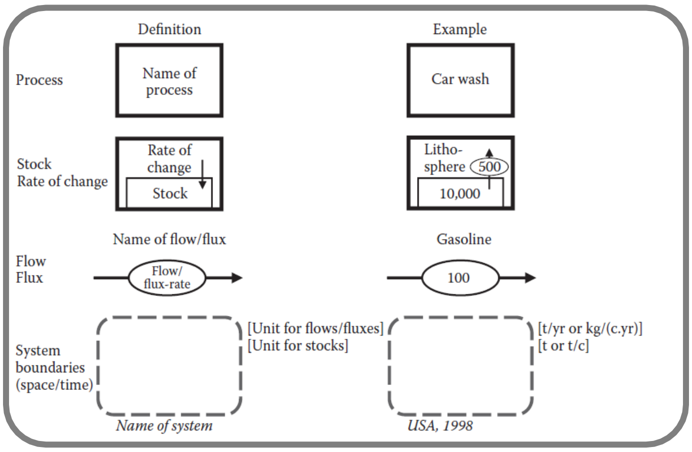
MFA in general is a term used to summarize a wide range of approaches to describe material and energy stocks and flows in systems defined in space and time. In contrast, several other tools also describe material and energy systems, such as Life Cycle Analysis (LCA) of footprint analysis, however, they use system boundaries that are defined through the choice of a functional unit, and that are therefore not specific in the characterization of space and time.

MFA is helpful in identifying the accumulation and depletion of materials in natural and anthropogenic stocks, such as buildings, or soil and sediments. Without it, it is impossible to identify the shift of material stocks from natural reserves to anthropogenic accumulations. The specific objectives of MFA are (Brunner and Rechberger, 2016):

- To understand a metabolic system qualitatively by selecting the relevant processes, material flows, and stocks in well-defined, uniform terms, and by creating a physical model selecting system boundaries and linking processes and material flows
- To follow the material system over time, with a focus on past developments or to forecast the future based on past and present trends based on assumptions about progress such as new technologies or changing drivers like consumer behaviour
- To reduce complexity of the system as far as possible while still guaranteeing a sound and robust basis for decision making
- To apply a mass-balance approach for cross-checking and identifying deficits
- To form a basis for sensitivity and uncertainty analysis to reveal key sensitivities and uncertainties of flows and stocks
- To serve as a basis and support for assessment tools
- To serve the management of environment, resources, and wastes

MFA has been applied in various fields, such as medicine (Santorio, 1737), social systems (Fischer-Kowalski, 1998) and urban metabolism (Baccini and Brunner, 1991), and is currently being increasingly applied in industrial ecology: a quickly developing field of research with mounting policy relevance (Bringezu and Moriguchi, 2002). The growing use of MFA can be attributed to resource-, environment-, economy- and health-related demands.

By balancing inputs and outputs, the flows of wastes and environmental loadings become visible and their sources can be identified (Brunner and Rechberger, 2016). The MFA terms based on the *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers* (Second Edition) (Brunner and Rechberger, 2016) are described in Figure 1.



Terms	Descriptions
Substances	Substances are any (chemical) element or compound that is composed of uniform units (atoms, molecules).
Goods	Goods are any economic entities of matter with a positive or negative economic value and are made up of one or several substances.
Materials	Material serves as an umbrella term for both substances and goods.
Processes	Processes are defined as the transformation, transport or storage of materials. The transport process can be a natural process.
Flows	Flows are defined as a mass flow rate with the ratio of mass per time.
Transfer coefficients	Transfer coefficients describe the partitioning of materials in a process.
System	System is the actual object of investigation. It connects the flows and stocks of materials and substances by processes, and is limited by system boundaries, which are defined in space and time.

Figure 1: Terminology and main symbols of MFA based on Brunner and Rechberger (2016) (Allesch, 2017).

The goal of MFA is to establish a mass balance for the system of study. The sum of all inputs into the system must equal all outputs plus/minus the changes in stock (Δs). The mass-balance must be observed on the level of goods, as well as substances.

$$\sum_{i=1}^{j} m_i = \sum_{i=1}^{k} m_i + \Delta s$$

Where j=number of inputs, k = number of outputs and m = substance or total material flow. Due to paucity of data and limited system understanding, MFA is naturally confronted with uncertainty. Data for material flow analysis originate from different sources and vary in terms of availability and quality, particularly if material stocks and flows of large-scale systems, such as regions or whole economies, are investigated (Laner and Rechberger, 2016).

MFA is the basis for modelling resource consumption as well as changes in stocks, and therefore, it is important in forecasting potential scarcity of resources. In general, resource management comprises three steps:

(1) analysis, planning, and allocation
(2) exploitation, upgrading, and utilization; and
(3) recycling and final disposal of resources.

MFA-based recycling efficiency evaluations often deal with metals, because of the high value of metals for society, the principally infinite recyclability, and the superiority of secondary to primary production from an environmental perspective. However, recycling is often inefficient due to social behaviour, product design, recycling technologies, and the thermodynamics of separation. In this context, MFA provides a suitable means of investigating the potential for improvement in resource-efficient metal utilization and management.

3.2 Attributes of MFA Approaches in the context of mineral and metal resources

We have reviewed most published studies applying MFA to minerals and metals and have evaluated how each MFA method addresses certain aspects of resource management. To perform the evaluation, MinFuture partners defined a set of criteria against which each MFA method is assessed, highlighting the advantages and disadvantages of each one. The criteria are grouped in the four dimensions explored by MinFuture described in the introduction (section 2): (i) stages, (ii) international trade, (iii) layers, and (iv) time as shown in Table 1. In addition, other criteria have been considered, such as those related to data and general issues, and are grouped together as "transversal".

Table 1: Criteria of the characterization scheme and their classification

Attributes		Criteria
Four dimensions	(i) Stages	Covered processes Losses / dissipation included
	(ii) Trade	Spatial level
	(iii) Layers / Linkages	Material/Substance End-use sector categories / products Environmental aspects
	(iv) Time	Time interval Modeling approach Lifetime modeled as
Transversal	Data	Is data available in database? Data requirements Type of analysis How is data visualized? Handling of data uncertainty
	General	Field of employment / purpose Contribution to decision making Shortcomings Callenges for the integration with non-material models

The four dimensions are analysed using different levels of granularity, which greatly affects the usefulness of the models for specific purposes. The following paragraphs describe each dimension in terms of application of MFA methods.

3.2.1 Dimensions (i) and (ii): stages and international trade

MFA models can have different spatial granularity, which includes both the stages and the trade flows considered.

- Models with **fixed or standardized system definition**: a fix or standardized system definition has the advantage that it makes different systems (or economies) *comparable* or *compatible*. Examples for fixed system definition approaches include EW-MFA / bulk-MFA and the first-generation Stocks and Flows (STAF) models developed at Yale University, or input-output models. The bulk-MFA approach includes one process (the economy) and analyzes the input and output flows and the stock change, using different indicators. The original STAF models employed a standardized system definition that includes 4 processes (production, manufacturing, use, and waste management). Input-output models tend to employ system definitions that are much more refined, using 50-400 sectors/processes. The granularity of these system definitions is defined by the data availability from the statistical offices. When developing multi-regional input output models (MR-IO), there is a need to harmonize or standardize the system definition between the different countries. This is necessary in order to make the country systems compatible for consistently including trade flows.
- Models with **flexible system definition**: a flexible system definition has the advantage that it allows for a more detailed analysis of critical parts of the system; the system definition is therefore more *problem- or case-oriented*, but less suitable for comparisons. MFAs and SFAs are typically using flexible and problem-oriented system definitions.

In more refined system definition approaches, the level of granularity is either determined by the problem or by the data availability. A main challenge of developing more refined system definitions is the fact that the granularity of production data is often very different from the granularity of the trade data available. The harmonization of production and trade data is therefore a key challenge for improving the quality of MFAs. For further information on system definition and data availability, see deliverable D2.2.

3.2.2 Dimension (iii): layers

MFA models usually aim at addressing one or several aspects of the stocks and flows of goods in a system (here called layers). The selection of the layers is a consequence of the problem description.

- **Total mass**: The total mass is either used as an indicator for the total material throughput through society, or it is often used as a starting point to derive other layers. Bulk-MFA or EW-MFA is an approach that uses the total mass as an indicator for total material throughput.
- **Substances**: The stocks and flows of individual substances or chemical elements are studied in order to analyze specific problems related to these substances, such as exploring the criticality of specific metals or controlling specific emissions. The element flows are calculated by either by multiplying the total mass of a good flow (total mass layer) with the element concentration within the good, or by mass balance on the layer of the element. SFA is an example of a tool that is focusing on individual elements or substances.
- **Energy**: The energy required during the life cycle of a material is studied to determine the energy intensity of resources or the efficiency of the processes. Special attention is often paid to the extraction phase, in order to compare the energy requirements of the end-of-life and recycle stages.
- **Monetary value**: The monetary values of metabolic systems are useful for economic analyses. The monetary value layer is usually the mother layer in input-output models. In addition, the monetary value layer is often a starting point for calculating total mass flows by dividing the monetary flow by the mass price of the

commodity. This is often the case when converting monetary trade data into physical units.

- **Multi-layer approaches**: The study of multiple layers is useful for studying more complex problems, such as the effects of material substitution, the use of by-products, or problem shifts under changes in technology use (multiple substances), or the economy-environment interactions (substances & monetary value). Multi-layer approaches are less common, but used in SFA/MFA and in hybrid input-output models. An example of this approach can be seen in Figure 2.

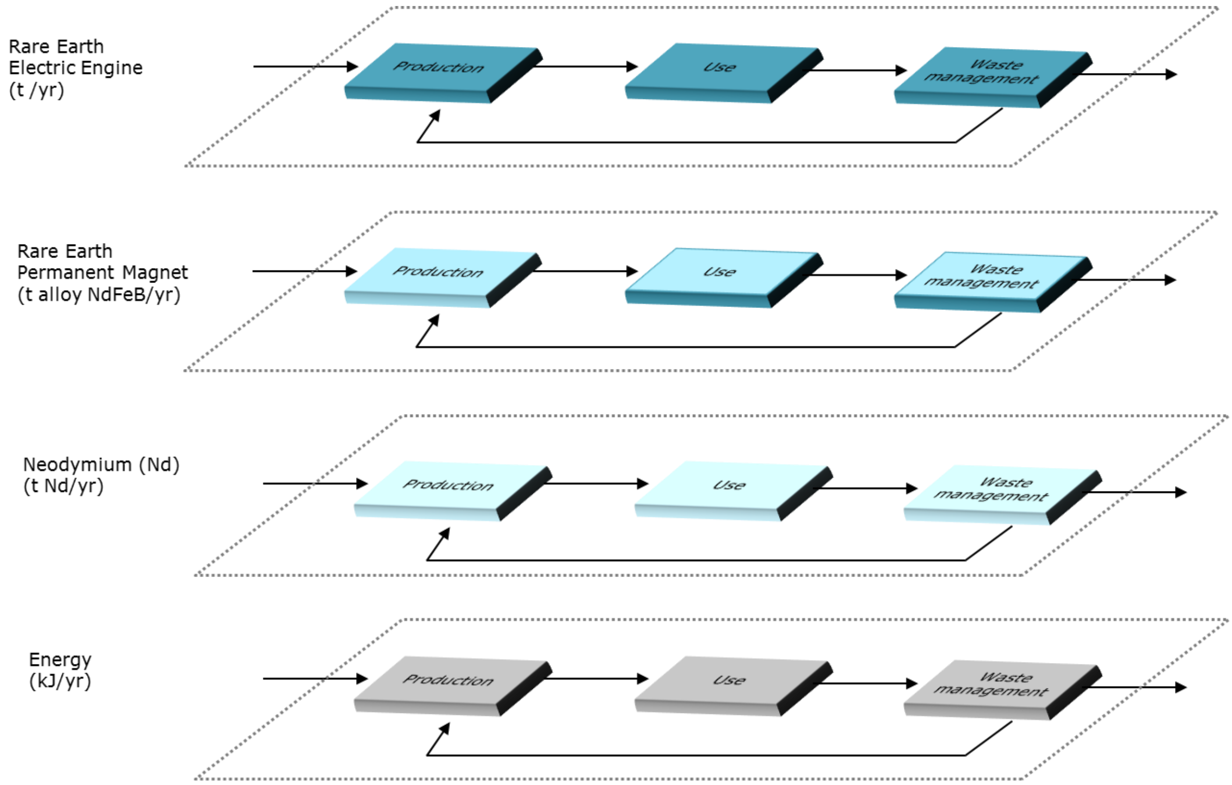


Figure 2: Illustration of the multi-level approach using an example of different physical units for rare earth electric engines.

Additional layers are often employed, such as "number of items" or "parts", "components", or "alloys". These layers can be critical for studying certain aspects (for example, determining the amount of Nd in passenger vehicles traded), however, these layers exist only at one stage of the supply chain. In contrast to the other layers, they cannot be balanced throughout the system. Since the mass balance principle holds for individual physical layer (total mass or substances), multi-layer approaches have a great potential to make the overall model more robust.

3.2.3 Dimension (iv): time

Models can examine time in different ways, as represented in Figure 3. There are four basic ways to differentiate time in models:

- **Static models** do not consider time at all – all system variables are invariant under time shift. We can run time forward or backward and this is not changing the system observed. This means that there are no flows, since flows are always something per time. If we would run time backward, the flows would turn into the opposite direction. An MFA is therefore never static (unless we have a system consisting of only stocks that have no inputs and no outputs). However, *LCA*s and footprint analyses are static (e.g., emissions per functional unit, but not per time).

- **Stationary models** consider time, however, things do not change over time – all system variables are invariant under time shift. Stationary models usually consist only of flows, while stocks are omitted or assumed to be not changing. Traditional *input-output models* are typically stationary models.
- **Quasi-stationary models** are similar to stationary models; however, the stocks may change linearly under time shift, while flows are still assumed to be constant. An example is a process with an input of 10 and an output of 7, resulting in a stock change of 3. Most *MFA balances* are essentially quasi-stationary models.
- In **dynamic models**, both stock and flow variables may change under time shift / are functions of time. Some MFA models are dynamic, typically when they describe systems with stocks over a longer time period.

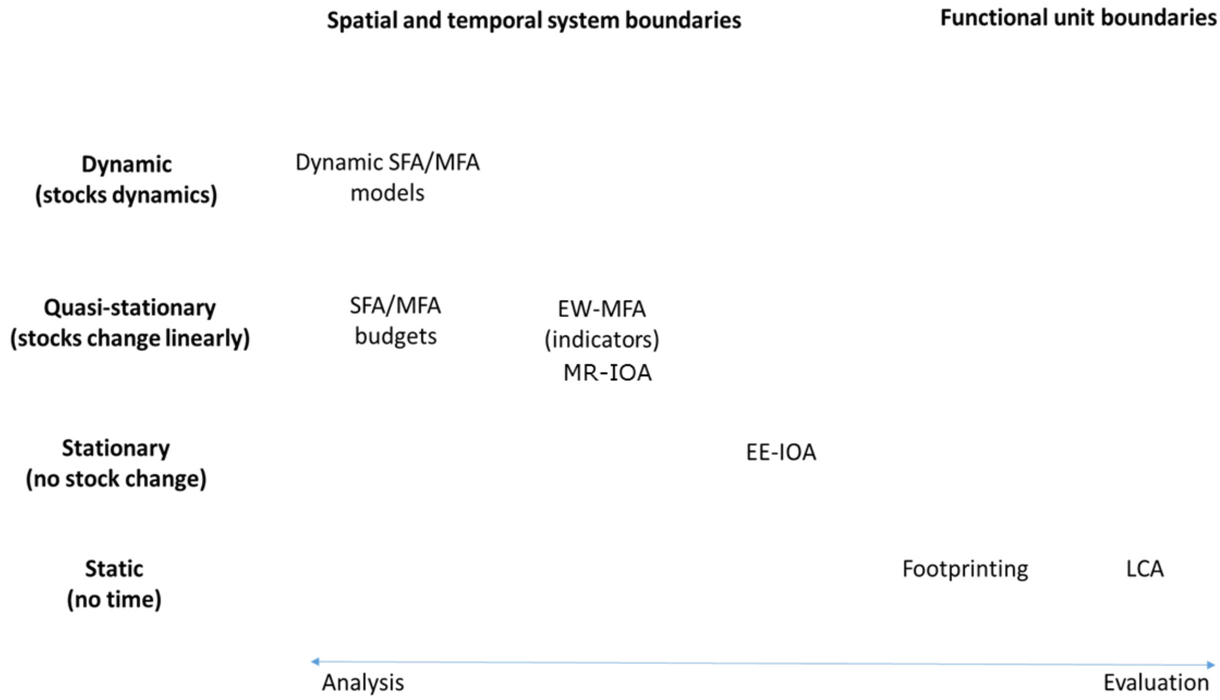


Figure 3: Assessment of different MFA and related tools according to the way they treat time (vertical axis) and space (horizontal axis).

A brief description of the criteria that are included in the transversal dimension are presented here:

Data:

- **Is data available in database**? In other words, is the data already available in a database in order to perform this type of MFA? For example, most of the data required to develop an economy-wide MFA (EW-MFA) is available from Eurostat database.
- **Data requirements.** These criteria address which type of information is needed in order to perform the MFA approach. It implies information about amounts of mineral/metal extracted from all sources, amounts in intermediate and end-uses, lifetime of products that embody the material, among others.

- **How is data visualized?** How are the main results of the MFA displayed? In a Sankey flow diagram? In different types of charts?
- **Handling of data uncertainty.** Is data uncertainty considered in the study? What approach is applied for analysing uncertainty in the MFA?

General:

- **Field of employment or purpose.** What is the purpose of using such a MFA method? Is it to calculate process efficiency? Or to quantify material extraction? Or quantify dissipation losses? Or determine depletion rate?
- **Contribution to decision-making.** What types of conclusions and recommendations are given for policymaking? In which action fields?
- **Shortcomings** What are the limitations of the chosen MFA approach? How can the performed MFA be improved in terms of data quality and methodological approach?
- **Challenges for the integration with non-material models.** For instance, is it possible carrying out an economic analysis based on the selected MFA approach?

3.3 Evaluating MFA approaches

3.3.1 Material and Substance Flow Analysis, stationary, quasi-stationary and dynamic

Although SFA analyses a specific substance (e.g. Cu P, Zn), it is always based on a MFA on the level of goods because the containing flows of the investigated substances are instrumental. The selection of substances depends on the purpose of the study and on the kind of system to be studied. If only one substance is the focus of an MFA study, it might be designated as substance flow analysis (SFA). SFA can be considered a special type of MFA. In most cases, the purpose of system design is to optimize substance flows, but this is usually done by changing flows of goods, because the substance is contained in a good. When focusing on the substance level with an SFA, one should keep in mind that both goods and substances (i.e., materials) are an integral part of MFA and SFA. MFA is the universal term compared to SFA (Brunner and Rechberger, 2016). SFA allows answering questions regarding the accumulation and depletion of beneficial as well as hazardous substances. A mass balance also prevents potentially harmful substances from becoming hidden or accumulated somewhere in the system, thereby preventing pollution of the environment or secondary resources (Allesch, 2017).

Stationary and quasi-stationary MFA and SFA methods describe the flows and stocks of a defined system for a specific time increment (typically one year). By contrast, dynamic MFA and SFA represent changes in system flows and stocks over time, providing the possibility of studying the stocks in society. In order to develop a dynamic model, socio-economic aspects are required, such as technological developments, and developments in population size, welfare and markets (Elshkaki, 2007). Stationary and quasi-stationary MFA and SFA methods enable a better understanding of a material system by identifying general patterns of material use and losses to characterize sources, pathways, and sinks of materials (Laner and Rechberger, 2016). Whereas dynamic MFA and SFA are applied to explore the stocks of materials in society (i.e., secondary resources) and in the environment (i.e., dissipative losses) (Brunner and Rechberger, 2016). The main advantage of dynamic MFA and SFA lies in its explanatory power by identifying trends over time and enabling extrapolation of system behaviour into the future. In this way, alternative scenarios with respect to resource use and environmental problems can be analysed, supporting investment planning in infrastructures for mining, production, and waste management (Brunner and Rechberger, 2016; Müller, 2006; Müller et al., 2014).

Overall, whether to use a dynamic or stationary model depends on the goal and scope of the MFA and SFA, the system under investigation, and the data availability. In the past, most MFA and SFA studies used stationary models to investigate material flow systems, but since the late 1990s, dynamic models have become increasingly popular, with the primary focus on the investigation of material stocks in society. Metals, in particular, have been subject to dynamic MFA and SFA due to the large accumulated metal stocks and their potential value as secondary raw materials (e.g. Chen and Graedel, 2012; Müller et al., 2014) (Brunner and Rechberger, 2016).

Assessment of the approach

Field of employment/Purpose

The general purpose of the reviewed literature is the study of the anthropogenic metabolism of a metal/mineral(s) determining the resource use in order to foster its/their sustainable management by analysing the potential of different strategies of resource management, such as security of supply, reduction of losses along the life cycle, and recovery and recycling from pre- and post-consumer scrap.

Material / Substance and End-use Categories / Products

Taking into account the scope of MinFuture, only articles in which metals and minerals are the materials under study have been considered. Most of the studies are focused on bulk metals (e.g. steel, aluminium, and copper), whereas articles studying less abundant metals are scarce. In the recent years, though, the amount of these is growing fast (Müller et al., 2014). Another interesting type of studies consists of showing interrelations and interdependencies among different metals (Glöser et al., 2013), such as byproduct metals or alloying metals. In addition, these metals/minerals can be further categorized based on material use in end-use sectors (Buchner et al., 2015; Cullen et al., 2013), products (most relevant or only of individual products) (Guyonnet et al., 2015; Rademaker et al., 2013; Schulze and Buchert, 2016), or both end-use sectors and products (Licht et al., 2015; Talens et al., 2013).

Data requirements

Information about specific generation rates and composition of materials, transfer coefficients of technologies, and other relevant data is necessary. The material and substance flow data has to comply with the mass balance constraints (for the system and for every process).

Data availability

The required data for a MFA or SFA is mainly depending on the objective of the study and the system in focus. Data included in MFA and SFA are not always available in data bases and come from various disciplines and heterogeneous sources (official statistics, scientific reports, market studies, expert estimates), with varying data reliability, implying a level of uncertainty in the obtained results. In this sense, although stationary and quasi-stationary models are more limited than dynamic models, they have a robustness of their own. They require far less data and the outflows can be described solely as a function of the inflows, due to the exclusion of many uncertainties (Elshkaki, 2007; MICA, 2017). By contrast, dynamic models are more complex and have a higher data demand than static models, which typically poses a challenge with respect to checking the plausibility of the results. In this respect, the combination of both types of MFA or SFA offers the chance of checking results of the dynamic model for specific points in time, for which detailed snapshots of the material or substance flows and stocks have been established (Brunner and Rechberger, 2016).

Covered processes

The number of processes necessary to describe the system depends on the objective of the study and on the complexity of the system. The selection of processes is a result of the course of understanding the system. Although there is heterogeneity in the processes considered in the life cycle of a metal/mineral, the most commonly included in MFA and SFA are: primary mining, raw material production, product manufacturing, use and waste management (Müller et al., 2014). Some efforts have been made in the standardization of the stages of a metal life cycle, such as the project STAF (Chen and Graedel, 2012). In addition, these stages are rather complicated consisting of various sub-stages, differently addressed in the existing literature and implying a different degree of detail (Chen and Graedel, 2012). Many of the reviewed articles consider the whole life cycle (from primary mining to landfill/environment) (Talens et al., 2013; Bio by Deloitte, 2015), or a part of it (usually from production to waste management) (Habib and Wenzel, 2014; Hoenderdaal et al., 2012). It is important to point out, that in dynamic modelling most models consider stocks only in the use phase, assuming that in the production, manufacturing and waste management processes, no material is stored (Müller et al., 2014).

System boundaries, spatial level, time interval

The spatial system boundary is usually determined by the scope of the study. It coincides often with a politically defined region (administrative regions such as nations, states, or cities), the premises of a company, or a hydrologically defined region such as the catchment area of a river. The most abundant ones are performed at regional and national scale in industrial countries (Buchner et al., 2014; Müller et al., 2014; Ott and Rechberger, 2012). Nonetheless, assessing the long-term sustainability of an element requires carrying out a MFA or SFA in a global perspective (Chen and Graedel, 2012). Another important issue related to the spatial dimension, which has not been yet deeply explored, consists in determining the location of a resource for future mining by analysing the spatial distribution of in-use and end-of-life stocks and processing it in geographic information systems (GIS) (Müller et al., 2014).

With respect to the time interval, stationary or quasi-stationary MFA and SFA are usually calculated for past flows in a concrete year, analysing past stocks and flows based on historical data, whereas dynamic MFA and SFA are estimated for past (retrospective) and future (prospective) flows, with a temporal scale commonly of one year. In the prospective approach, a data extrapolation is required.

Type of analysis (top-down or bottom-up)

In MFA, the in-use stock can be measured by two different methods: top-down and bottom-up (Brunner and Rechberger, 2004; Gerst and Graedel, 2008). The top-down approach analyses all flows into or out of a clearly defined system and aggregates stocks over time (Glöser et al., 2013), while the bottom-up is based on deriving the total stock from the material intensities in all relevant products (Brunner and Rechberger, 2016). In most articles stock is defined as the in-use stock and "hibernating" materials are not included, that is, those that have been retired and remain somewhere in storage (Daigo et al., 2007; Müller et al., 2014).

The top−down approach is the most applied method in the literature (Egle et al., 2014; Licht et al., 2015; Talens et al., 2013; Zoboli et al., 2016). The required time series of inflow data are often provided by production, trade, or consumption statistics. While data is mainly available for major metals/minerals, with information on production and international trade from producers and metal exchangers, data for minor metals is not so satisfactory because they are generally product of private transactions (Chen and Graedel, 2012). Due to the high aggregation of available inflow data, the top−down approach is less suitable for specific products or smaller regions (Müller et al., 2014). Bottom-up models are less abundant since the stock of a specific metal has to be estimated from all product groups containing that metal (Buchner et al., 2014; Habib and Wenzel, 2014; Kral et al., 2014). This requires a specific stock model for each product group as well as extensive data collection. Hence, this method is most suitable for analysing metals that are only used in a few products, or for focusing on a specific product (Müller et al., 2014). Detailed data generated by bottom-up models can also be used to calibrate and validate top-down models, which constitutes a relevant issue for future research (Müller et al., 2014).

Lifetime

Lifetime functions are mainly used within a dynamic MFA and SFA approach in order to estimate outflows, which are rarely measured (in contrast to often accessible historical data of inflows). Assigning lifetime distribution functions to specific products or end-use sectors is the most common method in order to quantify outflows (Müller et al., 2014). The most frequently used are the Dirac delta distribution, which represents average and constant lifetime, and the Weibull distribution. Furthermore, normal, log-normal, beta, and gamma distributions are used in dynamic MFA and SFA to derive output flows based on the residence time of products in the stock (Müller et al., 2014). In long-term studies, the assumption of constant lifetime can be an oversimplification, adding a significant error to the results. In addition, the forecasts of outflows can also be improved by introducing product mass functions incorporating the changing weight of products over time (Gregory et al., 2009; Müller et al., 2014).

Modelling approach

Combining the top-down and bottom-up methods with the temporal extent (retrospective and prospective), we can set up different types of modelling approaches (retrospective top-down, prospective bottom-up, etc.). In the case of dynamic MFA and SFA, the retrospective top-down and bottom-up approaches are calculated by means of the historical data and the lifetime distribution, whereas prospective top-down and bottom-up are estimated by applying extrapolation methods, such as consumption/stock models (constant, linear, exponential, etc.), regression models, intensity of use, etc. The retrospective top-down modelling is the most frequently chosen in the existing literature probably because of the better availability of inflow data compared to the stock data needed for bottom-up approaches (Licht et al., 2015; Müller et al., 2014; Zoboli et al., 2016). Concerning the extrapolation methods, it is noteworthy that they reveal various challenges. Extrapolation of inflow data is prone to oversimplification, due to fluctuation in inflow data depending on economic and technological developments, such as market crises or product substitutions. This makes this method only valid within a short time frame. Stocks, however, are less affected by short-term market fluctuations and thus provide a more robust basis for forecasts (Liu et al., 2013; Müller, 2006).

Losses, dissipation included

When dealing with MFA and SFA, another important aspect lies in the treatment of losses and dissipation along the life cycle of the metal/mineral. First, we have to clarify the difference between losses and dissipation. Dissipation is understood as “materials that have been irrecoverably dissipated into soil, groundwater, or surface water” (Ayres et al., 2002). Losses are the rest that is lost along the life cycle (such as landfill and identifiable mine waste dump). Earlier, dissipation and losses of metals were included in dynamic MFA and

SFA models focusing on heavy metal pollution. In recent years, losses and dissipation have also been addressed from a resource point of view (Müller et al., 2014). However, while data of losses is increasingly addressed by the authors (mainly in the production and manufacturing as well as the waste management stages), data of dissipation is extremely scarce. Besides, in most studies the share of losses and dissipation remains constant over time; only a few articles specifically focus on time-variant flows (Müller et al., 2014). Furthermore, metals can be lost or dissipated because of the design of the product through in-use dissipation and unrecyclability when discarded (the later mainly due to low concentrations in many products), as stated by Ciacci et al. (2015). Further research should then investigate new indicators of dissipation (Müller et al., 2014). A good candidate can be the statistical entropy analysis, developed by Rechberger and Graedel (2002), which measures the distribution pattern of a substance over its life cycle (how a system concentrates or distributes substances).

Environmental aspects

Environmental aspects are considered in some cases in terms of emissions to air, water and soil (Ott and Rechberger, 2012; Zoboli et al., 2016). Environmental impacts have most often been addressed in studies analysing heavy metals and their toxicity (Hedbrant and Stockhome, 2001; Elshkaki et al., 2004). In studies focused on resource use, however, environmental impacts, such as abiotic depletion or ecosystem degradation, are not frequently taken into account. We suggest that coupling MFA and SFA with the Life Cycle Assessment (LCA) method for raw material analysis is an attractive approach to determining a more complete picture about resource use and its corresponding environmental impacts.

Handling of data uncertainty

Due to paucity of data and limited system understanding, MFA and SFA are naturally confronted with uncertainty. Data for MFA and SFA originate from different sources and vary in terms of availability and quality, particularly if material stocks and flows of large-scale systems, such as regions or whole economies, are investigated. Various approaches at different levels of sophistication have been used to analyse uncertainty in MFA and SFA studies, aiming at evaluating and improving MFA and SFA input data, enabling the reconciliation of conflicting material flow data, identifying the uncertainty of material flow model results, and facilitating the assessment of the results' sensitivity. The treatment of data uncertainty is tackled by different means in the existing literature. Commonly is not considered, or it is only qualitatively discussed. When taken into account, sensitivity analysis (Glöser et al., 2013) and uncertainty intervals (Bio by Deloitte, 2015; Guyonnet et al., 2015) are usually the most applied. In the sensitivity analysis, it is shown how the model output reacts to parameter changes, whereas in uncertainty intervals confidence levels are assigned according to a confidence scale (Müller et al., 2014). Other approaches arising in new articles are the Gaussian error propagation (Bader et al., 2011; Liu and Müller, 2013a), and the probabilistic MFA or SFA (Laner et al., 2015). The Gaussian error propagation method consist in calculating the standard deviation of stocks and flows based on standard deviations that were defined for each input variable and parameter. The probabilistic MFA or SFA is a relatively new approach, where inflows, transfer coefficients, and concentrations are estimated as probability distributions. These methods are described in more detail in deliverable 3.3. For those studies performing uncertainty analysis, it becomes clear that besides lifetime distribution parameters there might be other parameters or variables with a strong influence on the model's output (Müller et al., 2014).

How is data visualized?

Regarding data visualization there is also heterogeneity in how the MFA or SFA is graphically represented. In its simplest form, flows and stocks are shown as flow diagrams and tables.

Many studies use Sankey diagrams to visualize the material or substance data in a system overview. The range of Sankey diagram styles varied across the studies, with each telling its own story of the stages, processes, flows and proportional flow quantities in the material or substance system. They provide, by contrast, a more detailed representation of inflows and outflows, in which the width of the arrows is presented proportionally to the flow quantity, helping thus in locating dominant contributions to the overall flow. Cullen et al. (2013) demonstrate the unique ability of the Sankey diagram to display complex and multi-dimensional data in a holistic way, as shown in Figure 4. This Sankey describes the global flow of steel in an ordered and visually clear fashion, especially when considering the complexity and scale of the system. Flows are clearly labelled and the layout is meticulous in detail and order. While Sankey diagrams are not the only method employed in visualizing data within MFA and SFA, they are one of the best in providing a balance between the detailed data and the context of the overall system. More information on visualization methods is provided in deliverable 3.4.

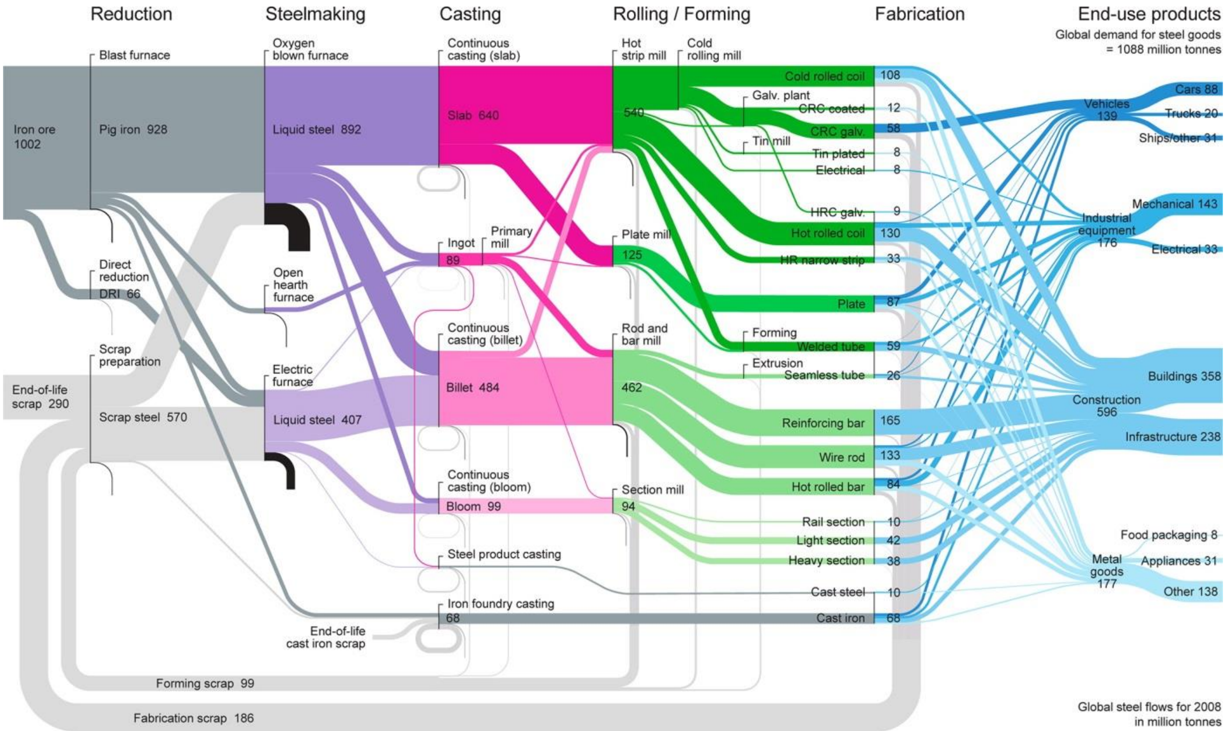


Figure 4: Mapping global flows of steel: from steelmaking to end-use goods (Cullen et al, 2013).

Shortcomings

As stated overall in this section, there are numerous shortcomings in the performance of MFA or SFA. In summary, we deem four potential improvements in this field. First, a weak point of many MFA or SFA is the data availability and reliability. Secondly, the heterogeneity and level of detail of the involved processes in the life cycle of the considered metal/mineral (s). Third, in the dynamic MFA or SFA, how dynamic modelling is carried out, that is, the method behind the quantification of outflows as well as the extrapolation methods applied. Another important aspect is how parameters and variables evolve over time (if they are considered constant or variable). Fourth, the treatment of data uncertainty, which is not frequently addressed, and should be therefore part of each MFA or SFA.

Contribution to decision-making

MFA and SFA can provide a sound basis for decisions related to environmental protection and resource conservation. The improvement of MFA or SFA is of the utmost importance, as they are crucial tools for a proper resource management. They constitute powerful tools, which provide us the required information of resource use for a proper policymaking. In this respect, however, MFA or SFA studies should make clear from the beginning the purpose as well as the target audience (Müller et al., 2014). In addition, apart from the above-explained shortcomings, MFA or SFA should be improved by combining it with socio-economic databases, geographic information systems, and life cycle assessment. In this way, MFA or SFA will be a far more robust tool for policymaking, assuring a sustainable mid- and long-term resource management.

Challenges for the integration with non-material models

Economic analysis can assign monetary values to the flows and stocks, and thus allows evaluation of a system in view of economic aspects.

3.3.2 EW-MFA, Economy-wide input-output model (physical and monetary)

As a follow-up to pilot studies such as work by Steurer (1992), Schutz and Bringezu (1993), the Ministry of the Environment Japan (1992), Adriaanse and colleagues (1997), and Matthews and colleagues (2000), a first attempt to standardize economy-wide material flow accounting (EW-MFA) was undertaken by the statistical office of the European Union, which published a method guide for economy-wide material flow accounts and derived indicators (Eurostat, 2001). The standardization process was continued with the publication of a "compilation guide" for EW-MFA (Weisz et al., 2007; Eurostat, 2013) and with the Organization for Economic Co-operation and Development (OECD) work program on material flows (OECD 2008). The aim of the EW-MFA is to quantify the physical exchange among a national economy, the environment, and foreign economies based on the total material mass flowing across the boundaries of the national economy. The ultimate goal of the analysis is to achieve a material balance - that is, the state when material inputs into the economy equal material outputs summed with additions to the physical stock of the economy (e.g., traffic infrastructure, buildings, and durable goods). Material flow accounts typically exclude water and air flows (Schandl et al., 1999; Eurostat, 2001). Based on the EW-MFA an array of material flow indicators has been defined, including domestic material consumption (DMC), domestic processed output (DPO) and total material requirements (TMR), for instance (Eurostat, 2001).

Assessment of the approach

Field of employment / Purpose

According to OECD (2008), EW-MFA data and indicators have three main purposes: a) Monitoring the material basis of national economies, b) Monitoring the material and resource productivity and c) Monitoring the implications of trade and globalization.

Material / Substance

Full EW-MFA includes all material entering national economies (biomass, fossil fuels, industrial minerals/ores, construction minerals, manufactured products) and all flows returning to the environment (emissions to air, emissions to water, solid waste, dissipative use of products and dissipative losses). The completeness of covered materials is therefore very high, but they are not too detailed.

End-use sector categories / products

EW-MFA includes materials transformed into products used by all end-used sectors of the economy.

Data requirements

Extraction of raw materials, agricultural production, wood logging, fish catch, imports and exports of raw materials and manufactured commodities, indirect flows associated to imports, emissions to air, emissions to water, landfilled waste, dissipative uses and losses, unused extraction from mining and quarrying, unused extraction from biomass harvest, soil excavation and dredging.

Data availability

EW-MFA data and indicators are included in a significant number of databases. Two most prominent examples include:

- Eurostat statistical database (http://ec.europa.eu/eurostat/data/database),
- UNEP database (http://uneplive.unep.org/downloader) and
- MFA Database (http://www.materialflows.net/materialflowsnet/home/)

Covered processes

As EW-MFA covers all materials entering and process within the economy, it also covers all processes that take place in the economy including primary mining, agricultural production, forestry, fishery and production/fabrication.

System boundaries, spatial interval, time level

System boundaries are points of extraction of natural resources, points of releasing emission flows into the environment and national borders for imported and exported commodities. The data and indicators are collected for various time intervals and most often for national economies, but there are also EW-MFAs for groups of countries, regions and cities.

Type of analysis: (top-down or bottom-up)

EW-MFA uses statistical data gathered through statistical surveys as well as calculations based on proxies like population, livestock numbers, stoichiometric coefficients and coefficients showing e.g. livestock feed requirements per head. Therefore, it is difficult to attribute EW-MFA to pure top down or bottom up approaches.

Lifetime

EW-MFA does usually not involve any lifetime modelling.

Modelling approach

EW-MFA uses a simple model of material balance assuming that all materials entering national economies are equal to material outputs summed with additions to the physical stock of the economy. It usually uses a retrospective approach and calculates the indicators for the past years.

Losses, dissipation included

EW-MFA includes dissipative uses of products such as fertilizers and pesticides spread on fields and dissipative losses such as corrosion of materials.

Environmental aspects

EW-MFA indicators express environmental pressures related to material use and emissions flows. They also indicate domestic waste potential and potential for future waste flows.

Handling of data uncertainty

Handling of data uncertainty is not in-built in EW-MFA. Some EW-MFA studies however provide simple or more elaborated assessments of data and indicator reliability. Eurostat database is a collection of data sets from statistical bodies and there is quality assurance, whereas UNEP has no quality assurance.

How is data visualized?

Data and indicators are visualized by various types of charts including line, column, area and cake charts.

Shortcomings

EW-MFA usually provides static picture for a certain period. Direct link to environmental impacts is missing.

Contribution to decision-making

EW-MFA data and indicators contribute to management of resource use, emissions flows and environmental pressures, to management of foreign trade dependency and shifts of environmental pressures among countries and world regions.

Challenges for the integration with non-material models

EW-MFA can be integrated with monetary data in environmentally extended input-output analysis (EE-IOA). The major challenges for the integration includes proper and coherent disaggregation of both monetary and physical data, validation of data composing monetary input-output tables and material extraction databases and the development of common terminology for EW-MFA and input-output analysis.

3.3.3 MR-IOA, Multiregional Input Output Analysis

Multi-Regional Input Output Analysis (MR-IOA) is a further development of EW-MFA. The challenge of EW-MFA particularly following an international focus is the transformation and counting of the trade data in the unit raw material equivalents. For the transformation of traded commodities into raw material equivalents, several approaches exist: Using coefficients derived from Life-Cycle-Inventories or -Assessments, using Domestic technology assumption without or with the integration of further multiregional information, or using the approach of MR-IOA. In MR-IOA, global extraction data is reallocated via a matrix, which includes the Input Output Tables (IOTs) of several countries or country groups and their trade. Currently, five major MR-IOA-approaches exist which can be differentiated by the number of countries or country groups, which they differentiate and by the number of economic sectors differentiated in the underlying IOTs. The approaches can be further differentiated by the use of only monetary units or hybrid or full physical units in the underlying IOTs and databases, by the years covered and the regularity of updates. The five major MR-IOT approaches are: (1) Exiobase, available in its second version (http://www.exiobase.eu); (2) The World Input Output Database: WIOD (http://www.wiod.org/home); (3) the EORA-Database (http://worldmrio.com/); (4) The OECD Inter-Country Input-Output (ICIO) Tables (www.oecd.org/sti/ind/input-outputtablesedition2015accesstodata.htm); and (5) the global trade analysis project GTAP (https://www.gtap.agecon.purdue.edu/). Exiobase approach is currently further developed to version 3 in which IOTs will be further disaggregated. OECD approach is regularly updated.

Assessment of the approach

Field of employment / Purpose

Main purpose of MR-IOT – as well as other models such as RME-Eurostat (see above) or URMOD or (see below) - is the allocation of global extraction data to the consumption in other countries than those where the material have been extracted. This is necessary because trade data is counted in the mass weight of the traded goods while extraction is counted as gross weight of the extracted raw materials.

Material / Substance

As EW-MFA-approach, MR-IOA includes all materials entering national economies (biomass, fossil fuels, industrial minerals/ores, construction minerals, manufactured products). Flows returning to the environment (emissions to air, emissions to water, solid waste, dissipative use of products and dissipative losses) are included. The completeness of covered materials is therefore very high, but they are not too detailed.

End-use sector categories / products

As EW-MFA-approach, MR-IOA includes materials transformed into products used by all end-used sectors of the economy.

Data requirements

Compared to EW-MFA, in MR-IOT the data requirements are higher as full extraction data (raw materials, agricultural production, wood logging, fish catch, minerals including metals, manufactured commodities, etc.) and high resolution IOTs of all countries globally are needed in high quality in order to get reliable results. So far, global extraction database such as www.materialflows.net or from UNEP-IRP are used which usually follow the guidelines from EUROSTAT for EW-MFA (see above). Thus, underlying databases are UN-data bases such as FAO-database or UNCOMTRADE and furthermore, databases from geological surveys such as BGS or USGS are used. IOTs are taken from national accounts.

Data availability

There are different databases, which are based on MR-IOTs, e.g.:

- WIOD (www.wiod.org)
- Exiobase (www.exiobase.eu)
- OECD-TiVA ICIO (oe.cd/icio)
- EORA (worldmrio.com)
- GTAP (www.gtap.agecon.purdue.edu)

Covered processes

The same as EW-MFA: MR-IOT-approaches cover all materials entering and process within the economy. It also covers all processes that take place in the economy including primary mining, agricultural production, forestry, fishery and production/fabrication.

System boundaries, spatial interval, time level

The same as EW-MFA: MR-IOT System boundaries are points of extraction of natural resources, points of releasing emission flows into the environment and national borders for imported and exported commodities. The data and indicators are collected for various time intervals and for national economies, often times MR-IOT-approaches accounts for industrialised countries, emerging economies and group developing countries in regional groups.

Type of analysis: (top-down or bottom-up)

The same as EW-MFA: EW-MFA uses statistical data gathered through statistical surveys as well as calculations based on proxies like population, livestock numbers, stoichiometric coefficients and coefficients showing e.g. livestock feed requirements per head. Therefore, it is difficult to attribute EW-MFA to pure top down or bottom up approaches.

Lifetime

The same as EW-MFA: EW-MFA does usually not involve any lifetime modelling.

Modelling approach

Basically, MR-IOT is a further step of EW-MFA. MR-IOT-approaches combine EW-MFA and Input Output Tables of different countries in a big matrix, including bilateral trade between the countries. The challenge is the differentiation of the IOTs and their linking to trade. So far, extraction data are grouped to the economic categories of the IOTs: if the IOT has only one category for mining, all extraction data of abiotic materials (metals, bulk minerals, coal, etc.) are counted in this category and in the next step the aggregated flow are allocated to the production and consumption (including export) sectors following the monetary flows. Due to the fact that this leads to severe uncertainties of the results, some approaches differentiate the IOTs further.

Losses, dissipation included

The same as EW-MFA: MR-IOT includes dissipative uses of products such as fertilizers and pesticides spread on fields and dissipative losses such as corrosion of materials.

Environmental aspects

The same as EW-MFA: MR-IOT indicators express environmental pressures related to material use and emissions flows. They also indicate domestic waste potential and potential for future waste flows.

Handling of data uncertainty

The same as EW-MFA: MR-IOT handling of data uncertainty is not in-built. Some studies however provide simple or more elaborated assessments of data and indicator reliability. However, so far there is no quality assurance of international extraction data in global material flows extraction data. Furthermore, there is no clear methodological common understanding how national IOTs can be further disaggregated and how quality of this disaggregation can be assured.

How is data visualized?

Data and indicators are visualized by various types of charts including line, column, area and cake charts.

Shortcomings

The same as EW-MFA: MR-IOA usually provides static picture for a certain time frame. Direct link to environmental impacts is only included if further information on environmental pressure are included in the approach.

Contribution to decision-making

The same as EW-MFA: MR-IOA data and indicators can contribute to management of resource use, emissions flows and environmental pressures, to management of foreign trade dependency and shifts of environmental pressures among countries and world regions.

Challenges for the integration with non-material models

The major challenges for the MR-IOA includes proper and coherent disaggregation of both monetary and physical data, validation of data composing monetary input-output tables and material extraction databases and the development of common terminology for EW-MFA and input-output analysis.

4 Indicators for efficient and/or effective raw materials use

4.1 Introduction

Indicators for efficient and effective raw materials use are used to define problems, to formulate policies, and to implement policies. The aim of the policies informed by raw materials indicators is always to change certain aspects of the socio-economic metabolism. Since the different parts of the socio-economic metabolism are all linked with each other, we can also say that the aim is to **transform the socio-economic metabolism in a desired direction**. This is a complex task, because (i) the socio-economic metabolism is highly complex (dynamic, multi-layer, international supply chains); (ii) the socio-economic metabolism is still poorly understood; (iii) indicators are drastic simplifications of the socio-economic metabolism; (iv) the desired direction is often not clearly defined; and (v) there are many, often diverging, interests of different stakeholders.

A careful selection of indicators or indicator sets is therefore of uttermost importance for transforming the socio-economic metabolism in a desired direction. If the system of the socio-economic metabolism is not reflected well in the indicator set, there is a risk that policies based on indicators have unintended side effects that impede rather than facilitate the overall goals. Indicators must be able to answer policy-relevant questions that address the systemic nature of material cycles, including their linkages with other materials, with energy use and with emissions. The use of indicators in policymaking is very tricky, because one wants to control a complex system, and a few well-intended but poorly selected indicators may not be able to capture the relevant parts of the system. Therefore, a poorly chosen set of indicators may lead to a situation where industry makes large efforts to reach the targets, but this has detrimental side effects on other parts of the system. One example for this is the EU's ELV Directive, which sets targets for "reuse & recycling" and "reuse & recovery". Compliance with these targets necessitates a focus on the most relevant bulk materials, thereby neglecting critical raw materials that are used in small amounts, and it entirely omits quality considerations of the materials recycled. It is therefore important that the indicator selection is rooted in a solid understanding of the socio-economic metabolism. This understanding is relevant to identify the most effective (sets of) indicators to reach certain goals and to avoid problem shifts that impede the achievement of the goals.

Furthermore, one should be careful when using any complex indicator, especially when it is calculated as the weighted average of several other indicators. These complex indicators usually represent the risk or performance of systems by taking into account various factors affecting the status of systems. However, the quality of each individual indicator and the choice of weightings can both lead to biased interpretation of the complex indicator. Therefore, the designer of these indicators should provide the flexibility for users to change the weightings or add/remove some individual indicators as they see fit. During the stakeholder workshop held by MinFuture in Vienna, the importance of the need to identify and improve ways of data/information exchange was stressed. About indicators, the workshop outcome can be summarized by these bullets:

- Indicators are extremely important, but their scope and availability is or can be limited
  - We do not have the data; we need a set of indicators that needs to be seen together –do not rely on one indicator;
  - Capturing systemic change with indicators is a challenge; we need to talk about the system and not about the indicators. How far can we use

visualization of systems to talk to stakeholders? Should we help stakeholders to learn how to see systems and not parts of the system?
    - The Raw Materials Scoreboard has created an awareness that the EC has not seen before.
- To create an indicator you need to have a good system (feedback loops) – people do not know how to change their indicator and make it better; you always need to go back to the system.

Here, we analyse different indicators in terms of their rooting in an understanding of the socio-economic metabolism and discuss potential advantages and pitfalls.

4.2 Characterization scheme for indicators

Existing indicators for raw material use and management are compiled and analysed against a set of criteria determined by WP leaders. MinFuture partners identified the following questions as key information indicators should measure:

- How much raw materials come available from discarded products yearly and what is the End of Life Recycling Rate?
- What are the cradle-to-gate environmental impacts of primary and secondary raw materials production for the present world demand?
- What is the consumption of raw materials in Europe and in which country is the raw material extracted?
- What mix of policy instruments should be proposed to put a resource efficient circular economy in place?
- What will be the changes in energy use and efficiency of future mining and refining processes?
- What are the environmental impacts of raw materials extraction of the future world demand?

The aim is not to answer these questions, but the questions served to identify some of the key points that indicators measuring the socio-economic metabolism (SEM) should reflect. Based on these questions, as well as knowledge gathered from the MICA project (www.mica-project.eu) that presented stakeholder needs in terms of raw material indicators an, an indicator characterization scheme was created against which the indicators were evaluated. The characterization scheme includes the following:

- Indicator, Description, Units, Reference, Life Cycle Stage
- Classification / Cluster
- Production: estimates size and location of resources, extraction rates, location of the extraction, sources and location of secondary supply, outputs from the value chain and their location.
- Use: determines in-use urban stock and its location
- End-of-life (EoL): estimates EoL stock and its location
- Recycling: determines EoL-recycling rate
- Future: estimates future extraction rates and demand
- Criticality
- Energy use, Environmental impacts, Social impacts

4.3 Evaluation of indicators

Next, indicators that have been compiled from various reports and publications are described in terms of the pertinent criteria introduced in the previous section.

4.3.1 Material flows and stocks indicators

The indicators presented in this section reflect material flows and stocks along the life cycle of metals/minerals. A brief description of them is given in Table 2, including definition, units, and the stage(s) of the life cycle in which they are considered.

Table 2: Material flows and stocks indicators.

INDICATOR	DESCRIPTION	UNITS	LIFE CYCLE STAGE	SOURCE
EU share of global production	EU share of global raw materials production	% of world mining (t/t)	Extraction	European Union, 2016
Geographical concentration and governance	Geographical concentration of raw material production and producer countries' governance levels	% production of the different producing countries	Extraction	European Union, 2016
Export restrictions	Proportion of global supply subject to export restrictions for a selection of raw materials	%	Extraction	European Union, 2016
Share of imports	Share of imports in the EU economy's use of raw materials	% of imports in EU compared to Direct Materials Input	Processing Manufacture of end-products	European Union, 2016
Spatial distribution of material flows	Global flows of different materials, among different regions or countries by types of trade commodities, are depicted in a trade-linked multilevel chart.		All stages	Liu and Müller, 2013
Consumption efficiency of material flows	The consumption efficiency is calculated based on the technological level of the countries ("efficient use", "moderately efficient use" and "inefficient use").	%	All stages	Nansai et al., 2014
In-use stock per capita	In-use stock per capita of a material for different countries.	Tonnes	Use	Pauliuk et al., 2012
Location of in-use stock	Spatial in-use density of a material (represented in a map).	Tonnes/km^2	Use	Zhu et al., 2017
Material flows in the circular economy	Circular use of raw materials in the EU economy (supply from recycled materials)	million tonnes	Recycling	European Union, 2016
Collection rate (CR)	End of life material contained in various discarded products collected and entering the recycling chain	%	Collection	UNEP, 2011
EoL recycling input rate (EoL-RIR)	Total material input into the production system coming from recycling of old scrap.	%	Recycling	UNEP, 2011
End of life Recycling Rate (EOL-RR)	Fraction of a material in discards that is actually recycled.	%	Recycling	UNEP, 2011
Recycled Content (RC)	Fraction of recycled material in input flow for fabrication and production.	%	Recycling	UNEP, 2011
Old Scrap Ratio (OSR)	The share of old scrap in the total scrap flow.	%	Recycling	UNEP, 2011
WEEE management	Collection, reuse and recycling of WEEE	kg per capita	Collection Recycling	European Union, 2016
Trade in secondary raw materials	Net exports of secondary raw materials	million tonnes	Losses Dissipation	European Union, 2016
In-use dissipation rate (IUDR)	Material flows that are not accumulated into anthropogenic stocks, and a lack of collection prevents any form of recovery at end-of-life, in which scattering and dispersion into the environment is planned by design.	%	Losses Dissipation	Ciacci et al., 2015
Current unrecyclability rate (CUR)	Material flows into use for which technological and/or economic barriers prevent elemental recycling.	%	Losses Dissipation	Ciacci et al., 2015
Potential recyclability rate (PRR)	Material flows for which today's technology is compatible with their recovery, enabling them to be functionally or nonfunctionally recycled/not recovered	%	Losses Dissipation	Ciacci et al., 2015

Next, the indicators are assessed against the criteria previously defined in the characterization scheme. In particular, those that are related to material flows and stocks along the life cycle of the metals/minerals.

Production

Within the extraction stage, the report "Raw Materials Scoreboard" (European Commission, 2016) considers three indicators: "EU share of global production", "geographical concentration and governance", as well as "export restrictions". Such indicators reflect in a proper way criteria related to extraction rate, and where it takes place. We find, however, that important aspects of the extraction stage are not taken into account. In particular, aspects so relevant such as the size of the reserves, or how the extraction rate will develop in the future, are not addressed. To solve this gap, we recommend setting up indicators that could properly reflect these criteria. In this respect, proposed indicators could consist in "EU share of global reserves", "EU share of global resources", "EU share of future global production" (establishing a determined time frame), "geographical concentration of reserves/resources". Other important set of indicators should further reflect the exact location of the mines/reserves/resources. Not only at a descriptive country level, but also at defining in more depth the specific places within the countries with the help of geographic information systems.

Regarding the processing, manufacturing and production stages, the report includes the indicator "Share of imports in the EU", comprising the import dependence for selected raw materials. Perhaps including an indicator of "Share of exports in the EU", which indicates the exports of processed raw materials as well as products containing the raw materials, would additionally reflect losses of raw materials in the EU. Another recommendation would be to separately indicate the share of imports of primary and secondary material.

The spatial dimension through the value chain has been insufficiently explored and hence represents an important aspect for future research. Some efforts have been made in various articles (Liu and Müller, 2013b; Nansai et al., 2014; Sun et al., 2017), where global flows of different metals, among different regions or countries by types of trade commodities, are depicted in maps. A more detailed representation of these global flows is given by the trade-linked multilevel analysis, in which the different countries involved in the global flows are plotted in each of the life cycle stages, showing their interrelations by means of horizontal (for domestic shipment) and slash links (for trade), with their widths proportional to the magnitude of flows (Liu and Müller, 2013b; Sun et al., 2017). This representation constitutes a clear indication of the sources, pathways, and destinations of the global anthropogenic mineral/metal journey across the world economy. Besides this spatial dimension, Nansai et al. (2014) incorporated an indicator of consumption efficiency to the flows of three critical metals (neodymium, cobalt and platinum), which were characterized according to the technological level of each country or region and divided into three types: green ("efficient use"), yellow ("moderately efficient use"), and red ("inefficient use"). In this way, a simple indicator focusing on the composition of the three coloured flows for each commodity is developed to identify trade commodities that should be prioritized for urgent technical improvement to reduce wasteful use of the metals. Nonetheless, considerable caution needs to be applied with respect to the technological levels assumed in the study, as these were determined solely based on information about the general scientific and techno- logical status of individual countries.

Use

In the use phase, it is of the utmost importance quantifying the in-use stocks of the different materials, due to their potential of becoming secondary supply for the EU. In the literature review, we find as indicator the "in-use stock per capita", applied by Pauliuk et al. (2012)

for estimating the in-use stocks of iron for 200 countries. They demonstrated how the per capita in-use stocks of steel in countries with a long industrial history is saturated or close to saturation.

Another important aspect to consider is the determination of the location of the in-use stock. Although there are not so many studies addressing it, recently it has become an issue of increasing interest in the research literature (Kleemann et al., 2016; Tanikawa et al., 2009; Van Beers and Graedel, 2007; Zhu et al., 2017). The usual way to indicate this aspect is a multi-level spatial characterization of the in-use stock, where spatial in-use densities of a specific mineral/metal are represented in form of maps. In these maps, the different mineral/metal concentration per area unit are shown in a colour scale. In the article by Zhu et al. (2017), in which the location of household electronic devices and their metal content is estimated, the results are presented in a series of maps contained in the online "Australian Recyclable Resource Atlas", initiative that we find very promising. Incorporating the time dimension in such studies constitutes a relevant future research line (Tanikawa et al., 2009; Zhu et al., 2017). In the before mentioned article, the annual updating of the maps is planned, providing in this way an overview of the dynamic evolution of the in-use stocks and their location over time.

End-of-life, Collection and Recycling

Analogously to the in-use stock, an interesting indicator for estimating End-of-Life (EoL) stocks would be the "EoL stock per capita", calculated for each material in the various EU countries, as well as other industrialized countries, such as U.S. or Japan.

With respect to the collection and recycling stage, different indicators have been developed by the International Resource Panel (UNEP, 2011) such as the "Old scrap collection rate" (CR), the "Recycling process efficiency rate", the "EoL recycling rate" (EoL-RR), the "Recycled content" (RC), and the "Old scrap ratio" (OSR). These indicators have been based on an explicit system definition, which constitutes a huge step forward. That is, before the definition of these indicators, every sector employed their own, usually opaque, method for calculating their recycling rates. Albeit the system definition used here might be further refined, it is however a relevant example for basing indicators on an explicit system definition.

The calculation of the RC is straightforward at the global level, but difficult if not impossible at the country level. The reason is that information on the recycled content of imported produced metals is typically not available, which in turns makes a precise calculation of the recycled content impossible (Graedel et al., 2011; UNEP, 2011). As stated by Graedel et al. (2011), policies should encourage a high OSR, in order to provide an incentive to increase the EoL-RR (i.e. increase the share of old scrap) and make processed more efficient (i.e. decrease the share of new scrap). At present, there are some examples in the existing literature applying these recycling rates, such as the article by Nassar (2017), investigating the global flows of tantalum, in which the author calculates the indicators EoL-RR, RC, and OSR.

Since the majority of the metals are contained in electrical and electronic equipment, it is important to estimate their collection, reuse and recycling (kg per capita), as included in the "Raw Materials Scoreboard" report. In addition to this, it would also be of use including the collection, reuse and recycling of End-of-Life vehicles (ELVs), since they are as well as relevant source of metals, and they will increasingly become a source of minor metals due to the electrification, connectivity and automation of the automotive sector.

Another noteworthy issue is if mass represents the proper unit for quantifying the recycling efficiency of a system. It has been recently demonstrated that recycling targets expressed in terms of mass enhance the recovery of bulk metals, but not the recovery of minor metals

(Andersson et al. 2016; Widmer et al. 2015). An indicator based on exergy instead of mass, called Thermodynamic Rarity, has been therefore proposed by Valero and Valero (2015a), and has been recently applied to the recycling process of passenger cars (Ortego et al., 2018). This indicator is further explained in detail in the subchapter of "Criticality indicators".

Losses and dissipation

The indicator of "Trade in secondary raw materials" could be used as a measure of the loss of secondary supply in the EU. There are however, other losses or outputs along the life cycle of the mineral/metal, which have to be taken into account, such as mineral/metal stocks in tailings, extractive waste, processing and manufacturing waste. These losses constitute potential sources of secondary supply. The article by Licht et al. (2015) represents a good example of a global substance flow analysis quantifying losses throughout the value chain, for the case on indium, gallium, and germanium. Perhaps a potential indicator for reflecting this aspect might be the share of losses of the metal/mineral along the life cycle, including the losses from extraction to recycling stages.

The dissipation aspect is even harder to tackle, as it considers the share of mineral/metal, which is irrecoverably dissipated into soil, groundwater, or surface water (Ayres and Ayres, 2002). While losses are increasingly addressed by the existing literature, information about dissipation is hardly to be found. Ciacci et al. (2015) studied the dissipation of 56 metals and metalloids due to the design of the product, finding that in many cases the resulting dissipation rates are higher than 50%. To determine the dissipation, they defined three metrics: "in-use dissipation rate" (IUDR), "current unrecyclability rate" (CUR), and "potential recyclability rate" (PRR), which were displayed in a graphic for each of the elements. Another good candidate for measuring dissipation can be the statistical entropy analysis, developed by Rechberger and Graedel (2002), which measures the distribution pattern of a substance over its life cycle (how a system concentrates or distributes substances). This indicator is explained in more depth in a specific subchapter.

4.3.2 Environmental and social sustainability indicators

Table 3: Environmental and social sustainability indicators.

INDICATOR	DESCRIPTION	UNITS	LIFE CYCLE STAGE	SOURCE
Abiotic depletion potential (CML)	Extraction rate of a substance in relation to the total existing resources (or reserves) of this substance	kg of antimony equivalent	Extraction	Van Oers et al., 2002
Cumulative Energy Demand	Energy needed to manufacture a product using the Life Cycle Approach.	J or KWh	Production	Valero, 2006
Acidification (Accumulated Exceedance - AE)	Processes that increase the acidity of water and soil systems by hydrogen ion concentration. It is caused by atmospheric deposition of acififying substances generated largely from emissions of NOx, SO2, and ammonia (NH3).	mole H+ eq - accumulated exceedance	Production Waste Managemen t	Seppälä et al., 2006
Ecotoxicity (freshwater) (USEtox)	Factors for toxicity effects on the environment are based on models that account for a chemical's fate in the enviroment, species exposure, and differences in toxicological response.	Comparative toxic unit for ecosystems (CTUe)	Production Waste Managemen t	Rosenbaum et al., 2008
Air emissions	Emissions of greenhouse gases and other air pollutant emissions from the production of raw materials in the EU	million tonnes CO2 eq million tonnes TOFP eq	Production	European Union, 2016
Water	Water use from the production of raw materials in the EU		Production	European Union, 2016
Extractive waste	Waste from the extraction and processing of minerals		Production	European Union, 2016
Occupational safety	Incidence rate of non-fatal accidents of the raw materials sector	Accidents per 100.000 employees	Production	European Union, 2016
Sustainability reporting	Raw materials companies publishing GRI reports	Number of companies	Production	European Union, 2016

Life Cycle Assessment indicators

Compared to other materials, metals have a high impact per kg (UNEP, 2010). However, other materials are used in far higher quantities. Agricultural resources and fossil fuels are important contributors to environmental impacts; metals now play a modest role. Nonetheless, it is possible that in the future metals become relatively more visible from an environmental impact point of view, due to rising demand, a shift towards a renewable energy system, and an expected increase in the energy intensity of the production of metals because of lesser grade ores (UNEP, 2013a).

The most important impacts of the metals' life cycles occur in the first stages of the life cycle: mining, beneficiation, metal extraction and refining (Nuss and Eckelman, 2014; UNEP, 2013a). Potential environmental impacts of primary metal mining and extraction revolve around water (consumption and quality aspects), mine wastes (tailings and waste rock), and energy sources (direct such as diesel and indirect such as coal-fired electricity) with the associated air emissions (sulphur dioxide, greenhouse gases, dusts and particulates). At the local level, mining can have large impacts related to human health and to the degradation of landscape and ecosystems, via mining waste and tailings, process emissions and accidents. At the global level, important potential impacts of metal production are related to the use of energy (UNEP, 2013a).

In the use and end-of-life stages of the life cycle, the environmental impacts are far much lower. With respect to the use stage, it is difficult to attribute impacts to metals in metal containing products. Only corrosion from stocks-in-use exposed to the weather is clearly related to the metals themselves. While in the end-of-life stage, impacts could occur via final waste treatment. Metals are emitted to the atmosphere (incineration), to surface water (wastewater treatment) and especially end up in landfills, where there is a risk they may leach into the environment. Increasing recycling rates in some cases already can be observed to reduce landfill of metals (UNEP, 2013a).

In relation to the life cycle of the metals, important Life Cycle Impact Assessment (LCIA) indicators are the Abiotic Depletion, the Global Warming Potential (or alternatively the Cumulative Energy Demand), the Acidification Potential, and the Ecotoxicity Potential. Recently, Nuss and Eckelman (2014) have assembled extensive information on the cradle-to-gate environmental burdens of 63 metals in their major use forms, and illustrated the interconnectedness of metal production systems, allowing a complete bottom-up estimate of life cycle impacts of the metals and mining sector globally. For some elements, these are the first life cycle estimates of environmental impacts reported in the literature.

While there is a large knowledge available for metals, there are gaps that needs to be closed to provide accurate life cycle assessments, such as the estimation of environmental impacts (e.g. toxicity), the lack of studies at global level, the methodology of allocation of multi-metal production, or the incomplete knowledge about linkages between different types of resources (metals, energy and water) (UNEP, 2013a).

Air emissions

The metal industry consumes around 8% of global primary energy use per year (UNEP, 2013a). Given that, the raw materials industry is an energy-intensive sector. Air emissions originate to a large degree from fuel use in mining, quarrying and from subsequent production and manufacturing processes (UNEP, 2013b). Using energy and fuels leads to the emission of greenhouse gases (GHG) such as carbon dioxide and methane. The raw materials sector also contributes to emissions of particulate matter, of gases that form tropospheric ozone and (secondary) particulate matter and substances causing acidification and eutrophication (European Union, 2016).

In order to measure the air emissions, the Raw Materials Scoreboard proposes two indicators (European Union, 2016). These are the production-corrected emissions of GHG and gases that form tropospheric ozone to air from economic subsectors within the raw materials industry for the EU-27 over time (Genty, 2012). Observing this trend, it is obvious that a decoupling between raw materials and energy use is taking place. If this is the case, and decoupling is occurring, it can be attributed to changes in the fuels used, increased energy efficiency and the installation of abatement measures (European Union, 2016). However, in the mining and quarrying stage it is to be expected that a lower decrease of air emissions takes place, due to the fact that technological improvements may have been offset by increased energy demand (lower ore grades and increasing ventilation requirements to access deeper mineral deposits) (European Union, 2016; UNEP, 2013b).

For the estimation of these indicators, the World Input-Output Database (WIOD) has been used, which implies some limitations, such as not including emissions of particulate matter (PM10 and PM2.5) (Genty, 2012). Future updates of environmentally extended input-output databases such as WIOD would make it possible to investigate other types of air emissions (European Union, 2016).

Water

The use and management of water is a major issue for the raw materials industry, especially in the extraction and processing stages. In addition, growing pressures on water availability as well as the water quality make numerous industries vulnerable to water limitations throughout their operations and supply chains (Barton, 2010; European Union, 2016; UNEP, 2013a).

Ideally, indicators should provide insights into the intensity of water use and the local availability of water resources (UNEP, 2013b. Unfortunately, although there are several indicators covering this aspect (European Environment Agency, 2017; Eurostat, 2017), no data have been found that meets the Scoreboard's quality requirements. In this respect, data are not available for a significant number of countries or are not disaggregated by economic sector. This is because of the complexity of factors involved in water use in the raw materials sector. Nonetheless, in the future, some existing and emerging approaches for water accounting may become suitable to be used as an indicator for water use, such as the ISO standard on water footprint (released in 2014) (ISO 2014) and life cycle data (European Union, 2016). Finally, to get a complete picture of water use in the raw materials sector, the information on water use and water discharges should be complemented with background information on water scarcity to reflect the different impact of water use under different water availability conditions (European Union, 2016).

Extractive Waste Management

Extractive waste, which includes waste from the extraction and processing of minerals, is one of the largest waste streams in the EU. This type of waste is significant from an environmental perspective because it can contain a variety of substances with differing pollution potentials. Furthermore, the risk associated with mining waste substances also varies greatly from site to site, depending on the materials being produced and the storage and treatment systems used (European Commission, 2017a; European Union, 2016). From an economic point of view, extractive waste can also be seen as a potential source of valuable materials as it contains many raw materials that are currently often not recovered. Therefore, increasing the recovery of raw materials from extractive waste through recycling could have a two-fold positive effect: First, it could reduce the need for treatment and storage of extractive waste and their associated environmental impacts. Second, it could reduce the need for primary extraction, which often has higher environmental impacts compared with secondary production (Bellenfant et al., 2013; European Union, 2016).

Unfortunately, until now there is insufficient data that would allow a comprehensive and accurate analysis of extractive waste generation and its environmental and economic implications. For instance, albeit waste generation reported by Eurostat includes mining and quarrying activities and the manufacturing of metals and non-metallic minerals, it is known that different reporting methods are used by the different countries (Eurostat, 2017). Therefore, this indicator does not meet the data quality requirements, although some potential data sources are arising. In particular, data could become available from the European Geological Surveys or EU-funded research projects, which are intended to provide sound information on mineral deposits, including mining waste (Eurogeosurveys, 2017; Minerals4EU, 2017; ProSUM, 2017). Nevertheless, such sources will probably face significant limitations, since the supply of data by the Member States and economic operators might not be always guaranteed, either for confidentially reasons or due to the lack of data (European Union, 2016).

Occupational Safety

Occupational safety and health (OSH) at work is important in the context of the social sustainability of any economic sector (European Commission, 2014a). In other words, a safe and healthy working environment is an important determinant of the level of acceptance of an industry by local communities and stakeholders (European Union, 2016).

Raw materials sector is relatively exposed to hazards leading to non-fatal accidents, but no more than other high-risk sectors. As a result, the current EU policy framework strongly encourages establishing preventive and protective measures to improve health and safety at work, and has had a large impact in recent years (European Commission, 2008; European Union, 2016).

Regularly reporting on rates of incidence of accidents and the understanding of the causes will help to achieve a continuing improvement in health and safety at work. In the report, two indicators are shown, which are the incidence rate for non-fatal accidents occurring at the working place in raw materials and other economic sectors as well as the trend over time for the incidence rate of non-fatal accidents for selected raw materials industries (Eurostat, 2015). It is important to note some limitations of this analysis. On the one hand, the average values for the EU might be not fully consistent with the data available at national levels (because of different reporting systems). On the other hand, the analysis does not include details on accident typologies, which could provide further insights into the severity of the accidents occurred (European Union, 2016).

Sustainability Reporting

Sustainability reporting is used by companies to measure, disclose and be accountable to internal and external stakeholders and the public with regard to their environmental, social, economic and organizational performance (van Wensen et al., 2011). For this reason, it is important to know if the EU raw materials sector is taking public concerns about environmental impacts and community relations seriously and are committed to improving their transparency and corporate social responsibility. Furthermore, the position of EU raw materials companies in sustainability reporting around the world is another aspect to be considered. These issues are thus addressed by means of two indicators that reflect the number of companies that have joined the Global Reporting Initiative by world region and for Europe (Global Reporting Initiative, 2017; European Union, 2016).

4.3.3 Criticality indicators

Table 4: Criticality indicators.

INDICATOR	DESCRIPTION	UNITS	LIFE CYCLE STAGE	SOURCE
EC criticality matrix	Matrix with two dimensions: economic importance of the material and supply risk.		All stages	European Commission, 2017
Criticality space proposed by Graedel	Three-dimension plot with three dimensions: supply risk, vulnerability to supply disruption and enviromental implications.		All stages	Graedel et al., 2012
Thermodynamic Rarity	Exergy cost required to obtain a mineral commodity from bare rock, using prevailing technology.	kJ or MJ	All stages	Valero and Valero, 2014

In the last decade, the concept of criticality has been gaining increasing attention especially in the U.S. and Europe (European Commission, 2010; European Commission, 2014b; Graedel et al., 2012; Graedel et al., 2015; USDOE, 2010; USDOE, 2011). Several methodologies have been developed at various levels (global, region, country or even corporate) in order to try to ascertain which raw materials have to be considered as critical from the supply viewpoint. At present, there is no international forum established, nor is there a common criticality methodology (Dewulf et al., 2016). In spite of that, there is a consensus about two main factors that should be reflected by the criticality concept: the supply risk and the economic importance (or vulnerability to that supply risk). These two factors are generally represented in a matrix as two independent dimensions (Dewulf et al., 2016; Graedel and Reck, 2016). As a third factor sometimes the environmental impact is considered. For instance, Graedel et al. (2012) encompasses the environmental factor as a third independent dimension in the criticality assessment, generating thus a threedimensional plot. The EC study on critical raw materials (CRMs) does not include this aspect in its current 2017 list on raw materials. It was however considered in the first 2010 list, where it was integrated into the supply risk, but afterwards removed in the 2014 list because of the lack of reliability of the Environmental Performance Indicator (EPI), in which this aspect was rooted. A fourth factor considers the thermodynamic dimension of the materials, denoted by the "Thermodynamic Rarity" (Rarity) variable, which accounts for the exergy cost required to obtain a mineral commodity from bare rock, using prevailing technology. We have chosen thus to include indicators developed by EC (European Commission, 2017b), Graedel et al., (2012, 2015), as well as Valero and Valero (2015a) that describe these four factors.

A general conclusion when analysing the different criticality approaches is the fact that the supply chain should be better evaluated for determining crucial supply chain actors (e.g., economic sectors) and bottlenecks (Blengini et al., 2017; Dewulf et al., 2016; European Commission, 2017b), as well as for identifying inefficiencies, dissipation losses, and recoverable fractions throughout the various stages of the supply chain (Licht et al., 2015). In this respect, Licht et al. (2015) conducted a global SFA for indium, gallium and germanium, which has drawn attention to the fact that there is more potential to recover at the extraction/refining stage than is currently exploited. In the last update of the report on CRM in the EU (2017) this aspect has been improved by taking into account the country concentration not only in the mining stage, but also in other subsequent stages, identifying in a more satisfactory manner the potential bottlenecks along the supply chain. Bearing in mind that an extensive understanding of the supply chain is crucial in determining criticality, new methodologies have recently been developed to this end. An example has been performed by Nuss et al. (2016a) applying the network analysis methodology to aluminium in the U.S. economy in 2007, in order to identify key sectors and their relative importance as well as potential bottlenecks in the supply chain. Nuss et al (2016a; 2016b) thereby proposed applying the network analysis to inter-sectoral supply chains exploring in detail the relationships connecting materials to the products that require them. In addition, they propose a set of network indicators (product complexity, producer diversity, supply chain length, and potential bottlenecks), with the purpose of identifying network bottlenecks and relative sector importance.

Furthermore, network-based metrics can complement the existing literature on resource criticality, and be part of a potential "Composite Risk Methodology" for metal supply chains that would consist of (a) Supply Chain Network Analysis, (b) Criticality Assessment, and (c) Scenario Analysis of future metals supply and demand (Nuss et al., 2016b). Another aspect for further research within criticality analysis is the concept of resilience (Dewulf et al., 2016; Sprecher et al., 2015). In other words, how resilient are economic systems and how do they respond in the context of inadequate supply of a given material, the consequences, and options to reduce these.

EC Criticality indicator

The EC methodology for raw material critical determination is based on two independent factors: economic importance (or vulnerable to supply disruption) and supply risk, which are represented in a two-dimension matrix. CRMs are both of high economic importance to the EU and vulnerable to supply disruption.

- Vulnerable to supply disruption means, that their supply is associated with a high risk of not being adequate to meet EU industry demand.
- High economic importance means that the raw material is of fundamental importance to industry sectors that create added value and jobs, which could be lost in case of inadequate supply and if adequate substitutes cannot be found (European Commission 2017b).

In the last update of the CRMs list (2017), the overall methodology has been applied, with some modifications in order to consider several policy needs, and thereby improving the CRM determination (Blengini et al., 2017). Next, these policy needs are described for both criticality factors.

Under the supply risk dimension, four policy needs were prioritized: (1) incorporate trade barriers and agreements, (2) adopt a more systematic supply chain approach, (3) take into account import dependency and a more accurate picture of the actual supply to the EU and (4) maintain a prominent role for recycling and improve the quality and representativeness of data for the EU (Blengini et al., 2017). For the Economic Importance (EI) dimension, two policy needs were prioritized: (1) a more detailed and transparent allocation of raw materials uses to their corresponding NACE (Statistical Classification of Economic Activities in the European Community) sectors, and (2) use of a raw materials-specific substitution index in the calculation of EI to allow for a reduction in the potential consequences to the European economy due to inadequate raw materials supply (Blengini et al., 2017).

Criticality indicator developed by Graedel et al. (2012)

The criticality indicator proposed by Graedel et al. (2012) considers economic importance and supply risk, as per the EC, and additionally includes environmental implications. By doing so, a three dimension-plot is displayed based on the three dimensions (axis) of supply risk, vulnerability to supply restriction, and environmental implications.

The methodology to measure criticality proposed by Graedel and co-authors has been presented in numerous articles (Graedel et al., 2012; 2015; Harper et al., 2015; Nassar et al., 2015a; Panousi et al., 2016). Each criticality aspect is calculated using several indicators. For instance, the supply risk encompasses not only geopolitical aspects such as the country concentration index, or the political stability of the involved countries, but also social or geological indicators (e.g. for social the policy potential index and the human development index; for geological and technological the depletion time and the companion metal fraction). The environmental factor takes into account the environmental impacts of metals because of their toxicity, the use of energy and water in processing, or emissions to air, water, or land. It is determined based on inventory data from the ecoinvent database including the damage categories human health and ecosystems. The third damage category according to this method, resource availability, is not incorporated into the environmental implications evaluation because it is addressed in the supply risk methodology.

Another relevant aspect of this criticality assessment is that it has been developed at three different levels, global, national and corporate, so that the framework has been constructed to permit flexibility by the user in its application. It is important to note, that a different temporal dimension (short to long term) is implicit depending on the assessment level.

An important limitation of both criticality methodologies (EC and the developed by Graedel) is that an assessment involving composite indicators and ordinal scales might be not sufficiently precise. On the one hand, there is some degree of overlap among some indicators and on the other hand, a number of potentially relevant indicators have not been included. Nonetheless, the incorporated indicators have an overall applicability as has been shown in several studies (Graedel et al., 2012; 2015; Harper et al., 2015; Nassar et al., 2015a; Panousi et al., 2016), and the data to determine them are generally available.

Thermodynamic Rarity (Rarity)

Overall, we find that these methods leave behind one relevant factor, which is the physical quality of the substances, in other words, exergy. Traditionally, the studies based on exergy and natural resources are focused on calculating the amount of exergy required for the production of a certain commodity (Ayres et al., 2006; 2011; Szargut et al., 2002). In recent years, however, Valero and Valero (2015a) have developed the variable denoted "thermodynamic rarity" for estimating the exergy of minerals, which is based on thermoeconomics.

In the article by Calvo et al. (2017a) an additional dimension to the EC criticality factors "supply risk" and "economic importance" is proposed through the variable of "thermodynamic rarity" (rarity), which accounts for the exergy cost required to obtain a mineral commodity from bare rock, using prevailing technology. In this way, this approach provides an assessment independent of market and political arbitrariness and that is rooted in the geological and physicochemical characteristics of minerals.

Defining more in detail the concept of rarity, we can say that it incorporates two types of costs: first, the embodied exergy (or exergy cost, kWh) of the mineral from mine to market. Second, a hidden cost, understood as the free natural bonus provided by nature for having minerals concentrated in mines instead of dispersed throughout the crust. The latter is represented by the "exergy replacement cost" (ERC), defined as the exergy cost that would be needed to extract a mineral from ordinary rocks to the conditions of concentration and composition found in the mine, using prevailing technology. Because of this definition, a given raw material will be thermodynamically rare if it is: (1) currently energy intensive to obtain and (2) scarce in nature (Calvo et al., 2017a; Valero and Valero, 2015a).

As a consequence of adding a new dimension to the EC assessment, if a given commodity presents a high risk in two of the three dimensions (economic importance, supply risk, and thermodynamic rarity), it is proposed to be critical (Calvo et al., 2017a).

One may say that thermodynamic rarity values are not static, because they depend on the state of technology. However, while there are no significant technological improvements, thermodynamic rarities will stay within the same range of values. That said, it is important to state that even if rarity values might change with technological improvements and/or global ore grade decline, figures are more stable than those related with economic importance or supply risk, which fluctuate more strongly with market volatility or political instability (Calvo et al., 2017a).

Usually, the geological aspect is reflected by the depletion time indicator. This ratio represents the number of years of which the current level of production can be sustained by the available reserves, dividing the proved reserves by the production data of a specific year, and it has been used to forecast the future availability of a resource. Yet, the R/P ratio is a static value, as it assumes that production is constant over time. As this tendency has been clearly proved wrong over the years, it can only be regarded as an early warning indicator (Calvo et al., 2017b; Scholz and Wellmer, 2013). Furthermore, new discoveries, changes in production rate or technology or even changes in the economic situation or environmental or governmental restrictions can produce significant variations in this R/P ratio in a short period of time (Calvo et al., 2017b; Feygin and Satkin, 2004). For this reason, we consider that "thermodynamic rarity" is the rightful indicator in order to address the geological and physical aspect of raw materials supply.

The case study by Ortego et al. (2018) at the end of this report shows an example of the use of this indicator to conventional and electric vehicles. This article highlights the importance of applying the rarity variable (based on exergy) instead of mass, in order to realize about the physical value of critical metals (CMs) with a low weight contribution above the total vehicle mass, as well as to quantify their specific importance in the vehicle as a whole.

4.3.4 Policy indicators

Table 5: Policy indicators.

INDICATOR	DESCRIPTION	UNITS	LIFE CYCLE STAGE	SOURCE
Mining activity in the EU	Geographic location and approximate production size of metal mines in the EU	tonnes	Extraction	European Union, 2016
Minerals exploration	Metallic mineral exploration in the EU per development stage / Mineral deposits, occurrences and showings / Exploration budget	Development stage / tonnes / Billion USD	Exploration	European Union, 2016
National minerals policy framework	Policy perception index / Investment Attractiveness Index	%	Exploration Extraction	European Union, 2016
Public acceptance (of mining)	Public perception of the efforts of various types of company to behave responsibly towards society / Public perception by country about the efforts of mining companies to behave responsibly towards society	%	Exploration Extraction	European Union, 2016
Industry structure in EU	SME ratio of companies involved in a determined life cycle stage	%	All life cycle stages	BIO by Deloitte, 2015
Typical time required for production of primary material in EU and rest of the world	Past typical time range to obtain necessary permits and to begin the production of primary material in the mine, pit or quarry in EU, including a sub-distinction between 2 timeframes: the average timeframe for the completion of the administrative process; the average timeframe to open the mine once the necessary permits have been obtained.	Years	Extraction	BIO by Deloitte, 2015

As policy indicators, we have mainly included indicators describing the mining context in the EU, because they provide crucial information on decision making for the EU raw materials strategy on primary supply. These indicators are the mining activity, the minerals exploration, the national minerals policy framework, the public acceptance of the mining sector (all related to the EU), as well as the typical time required for production of primary material. In addition, the industry structure in EU along the life cycle of the material has been considered. Next, the indicators that required further explanation are described below.

Mining activity and minerals exploration indicators

While the EU is highly self-sufficient in terms of construction minerals and most of the industrial minerals, it is largely dependent on imports for metals. For this reason, indicators that provide detailed information on active metal mines as well as areas for future mining activity are essential to understanding the EU's current and future metal supply (BRGM, 2016; SNL Metals and Mining, 2016). These indicators are represented in maps, giving information about the geographic location of metal mines, metallic mineral exploration, and mineral deposits, occurrences and showings. In the case of metal mines, the approximate production size is also displayed. However, two observations can be made regarding the coverage of this map. The first is that it only shows primary commodities, although for many mines several other commodities are mined as by-products. Second, the current production capacity of these mines might differ in a single year, given that mine production is particularly dependent on fluctuating market prices (European Union, 2016).

The combined information depicted on the maps of exploration projects and the identified mineral deposits indicates if the EU's metallic minerals potential is under-explored and therefore under-exploited. This is of vital importance for the EU's policy on raw materials primary supply (European Union, 2016).

In order to analyse the situation of mineral exploration, it is further important to take into account the budgets allocated to metal exploration in a certain period. With this indicator, one can clearly observe how investment in exploration evolves over time, and is driven by commodity prices (European Union, 2016; SNL Metals and Mining, 2016; Wilburn et al., 2014).

National minerals policy framework indicators

With respect to national minerals policy, the framework and regulatory structure in the different countries can either impede or expedite the development of mining operations and thereby influence the overall security of raw materials supply. Key factors determining the adequacy of minerals policies include the level of enforcement of existing mining policies, environmental regulation, political stability, and the state of the legal system (European Union, 2016).

Although it is rather difficult to quantify this aspect, the Fraser Institute Annual Survey of Mining Companies provides a useful indicator, which is the Policy Perception Index. This assesses the public regulatory framework that affects investment (Jackson, 2014). Nonetheless, the policy framework is not the only determinant of the performance of mining sectors and decisions on further investment. As a result, the information provided by the Policy Perception Index is complemented by the Investment Attractiveness Index, which combines executives' perception of the policy framework with their perception of a jurisdiction's geological attractiveness (Jackson, 2014; European Union, 2016).

Public acceptance indicators

Public acceptance is a prerequisite for the development of any economic activity. For the mining sector, public acceptance is a particular challenge, both for existing mines and for the development of new mining activities. The level of acceptance of extractive activities is difficult to quantify and is determined by many different factors. These include concerns about environmental impacts, highly publicized accidents and the "Nimby" effect (not in my backyard) (European Union, 2016). Two indicators have been proposed for assessing public acceptance, which consist in the public perception of the efforts of various types of company to behave responsibly towards society and the public perception by country about the efforts of mining companies to behave responsibly towards society (European Commission, 2013; European Union, 2016).

4.3.5 Competitiveness and innovation

Table 6: Competitiveness and innovation indicators.

INDICATOR	DESCRIPTION	UNITS	LIFE CYCLE STAGE	SOURCE
Domestic production	Domestic production (and extraction) of raw materials.	million tonnes	Production	European Union, 2016
Value added and jobs	Value added at factor cost and number of jobs for raw materials economic sectors.	Billion € Million jobs	Production	European Union, 2016
Corporate R&D investment	Annual R&D investment for companies with their headquarters in the EU (by top companies in the raw materials sector and by public organisations)	Million €	Production	European Union, 2016
Patent applications	Number of raw materials patent applications from EU-28 Member States (and compared to international reference countries). Proportion of patents by type of applicant (company, university, individual, …).	Number of patent applications %	Production	European Union, 2016
Knowledge and skills	Number of educational programmes related to raw materials by country. Qualification levels and participation in education and training in the EU mining and quarrying sector.	Number of educational programms %	Production	European Union, 2016

Domestic production indicator

Domestic production of raw materials is an essential part of the EU economy. It creates billions of added value (European Union, 2016), million jobs (European Union, 2016), and provides a reliable supply of inputs to many downstream industries. To be used as an indicator of competitiveness needs, the domestic production indicator needs to be seen in the right perspective. In the global context, it should be compared with global material use, with the EU's share of global production and with the share of imports in the EU's consumption of raw materials. Ideally, it should be also complemented with data on the cost of production, as well as the environmental and social implications of the production processes (European Union, 2016).

Two indicators have been selected in the report (European Union, 2016): the domestic extraction (UNEP, 2016) and the domestic production (Minerals4EU, 2016) in the EU. By comparing both indicators, it can be observed that the EU processes more raw materials than it extracts. The difference can be explained by the inputs to production coming from imports and recycling (European Union, 2016).

Value added and jobs indicators

Raw materials are an essential building block of the EU's economy, with many downstream sectors relying on raw materials supply. The value added and the number of jobs associated are key economic indicators that provide useful information on the economic importance of the raw materials sector. To demonstrate the importance of raw materials to the rest of the economy it is important to consider also the value added and jobs related to entire supply chain, from mining to the downstream manufacturing. In the report "Raw Materials

Scoreboard", these indicators were calculated for the case of metals, and not for other types of minerals, due to data limitations. For similar reasons, given the high level of data aggregation, recycling activities of minerals/metals were also not included (European Union, 2016).

Corporate R&D Investment

To remain competitive internationally, the EU needs innovative businesses that create added value. Innovation is difficult to cover by a single indicator. Therefore, the Raw Materials Scoreboard brings together information on R&D investment, patent applications, knowledge and skills (European Union, 2016). Since it is important to quantify the R&D investment in view of the challenges ahead (such as increasing demand, global competitive pressure, increasing environmental standards and energy efficiency requirements), the R&D intensity of the mining sector as well as its trend over time have to be estimated (European Union, 2015; 2016).

Patent applications

By focusing on the marketable outputs of R&D activities, patents are mostly an indicator of technological innovation. In the report "Raw Materials Scoreboard", the number of patent applications in the raw materials sector in the EU and in a group of six major industrialized non-EU countries is analysed, as well as the proportion of patents by type of applicant (company, university, etc.). The measurement of this indicator is especially important in the mining sector bearing in mind that it is a sector, which relies on mature technologies. Consequently, innovative activities do not necessarily give rise to patents. In addition, the proportion of patents by type of applicant gives relevant information about the different structure of the R&D and innovation landscape among different regions. While patent applications are filed mainly by companies, patenting by universities in general leads to additional funding research, spurring new start-ups. As a limitation of this analysis, it is important to note that, due to technical limitations, patents in substitution of critical raw materials are not included (European Union, 2016; PATSTAT, 2015).

Knowledge and skills

Knowledge and skills are key for innovation in firms. Skilled labour can contribute to innovation and growth by generating new knowledge, developing incremental innovations, supporting firms in the identification of business opportunities, among others (European Union, 2016).

The mineral exploration, mining and processing sector is reported to be characterized by a talent shortage (Shillito, 2015). It suffers from and ageing workforce and young graduates are often attracted to other sectors with equally high salaries but with more attractive work locations (European Union, 2016). Even though little quantitative data are available, there are indications that the number of educational programmes dedicated to the raw materials sector is declining in the EU (European Union, 2016; McDivitt, 2002). This number of educational programmes is one possible indicator to reflect the aspect knowledge and skills (Sand and Rosenkranz, 2014).The other possible indicator is the qualification levels and participation in education and training in the EU mining and quarrying sector (EU Skills Panorama, 2017).

Finally, while talent shortage is recognized to be a significant problem in the raw materials sector, it is very hard to find reliable statistics on the number of graduates of the number of vacancies that cannot be filled (European Union, 2016).

4.3.6 Eurostat raw material use indicators

In order to monitor the European Commission's EU 2020 flagship initiative 'Towards a resource efficient Europe', Eurostat has established an indicator scoreboard in which resource productivity is the lead indicator. To measure resource productivity, domestic material consumption (DMC) is related to gross domestic product (GDP). However, the value of the DMI as a basis for the DMC depends strongly on the origin of the input. If e.g. metal ore is extracted domestically the total amount of ore is accounted for, but if metals are imported, only their imported mass (product weight) is used. This asymmetry led to the proposal to express all imported goods (also exported goods) in terms of raw material equivalents (RME). Thus, the European Commission has expressed the aim to integrate indirect or embodied material consumption into the lead indicator measuring resource productivity. Currently, Eurostat also publishes the resource productivity measured as GDP per RMC.

Eurostat furthermore publishes raw material use indicators regarding input, consumption and output. Major input indicators include domestic extraction used (DE), direct material input (DMI) and raw material input (RMI). Consumption indicators include domestic material consumption (DMC), raw material consumption (RMC), net additions to stock (NAS) and physical trade balance (PTB) measured as direct flows as well as calculated in raw material equivalents. Major output indicators include domestic processed output (DPO). Furthermore, the indicator total material input (TMI) include the flows from extraction, which are not used in the economy. The indicator total material consumption (TMC) subtracts those flows, which are linked to exports; however, these indicators are not use by Eurostat, thus they will not be described in the following. For detailed definitions of all indicators see e.g. Eurostat 2001.

Assessment of the indicators

Indicators

DE, DMI, RMI, DMC, RMC, NAS, PTB, DPO

Description

Input indicators describe extraction of raw materials from domestic territory (DE), input of materials into the economy in terms of extraction of raw materials and imports (DMI) and in terms of extraction of raw materials and raw material equivalents of imports (RMI). Consumption indicators subtract exports/raw material equivalents of exports from input indicators to arrive at DMC and RMC. NAS measures newly added stocks to physical stock of the economy and PTB shows the balance of imports and exports in terms of direct mass flows or in terms of raw material equivalents. Output indicator DPO measures material flows to the environment including emission and waste flows, dissipative uses of products and dissipative losses.

The indicators include all physical flows, covering all kinds of biomass, metals and non-metal minerals as well as fossil energy carriers. Biomass is converted to dry mass; metal is counted as gross ore. Water and gaseous substances are not included.

Eurostat publishes a methodological guide for the calculation of domestic extraction and direct imports including a detailed set of conversion factors. The guide is regularly updated, last time in 2013. The values are delivered yearly by the statistical bodies of the European countries and Eurostat provides a quality check of the data.

For the calculation of the raw material equivalents of the traded goods, the “RME model” was developed by SSG, IFEU and CUNI. The RME model converts the internationally traded product flows into raw material equivalents. It is based on a Leontief’s input-output analysis: Raw material inputs into an economy are allocated to product groups by using the information of an input-output table (IOT) which is depicting the interrelationships between economic production activities. The core of the RME model is a high resolution IOT with 182x182 product groups (In comparison, monetary standard IOTs distinguish between 30 and 65 products groups). For selected product groups the sales structures are expressed in physical instead of monetary units (hybrid IOT), because some product groups, amongst other metals in the stage as raw materials and firstly processed raw products, are represented more accurately by physical than by monetary relationships. The input data into the model includes a high number of statistical data, amongst other from Comext (trade data), Prodcom (production), Energy statistics, agricultural production data and data from USGS and BGS regarding metal mining and recycling outside Europe. Eurostat (2016) publishes a methodological description which is yearly updated as the model is continuously further developed, e.g. in 2016 regarding the transition to NACE 2 and the inclusion of regional input data of recycling rates and energy mixes of countries from outside Europe.

Units

Metric tonnes per year

Reference

Major references include Eurostat 2001, OECD 2008 and Eurostat webpage on EW-MFA http://ec.europa.eu/eurostat/web/environment/material-flows-and-resource-productivity.

Last Eurostat compilation guide:

- http://ec.europa.eu/eurostat/documents/1798247/6191533/2013-EW-MFA-Guide-10Sep2013.pdf/54087dfb-1fb0-40f2-b1e4-64ed22ae3f4c

Eurostat RME model last description:

- http://ec.europa.eu/eurostat/documents/1798247/6191533/Documentation-EU-RME-model/

Life cycle stage

Extraction (DE), extraction, processing, construction activities, manufacturing of end-products (all other indicators).

Classification / Cluster

The parameters are representing physical flows of materials in one year. The major goals of the indicators in the Economy-wide MFA-family are generally three-fold:

a) Monitoring the material basis of national economies and thus estimate the material size of the economy,
b) Monitoring the material and resource productivity and
c) Monitoring shifts in environmental pressures among countries and world regions due to foreign trade and globalization (OECD, 2008).

Energy use

Eurostat raw material use indicators include all fossil fuels (oil, gas, coal, peat) and include as well biomass for energetic use in metric tons. Material inputs for all power plants (construction and maintenance) and further infrastructure (e.g. grids) are also included in the economy-wide calculations.

Environmental impacts

Eurostat raw material use indicators are environmental pressure indicators with some weak connections to environmental impacts. These connections are stronger for indicators, which include up-stream material flows such as RMI and RMC.

4.3.7 Statistical Entropy Analysis (SEA)

Material flow analysis is a technique that tracks the flows of goods and substances between processes and through a defined system (Baccini and Brunner, 1991). Processes that transform input goods into different output goods concentrate and dilute various substances. Such concentration and dilution phenomena can be quantified by Statistical Entropy Analysis (SEA), and the following description of SEA is based on Rechberger and Brunner (2002) and a doctoral thesis (Sobańtka 2013) based on this work.

The probability of an event is transformed into the probability of appearance of a chemical element, expressed by its concentration. Therewith, statistical entropy becomes a tool used to quantify the distribution of conservative substances[1]. it is a tailor-made evaluation tool for MFA studies (the MFA terminology and term definitions are based on Brunner and Rechberger (2016)). The method is based on the entropy concept as it is used in the science of statistics. Statistical entropy as utilized here measures the distribution pattern of a substance during its route (life cycle) through a system. The changes in the distribution patterns taking place due to the transformation of material flows in the system can be expressed quantitatively as a change in the statistical entropy.

SEA is a quantitative evaluation method that determines the extent of concentration respective, dilution of a substance caused by a process or system. SEA has been repeatedly used for the assessment of losses of heavy metals from waste treatment facilities leading to a better understanding of the significance of concentration processes for sustainable materials recycling (Sobańtka, 2013).

Statistical entropy based indicators

(Laner and Rechberger, 2016; Rechberger and Brunner, 2002; Sobańtka, 2013)

Statistical entropy based indicators are established on a comprehensive material flow analysis and Shannon's statistical entropy function that is transformed by a three-step procedure. The result is a new function that can be applied to any defined system with known mass-flows and substance concentrations. In combination with materials balances, the method yields quantitatively the Relative Statistical Entropy (RSE) and the Substance Concentrating Efficiency (SCE) of a given system.

Description

A life cycle can be conceived as a chain of concentration (flotation, smelting, refining, collecting, recovering) and dilution (producing all kinds of waste, mixing of materials, emissions) steps. Rechberger and Brunner (2002) used statistical entropy (SE) to describe such concentration and dilution phenomena. The input and the output of a process are both defined by a set of material flows. Consequently, the Relative Statistical Entropy (RSE) for a process is determined once for the input and once for the output. The entropy change ($\Delta RSE = RSE_{Output} - RSE_{Input}$) caused by the process can be negative, zero, or positive depending on whether the process dilutes, concentrates, leaves unchanged, or concentrates a substance. The overall performance of a system can be most simply quantified by the difference between the RSEs for the first and the final

[1] Substances which are not transformed within processes (e.g. Cd)

stage. If ΔRSE>0 means that overall the investigated substance is diluted and/or dissipated during its transit through the system. It is safe to assume that such an increasing trend marks non-sustainable metals management since such a trend cannot be maintained indefinitely. In contrast, scenarios with high recycling efficiencies, advanced waste management, and non-dissipative metals use show balanced or decreasing overall trends (ΔRSE≤0 %). Low entropy values at the end of the life cycle mean that only small amounts of the resource have been diluted (e.g. as an additive in paint) or dissipated (in the case where emissions are considered), the large part of the resource appearing in concentrated (e.g. copper in brass) or even pure form (e.g. copper pipes). The difference in the RSE_j between the in- and output of a system can be defined as Substance Concentrating Efficiency (SCE) of the system. The SCE_j is given as percentage and ranges between a negative value, which is a function of the input, and 100%. A SCE_j-value of 100% for substance j means the following: Substance j is transferred to 100% into one pure output-good. $SCE_j = 0$ results if RSE_j-values of the in- and output are identical. This means that the system neither concentrates nor dilutes substance j. The indicator may well be combined with other evaluation criteria like energy efficiency (% SCE/kWh) and costs (% SCE/$).

Units

RSE [dimensionless], SCE [%]

Reference

Rechberger, H. and Graedel, T. E. (2002): The contemporary European copper cycle: statistical entropy analysis. Ecological Economics 42: 1–2 59-72.
Rechberger, H. and Brunner, P. H. (2002): A new, entropy-based method to support waste and resource management decisions. Environmental Science & Technology 36: 4 809-816.

Life Cycle Stage

The Statistical entropy based indicators are not specific to any life cycle stage. They can be used to describe concentrations and dilutions of substances. They indicate if a process or the total system is a concentrating or diluting entity. The whole life cycle can be conceived as a chain of concentration (flotation, smelting, refining, collecting, recovering) and dilution (producing all kinds of waste, mixing of materials, emissions) steps.

Comments

The indicators improve the understanding of the "metabolism" of a system. By assessing the concentrating and diluting potential, they provide new insights that are complementary to the results of existing methods for decision making in environmental and resource management such as LCA.

4.3.8 Circularity Index

The Circularity Index (CI) indicator provides a useful measure for assessing the circularity of energy intensive material loops. Perfect circularity implies meeting the demand for material using only EOL materials, and without any loss of material quality in the loop. Cullen (2017) defines this index as:

$$\mathrm{CI} = \alpha\beta$$

where α is the ratio between recovered EOL material and new demand (quantity),

$$\alpha = \frac{\text{recovered EOL material}}{\text{total material demand}}$$

and β is the ratio between the energy needed for material recovery and the energy required for primary material production from virgin ore (quality).

$$\beta = 1 - \frac{\text{energy required to recover material}}{\text{energy required for primary production}}$$

A return value of $\alpha = 1$ would describe a perfect circularity of quantity, where the supply of material that is recovered by EOL matches the demand of the material. A return value of $\beta = 1$ would also indicate perfect circularity but specifically for the quality of the material in which there is no loss of material quality within each material cycle.

A perfectly circular economy therefore, would exhibit a CI = 1, although this is a theoretical ideal which is impossible to obtain in real processes. Consequently, the concept of a perfect circular economy becomes a 'holy grail', much like the perpetual motion machine.

4.3.9 By-products indicators

Byproduct fraction

Description

This indicator is defined for the system of a pair of metals, the byproduct metal and the carrier metal. Byproduct metals are metals whose production cost cannot be covered by their values alone. Instead, they are produced as by-products of their carrier metals, often more common base metals. Byproduct fraction, B, is defined as $B = Q_C / Q_{tot}$ where Q_C is the production rate of a byproduct related to a specific carrier and Q_{tot} is its total extraction rate of the byproduct. For example, if the annual production of germanium is 100 tons and 60 tons is produced as byproduct of zinc, then the byproduct fraction of coal/germanium is 60%.

Reference

Fu, X., Polli, A., Olivetti E. (2017) "High-resolution insight into materials criticality: Quantifying risk for byproduct metals", under review at Journal of Industrial Ecology

Unit

Unitless indicator, ratio or percentage

Life cycle stage

Extraction

Where extraction takes place

Global

Comments

While the material criticality research community generally recognizes the role of byproduct status as a criticality indicator, the only quantitative indicator specific to byproduct metals so far is the 'companionality' (Nassar et al., 2015b) or 'byproduct share' (Nuss et al., 2014). Although the use of this indicator does provides a useful screening tool, one essential aspect specific to the byproduct metal problem are understated. Firstly, the use of byproduct dependency overlooks the fact that the carrier-byproduct dynamics is based on one-to-one (or many-to-one) connection. For example, while gallium and germanium are both extracted almost 100% as byproduct of other materials, gallium is byproduct of aluminium (bauxite) only and germanium is associated with both zinc and coal. The upper limit of gallium supply, which only depends on bauxite production, is clearly different from the case of germanium that is dependent on the dynamics and interaction of both zinc and coal. Therefore, we make this distinction clear by defining byproduct fraction based on a byproduct/carrier pair.

However, since many byproduct metals are also minor metals whose production data is limited, the calculation of byproduct indicator is also limited by data availability. Ideally, we would like to calculate byproduct fraction as a function of time, and we need the time series data of total production rate of a byproduct metal along with production rate as byproduct of a specific carrier. The latter data is often difficult to find even for just a single data point, let alone the time series.

Value ratio of byproduct/carrier

Description

This indicator is also defined for the system of a pair of metals, the byproduct metal and the carrier metal. Value ratio, V, is defined as the global average ratio between the monetary value of a byproduct B and a carrier C in all the mines, which produce B as byproduct of C. Value ratio is calculated using the following formula:

$$V = \frac{C_B}{C_C} \times \frac{P_B}{P_C} \times \frac{\eta_B}{\eta_C} .$$

The three terms on the right hand side correspond to the average ratio between mineral concentration, C, unit price, P, and extraction efficiency η, respectively. Byproduct and carrier materials are subscripted by B and C, respectively. For example, if the byproduct is germanium and the carrier is zinc, we have the following estimates: the average concentration of germanium in sphalerite (64% contained zinc) is 52 ppm, the price of germanium is 800$/lbs, price of zinc is 0.9$/lbs, the extraction efficiency of germanium is 86%, and extraction efficiency of zinc is assumed to be 100 %. Thus, we have

$$V = \frac{52\,ppm}{64\%} \times \frac{800}{0.9} \times \frac{86\%}{100\%} = 0.062$$

as the global average value ratio.

Reference

Fu, X., Polli, A., Olivetti E. (2017) "High-resolution insight into materials criticality: Quantifying risk for byproduct metals", under review at Journal of Industrial Ecology

Unit

Unitless indicator, ratio or percentage

Life cycle stage

Extraction

Where extraction takes place

Global

Comments

Metals are produced as by-products not because the physics prohibits them from being produced as primary products, but rather that the cost of doing so cannot be covered by the value of those metals. Therefore, an economic analysis of the metal markets is indeed a necessary complement to MFA in metal criticality assessments. A first important point would be to calculate on average how much the byproduct accounts a mine's profit. The less this value ratio is, the more dependent on the carrier would a byproduct be.

Similar to the considerations for the byproduct fraction, estimation of the value ratio is also limited by data availability.

Price elasticity of supply/demand

Description

In economic terms, the responsiveness of the quantity supplied/demanded of a product to a change in its price is called price elasticity of supply/demand, or simply supply/demand elasticity. Mathematically, we assume that quantity of supply/demand Q can be expressed in Cobb-Douglas (1928) form such that $Q \propto P^e$ where P is price of the material, and the power index e is the value of supply/demand elasticity. The good is said to be elastic when $e > 1$ and inelastic when $e < 1$; $e = 0$ is called perfectly inelastic. Formally, price elasticities should be estimated through econometric modelling approaches, which we will show in a case study later.

Reference

Fu, X., Polli, A., Olivetti E. (2017) "High-resolution insight into materials criticality: Quantifying risk for byproduct metals", under review at Journal of Industrial Ecology

Unit

Unitless indicator

Life cycle stage

Not specific to any life cycle stage, but it is more appropriate to discuss supply elasticity for the extraction stage and discuss demand elasticity for the use stage.

Where extraction takes place

Price elasticity should be calculated for a specific market, and the size of the market could be either on a global, regional, or country level.

Comments

To quantify physical flows of metals in their whole life cycles, diagnostic tools such as MFA have been employed in the assessment of a wide variety of critical metals, such as gallium (Licht et al., 2015, Løvik et al., 2016), germanium (Licht et al., 2015), indium (Licht et al., 2015) and metals essential to clean technologies (Nansai et al., 2014; Busch et al., 2014). The MFA model assumes that past patterns of behaviours will be consistent with those into the future, and therefore does not account for effects of changing economic conditions. However, the changes in metal supply and demand, represented by the fluctuations in price, are essential to byproduct metals. One specific point we are interested in is whether or not byproduct metal supply is able to respond quickly to changes in demand and price, because a lack of response could lead to high price volatility (Redlinger and Eggert, 2016) and potentially increase risk to manufacturers across the supply chain.

In addition, the role of price elasticities is important in estimating the impact of recycling. In order to fully understand the avoided impact of recycling the displaced primary production needs to be calculated (Zink et al., 2016). The displacement rate is essentially a function of the supply and demand elasticities of the primary and the secondary products.

Gibbs free energy of mineral and ore grade

Description

These two indicators can be used together as criticality indicators and they are specifically useful for estimating the possibility to decouple a byproduct metal from its carrier. For a specific mineral, Gibbs free energy of formation

$$\Delta G_f$$

is the change of Gibbs free energy from its pure constituent elements to the mineral compound. It is usually measured based on 1 mole of compound, and both the constituent elements and the compound are in their standard states. It provides a rough estimate of the thermodynamically minimal energy required to extract a metal to its pure form from a mineral compound. Ore grade refers to the metal content in a mineral. If the ore grade is relatively higher, a smaller amount of minerals is needed to extract the same amount of metal contents.

Reference

Phillips, W. G. B., and D. P. Edwards. "Metal prices as a function of ore grade." Resources policy 2.3 (1976): 167-178.

This paper is using Gibbs free energy and ore grade of mineral as a means to predict metal prices, but we could expand on that idea and instead compare the predicted cost and the real metal price.

Unit

Gibbs free energy of mineral is usually measured in kJ/mol, and ore grade is a unitless indicator usually measured in percentages or parts per million (ppm)

Life cycle stage

Extraction

Criticality assessment

These two indicators themselves can be used as criticality indicators, which represents the rarity of metal elements. Gibbs free energy provides a rough lower bound estimate of the processing energy required for the mineral compound. If the Gibbs free energy is high, then the difficulty and energy cost required to extract the metal will be higher as well. This idea is similar to the concept of thermodynamic rarity introduced by Valero and Valero (2015b), but it is more about providing a lower bound then getting the accurate energy needed. Ore grade should also be seen as an important criticality indicator, and the declining ore grade for several metals have raised attentions to the scarcity of such metals (Mudd 2007, 2010; Northey et al., 2014).

Also, these two indicators have an important connection with the criticality assessment of byproduct metals. If the cost of metal extraction can be covered by the value of metal on its own, then the metal can be produced as a primary product instead of a byproduct. We can express the total mining cost as follows,

$$C_{tot} = C_m + C_p = \beta_1 \frac{1}{c} + \beta_2 E$$

where the total extraction cost per unit weight C_{tot} is consisted of two parts, the mining cost C_m and the processing cost C_p. Mining cost can be further expressed as $\beta_1 \frac{1}{c}$ where β_1 is mining cost per unit weight of ore and $\frac{1}{c}$ is the inverse of ore grade. Processing cost can be expressed as $\beta_2 E$ where β_2 is cost of kJ of energy and E is processing energy per unit weight of mineral compound. The role of Gibbs free energy in here is that it can be used as an estimate of processing energy per unit weight of mineral compound. By plugging in realistic values for different metals and minerals, and compare that to the price of the metal, we will have a standard about whether it is possible to economically produce a metal on its own, or whether a byproduct metal is 'decoupleable'. We refer to that standard as 'decoupleability'. This concept of decoupleability should complement other byproduct specific criticality indicators. Even if a byproduct metal is considered critical because of its byproduct status, it is possible that with a more cost-efficient extraction technology, the metal can be produced on its own, therefore eliminating the concern around its byproduct status.

Supply potential

Description

This indicator is defined as the maximum amount of byproduct metal that can be extracted with the production of carrier metal, under the extraction efficiency of current technology. The underlying assumption in the concept of supply potential is that the influence of a byproduct metal on a mining company's total profit is negligible, so that the production quantity of carrier metal would be independent from the production quantity of the byproduct. Therefore, supply potential of a byproduct B from a carrier metal C would be determined by the following formula:

$$SP_B = \frac{C_B}{C_C} \times \frac{\eta_B}{\eta_C} \times Q_C \, .$$

The first two terms on the right-hand side correspond to the average ratio between mineral concentration C and extraction efficiency η, between the byproduct and the carrier. The third term Q_C is the global production quantity of carrier C. For example, if the byproduct is germanium and the carrier is zinc, we have the following estimates: the average concentration of germanium in sphalerite (64% contained zinc) is 52 ppm, extraction efficiency of germanium is 86%, extraction efficiency of zinc is assumed to be 100%, and 2014 annual zinc mining production is 13.3 million metric tons. Thus, we have $SP_B = \frac{52\,ppm}{64\%} \times \frac{86\%}{100\%} \times 1.33 \times 10^7 = 928$ tons, which is germanium's supply potential from zinc in 2014.

Reference

Fu, X., Polli, A., Olivetti E. (2017) "High-resolution insight into materials criticality: Quantifying risk for byproduct metals", under review at Journal of Industrial Ecology.

Frenzel, Max, Raimon Tolosana-Delgado, and Jens Gutzmer. "Assessing the supply potential of high-tech metals–A general method." Resources Policy 46 (2015): 45-58.

Unit

Unit of weight, such as metric tons.

Life cycle stage

Extraction

Where extraction takes place

Global

Comments

The comparison between actual supply and supply potential of a byproduct metal can be used to measure the level to which a byproduct is constrained by a carrier. For example, in the case mentioned above in description, global germanium production in 2014 is around 150 tons, so theoretically it could grow by six times without increasing zinc production. Therefore, we could not simply say that availability of germanium is bounded by production of zinc, and a more detailed investigation of germanium's market structure should be necessary.

The similar data availability issue for byproduct metals also applies here, as we have discussed for byproduct fraction and value ratio. Frenzel et al. (2016) have developed a model to measure supply potential based on detailed information of mineral composition distributions, but again a complete dataset does not exist for a variety of minor metals.

5 Case Studies: Examples of MFA based indicators

5.1 Case Study 1: Indicators to support phosphorus management in Austria

The following example illustrates the need for MFA based indicators to capture systemic changes. This example is based on the following publication:

- Supporting phosphorus management in Austria: Potential, priorities and limitations (Zoboli et al., 2016a)
- Added Values of Time Series in Material Flow Analysis (Zoboli et al., 2016b)

Protecting water bodies from eutrophication, ensuring long-term food security and shifting to a circular economy represent compelling objectives to phosphorus management strategies. This study determines how and to which extent the management of phosphorus in Austria can be optimized. A detailed national model, obtained for the year 2013 through Material Flow Analysis, represents the reference situation (see 5). Within this study, applicability and limitations are discussed for a range of actions aimed at reducing consumption, increasing recycling, and lowering emissions. The potential contribution of each field of action is quantified and compared using different indicators. Table 7 shows together with Figure 5 examples how to derive MFA base indicators.

Table 7: Examples of MFA based indicators.

Indicator	Result	Calculation *(see figure 1)*
Net mineral fertilizer consumption	14.000 tP y^{-1}	*=(A+B)-N*
Net P for food consumption	17.900 tP y^{-1}	*=(A+B+C+D)-(L+M+N)*
Crop farming efficiency	41 %	*=N / (P+F+G+J+Q+R+S)*
Animal husbandry efficiency	26 %	$=I_1 / (E+H)$
P removed in waste water treatment	88 %	$=I_2 / (O+T+U+V)$
Loss to water bodies	5.430 tP y^{-1}	*=X-Y*
P recycling efficiency of waste management	39 %	$=(o_{2\text{-}6} + J) / (I_{2\text{-}13})$
(others are possible)	…	…

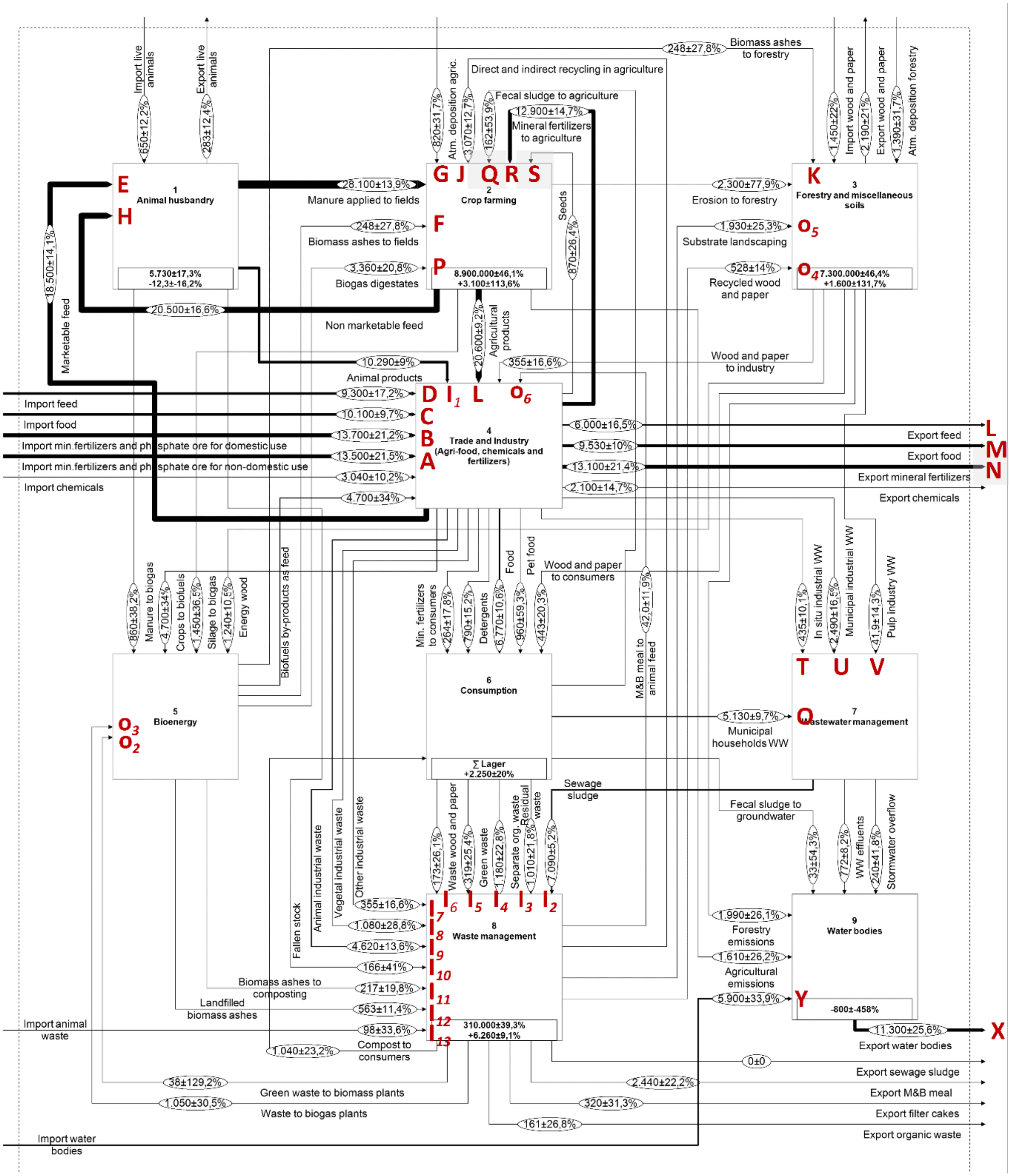


Figure 5:Austrian phosphorus budget for the reference year 2013 (unit: tP y−1) based on Zoboli et al. (2016a).

Further, within these studies, a detailed multiyear model of the Austrian phosphorus budget covering the period 1990–2011 was developed to investigate its behaviour over time and test the hypothesis that a multiyear approach can also contribute to the improvement of static budgets.

Figure 6 shows only two examples of a time series for the indicator "Net mineral fertilizer consumption" and "P recycling efficiency of waste management". The variations demonstrate the need to consider and observe different periods when evaluating an indicator. From a methodological point of view, the multiyear approach has broadened the conceptual model of the budget, making it more suitable as a basis for material accounting and monitoring. Moreover, the analysis of the data reconciliation process over a long time proved to be a useful tool for identifying systematic errors in the model.

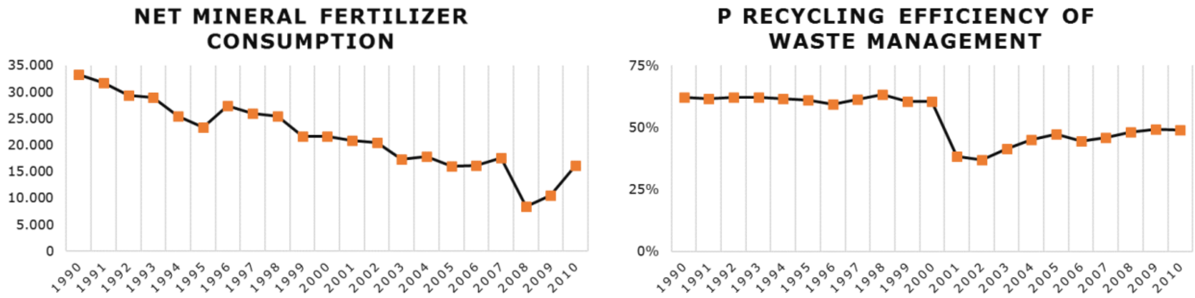


Figure 6: a) Time series of net mineral fertilizer consumption (tP y−1) and b) of P recycling efficiency of waste management based on Zoboli et al. (2016b).

The brief summary of the phosphorus study shows the importance to design a model as a fundamental complement to a comparative assessment. Looking only at the numbers will lead to wrong conclusion. An important outcome is the essential role played by the MFA systemic approach.

- First, it has allowed the accurate identification and quantification of the flows and stocks involved in the different fields of action.
- Second, it has enabled the quantification of the relative effect through the use of different indicators. Without the MFA, a proper comparative assessment would have not been possible.
- Further, it has shown the need to consider and observe different periods when evaluating an indicator.

The resulting concise though exhaustive overview can be very useful to support decision makers in designing national management strategies and setting priorities, as well as to assist to main experts in fitting their work into a broader context.

5.2 Case Study 2: Thermodynamic rarity as an indicator for resource management

The European Union is developing strategies for fostering electric mobility (EM); however, there are risks that threaten the development of this emergent technology, which must be considered and evaluated. One important concern is the long-term supply of critical metals (CMs) used in the manufacturing of vehicles, which are necessary for their high-performance properties. The objective of this case study developed by Ortego et al. (2018) is to perform an assessment of the use of CMs in vehicles. This is achieved by: i) establishing average composition of several types of vehicles, ii) performing a thermodynamic rarity assessment of vehicles.

The methodology is based in the application of the "Thermodynamic Rarity" concept Valero and Valero (2015a). Thermodynamic Rarity can be defined as the amount of exergy resources needed to obtain a mineral commodity from the ordinary rock using the prevailing technology. Hence, it allows taking nature into account as it apprehends both ideas: 1) conservation, because it advices to preserve those minerals that are scarce through exergy replacement costs and 2) efficiency, because embodied exergies indicate real energy expenditures that should be decreased in order to be cost-effective. Thermodynamic rarity is here proposed as an alternative unit of measure than mass for material assessment, as it gives a greater weight to those substances that are more valuable from a physical point of view.

The methodology is applied to 33 metals used in different vehicle technologies: conventional passenger vehicles, plug-in hybrid electric vehicle with NiMH battery, plug-in hybrid electric vehicle with Li-ion battery and battery electric vehicles. A comparison of the mass of materials with their exergy unveils the value of CMs with respect to bulk materials that would potentially be lost in the future if recycling targets continue to be measured in terms of mass. We build upon previous work by Valero and Valero (2015a) to calculate a complementary exergy-based indicator for material value in passenger cars.

An assessment of materials used in cars requires a definition of which vehicles should be covered, taking into account that a very significant change in passenger vehicle fleet is expected in the near to medium term. According to sales projections by type of vehicle published by the following entities: Spanish association of vehicle manufacturers ANFAC (2010); European Environmental Agency (2010) and Internaltional Energy Agency (2010) and (2012), Plug-in Hybrid Electric Vehicle (PHEV) and Battery Electric Vehicle (BEV) world sales will surpass Internal Combustion Engine (ICEV) sales in 2029 and 2038, respectively. To identify what metals are used in these three types of vehicles, a state of the art obtained from the revision of scientific bibliography has been undertaken. Annex 3A contains data obtained through the bibliographic revision carried out. A comparison between mass and rarity contribution of each type of vehicle is shown in the following figure.

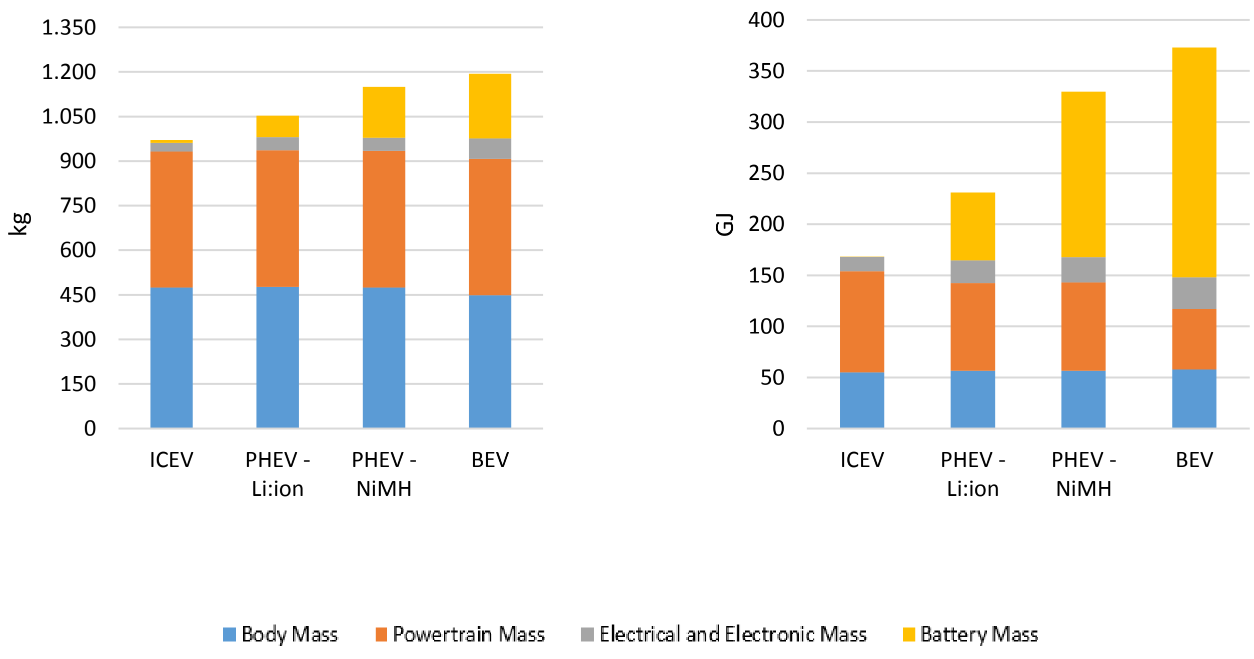


Figure 7: Mass and Rarity by component and type of vehicle.

Both approaches point to the BEV as being the most material-intensive from all types. While the heaviest parts (body, brakes, suspensions, steering) are similar in the four analysed cases, BEV has an extra weight caused mainly by batteries and electronic components. It is also remarkable that PHEV weight grows from 1,048 to 1,145 kg if the NiMH battery is used instead of Li:ion one. This is because of the lower power density of metallic hydrides with respect to Li:ion. Besides, electrical and electronic component´s BEV weight is 68 kg on average, whereas that for PHEV and ICEV only 44 kg and 28 kg, respectively. In BEV and NiMH-PHEV and contrary to the other cases, electrical and electronic components and chemical storage devices together are even more important from a rarity point of view than the body and powertrain. Special attention should be paid to Co, Ni, La and Li (batteries) and Cu, La, Mo and In (electric and electronic components). From a material point of view measured through rarity, even if BEV are also the highest material intensive vehicles, the distance to the other two types, especially to the ICEV, is far more pronounced. The rarity of a BEV is 2.21 times that of the ICEV, yet it is only 22% heavier. With respect to the Li:ion-PHEV, BEV has a rarity content that is 61% greater (but 13% heavier).

The application of the rarity approach, allows not only to realize about the physical value of those materials with a low weight contribution above the total vehicle mass, but also to quantify their specific importance in the vehicle as a whole. If recycling policies use targets based on mass, even if they are ambitious, they fail in enhancing the recycling of CM. This could be solved by using thermodynamic rarity as the unit of measure instead.

The proposed approach also helps automobile manufacturers to quantify the impacts of using and not recovering a particular metal in their vehicles, serving as a guideline for eco-design. With a detailed rarity analysis, it would be possible for instance to identify which parts of the car should be easily disassembled to recover individually each type of material and so be used again for the same functionalities as it was manufactured. Equally, it would allow identifying where to enhance more research on substitution materials. Substitution should especially be focused on those elements with higher rarities. As was seen, high-rarity materials are going to form part of the new generation of vehicles. This will probably lead to a future supply risk that may hinder the very development of the electric vehicle.

5.3 Case Study 3: Circular economy: theoretical benchmark or perpetual motion machine?

In an economy where perfect circularity of materials occurs, there is no waste or material loss. There is no quality dissipation and materials can be reused indefinitely. This is a utopian ideal and in reality, it would be next to impossible to achieve. Yet there can be significant benefits in pursuing this ideal and the CI indicator can be used to assess the current circularity or material loops and the economy. Cullen (2017) employs the use of the CI to assess the current state of circularity for a number of materials, citing data from multiple sources in ~2014. Table 8 shows the results for five energy intensive materials; steel, concrete, plastic, paper and aluminium. Working on the premise that a perfectly circular economy exhibits CI=1 it is clear that by current operating standards none of the materials mentioned comes close to the utopian ideal (all <20%).

It is worth noting that, for aluminium, the energy required to material recovery evaluated against the energy required for primary production comes close to perfect quality circularity (β = 0.96). However overall, aluminium is only 20% of the way to a circular economy due to the demand for the material being almost five times that of the supply from end-of-life (EOL) sources. What this indicator demonstrates is the need for better understanding of each material system and how energy and materials interact. A complete mapping of each material would be required to understand where the losses occur and inform areas for continued development.

Table 8: Circularity index for five energy intensive materials.

	Steel	Concrete	Plastic	Paper	Aluminium
Recovered EOL material (Mt)	298	660	28	156	11
Total material demand (Mt)	1,500	32,800	299	408	54
α	**0.2**	**0.02**	**0.09**	**0.38**	**0.21**
Energy required to recover material (MJ/kg)	6.7	3.4	9.6	23.4	7.6
Energy required for primary production (MJ/kg)	21.7	3.4	38.4	26.2	174
β	**0.69**	**0**	**0.75**	**0.11**	**0.96**
Circularity Index, CI	**0.14**	**0**	**0.07**	**0.04**	**0.20**

Notes: *α = recovered EOL material / total material demand. β = 1 – energy required to recover material / energy required for primary production. Circularity Index (CI) = $\alpha\beta$, maximum value =1. Data sources: Material estimates from various sources (~2014); energy intensities, best practice, mostly from Worrell et al. 2008); steel (worldsteel) EOL material excludes home/prompt scrap; concrete (CSI) EOL includes recycled concrete aggregate (RCA), and requires equal amounts of cement/energy to bind crushed aggregate in recycled concrete; plastic (various) mass for PET, PS, PVC, HDPE, LDPE, PP, other, energy values for PET (indicative); paper (CEPI) energy for graphic papers/newsprint, packing/board, sanitary/tissue, weighted by mass; aluminium (World Aluminium), EOL material excludes home/prompt scrap.*

Provided that the data requirements are met for each material, the CI indicator would provide a clear methodology for assessing the circularity of material loops, and perhaps entire economies. Working at a global level and country specific level, this indicator would yield valuable insight into development of processes and methods currently employed in fabrication, consumption and recycling/ upcycling/ downcycling of materials. If the target is to aim towards a circular economy then this indicator will prove vital in assessing and monitoring the progression towards that utopian ideal.

5.4 Case Study 4: Shifts and trends in the global anthropogenic stocks and flows of tantalum

The supply and demand of tantalum has undergone a number of significant shifts over the past few decades. The purpose of this article by Nassar (2017) is to quantify how these shifts have affected tantalum's global material cycle. A global stocks and flows model for tantalum has thus been developed for the years 1970–2015. The results indicate that the overall quantity of tantalum prompt scrap generated during manufacturing has increased notably due to tantalum's increased use as an alloy additive and sputtering target. In contrast, the amount of tantalum contained in recycled obsolete scrap, mainly in the form of used carbides, is estimated to have remained relatively constant since the late-1980s. Moreover, tantalum's overall end-of-life recycling rate (EoL-RR) seems to have declined from a high of 22–25% in the 1990s to approximately 18% today. This decline is also attributable to the shift in tantalum's use from carbides to sputtering targets and chemicals that, along with tantalum's use in capacitors, have not been recycled at the end-of-life (EoL) in significant quantities. The results also indicate that 21–25% of tantalum produced since 1970 is still in use today, with the remainder having been lost during processing, manufacturing, use, or at the EoL. However, a portion of the EoL "discards" may actually still be retained by the end-user as "hibernating" stocks that could potentially be recycled if the economic, technical, and behavioural challenges of recycling obsolete electronics are overcome.

From the material flows, one is able to derive three fundamental recycling indicators: the EoL-RR, the recycled content (RC), and the obsolete scrap ratio (OSR) (Graedel et al., 2011). The EoL-RR is calculated as the fraction of the total flow out-of-use that is recycled (as obsolete scrap) in a given year. RC is calculated as the ratio of the quantity of total recycled material (obsolete scrap and prompt and internal manufacturing scrap) to the sum of the total recycled material and primary production. Note that internal recycling at the processor is not included in this calculation. Finally, OSR is calculated as the fraction of the total recycled material that is from obsolete scrap. Estimates for these recycling indicators are presented in Figure 8. Importantly, although estimates are presented for all modelled years (i.e., 1970–2015), the first few years of data should be ignored given that the tantalum that would have entered use in the 1960s or before and that would have exited use during the 1970s or later is not captured in the model. As a result, the flow of tantalum out-of-use and all subsequent flows (and related indicators) would be underrepresented for the first few years of the model.

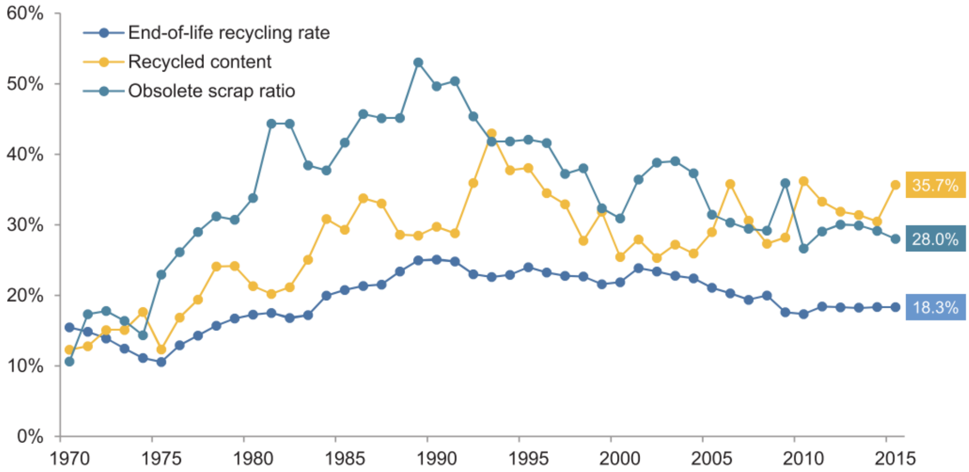


Figure 8: Modelled estimates of tantalum's end-of-life recycling rate (EoL-RR), recycled content (RC), and obsolete scrap ratio (OSR) for the years 1970–2015 (horizontal axis).

EoL-RR for tantalum increased during the 1980s until reaching a peak value of approximately 25% in the early-1990s. The EoL-RR seems to have stagnated at a level of 22–25% throughout the 1990s but then began to decline modestly beginning in the early-2000s reaching its current level of approximately 18% in the year 2015. The general early increase in EoL-RR in the 1980s can mainly be attributed to the increased use and recycling of tantalum carbides, while the later decline since the early-2000s can be attributed to the increased use and disposal of tantalum in electronics (i.e., its use in sputtering targets, certain chemicals, and capacitors). These contemporary EoL-RR estimates are very similar to the estimate of 17.5% suggested by Gille and Meier (2012) for the year 2011. Estimates of the OSR follow a similar, albeit more exaggerated, pattern as the EoL-RR: a general increase followed by a general decline. This trend can also be attributed to the same factors affecting the EoL-RR, namely the increased use and recycling of tantalum carbides followed by the increased use and discard of tantalum in electronics and other applications that are not recycled at the EoL. In contrast, RC has generally tended to increase over this time period, albeit with noticeable volatility. This is because while the amount of tantalum scrap recycled has increased significantly throughout this time period the amount of primary production has remained on the same order of magnitude. The RC of the past few years is estimated to have ranged from 25 to 36%. Calculating the RC for only the input of materials at the processing stage results in percentages that range from 17 to 24% for the past few years.

The recycling indicators EOL-RR, RC and OSR applied in this study have been developed by the International Resource Panel (UNEP, 2011). These indicators have been based on an explicit system definition, which constitutes a huge step forward. That is, before the definition of these indicators, every sector employed their own, usually opaque, method for calculating their recycling rates. Albeit the system definition used here might be further refined, it is however a relevant example for basing indicators on an explicit system definition. It is also important to note that by determining these three indicators in the case study; one can obtain a holistic picture about recycling, as well as determine the most relevant stocks for recycling (prompt and old scrap).

5.5 Case Study 5: Analysis and forecasting of resource demand and efficiency in Germany using MFA-model URMOD

The project "Structural and Technical Determinants of Resource Efficiency: Analysis of Path Dependencies, Structural Effects and Technological Potentials on the Future Development of Raw Material Productivity (DeteRess)" assessed the chances and limitations of a technology-oriented dematerialization policy in Germany using the environmental-economic model URMOD. Scenarios were developed to estimate the effect of changes in the material-intensive sectors of energy, construction and transport. The scenario "Expected Future Development (AZE)" estimates raw material use in 2030 based on known general developments and already adopted policies and measures to be implemented in the future. The scenario "Technological Change" (TW) shows the additional reduction potential resulting from the use of selected innovative technologies.

The essential methodological requirement was that imports and exports are recorded in raw material equivalents. This is necessary in order to be able to determine total raw material productivity (GDP + Imports / RMI) as indicated in ProgRess II. Therefore, the environmental-economic raw material model (URMOD) was developed. In URMOD data on raw material input into the economy is linked with the economic production and consumption activities. The basis is an economy-wide input-output table (IOT) including all production chains and cross-relations of an economy. The IOT for the base year 2010 developed for URMOD subdivided into 274x274 product groups and 41 categories of final use. The underlying IOT of the model is the Destatis IOT differentiated by 72 product groups. For the URMOD-IOT, raw material extraction, primary processing of raw materials (especially in the field of metals and mineral construction materials) and generation of electricity as well as material-intensive activities (in the area of construction, traffic, power generation and recycling) were disaggregated further.

The data on domestic extraction of raw materials is largely based on the results of the material flow calculations of the Environmental Economic Accounts (UGR) by the Federal Statistical Office. The raw material classification is based on the classification of the delivery table for Eurostat (EW-MFA, Domestic Extraction). The main data source for the disaggregation of the URMOD-IOT are the revenue and use tables of the national accounts of the Federal Statistical Office (Destatis), which are subdivided into 2,600 product groups. In addition, a large number of other sources, such as a highly differentiated agricultural input-output table (46 production processes) as well as sector studies (energy market, construction industry and transport) were used. The procedure for the assignment of raw materials to products follows the so-called Leontief approach of input-output analysis. With a sequence of matrix operations, the primary inputs into the economy (in our case the primary raw materials) are allocated to the goods of final use and imported goods.

The determination of the raw material equivalents of imports is based on a three-region model, which was designed to account for different production technologies in the countries of origin to estimate raw material equivalents of imports. In order to calculate the raw material content of German imports from non-EU countries, the coefficient matrix for EU-imports is used. This matrix is developed for the Eurostat RME model (see above). The usage of the EU coefficients has the advantage that crucial national information on import-regions of non-EU countries is considered. The import-coefficients are estimated with a two-stage approach. Firstly, all imports are considered to be produced with national technology standards. Secondly, if imports from other countries differ significantly from European standards, a partial multi-regional model will be applied. This model considers central country-specific information such as ore-grades, secondary shares of imported metals (direct and indirect) and energy contents of imported electricity (direct and indirect). An important instrument within the model is the consideration of physical usage structures, which allow a reliable estimation of raw material content of most of directly imported raw materials (especially oil and gas). In order to estimate raw material contents of imports from EU-countries a similar approach is applied. The estimates of average coefficients are usually available for the EU (FL matrix). However, for many EU-countries the production technology largely differs from the EU average. This especially accounts for electricity generation and the share of secondary metal within the metal production. Thus, a partial multi-regional model was also applied for the EU-region. This model considers country-specific information for the 27 EU member states such as the energy mix and secondary metal share. This approach takes into account the most significant differences of production technology within the EU.

For the base year 2010, the base model provides a complete, consistent and empirically sound description of the flows of goods and raw materials in the German economy based on a high-resolution IOT. New system conditions are simulated by parameter variations such as changes in production technologies, e.g. substitution of fossil fuel power plants by renewable energy based plants, increase of electro mobility (production sector of personal and heavy-good vehicle as well as use phase within the projection year), changes in construction sector towards resource efficient construction materials and construction technologies, changes in recycling rates differentiated by material groups and so forth. The logical consistency and coherence of the model is fully ensured even after parameter variations. Thus, the derived system states each embody consistent system descriptions.

The results show the material demand and the derived material productivity in the prospected year. The results are analysed by the effects of each change of technology and consumption pattern and furthermore by the impact of the aging of the population and by the change of consumption pattern due to an assumed increase of average income. In addition, the model allow an analyses of the material flows into each of the differentiated 41 category of final demand by the 56 materials and material groups, and reports the use of secondary flows (of biomass, plastics, metals and minerals) for material recycling and for energetic purposes.

In the project, the overall difference between the scenarios shows that a technology-oriented dematerialization policy can contribute to both: A reduction in primary raw material use and an increase in total raw material productivity. More than the indicator material productivity the method and the model itself are important in the MinFuture context as they allow comprehensive and detailed analysis of material input flows by the differentiated 274 sectors and by 41 final use categories. For example, not only the extraction of the 56 material groups (according to Eurostat) is included as it is done by most EW-MFA models; URMOD allocates the material groups in a high resolution of the sectors throughout the economy on a high quality empirical basis. For example, the input flows into the iron, aluminium; copper (and so forth) processing industries are highly differentiated as well as further processing industries such as vehicle production. Furthermore, the input flows into different service sectors such as ITC-using sectors or medicine can be differentiated which is often times subsumed in only one service sector; but given the projection of important changes in information technologies, the material input flows of service sectors will change significantly. The differentiation of the use categories allows the analyses of the yearly input flows into, amongst other, a high variety of infrastructure sub-categories such as wind power plants, grids, road or track construction (both, with and without electricity supply); it allows the projection of material input flows into conventional vehicles versus electric vehicles, both: personal cars as well as trucks, busses and so forth.

The model is currently further developed to calculate Germany's material demand assuming the '*Energiewende'* and further policies, particularly in the field of resource efficiency, will be fully implemented. In this context, emissions are integrated as well in URMOD, thus the model can be called environmentally extended.

Source: Dittrich, M.; Schoer, K.; Sartorius, C.; Kämper, C.; Ludmann, S.; Marscheider-Weidemann, F.; Ewers, B.; F.; Giegrich, J.; Hummen, T. (forthcoming 2017): Strukturelle und produktionstechnische Determinanten der Ressourceneffizienz: Untersuchung von Pfadabhängigkeiten, strukturellen Effekten und technischen Potenzialen auf die zukünftige Entwicklung der Rohstoffproduktivität (DeteRess). Heidelberg/ Wiesbaden/ Karlsruhe. On behalf of the Federal Environment Agency of Germany.

5.6 Case Study 6: Economy-wide material flow accounting (EW-MFA)

Weizs et al. (2006) investigated what determines observed differences in economy-wide material use among the EU-15 member states in 1970-2001. Steinberger et al. (2010) presented a global material flow dataset compiled for the year 2000, covering 175 countries, including both extraction and trade flows, quantified the variability and distributional inequality in international material consumption and measured the influence of the drivers' population, GDP, land area and climate on material consumption. West and Schandl (2013) provided the first broad based estimate of material use and material efficiency for Latin America in 1970-2008 and examined main drivers of material consumption change using and IPAT framework. Kovanda and Weinzettel (2013) presented a comparison of EW-MFA indicators compiled for the Czech Republic for 1995-2010 and argued that the calculation of indicators, which include raw material equivalents, was useful, as it provided some important information, which was not obvious from imports, exports and domestic material consumption indicators. West et al. (2014) studied the effect of dissolution of the Soviet Union on material consumption in its successor states and examined influence of the different starting conditions of three nations on the development path they subsequently followed, and the attendant socio-metabolic profiles, which resulted. Raupova et al. (2014) assessed the physical dimensions of Uzbekistan's economy during 1992–2011 with the use of EW-MFA indicators and showed that although national economic performance showed particularly remarkable success, indicators measuring material inputs reveal an insignificant increase during the period of study. Schaffartzik et al. (2014) traced patterns and trends in material flows for six major geographic and economic country groupings and world regions in 1950-2010 as well as their contribution to the emergence of a global metabolic profile during a period of rapid industrialization and globalization. Infante-Amate et al. (2015) reconstructed the main EW-MFA indicators for the Spanish economy between 1860 and 2010 and showed that from 1960 onward, the country saw a very rapid industrial transition based on the domestic extraction of quarry products and the import of fossil fuels and manufactured goods. Kovanda (2017) went beyond standard emission and waste statistics and calculated total residual output flows of the Czech Republic in 1990-2014 based on EW-MFA indicators. He identified a few major driving forces behind the development of the indicators, including changes in the structure of the economy, changes in the structure of TPES, technological change, advances in waste management, and changes in the agricultural system of the Czech Republic. Dong et al. (2017) examined a development of EW-MFA indicators in China, South Korea and Japan in

1970-2008 and identified reasons for differences in resource efficiency, productivity and consumption patterns in these countries.

A common feature of all above studies is an effort to relate EW-MFA indicators to various socio-economic factors like population, economic performance, technological change, structure of the economy, structure of TPES and others and to various policy measures, which have been adopted over the period of monitoring the indicators. This is crucial for understanding the dynamics of the indicators and for management of future material flows and their environmental impacts. From the viewpoint of the MinFuture context, it is important so that all common methodologies developed for monitoring material flows were able to capture the relation between material flows and socio-economic factors/policy measures in order to be useful tools for transition towards more sustainable modes of consumption and production.

5.7 Case Study 7: use of waste from tailing dumps – ZG Bolesław

ZGH Boleslaw SA is one of the largest companies processing zinc in Poland. Company conducts zinc and lead ore mining in Olkusz Pomorzany mine. Excavated output is transported to the mechanical processing, where with flotation process concentrates of zinc and lead are obtained. Zinc concentrates are directed to the smelters, where with pyro and hydrometallurgical process ZGH is obtaining metallic zinc and zinc alloys. Mining-metallurgical sector cannot exist without the production and storage of waste. The Olkusz Pomorzany mine is source for poor ore with approx. 4% total content of Zn + Pb. Department of Mechanical Processing in Olkusz converts it and sends in the form of concentrates to the smelters, but almost 60% of material that is delivered to smelters are flotation tailings, (combination of water with crushed rock) that are later transport to the tailing ponds - a waste facility. Technological waste produced by the metallurgical process line are almost entirely used within the ZGH Boleslaw capital group.

Table 9: Technological waste of ZGH Boleslaw.

The total mass of ZGH Boleslaw technological waste by type of waste and methods of dealing with	Unit of measure (thousands)	2015
The total mass of waste, including:	Mg/r	1 500,3
hazardous waste	Mg/r	54,0
non-hazardous waste	Mg/r	1 446,3
Total weight of waste by dealing methods, including:	Mg/r	1 500,3
recovery	Mg/r	1462,0
mining waste stored on-site disposal	Mg/r	38,3

Industry mining and processing is rarely associated with progress and innovation that would fundamentally change its face in the short term. Led by ZGH Boleslaw SA activity indicates, however, that it could be otherwise. Commitment to research and development in company is accompanied almost since its inception, which is confirmed by the implementation of technological solutions and implementation of projects aimed at maintaining high standards of environmental protection; increase in technological efficiency and with reduction of production costs. The current activity of the company is focused on improving the efficiency of production processes, the development of technology in the waste processing with protection of the resource base (concentrates and scrap) in the context of the liquidation of the mine. The primary objective pursued by ZGH Boleslaw SA waste management is to maximize use of waste from its own production lines at all stages of production to recovery zinc and associated metals within ZGH Boleslaw SA capital group. This approach maximizes amount of main metal used by company, (zinc) and associated metals in the framework of its technical and technological potential.

An example of the efficient processing own and foreign zinc wastes (sludge of zinc and metallurgical dust) is a zinc-lead concentrate (zinc oxide) produced in the re-rolling process in rotary kilns (Waelz process) in Boleslaw Recycling Ltd (The company is part of the ZGH Boleslaw capital group). The concentrate is an additional input of raw materials for the production zinc metal in RLE (Roast-Leach-Electrowin) and ISP (Imperial Smelting Process) technologies in zinc smelter in Miasteczko Slaskie SA (company is part of the ZGH Boleslaw capital group). Produced in rotary technology kiln slag is used as a filling material in the opencast mining areas (own and foreign). At the production stage of zinc, metal waste is produced according to the RLE technology, which, depending on the chemical composition are transported for further processing (recovery). Zinc sludges are subjected to flotation enrichment which purpose is production of collective concentrate of Zn-Pb-Ag, as a result waste are transported to the final processing rotary kilns in Boleslaw Recycling Ltd. While dross zinc, cadmium and sludge lead sulfate waste are transported to smelters to recover zinc, lead and cadmium.

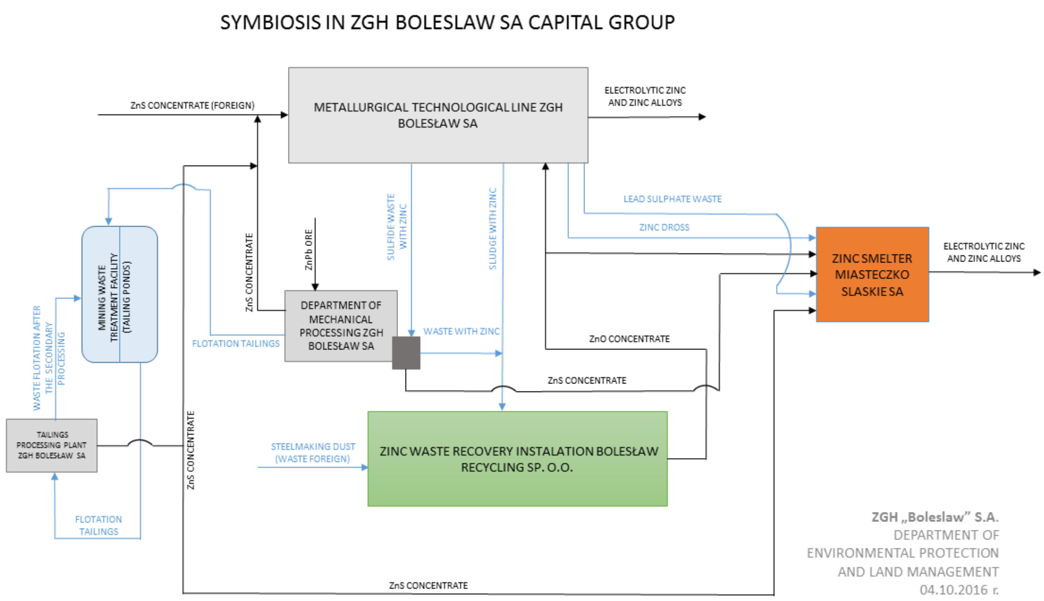


Figure 9: Symbiosis in ZGH Boleslaw SA Capital Group.

ZGH Boleslaw SA treats raw materials policy and builds its future on that priority in all its activities. Currently implemented measures confirm the possibility of maximum use of zinc waste materials to deliver products of quality that is not resigning with products from natural raw materials. This action and is a plan for the future due to gradual depletion of ZGH Boleslaw SA own natural resources of Zn-Pb ores. To meet this challenge ZGH Boleslaw SA based on its own-patented technology started secondary process of tailings deposited in tailings ponds. Construction and commissioning of technical and technological tailings processing plant (ZPOP) is unique - not only in the country but also in the world - this technology will allow to produce zinc concentrates from tailings deposited in tailings ponds

Their production is based on enrichment of tailings, which resources are considerable and contrary to the ore. They do not require high cost operations such as crushing or pre-enrichment, developed technological scheme includes a preliminary classification of waste for the bifurcation of the coarse fraction, grinding of this fraction and classification for the separation for mud fractions, and then a separate flotation fraction of mud and grinding fraction. The final step in the process is cleaning flotation, where we obtain the final product - the zinc concentrate. It will be used as an additional input for ZGH Boleslaw SA smelters. This action is an example of the maximum use of the available waste as a raw material in accordance with the principle of sustainable development.

5.8 Case Study 8: Flows and stocks of critical materials in the European Economy

The following example illustrates the need for indicators to capture the flows and stocks of critical raw materials in the European economy. Indeed, a comprehensive data inventory of the materials flows in industry and society would be essential to get the solid ground for informed discussion and decision making on supply of raw materials. Such data on the quantity and quality of raw materials in each life cycle stage would allow more decisions that provide balanced, secure and sustainable supply throughout the entire materials flows.

It is based on the following publication:

- Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials (Bio By Deloitte for DG GROW, 2015)

The main objective of this exercise is to respond to the needs of information on non-energy material flows and to assist the European Commission on the development of a full Material System Analysis (MSA) for several key raw materials in the European Union. Within the framework of this exercise, the MSA consists of:

- a map of the flows of material through the European economy (EU28), as raw materials or as parts of basic materials, components or products, in terms of:
- entries into the economy (extraction and import),
- movements through the economy (production, consumption, export),
- additions to stock,
- and end of life,
- additional information related to security of supply (company concentration, country concentration…), substitutes, future supply and demand changes of materials.

The MSA includes the entire life cycle of materials, including exploration, extraction, processing, manufacturing, use and end of life through either disposal or recovery. Upstream to the MSA elaboration, several steps have to be carried out:

- a review of literature and data sources potentially usable for MSA (including for example geological surveys databases, Eurostat PRODCOM and ComExt databases, industry reports, commercial datasets and reports, life cycle assessment case studies…),

- an evaluation of the identified datasets from the viewpoint of their usability for the MSA of the materials studied (including for example an assessment of their frequency of update, their reliability, their conditions of use in terms of Intellectual Property Rights, their cost…),
- an identification of the main data gaps,
    - securing a consistent use of terms and definitions in the field of MSA,
    - defining the common list of parameters and the flow chart constituting the MSA of the different materials studied,
    - defining calculation formulas for some specific parameters,
    - establishing a procedure to prioritize and validate existing data sources for MSA,
    - establishing a procedure to fill data gaps by techniques of approximation from existing sources or expert consultation,
    - developing a structure for storing and displaying information on the MSA in an Excel file (data sources, assumptions, calculations and results) and in a Sankey diagram,
    - assessing the possibility to establish future routines to facilitate updates for relevant information.

The content of the MSA is specified by:

- a list of parameters,
- a flow chart, which can be displayed with detailed and simplified Sankey diagrams,
- and a reference unit.

The list of parameters validated by the European Commission's services to be studied in the MSA includes 52 required parameters and 11 optional parameters divided in 3 groups:

- Group 1 parameters = parameters representing physical flows and stocks of a material (such as reserves in EU, imports to EU of products…),
- Group 2 parameters = parameters relating to policy objectives and criticality (such as governance risk supply, economic importance…),
- Group 3 parameters = parameters relating to future supply and demand change (such as resources in EU, future demand…).
- All the parameters are defined with a code including:
- a capital letter referring to the life cycle step (A to G, A for Exploration, B for extraction, C for processing, D for manufacture, E for Use, F for Collection and G for Recycling),
- a first number referring to the group of the parameter (1 to 3),
- and an incremental number.
- The parameters are described in Annex 3B.
- The flow chart of the MSA aims to give a visual presentation of the flow and stock parameters (group 1 parameters).
- The flow chart is presented in 10.
- Based on this general flow chart, detailed and simplified Sankey diagrams specific to each studied material are developed. These Sankey diagram allow:
- to show the results of the flow parameters, with the width of the arrows displayed proportionally to the flow quantity,

- to present the results of the stock parameters, with the value of the stock and the annual addition to this stock.

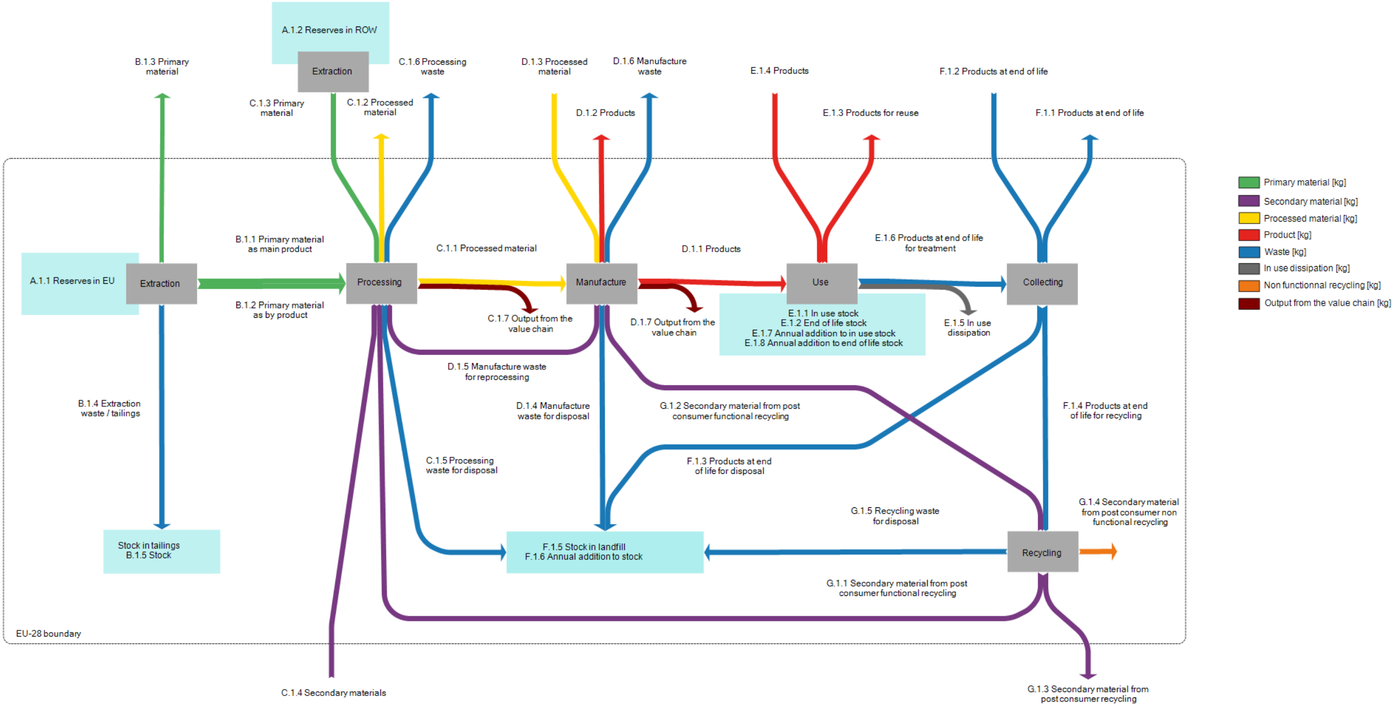


Figure 10: Flow chart of the MSA presenting the flow and stock parameters (group 1 parameters).

6 Conclusions and recommendations

The characterization of the MFA methods used in the context of raw materials is summarized in Table 10. Albeit a great advantage of MFA or SFA consists in the level of detailed information that it can provide (compared to EW-MFA), in the context of MinFuture it would be desirable the establishment of a standardized system definition in the four dimensions of MFA. This implies, for instance, a precise definition of the life cycle stages, the required layers, as well as the methodology for estimating outflows in a prospective modelling approach. Regarding the life cycle stages, there is great heterogeneity in the literature, and important flows, such as losses and dissipation are not widely addressed. In the layers dimension, in particular, a multi-level approach is needed, including environmental and economic aspects, in order to address the MFA or SFA in a holistic manner. In addition to this, at the "substance" layer, we find that it would be valuable information to account the quality of the substance in addition to the quantity. This is especially relevant for critical substances, which otherwise would be negligible, and therefore dismissed, in a mass flow context. As has been described by the various examples and case studies in this document, MFA models can be used to serve different purposes in raw material management such as monitoring systems or evaluating alternative strategies.

However, regardless of the MFA methods used, MFAs need to include the components depicted in Figure 11. The components are structured hierarchically, indicating that the robustness of the components at higher levels depends on the robustness of the ones at the lower levels.

Figure 11: The hierarchical pyramid of MFA components.

Systems represent the totality of the stocks and flows within boundaries defined in space and time at a chosen level of (dis-) aggregation. They include observed and unobserved stocks and flows. Adding a system definition to observed data adds information: Systems define the context of observed flows and they allow for calculation of unobserved flows using mass balance.

Data form the foundation of MFAs. They represent observations of either stocks (at a given point in time) or flows (over a given time period).A finding of this report is the lack of raw material data available in a centralized database. Data is often kept hidden in government, commercial and academic databases and remains inaccessible to the outside world. Therefore, the compiling of data for static SFAs involves much manual work and many different and sometimes conflicting data sources. The often results in SFA studies with limited scope or clear gaps in the data. It is important that this shortcoming of data accessibility is acknowledged and acted upon as part of the MinFuture project, not only to ensure that the quality of the data but to allow greater insight and analysis to be carried out in future studies. One approach to address this issue, which is employed Cullen and colleagues at Cambridge University, is to provide comprehensive Supporting Information documents with every journal paper, sometime up to 80 pages in length, to provide complete traceability and repeatability of the data and study. A recent example is the global petrochemical map Levi and Cullen (2017), where for the first time, a comprehensive picture of the sector has been provided outside of the commercial databases. Every data values and source for the study is included in the Supporting Information and the data set has been uploaded to an open database. The MinFuture project needs to consider this issue of providing a centralized and comprehensive database or repository where academics and companies can share and analyse the complex nature of MFA/SFA data.

Models in this context are mathematical representations of material cycles. They reflect the system definition and the drivers of cycles such as population growth or technologies used. They are used to simulate MFA-based trends and developments. **Scenarios** are assumptions of plausible future cycles that are consistent with the mass balance principals and the assumed drivers. They can be used to make forecasts or to evaluate the effectiveness of alternative strategies.

Uncertainty is inherent in all MFAs of historical or future cycles due to errors in system definitions and the data used. Approaches to uncertainty analysis aim at making uncertainties transparent and reducing them. They enable the modeller to make assumptions that are more robust and become aware of the model’s strengths and limitations.

Indicators stand for quantitative measures that aim to reflect the status of complex systems. They are used to analyse and compare performance of businesses, sectors or economies across countries and to determine policy priorities. The use of indicators in policymaking is very tricky. On the one hand, one indicator should provide a basis to control a complex system but in the other hand, few well-intended but poorly selected indicators may not be able to capture the relevant parts of the system. A poorly chosen set of indicators may lead to a situation where industry makes large efforts to reach the targets, but this has detrimental side effects on other parts of the system. One example for this is the EU's ELV Directive, which sets targets for "reuse & recycling" and "reuse & recovery". Compliance with these targets requires a focus on the most relevant bulk materials, thereby neglecting critical raw materials that are used in small amounts, and it entirely omits quality considerations of the materials recycled. For this reason, a recommendation of this report is that raw material indicators that are used in policy should consider the physical quality and criticality of the materials, as was described in section 4.3.4 "Criticality indicators."

Further, the MinFuture workshop 'Enhancing data robustness on global level' at the end of November 2017 highlighted that indicators are needed to represent both the goal and the means to achieve goals. Indicators should primarily provide information if goals are achieved and secondarily, how they will be achieved. Hence, there is a need to differentiate between goals (e.g. increase resource efficiency, reduce environmental impact) and the means to reach that goal (i.e. increase recycling, use renewable energy). In general, there is a trend for a service-oriented economy and indicators should reflect this shift from owning to using. For example, people are not interested in having natural gas to heat their house, but they are interested in having a warm house. Consequently, materials are not in focus but the service these materials provide.

Different stakeholders should be able to understand the definition of the indicators and loopholes must be closed, so that indicators should not me be miss-used. Quantitative physical indicators need to be complemented - a set of different indicators for different purposes should be used together: environmental, financial, social indicators. Another recommendation by MinFuture is to complement indicators with a consistent monitoring of the socio-economic metabolism (SEM) by government authorities. This would have several advantages:

- The individual indicators can be defined using MFA
- The selection of the indicators in an indicator set can be adjusted to the properties of the system
- MFAs can be used to reflect on the reasons for certain regions to reach the required levels easily while other regions have difficulties to reach them.
- MFA scenarios can be used in order to test the usefulness and the effectiveness of different indicators / indicator sets.
- These scenarios help to identify potential synergies and goal conflicts between individual indicators.

Concluding it is important to do not rely entirely on indicators. It is not possible to represent the systemic nature of metal cycles with only indicators. Policy and decision makers need to have an understanding of the system in focus.

VISUALISATION

Visualisations are different maps of complex systems. They can inform decision making in industry and government, by visualizing status and historical trends, and potential future developments under different conditions. Visualization tools are developed to support the recording (monitoring), exploration (analysis), and explanation (interpretation) of information.

Table 10: Summary of the characterization of the MFA methods.

MFA Approach	Attributes					
	Four dimensions				Transversal	
	(i) Stages	(ii) Trade	(iii) Layers / Linkages	(iv) Time	Data (Availability, Requirements, Type of analysis, Visualization, Uncertainty)	General (Purpose, Decision making, Shortcomings)
Stationary & quasi-stationary Substance Flow Analysis	Flexible system definition All life cycle (primary mining, raw material production, product manufacturing, use and waste management)	Flexible system definition Global Region Country City	Substance Multi-layer approach: Product End-use sector Energy Exergy (Thermodynamic Rarity) Environmental aspect	Stationary Quasi-stationary Retrospective	No database (heterogeneous sources) Generation rates and composition of products, transfer coefficients of technologies Top-down / Bottom-up Sankey diagram Different uncertainty analysis approaches	Resource conservation and environmental protection Data availability and reliability, heterogenity in the covered processes, treatment of uncertainty
Dynamic Substance Flow Analysis	Flexible system definition All life cycle (primary mining, raw material production, product manufacturing, use and waste management)	Flexible system definition Global Region Country City	Substance Multi-layer approach: Product End-use sector Energy Exergy (Thermodynamic Rarity) Environmental aspect	Stationary Quasi-stationary Retrospective Prospective (lifetime distribution function)	No database (heterogeneous sources) Generation rates and composition of products, transfer coefficients of technologies Top-down / Bottom-up Sankey diagram Different uncertainty analysis approaches	Resource conservation and environmental protection Data availability and reliability, heterogenity in the covered processes, dynamic modeling approach, treatment of uncertainty
Stationary & quasi-stationary Material Flow Analysis	Flexible system definition All life cycle (primary mining, raw material production, product manufacturing, use and waste management)	Flexible system definition Global Region Country City	Material Multi-layer approach: Product End-use sector Energy Exergy (Thermodynamic Rarity) Environmental aspect	Stationary Quasi-stationary Retrospective	No database (heterogeneous sources) Generation rates and composition of products, transfer coefficients of technologies Top-down / Bottom-up Sankey diagram Different uncertainty analysis approaches	Resource conservation and environmental protection Data availability and reliability, heterogenity in the covered processes, treatment of uncertainty
Dynamic Material Flow Analysis	Flexible system definition All life cycle (primary mining, raw material production, product manufacturing, use and waste management)	Flexible system definition Global Region Country City	Material Multi-layer approach: Product End-use sector Energy Exergy (Thermodynamic Rarity) Environmental aspect	Stationary Quasi-stationary Retrospective Prospective (lifetime distribution function)	No database (heterogeneous sources) Generation rates and composition of products, transfer coefficients of technologies Top-down / Bottom-up Sankey diagram Different uncertainty analysis approaches	Resource conservation and environmental protection Data availability and reliability, heterogenity in the covered processes, dynamic modeling approach, treatment of uncertainty
Economy wide Material Flow Accounting	Standardized system definition All life cycle (primary mining, raw material production, product manufacturing, use and waste management)	Standardized system definition Region Groups of countries Country City	Total mass of different materials Environmental aspect (emissions, waste, losses and dissipation)	Quasi-stationary Retrospective	Significant number of databases (Eurostat, UNEP) Extraction, production, imports, exports, emissions, waste, losses and dissipation Various types of charts (line, column, area and cake charts) Uncertainty analysis is not in-built (Eurostat quality assurance)	Monitoring material basis of national economies, the material and resource productivity, and the implications of trade and globalisation Static picture for a certain time frame, direct link to environmental impacts is missing
Multiregional Input Output Analysis	Standardized system definition All life cycle (primary mining, raw material production, product manufacturing, use and waste management)	Standardized system definition Region Groups of countries Country City	Total mass of different materials Environmental aspect (emissions, waste, losses and dissipation)	Quasi-stationary Retrospective	Significant number of databases (WIOD, Exiobase) Extraction, production, imports, exports, emissions, waste, losses and dissipation (Higher data requirements than EW-MFA as full extraction data and high resolution Input-Output tables are needed) Various types of charts (line, column, area and cake charts) Uncertainty analysis is not in-built.	Monitoring material basis of national economies, the material and resource productivity, and the implications of trade and globalisation Static picture for a certain time frame, direct link to environmental impacts is missing

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8 Annex

Annex 1. Characterization scheme for MFA approaches.

	MFA approach	Person who prepared this information	Case study of application	Is data available in database?	Field of employment / Purpose	Material / Substance	Spatial level	Time Interval	Covered Processes	Type of analysis	Modeling approach	Data requirements	How is data visualized	End-use sector categories / products	Lifetime modeled as	Losses, dissipation included	Environmental Aspects	Handling of data uncertainty	Contribution to decision-making	Shortcomings
1	Static SFA	Gara Villalba, Marta Iglesias (UAB)	Licht, C; Talens, L.; Villalba, G. (2015) Global Substance Flow Analysis of Gallium, Germanium, and Indium – Quantification of Extraction, Uses, and Dissipative Losses within their Anthropogenic Cycles. Journal of Industrial Ecology 19(5): 890-903. DOI: 10.1111/jiec.12287	No	To evaluate recovery potential in various life cycle stages, to quantify use-stock, end-of-life stock, future demand versus supply	Gallium, Germanium, Indium	Global	2011	Primary mining Production/Fabrication Use	Top-down	Retrospective, year 2011 Lifetime data in literature	Amounts extracted from all sources; amounts in intermediate and end uses; life time of products that embody the substance	Sankey diagrams	Metals are accounted for intermediate and end-uses. The end-use sectors are: mobile phones, LCD, LED, phosphorus applications, photovoltaic panels, defense applications, lasers, R&D, defense.	Average lifetime constant over time	dissipative and recoverable losses are accounted for during entire life cycle of metals.	Not considered (losses are not quantied in terms of air, water emissions, etc).	Data comes from heterogeneous sources, official statistics (i.e USGS), scientific models, or expert estimations. No statistical method employed because data are isolated values. Uncertainty intervals of concentrations for extraction.	Identifies which substance is most critical for recovery, which life cycle stage is most inefficient and has biggest opportunities for improving resource efficiency	Provides a static picture for a certain time frame Offer no information about the dynamics of resource use and resulting changes in stocks and flow.
2	Static SFA	Gara Villalba, Marta Iglesias (UAB)	Talens Peiro, L., Villalba, G., Ayres, R. (2013). "Material flow analysis of scarce metals: sources, functions, end-uses and aspects for future supply." Environmental Science & Technology, 47 (6), pp 2939–2947.26. DOI: 10.1021/es301519c	No	To illustrate the industrial metabolism from sources to products, and potential future recycling	Cobalt, Gallium, Germanium, Indium, Niobium, Molydebnum, Rhenium, Selenium, Tantalum, Tellurium, PGMs, and REEs	Global	2010	Primary mining Production/Fabrication Use	Top-down	Retrospective, year 2010 Lifetime data in literature	Amounts extracted from all sources; amounts in intermediate and end uses; unit sales; market share; life time of products that embody the substance; EoL recycling rate	Flow diagrams and tables	Metals are accounted for intermediate and end-uses. The end-use sectors are: electric and electronical devices, electric vehicles, internal combustion vehicles, glass products, LCDs, plasma panels, lighting, PV panels, wind turbines, magnetic resonance imaging, magnetic cooling, cemented carbides	Average lifetime constant over time	dissipative and recoverable losses are accounted for during extraction and refining	Not considered (losses are not quantied in terms of air, water emissions, etc).	Data comes from heterogeneous sources, official statistics (i.e USGS), scientific models, or expert estimations. No statistical method employed because data are isolated values.	Provides insight on the limitations and potential of the future supply from primary sources and end-products. Shows the products that concentrate higher amounts of scarce metals and pose more interest for recycling. Challenges for recovering the metals in terms of collection rates and product design (dissipative uses).	Static picture for a certain time frame. Offer no information about the dynamics of resource use and resulting changes in stocks and flow.
3	Static SFA	Gara Villalba, Marta Iglesias (UAB)	Talens Perio, L, Villalba G., Ayres, R. (2013) Lithium: sources, production, uses and recovery outlook. The Journal of The Minerals, Metals & Materials Society. 65 (8) 986-996. DOI: 10.1007/s11837-013-0666-4	No	To describe the estimated reserves and production (including the material and energy requirements), the current uses, and opportunities for recovery and recycling and the future demand forecast.	Lithium	Global	2011	Primary mining Production/Fabrication Use Waste Management	Top-down/Bottom-up	Retrospective, year 2011 Lifetime data in literature	Amounts extracted from all sources; amounts in intermediate and end uses; unit sales; market share; life time of products that embody the substance; EoL recycling rate	Flow diagrams and tables	Metals are accounted for intermediate and end-uses. The end-use sectors are: aluminum, casting, ceramics and glass, lubricants and greases, batteries, rubber and thermoplastics, pharmaceuticals, air treatment, catalyst, absorber, sanitation, solutions	Average lifetime constant over time	Dissipative uses	Not considered (losses are not quantied in terms of air, water emissions, etc).	Data comes from heterogeneous sources, official statistics (i.e USGS), scientific models, or expert estimations. No statistical method employed because data are isolated values.	Presents dissipative and non-dissipative uses. Shows the future increase in the demand for batteries (specially for electric vehicles), and the potential recovery and recycling from this application, in order to ensure long-term viability of the metal.	Static picture for a certain time frame. Offer no information about the dynamics of resource use and resulting changes in stocks and flow.
4	Static SFA	Gara Villalba, Marta Iglesias (UAB)	Talens, L; Villalba G., (2013) Material and energy requirement for extraction and refining of Rare Earth Metals. The Journal of The Minerals, Metals & Materials Society. 65 (10) 1327-1340 DOI: 10.1007/s11837-013-0719-8.	No	To estimate the material and energy requirements for the production based on the theoretical chemical reactions and thermodynamics.	REEs	Global		Primary mining Production/Fabrication		Retrospective	REO grade (%) from mines; amounts extracted from reserves; material and energy input, as well as recovery yield of each process					Not considered (losses are not quantied in terms of air, water emissions, etc).	Data comes from heterogeneous sources, official statistics (i.e USGS), scientific models, or expert estimations. No statistical method employed because data are isolated values.	Material and energy requirements varies greatly depending on the type of mineral ore, production facility, and benefitiation process. Greatest loss occurs during mining and benefitiation. Improving recovery yields involves a significant reengineering of extraction and refining processes.	Based on current technologies, which are generally confidential and off limits in terms of process information. These estimates are based on process descriptions and thermodynamics. Information about the composition of gangue minerals and tailings is hard if not impossible to find.
5	Dynamic SFA	Gara Villalba, Marta Iglesias (UAB)	Rademaker, J.; Klejn, R.; Yang, Y. (2013) Recycling as a Strategy against Rare Earth Element Criticality: A Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling. Environmental Science and Technology, 47, 10129−10136 DOI: 10.1021/es305007w	No	Future demand and supply (virgin and secondary)	Neodymium, Dysprosium	Global EU-27	2011-2030	Use Waste Management	Bottom-up	Prospective, individual consumption scenarios Historical data Lifetime data in literature	Unit sales; market share of the technologies; amounts in end uses; life time of products; collection rate		3 products (key main end-uses of permanent magnets): wind turbines, hybrid and electric vehicles, and hard disk drives in personal computers.	Average lifetime constant over time	No	Not considered (losses are not quantied in terms of air, water emissions, etc).	Data comes from heterogeneous sources (industrial reports, scientific articles, sales forecasts, expert opinions).	Indication of the end-of-life recycling maximum potential yield. Secondary supply constitutes a substantial part of the total demand in the long term. It is required the development of recycling technology and infrastructure.	Confidential information of composition; Current collection rate is not considered in some sectors; Some end-uses are not considered.
6	Dynamic SFA	Gara Villalba, Marta Iglesias (UAB)	Habib, K.; Wenzel, H. (2014) Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. Journal of Cleaner Production, 84 (2014) 348-359 DOI: 10.1016/j.jclepro.2014.04.035	No	Future demand and supply (virgin and secondary). Reserves depletion with/without recycling until 2100.	Neodymium, Dysprosium	Global	2007-2050	Use Waste Management	Bottom-up	Prospective, individual consumption scenarios Historical data Lifetime data in literature	Unit sales; market share of the technologies; amounts in end uses; life time of products; collection rate; recycling yield; reserves; supply		Main end-uses: wind turbines, electric vehicles, electric bicycles, computers, electric motors, audio systems	Average lifetime constant over time	No	Not considered (losses are not quantied in terms of air, water emissions, etc).	Data comes from heterogeneous sources (industrial and official reports, scientific articles, sales forecasts, expert opinions).	BAUD projected primary supply is not enough to meet the forecasted future demand. Recycling is not able to reduce the demand for virgin material in the short-to-medium term due to the long lifetimes of end-use products. The depletion of these reserves is not a concern for several hundred years ahead. The supply risk issue is found to be a bottleneck issue of opening new mines at an accelerated rate to satisfy the future high demand in the period from now until 2050	Future potential production is based on simple projection of the historical mining data from 1995 to 2010; Assumptions in recycling rates; It is assumed the reserve value of 2011 (constant).
7	Dynamic SFA	Gara Villalba, Marta Iglesias (UAB)	Hoenderdaal, S.; Tercero Espinosa, L.; Marscheider-Weidemann, F.; Graus, W. (2012) Can a dysprosium shortage threaten green energy technologies?. Energy, 49 (2013) 344-355 DOI: 10.1016/j.energy.2012.10.043	No	Projected demand and recycling	Dysprosium	Global	2010-2050	Use Waste Management	Bottom-up	Prospective, individual consumption scenarios Historical data Lifetime data in literature	Unit sales; market share of the technologies; amounts in end uses; life time of products; recycling rate; reserves; supply		Main end-uses: electric vehicles, DD-wind turbines, industrial motors, computers (HDD, DVD, CD), speakers, MLCC, Terfenol-D	Average lifetime constant over time	No	Not considered (losses are not quantied in terms of air, water emissions, etc).	Data comes from heterogeneous sources (industrial and official reports, scientific articles, sales forecasts, expert opinions).	In the short term (up to 2020) a deficit is expected as demand is likely to outgrow supply. Insuficient supply is due to production capacity, not to absolute geological reserves.	Estimated future production (some production rates are considered constant). Unknown reserves. Assumptions in recycling rates. Country metal shares in the ore are used to calculate the output of a mine in that country.
8	Dynamic MFA/SFA	Gara Villalba, Marta Iglesias (UAB)	Schulze, R.; Buchert, M. (2016) Estimates of global REE recycling potentials from NdFeB magnet material. Resources, Conservation and Recycling, 113 (2016) 12-27 DOI: 10.1016/j.resconrec.2016.05.004	No	Global recycling potential from end-of-life magnets from different applications and industrial scrap	NdFeB, Neodymium, Praseodymium, Dysprosium, Terbium	Global	2020-2030	Production/Fabrication Use Waste Management	Top-down/Bottom-up	Prospective, individual consumption scenarios Historical data Lifetime distribution	Unit sales; market share of the technologies; amounts in end uses; life time of products; collection rate; disassembly rate; recycling yield; process material efficiency in production stage.		Main end-uses of permanent magnets: electric two-wheelers, air conditioners, (H)EVs, MRI scanners, wind generators, HDD, acoustic transducers, separators	Normal distribution	Losses from Waste Management stage	Not considered (losses are not quantied in terms of air, water emissions, etc).	Data comes from heterogeneous sources (industrial and official reports, scientific articles, sales forecasts, expert opinions).	Te most important NdFeB application groups in terms of recycling potentials are identified. Recycling will have a significant contribution in the midterm (2030) Global supply of secondary NdFeB material from pre-consumer sources is likely to exceed the potential supply from EoL magnets.	Data quality of metal content in EoL applications. Historical production data was not available for some applications. Assumptions in values of collection rates, disassembly rates and recycling yields, and are kept constant for all years considered.
9	Static SFA	Gara Villalba, Marta Iglesias (UAB)	Guyonnet, D.; Planchon, M.; Rollat, A.; Escalon, V.; Tuduri, J.; Charles, N.;Vaxelaire, S.; Dubois, D.; Fargier, H. (2015) Material flow analysis applied to rare earth elements in Europe. Journal of Cleaner Production, 107 (2015) 215-228 DOI: 10.1016/j.jclepro.2015.04.123	No	Flows and stocks, taking into account both primary and secondary sources (year 2010), and identifying imports, losses and recycling potentials.	Neodymium, Praseodymium, Dysprosium, Terbium, Europium, Yttrium	European Union	2010	Primary mining Production/Fabrication Use Waste Management Landfill/Environment	Top-down/Bottom-up	Retrospective, year 2010 Lifetime data in literature	Imports/exports; Geological resources in Europe; amounts in intermediate and end uses; unit sales; market share; life time of products that embody the substance; EoL recycling rate		Intermediate and end-uses: fluorescent lamp phosphors, permanent magnets, NiMH batteries	Average lifetime constant over time	Losses from Waste Management stage	Not considered (losses are not quantied in terms of air, water emissions, etc).	Data comes from heterogeneous sources (industrial and official reports, scientific articles, sales forecasts, expert opinions).	Future supply from recycling and geoligical resources in Europe.	Static picture for a certain time frame. Data are best estimates based on available (and sometimes conflicting) information.
10	EW-MFA	Kovanda, Jan (CUNI)	Helga Weisz, Fridolin Krausmann, Christof Amann, Nina Eisenmenger, Karl-Heinz Erb, Klaus Hubacek, Marina Fischer-Kowalski, The physical economy of the European Union: Cross-country comparison and determinants of material consumption, Ecological Economics, Volume 58, Issue 4, 1 July 2006, Pages 676-698, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2005.08.016	Yes	Material extraction, material consumption, physical trade balance, material efficiency, assessment of determinants of material use	Biomass, Fossil fuels, Industrial minerals, Construction minerals	European Union	2000	Primary mining, Agricultural production, Forestry, Fishery, Production/Fabrication	Top-down/Bottom-up	Retrospective, year 2000	Extraction of raw materials, agricultural production, wood logging, fish catch, imports and exports of raw materials and manufactured commodities	Column charts	Total end-use of the economy		No	Indication of environmental pressure realted to material use, indication of domestic waste potential	Data mostly comes from official statistics, no method for assessment of uncertainties applied	Management of resource use and environmenal pressures, foreign trade dependency	Static picture for a certain time frame. Direct link to environmental impacts is missing.
11	EW-MFA	Kovanda, Jan (CUNI)	Julia K. Steinberger, Fridolin Krausmann, Nina Eisenmenger, Global patterns of materials use: A socioeconomic and geophysical analysis, Ecological Economics, Volume 69, Issue 5, 15 March 2010, Pages 1148-1158, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2009.12.009.	Yes	Material extraction, material consumption, physical trade balance, material efficiency, assessment of determinants of material use	Biomass, Fossil fuels, Industrial minerals/Ores, Construction minerals	Global	2000	Primary mining, Agricultural production, Forestry, Fishery, Production/Fabrication	Top-down/Bottom-up	Retrospective, year 2000	Extraction of raw materials, agricultural production, wood logging, fish catch, imports and exports of raw materials and manufactured commodities	Plot charts	Total end-use of the economy		No	Indication of environmental pressure realted to material use, indication of domestic waste potential	Data mostly comes from official statistics, no method for assessment of uncertainties applied	Management of resource use and environmenal pressures, foreign trade dependency	Static picture for a certain time frame. Direct link to environmental impacts is missing.
12	EW-MFA	Kovanda, Jan (CUNI)	James West, Heinz Schandl, Material use and material efficiency in Latin America and the Caribbean, Ecological Economics, Volume 94, October 2013, Pages 19-27, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2013.06.015.	Yes	Material extraction, material consumption, physical trade balance, material efficiency, assessment of determinants of material use	Biomass, Fossil fuels, Industrial minerals/Ores, Construction minerals	Latin America countries	1970-2008	Primary mining, Agricultural production, Forestry, Fishery, Production/Fabrication	Top-down/Bottom-up	Retrospective, years 1970-2008	Extraction of raw materials, agricultural production, wood logging, fish catch, imports and exports of raw materials and manufactured commodities	Line and column charts	Total end-use of the economy		No	Indication of environmental pressure realted to material use, indication of domestic waste potential	Data mostly comes from official statistics, no method for assessment of uncertainties applied	Management of resource use and environmenal pressures, foreign trade dependency	Static picture for a certain time frame. Direct link to environmental impacts is missing.
13	EW-MFA	Kovanda, Jan (CUNI)	Jan Kovanda, Jan Weinzettel, The importance of raw material equivalents in economy-wide material flow accounting and its policy dimension, Environmental Science & Policy, Volume 29, May 2013, Pages 71-80, ISSN 1462-9011, http://doi.org/10.1016/j.envsci.2013.01.005.	No	Material extraction, material consumption, physical trade balance, material efficiency, calculation of raw material equivalents, assessment of determinants of material use	Biomass, Fossil fuels, Metal ores, Non-metallic minerals	Czech Republic	1995-2010	Primary mining, Agricultural production, Forestry, Fishery, Production/Fabrication	Top-down/Bottom-up	Retrospective, years 1990-2010, environmentally extended input-output modelling	Extraction of raw materials, agricultural production, wood logging, fish catch, imports and exports of raw materials and manufactured commodities	Line and area charts	Total end-use of the economy		No	Indication of environmental pressure related to material use	Data mostly comes from official statistics, no method for assessment of uncertainties applied	Management of resource use and environmenal pressures, foreign trade dependency	Static picture for a certain time frame. Direct link to environmental impacts is missing.
14	EW-MFA	Kovanda, Jan (CUNI)	James West, Heinz Schandl, Fridolin Krausmann, Jan Kovanda, Tomas Hak, Patterns of change in material use and material efficiency in the successor states of the former Soviet Union, Ecological Economics, Volume 105, September 2014, Pages 211-219, ISSN 0921-8009, http://doi.org/10.1016/j.ecolecon.2014.06.013.	No	Material extraction, material consumption, physical trade balance, material efficiency, assessment of determinants of material use	Biomass, Fossil fuels, Industrial minerals/Ores, Construction minerals	Former Soviet Union countries	1992-2008	Primary mining, Agricultural production, Forestry, Fishery, Production/Fabrication	Top-down/Bottom-up	Retrospective, years 1992-2008	Extraction of raw materials, agricultural production, wood logging, fish catch, imports and exports of raw materials and manufactured commodities	Line and column charts	Total end-use of the economy		No	Indication of environmental pressure realted to material use, indication of domestic waste potential	Data mostly comes from official statistics, no method for assessment of uncertainties applied	Management of resource use and environmenal pressures, foreign trade dependency	Static picture for a certain time frame. Direct link to environmental impacts is missing.
15	EW-MFA	Kovanda, Jan (CUNI)	Ozoda Raupova, Hirotsugu Kamahara, Naohiro Goto, Assessment of physical economy through economy-wide material flow analysis in developing Uzbekistan, Resources, Conservation and Recycling, Volume 89, August 2014, Pages 76-85, ISSN 0921-3449, http://doi.org/10.1016/j.resconrec.2014.05.004.	No	Material extraction, material consumption, physical trade balance, assessment of determinants of material use	Biomass, Fossil fuels, Industrial minerals/Ores, Construction minerals	Uzbekistan	1992-2011	Primary mining, Agricultural production, Forestry, Fishery, Production/Fabrication	Top-down/Bottom-up	Retrospective, years 1992-2011	Extraction of raw materials, agricultural production, wood logging, fish catch, unused domestic extraction, imports and exports of raw materials and manufactured commodities, indirect flows associated to imports	Line and column charts	Total end-use of the economy		No	Indication of environmental pressure realted to material use, indication of domestic waste potential	Data mostly comes from official statistics, no method for assessment of uncertainties applied	Management of resource use and environmenal pressures, foreign trade dependency	Static picture for a certain time frame. Direct link to environmental impacts is missing.
16	EW-MFA	Kovanda, Jan (CUNI)	Anke Schaffartzik, Andreas Mayer, Simone Gingrich, Nina Eisenmenger, Christian Loy, Fridolin Krausmann, The global metabolic transition: Regional patterns and trends of global material flows, 1950–2010, Global Environmental Change, Volume 26, May 2014, Pages 87-97, ISSN 0959-3780, http://doi.org/10.1016/j.gloenvcha.2014.03.013.	No	Material extraction, material consumption, physical trade balance, material efficiency, assessment of transition from agrarian to industrial regimes	Biomass, Fossil fuels, Industrial minerals/Ores, Construction minerals	Global, world regions	1950-2010	Primary mining, Agricultural production, Forestry, Fishery, Production/Fabrication	Top-down/Bottom-up	Retrospective, years 1950-2010, discrete data	Extraction of raw materials, agricultural production, wood logging, fish catch, imports and exports of raw materials and manufactured commodities	Line and column charts	Total end-use of the economy		No	Indication of environmental pressure realted to material use, indication of domestic waste potential	Data mostly comes from official statistics, assessment of uncertainties by comparison with similar studies	Management of resource use and environmenal pressures, foreign trade dependency	Static picture for a certain time frame. Direct link to environmental impacts is missing.
17	EW-MFA	Kovanda, Jan (CUNI)	Infante-Amate, J., Soto, D., Aguilera, E., García-Ruiz, R., Guzmán, G., Cid, A. and González de Molina, M. (2015), The Spanish Transition to Industrial Metabolism: Long-Term Material Flow Analysis (1860–2010). Journal of Industrial Ecology, 19: 866–876. doi:10.1111/jiec.12261	No	Material extraction, material consumption, physical trade balance, assessment of transition to transition from agrarian to industrial regimes	Biomass, Fossil fuels, Ores, Non-metallic minerals	Spain	1860-2010	Primary mining, Agricultural production, Forestry, Fishery, Production/Fabrication	Top-down/Bottom-up	Retrospective, years 1860-2010	Extraction of raw materials, agricultural production, wood logging, fish catch, imports and exports of raw materials and manufactured commodities	Line and column charts	Total end-use of the economy		No	Indication of environmental pressure realted to material use, indication of domestic waste potential	Data mostly comes from official statistics, simple assessment of data reliability included	Management of resource use and environmenal pressures, foreign trade dependency	Static picture for a certain time frame. Direct link to environmental impacts is missing.
18	EW-MFA	Kovanda, Jan (CUNI)	Jan Kovanda, Total residual output flows of the economy: Methodology and application in the case of the Czech Republic, Resources, Conservation and Recycling, Volume 116, January 2017, Pages 61-69, ISSN 0921-3449, http://doi.org/10.1016/j.resconrec.2016.09.018.	No	Emission flows, dissipative flows, unused domestic extraction, assessment of determinants of output material flows	Output flows including all materials	Czech Republic	1990-2014	Primary mining, Agricultural production, Forestry, Fishery, Production/Fabrication, Consumption	Top-down/Bottom-up	Retrospective, years 1990-2014	Emissions to air, emissions to water, landfilled waste, dissipative uses and losses, unused extraction from mining and quarrying, unused extraction from biomass harvest, soil excavation and dredging	Line, area and column charts	Total end-use of the economy		Yes, inclusion of dissipative uses and dissipative losses	Indication of environmental pressures realted to output flows of th economy	Data mostly comes from official statistics, assessment of uncertainties included	Management of emission flows	Static picture for a certain time frame.

	MFA approach	Person who prepared this information	Case study of application	Is data available in database?	Field of employment / Purpose	Material / Substance	Spatial level	Time Interval	Covered Processes	Type of analysis	Modeling approach	Data requirements	How is data visualized	End-use sector categories / products	Lifetime modeled as	Losses, dissipation included	Environmental Aspects	Handling of data uncertainty	Contribution to decision-making	Shortcomings
19	EW-MFA	Kovanda, Jan (CUNI)	Liang Dong, Ming Dai, Hanwei Liang, Ning Zhang, Nabeel Mancheri, Jingzheng Ren, Yi Dou, Mingming Hu, Material flows and resource productivity in China, South Korea and Japan from 1970 to 2008: A transitional perspective, Journal of Cleaner Production, Volume 141, 10 January 2017, Pages 1164-1177, ISSN 0959-6526, http://doi.org/10.1016/j.jclepro.2016.09.189.	Yes	Material extraction, material consumption, physical trade balance, material efficiency, assessment of determinants of material use	Biomass, Fossil fuels, Industrial minerals/Ores, Construction minerals	China, South Korea, Japan	1970-2008	Primary mining, Agricultural production, Forestry, Fishery, Production/Fabrication	Top-down/Bottom-up	Retrospective, years 1970-2008	Extraction of raw materials, agricultural production, wood logging, fish catch, imports and exports of raw materials and manufactured commodities	Line, column and cake charts, maps	Total end-use of the economy		No	Indication of environmental pressure realted to material use, indication of domestic waste potential	Data mostly comes from official statistics, no method for assessment of uncertainties applied	Management of resource use and environmenal pressures, foreign trade dependency	Static picture for a certain time frame. Direct link to environmental impacts is missing.
20	Static economy-wide input-output model (physical and monetary)	Dittrich, Monika (IFEU)	Schoer, K., Dittrich, M., Kovanda, J., Weinzettel, J., Ewers, B., Moll, S., Bouwmeester, M. (2016): Eurostat Documentation of the EU RME Model, December 2016, URL: http://ec.europa.eu/eurostat/documents/1798247/6191533/Documentation-EU-RME-model/		Calculation of raw material use (RMC, RMI) within the European Union including raw material equivalents of imports and exports	52 raw material categories	European Union	2000-2014	Domestic extraction, use (production, imports and exports, share of secondary material - flows)	Top-down (input-output analysis)	Retrospective, time series 2000-2014	Disaggregated input-output tables, trade data, share of secondary material, electricity mix in countries of origin…		282 sectors/product groups	None	Indirectly (share of secondary materials included)	Not considered	Data basically from statistical offices, additional data comes from heterogeneous sources	Current raw material use and productivity including raw materials required for the production of imports and exports	Partly confidential information which cannot be published; data quality of some of the data sources; partly regionalized production technologies
21	Static economy-wide input-output model (physical and monetary)	Dittrich, Monika (IFEU)	Dittrich, M., Schoer, K., Kämper, C., Ludmann, S., Ewers, B., Giegrich, J., Sartorius, C., Hummen, T., Marscheider-Weidemann, F. (forthcoming): Structural and technical determinants of resource efficiency: analysis of path dependencies, structural effecs and technological potentials on the future development of raw material productivity (DeteRess). On behalf of UBA, Germany. Heidel-berg/Wiesbaden/Karlsruhe.		Projected raw material use (RMC, RMI) measured in raw material equivalents of Germany in 2030 based on different scenarios/implementation of policies	52 raw material categories	Germany	2010, 2020, 2030	Domestic extraction, use (production, imports and exports, share of secondary material - flows)	Top-down (input-output analysis)	Prospective, Economy-wide scenarios based on use structure and production technology in 2010	Disaggregated input-output tables (partly based on confidential data), trade data, share of secondary material, electricity mix in countries of origin, material efficiency improvement potential, assumptions on economic development (growth,		274 sectors/product groups	Exogenous assumption - either constant or assumption of one-time increase due to technological improvement	Indirectly (share of secondary materials included)	Not considered	Main data source from statistical bodies; additional data comes from heterogeneous sources	Estimation of the impact of specific measures on raw material demand and efficiency (e.g. technological improvements and implementation of material efficiency policies)	partly confidential information which cannot be published; Static IOT, changes modeled with exogenous assumptions; no underlying endogenous economic model and model assumptions
22	Static Dynamic SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Buchner, H., Laner, D., Rechberger, H., and Fellner, J. (2015): Dynamic Material Flow Modeling: An Effort to Calibrate and Validate Aluminum Stocks and Flows in Austria. Environmental Science & Technology 49: 9 5546-5554.	No	to develop a calibrated dynamic model of Austrian Al flows from 1964 to 2012 for determining in-use stocks and scrap flows	Aluminum	Austria	1964-2012	Production, Processing, Manufactoring, In-Use, Waste management, Scrap market	Bottom-up	Retrospective, year		Sankey diagrams	Scrap trade (processing scrap, manufacturing scrap, old scrap		collection losses, processing losses	Not considered (losses are not quantied in terms of air, water emissions, etc).	Yes (Parameter uncertainties are evaluated using MCS)	to understand national Al consumption and scrap generation and utilization and serve as a basis to derive recommendations for administrative and regulatory authoritie	From the comparison of national with aggregated (global) models, it can be stated that certain flows such as EOL export or exports of empty and filled packaging are potentially only captured on a national level since they are not reported in official (aggregated) statistics. Especially for countries within an open trade area (e.g., European Union), these flows are relevant in view of the total Al turnover.
23	Static SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Buchner, H., Laner, D., Rechberger, H., and Fellner, J. (2014): In-depth analysis of aluminum flows in Austria as a basis to increase resource efficiency", Resources, Conservation and Recycling. Resources, Conservation and Recycling 93: 112-123.	No	to establish the Austrian Al budget for the year 2010 as a basis for anthropogenic resource management.	Aluminum	Austria	2010	Production, Processing, Manufactoring, In-Use, Waste management, Scrap market	Bottom-up	Retrospective, year		Sankey diagrams	Transport, Buildings and Infrastructure, Mechanical Engineering, Electrical Engineering, Consumer products, and Packaging.	specific Weibull lifetime, average lifetimes	collection losses, processing losses	Not considered (losses are not quantied in terms of air, water emissions, etc).	Yes (Hedbrant and Sörme, 2000).	conclusions about the utility of MFAs on a national level for Al resource management and an outlook on future research activities are provided	
24	Dynamic SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Buchner, H., Laner, D., Rechberger, H., and Fellner, J. (2015b): Future Raw Material Supply: Opportunities and Limits of Aluminium Recycling in Austria. Journal of Sustainable Metallurgy 1: 1-10.	No	to promote sustainable production by using secondary raw material from existing material stocks, complementary to primary raw material, information about the future availability of secondary resources constitutes a prerequisite	Aluminum	Austria	2010-2050	Production, Processing, Manufactoring, In-Use, Waste management, Scrap market	Bottom-up	Historical data and forecasting of of in-use stocks and old scrap generation (stock-driven or an input-driven approach)		Sankey diagrams	Transport, Buildings and Infrastructure, Mechanical Engineering, Electrical Engineering, Consumer products, and Packaging.	Average lifetimes	collection losses, processing losses	Not considered (losses are not quantied in terms of air, water emissions, etc).	Yes (parameter uncertainties (historical model)and scenario uncertainties	A mix of old scraps from different applications could therefore lead to undesirable levels of certain alloy elements present in the scrap, which would put a limit on the maximum amount of old scrap to be used in secondary production.	an increasing self-supply via old scrap may result in unsuitable alloy compositions for remelting, which was not considered in the present study
25	Static MFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Kral, U., Lin, C.-Y., Kellner, K., Ma, H.-W., and Brunner, P. H. (2014): The Copper Balance of Cities. Journal of Industrial Ecology 18: 3 432-444.	No	to analyze and evaluate the Cu flows and stocks on an urban scale, present and compare the results for two cities	Copper	Vienna and Taiwan	2008/2009	Urban Industry, Transport and Energy, Vehicles, Private Household, Waste management, Waste water treatment	Bottom-up	Retrospective, year 2008/2009		Sankey diagrams	-	Average lifetimes	Yes (soil, water and air)	Yes (soil, water and air)	Yes (Hedbrant and Sörme, 2000).	Rapid growth in a young city such as Taipei is characterized by low amounts of Cu stocks and relatively high annual stock increases. In contrast, Cu stocks in older Vienna are relatively high, and thus the relative stock change is smaller than in Taipei.	
26	Static MFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Ott, C. and Rechberger, H. (2012): The European phosphorus balance. Resources, Conservation and Recycling 60: 159-172.	No	to develop an SFA model for the EU15 and adopt it to the special requirements for an EU15 wide analysis	Phosphorus	Europe (EU 15)	one year (2006-2008)	Industry and Trade, Consumption, Waste water treatment, Agriculture, Waste management)	Top-down/Bottom-up	Retrospective, year	five key processes and 36 flows	Sankey diagrams	-	Average lifetimes	Yes to water and air	Yes (water and air)		provides a general understanding of the flows and stock changes in the EU15. Further research to develop tailor-made strategies for an optimized P management considering economic, technical and environmental constraints should focus on the regional level by establishing and analyzing substance flow analyses of P balances at the regional scale (country or smaller).	
27	Static MFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Van Eygen, E., Feketitsch, J., Laner, D., Rechberger, H., and Fellner, J. (2016): Comprehensive analysis and quantification of national plastic flows: The case of Austria. Resources, Conservation and Recycling1-12.	No	to connect the sources (e.g. imports), the pathways (e.g. transfer coefficients from manufacturing to consumption) and the intermediate (e.g. consumption) and final sinks (e.g. waste management) of materials	Plastic (household)	Austria	2010	Chemical industry, trade of primary plastics, Manufacturing and preparation, Trade and distribution, collection and sorting	Top-down/Bottom-up	Retrospective, year 2010	total material household of plastics in Austria different processes were used	Sankey diagrams	Packaging, Furniture, Household Goods, Building and Construction, Agriculture, Others, Transport, Medicine, Non-plastic Applications, Electronic#	Average lifetimes	Yes (air, landfill)	Yes (air)	Yes (Laner,Feketitsch, Rechberger and Fellner 2015)	total flows of plastics in a region highlights the most relevant streams. Especially for waste management, it is crucial to know what kind of waste streams are generated, on a qualitative and quantitative basis. In connection with the stocks and lifespans of the various products, predictions for future waste quantities can be made.	
28	Static SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Zoboli, O., Laner, D., Zessner, M., and Rechberger, H. (2016b): Added Values of Time Series in Material Flow Analysis: The Austrian Phosphorus Budget from 1990 to 2011. Journal of Industrial Ecology 20: 6 1334-1348.	No	to identify and assess the extent of the temporal changes that occurred in the system during the last two decades	Phosphorus	Austria	1990-2011	Animal husbandry, Crop farming, Forestry, Chemical industry, Industry, Water bodies, Consumption, Waste management, Waste water management,	Top-down	Retrospective 20 years	64 flows (plant products, fertilizer, animal waste….)	Sankey diagrams	-	-	Yes	Yes (water and soil)	Yes (Hedbrant and Sörme, 2000).	detailed description of the P balance has considerable value as decision support tool for resource and waste management. First, they could identify and detect negative trends of flows, stocks, efficiencies, and recovery rates. Second, they could monitor the effectiveness of regulations and directives. Last, they could aid in optimizing the national data collection by identifying the specific contribution of different areas to the uncertainty of the	
29	Static SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Egle, L., Zoboli, O., Thaler, S., Rechberger, H., and Zessner, M. (2014): The Austrian P budget as a basis for resource optimization. Resources, Conservation and Recycling 83: 152-162.	No	To develop a national P balance	Phosphorus	Austria	one year (2004-2008)	Animal husbandry, Crop farming, Forestry, Chemical industry, Industry, Water bodies, Consumption, Waste management, Waste water management,	Top-down	Retrospective, year	64 flows (plant products, fertilizer, animal waste….)	Sankey diagrams	-	-	Yes	Yes (water and soil)	Yes (Hedbrant and Sörme, 2000).	detailed description of the P balance has considerable value as decision support tool for resource and waste management. The results of this study will be the basis for the development of concepts and scenarios for future improvement options for P management, with a particular focus on recycling P from wastewater.	
30	Static SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Allesch, A. and Brunner, P. H. (2015): Material Flow Analysis as a Decision Support Tool for Waste Management - A Literature Review. Journal of Industrial Ecology 19: 5 753-764.	No	to demonstrate how MFA can be used as tool to design WM-systems, to point out how MFA can be applied as a base for assessment o in view of given objectives	Materials and C, Cd, Cr, Cu, Fe, Hg, N, Ni, P, Pb, Zn	Austria	2012	Waste management (collection, transport, treatment, landfill)	Top-down/Bottom-up	Retrospective, year		Sankey diagrams	Recycling product and refuse derived fuel	Average lifetimes	Yes	Emissions to air and water	Yes (Laner,Feketitsch, Rechberger and Fellner 2015)	to help understanding WM-systems and facilitate well-founded and goal-oriented decisions	Data limitations.
31	Static SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Spatari, S., Bertram, M., Fuse, K., Graedel, T. E., and Rechberger, H. (2002): The contemporary European copper cycle: 1 year stocks and flows. Ecological Economics 42: 1–2 27-42.	No	to capture at least 80% of relevant copper movement and use within continental Europe	Copper	Europe	1994	Production, Fabrication Use, Waste Management Landfill	Top-down/Bottom-up	Retrospective, year 1994	Imports/exports; Geological resources in Europe; amounts in intermediate and end uses, recycling rate	Sankey diagrams	-	-	Yes	No	Yes	most of the copper processed during the last few decades still resides in society, mostly in non-dissipative uses	However, the level of detail and availability of data for product manufacturing and waste management can be further elaborated upon and improved.
32	Static SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Rechberger, H. and Graedel, T. E. (2002): The contemporary European copper cycle: statistical entropy analysis. Ecological Economics 42: 1–2 59-72.	No	To introduce an alternative and useful method(statistical entropy analysis) for evaluating material flows only.	Copper	Europe	1994	Production, Fabrication Use, Waste Management Landfill	Top-down/Bottom-up	Retrospective, year 1994	Imports/exports; Geological resources in Europe; amounts in intermediate and end uses, recycling rate	Sankey diagrams	-	-	Yes	No	Yes	Statistical entropy is a tool that helps to visualize and quantify the characteristics of a system with regard to concentration versus dilution of a substance. Furthermore, it helps to better understand the substance's metabolism	It is not a methodological problem to include emissions into the atmosphere and hydrosphere in the statistical entropy analysis so long as emissions data are available. Until these data are derived, however, it cannot be predicted whether the emissions would be relevant for the copper cycle and its RSE.
33	Static SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Laner, D.; Rechberger, H.; Astrup, T. (2015) „Applying Fuzzy and Probabilistic Uncertainty Concepts to the Material Flow Analysis of Palladium in Austria", Journal of Industrial Ecology, 19, 0, p. 1-15, ISSN 1088-1980. DOI: 10.1111/jiec.12235	No	to investigate the effect of a rigorous uncertainty analysis on the evaluation of the Austrian Pd resource system	Palladium	Austria	2011	Use and Collection, Waste Management, Automotive Industry	Bottom-up	Retrospective, year 2011	Products and semifinished poducts, waste, recycling,	Sankey diagrams	-	-	Yes	Yes	Yes	The systematic evaluation of uncertainty in MFA is important to understand the robustness of material flow estimates, independent of the approach used for expressing uncertainty. No matter whether a traditional probabilistic or a fuzzy approach is used in the uncertainty analysis, the characterization of MFA data should be seen as a crucial step and needs to be as transparent as possible.	
34	Static SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Klinglmair, M.; Lemming, C.; Jensen, L.S.; Rechberger, H.; Astrup, T.F., Scheutz, Ch. (2015) "Phosphorus in Denmark: National and regional anthropogenic flows", Resources, Conservation and Recycling, Vol. 96, p. 311-324, dx.doi.org/10.1016/j.resconrec.2015.09.019, ISSN 0921-3449	No	to assess anthropogenic P flows for Denmark, both at the scale of the entire country and its economy, and on a smaller, regional level.	Phosphorus	Denmark	2011	Industry, Consumptopn, Waste water treatment, Agrigulture, Waste managmeent	Top-down/Bottom-up	Retrospective, year 2011		Sankey diagrams	-	-	Yes	Yes	Yes	Current potential amounts of recoverable P cannot be expected to change the reliance on mineral P.	
35	Static SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Graedel, T. E.; Beers, D. v.; Bertram, M.; Fuse, K.; Gordon, R. B.; Gritsinin, A.; Kapur, A.; Klee, R. J.; Lifset, R. J.; Memon, L.; Rechberger, H.; Spatari, S.; Vexler, D. (2004) "Multilevel Cycle of Antropogenic Copper", Environmental Science & Technology, 38 (4), p. 1242-1252	No	Goal has been to attempt to capture at least 80% of the magnitude of each flow stream by evaluating countries which extract, fabricate, and/or use significant quantities of copper.	Copper	54 countries	1994	Production, Fabrication Use, Waste Management Landfill	Top-down/Bottom-up	Retrospective, year 1994	Country level statistics on production (P), import (I), and export (E) (hereafter, designated as PIE data) of copper concentrate, blister copper, and copper cathode	Sankey diagrams	-	-	Yes	Yes	No	the first multilevel cycle for any of the elements dominated by human activity.	
36	Static SFA	Helmut Rechberger and Astrid Allesch (TU Wien)	Bertram, M., Graedel, T.E., Fuse, K., Gordon, R., Lifset, R., Rechberger, R., and Spatari, S. The copper cycles of European countries. Regional Environmental Change, 2003, Vol. 3, 119-127.	No	the goal was to capture at least 80% of relevant copper movement and use within continental Europe.	Copper	European countries	1994	Production, Fabrication Use, Waste Management Landfill	Top-down/Bottom-up	Retrospective, year 1994		Sankey diagrams	-	-	Yes	Yes	No	It turns out that there are aspects of the cycles that suggest different thinking about resource cycling as a function of spatial and governmental scale	An unfortunate aspect of the country-level analysis is that the results cannot be directly compared with European country-level copper cycles devised by others. Data limitations.
37	Static SFA	Jonathan Cullen (Ucam)	Cullen JM, Allwood JM (2010) The efficient use of energy: tracing the global flow of energy from fuel to service. Energy Policy, 38(1)75–81		Energy planning an decision making. Tracing energy flows from fuels through to final services.	Energy / Exergy	Global	2005	Energy sources Electricity generation Conversion devices Passive systems Final services	Top-down	Retrospective, year 2005	Energy/exergy flows for world. Breakdown by conversion devices (engines, motors, burners, etc), passive systems (vehicle, buildings, etc) and final services (transport, thermal comfort, illumination, etc)		Passenger transport, freight transport, strucutre, sustenance, hygiene, thermal comfort, communication , illumination		Allocation of energy/exergy only (losses not shown)	Global emissions from fossil fuels shown	Energy flows < 1EJ (exajoule) not shown	Scale of global energy flow from fuel to final service. Userd for targeting action to reduce emissions.	Static picture (although 1970 to current now mapped dyanmically). Losses not shown

	MFA approach	Person who prepared this information	Case study of application	Is data available in database?	Field of employment / Purpose	Material / Substance	Spatial level	Time Interval	Covered Processes	Type of analysis	Modeling approach	Data requirements	How is data visualized	End-use sector categories / products	Lifetime modeled as	Losses, dissipation included	Environmental Aspects	Handling of data uncertainty	Contribution to decision-making	Shortcomings
38	Static SFA	Jonathan Cullen (Ucam)	Cullen JM, Allwood JM (2010) Theoretical efficiency limits for energy conversion devices. Energy, 35(5)2059–2069		Energy planning an decision making. Analysing energy conversion efficiencies at the global level.	Energy / Exergy	Global	2005	Energy sources Electricity generation Conversion devices Useful energy/exergy Exergy losses	Top-down	Retrospective, year 2005	Energy/exergy flows for world. Breakdown by conversion devices (engines, motors, burners, etc), useful exergy (motion, heat, etc) and exergy losses (combusoin, heat transfer, other)		Useful exergy: motion, heat, cooling/light/sound		Allocation of energy/exergy with losses shown	Global emissions from fossil fuels shown	Energy flows < 1EJ (exajoule) not shown	Efficiency of the global energy system and the conversion of energy. Overall efficeincy of 11%. Exergy loss breakdown shown for the first time	Overall exergy efficiency is sometimes misunderstood, as many of the exergy losses cannot be reduced. The conversion device efficiencies are difficult to estimate
39	Static SFA	Jonathan Cullen (Ucam)	Cullen JM, Allwood JM, Bambach MD (2013) Mapping the global flow of steel: from steelmaking to end-use goods. Environmental Science and Technology, 46(24)13048–55		Mapping the steel system, including iron/steel flows, recycling, products	Iron, steel, scrap, products	Global	2008	Reduction Steelmaking Casting Rolling/Forming Fabrication End-use products	Top-down / bottom-up	Retrospective, year 2008 Modelling for allocation to end-use products, and yield losses	Material flows for steel, iron, scrap, semi-products, products		Vehicles, Indsutrial equipent, Construction, Metal Goods		Yield losses included		Mass flows <1Mt (million tonnes) not shown	Scale of steel system flows. Linking steelmaking to final products. Used for material efficiency mitigation calculations	Static picture for 2008. Data for steel scrap collection and breakdown of end-use categories needs work
40	Static SFA	Jonathan Cullen (Ucam)	Cullen JM, Allwood JM (2013) Mapping the global flow of aluminum: from liquid aluminum to end-use goods. Environmental Science and Technology, 47(7)3057−64		Mapping the aluminium system, including aluminium, scrap and product flows	Aluminium, scrap, products	Global		Electrolysis/Melting Casting (Wrought/Cast) Rolling/Forming/Casting Fabrication End-uses	Top-down / bottom-up	Retrospective, year 2007 Modelling for division between wrought and cast aluminium, yield losses and recycling flows	Material flows for aluminium, scrap, semi-products, products		Vehicles, Indsutrial equipent, Construction, Metal Goods		Yield losses included		Mass flows <0.1Mt (million tonnes) not shown	Scale of aluminium system flows. Linking aluminium product to final products. Used for material efficiency mitigation calculations.	Static picture for 2007. Data for cast aluminium processes is limited.
41	Static SFA	Jonathan Cullen (Ucam)	Bajzelj B, Allwood JM, Cullen JM (2013) Designing climate change mitigation plans that add up. Environmental Science and Technology, 47(14) 8062–9		Mapping the global green house gas emissions, and allocation to human activity	Greenhouse gases (CO2, CH4, N2, F-gases)	Global		Emissions Fuel Final energy Device Equipment Sector Final service	Top-down	Retrospective, year 2010			GHG emissions, and linkages to human activities		Allocation only.		GHG flows <0.1 GtCO2e not shown	Impact of human activity on GHG emissions. Highlighted the importance of food and meat in GHG emissions.	Static picture for 2010. Complicated Sankey.
42	Static SFA	Mariane Planchon (Deloitte)	Dominique Guyonnet, Mariane Planchon, Alain Rollat, Victoire Escalon, Johann Tuduri, et al..Material flow analysis applied to rare earth elements in Europe. Journal of Cleaner Production, Elsevier, 2015, 26 p.	Yes, internal data at Deloitte	Mapping the rare earths flows and stock in the EU	Rare earths : Nd, Eu, Tb, Y	EU28	2012	Lithosphere, separation, fabrication, manufacture, use, waste management, landfill and environment	Top-down / bottom-up	Retrospective, year 2012	Material flows and stocks for primary and secondary products, semi-finished and finished products	STAN sankey diagram	all	lifespan of representative products	losses and dissipation along the value chain included	landfill and losses dissipated in the environment	uncertainties due to data, uncertainty analysis was performed using the data reconciliation methodology proposed by Dubois et al. (2014). The interval limits are typically between 10 and 50% of the best	Scale of REE system flows. Linking REE to final products and urban mine	Static picture for 2012. Data for REE trade is extrapolated from aggregated trade codes.
43	Static SFA	Mariane Planchon (Deloitte)	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW.	Yes, internal data at Deloitte + future EC database	Mapping flows and stock in the EU of 21 materials (19 criticals from 2014 list + aggregates and lithium)	aggregates, Sb, Be, B, Cr, Co, coking coal, fluorspar, Ga, Ge, In, Li, Mg, magnesite, natural graphite, Nb, Pd, Pt, Rh, phosphate rock, Si, W, Eu, Tb, Nd, Dy, Er, Y, Pr	EU28	2012	Exploration, extraction, processing, manufacture, use, collecting, recycling	Top-down / bottom-up	Retrospective, year 2012	Material flows and stocks for primary and secondary products, semi-finished and finished products	E!Sankey diagram	all	lifespan of representative products	losses and dissipation along the value chain included	landfill and losses dissipated in the environment	uncertainties due to data, scoring 1-4 to assess data quality	Scale of critical materials system flows. Linking critical materials to final products and urban mine	Static picture for 2012. Data often lacking : hypothesis and extrapolation done
44	Static SFA	Mariane Planchon (Deloitte)	Ayres, R.U., 1989. Industrial metabolism technology and environment. National Academy Press, Washington, DC	No			Global													
45	Static SFA	Mariane Planchon (Deloitte)	Baccini, P., Brunner, H.P., 1991. Metabolism of the anthroposphere. Springer, New York	No			Global													
46	Dynamic SFA	Mariane Planchon (Deloitte)	Bader, H.P., Scheidegger, R., Wittmer, D., Lichtensteiger, T., 2011. Copper flows in buildings, infrastructures and mobiles: a dynamic model and its application to Switzerland. Clean Techn. Environ. Policy 13, 87-101	No	Mapping flows and uses of copper in construction sector	Cu	Global, Switzerland		all					construction, mobiles					application in Switzerland	
47	Static SFA	Mariane Planchon (Deloitte)	Bertram, M., Martchek, K.J., Rombach, G., 2009. Material flow analysis in the aluminium industry. Journal of Industrial Ecology 13(5), 650-654	No	Mapping flows of aluminium industry	Al	Global		Porcessing, Manufacture, Recycling											
48	Dynamic SFA	Mariane Planchon (Deloitte)	Bonnin, M., Azzaro-Pantel, C., Pibouleau, L., Domenech, S., Villeneuve, J. 2013. Development and validation of a dynamic material flow analysis model for French copper cycle. Chemical Engineering Research and Design, 91(8):1390–1402	No	Mapping flows of copper in France	Cu	France		all											
49	Static SFA	Mariane Planchon (Deloitte)	Brunner, P.H., Rechberger, H., 2004. Practical Handbook of Material Flow Analysis. Lewis Publishers	No			Global		all											
50	Static SFA	Mariane Planchon (Deloitte)	Du, X., Graedel, T.E., 2011a. Uncovering the global life cycles of the rare earth elements. Scientific Reports 1(145): 1-4.	No	Mapping flows of REE	REE	Global		all											
51	Static SFA	Mariane Planchon (Deloitte)	Du, X., Graedel, T.E., 2011b. Global rare earth in-use stocks in NdFeB permanent magnets. Journal of Industrial Ecology 15(6): 836-843	No	Defining in-use stocks of REE	REE	Global		all					NdFeB magnets						
52	Static SFA	Mariane Planchon (Deloitte)	Du, X., Graedel, T.E., 2011c. Global in-use stocks of the rare earth elements: a first estimate. Environ. Sci. & Technol. 45, 4096-4101.	No	Defining in-use stocks of REE	REE	Global		all											
53	Static SFA	Mariane Planchon (Deloitte)	Dubois, D., Fargier, H., Guyonnet, D., Ababou, M., 2014. A fuzzy constraint-based approach to data reconciliation in material flow analysis. International Journal of General Systems 43(8), 787-809	No	Data reconciliation and uncertainty	all	all													
54	Dynamic SFA	Mariane Planchon (Deloitte)	Hatayama, H., Daigo, I., Matsuno, Y., Adachi, Y., 2010. Outlook of the world steel cycle based on the stock and flow dynamics. Environ. Sci. Technol. 44, 6457-6463	No	Mapping flows and stocks of steel	Steel	Global		all											
55	Static SFA	Mariane Planchon (Deloitte)	Nansai, K., Nakajima, K., Kagawa, S., Kondo, S., Suh, S., Shigetomi, Y., Oshita, Y., 2014. Global flows of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt, and platinum. Envir. Sci. Technol. 48, 1391-1400	No	Mapping flows and stocks of critical metals in green technologies	Nd, Co, Pt	Global		all					low-carbon technologies						
56	Dynamic SFA	Mariane Planchon (Deloitte)	Park, J., Hong, S., Kim, I., Lee, J., Hur, T., 2011. Dynamic material flow analysis of steel resources in Korea. Resources, Conservation and Recycling 55, 456-462	No	Mapping flows and stocks of steel	Steel	Korea													
57	Static SFA	Mariane Planchon (Deloitte)	Reck, B.K., Chambon, M., Hashimoto, S., Graedel, T.E., 2010. Global stainless steel cycle exemplifies China's rise to metal dominance. Environ. Sci. & Technol. 44, 3940-3946	No	Mapping flows and stocks of steel	stainless steel	China													
58	Static SFA	Mariane Planchon (Deloitte)	Van Beers, D., van Berkel, R., Graedel, T.E., 2005. The application of material flow analysis for the evaluation of the recovery potential of secondary metals in Australia. Presented at the 4th Australian LCA Conference, Sydney, Australia, 23-25 February 2005	No	Evaluation of the recovery potential of secondary metals in Australia	Cu, Zn	Australia													

Annex 2. Characterization scheme for indicators.

Annex 2: MinFuture - Deliverable 3.2 (Work Package 3)

	Indicator	Person preparing this information	Description	Units	Reference	Life Cycle Stage	ion / Cluster (according to t	economic, reserv	(economic, reso	n rates of main	n rate of by-prod	extraction takes	action rate deve	tes in-use urban	cation of in-use	re demand deve	timates EoL sto	es location of Eo	EoL recycling rat	ctive waste, pro	extractive waste,	npurities, non-fu	on of Output from	ticality Assessme	Energy use	vironmental impa	Social impacts	Comments
1	EU share of global production	Marta Iglesias and Gara Villalba (UAB)	EU share of global raw materials production	% of world mining (t/t)	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Extraction	Raw materials in the global context	no	no	yes (as region)	yes (as region)	yes (as region)	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
2	Mining equipment exports	Marta Iglesias and Gara Villalba (UAB)	Net exports of mining equipment by world region	million USD	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Manufacture of end-products	Raw materials in the global context	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
3	Share of imports	Marta Iglesias and Gara Villalba (UAB)	Share of imports in the EU economy's use of raw materials Import dependence for selected raw materials	% of imports in EU compared to Direct Materials Input (million t/ million t)	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Processing Manufacture of end-products	Raw materials in the global context	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
	Geographical concentration and governance	Marta Iglesias and Gara Villalba (UAB)	Geographical concentration of raw material production and producer countries' governance levels	% production of the different producing countries	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Extraction	Raw materials in the global context	no	no	no	no	yes (country level)	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	yes	
	Export restrictions	Marta Iglesias and Gara Villalba (UAB)	Proportion of global supply subject to export restrictions for a selection of raw materials	%	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Extraction	Raw materials in the global context	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but it is a factor that influences the criticality	no	no	no	
	Domestic production	Marta Iglesias and Gara Villalba (UAB)	Domestic production (and extraction) of raw materials	million tonnes	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Extraction Processing	Competitiveness and innovation	no	no	yes (for domestic extraction)	yes (for domestic extraction)	yes (for domestic extraction)	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
	Value added and jobs	Marta Iglesias and Gara Villalba (UAB)	Value added at factor cost and number of jobs for raw materials economic sectors	Billion € Million jobs	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Processing Manufacture of end-products Recycling	Competitiveness and innovation	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	
	Corporate R&D investment	Marta Iglesias and Gara Villalba (UAB)	Annual R&D investment for companies with their headquarters in the EU (by top companies in the raw materials sector and by public organisations)	Million €	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Processing Manufacture of end-products Recycling	Competitiveness and innovation	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	
	Patent applications	Marta Iglesias and Gara Villalba (UAB)	Number of raw materials patent applications from EU-28 Member States (and compared to international reference countries) Porportion of patents by type of applicant (company, university, individual, …)	Number of patent applications %	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Processing Manufacture of end-products Recycling	Competitiveness and innovation	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	
	Knowledge and skills	Marta Iglesias and Gara Villalba (UAB)	Number of educational programmes related to raw materials by country Qualification levels and participation in education and training in the EU mining and quarrying sector	Number of educational programms %	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Processing Manufacture of end-products Recycling	Competitiveness and innovation	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	
	Mining activity in the EU	Marta Iglesias and Gara Villalba (UAB)	Geographic location and approximate production size of metal mines in the EU	tonnes	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Extraction	Framework conditions for mining	yes (EU countries)	yes (EU countries)	yes (EU countries)	yes (EU countries)	yes (EU countries)	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
	Minerals exploration	Marta Iglesias and Gara Villalba (UAB)	Metallic mineral exploration in the EU per development stage / Mineral deposits, occurrences and showings / Exploration budget	Development stage / tonnes / Billion USD	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Exploration	Framework conditions for mining	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
	National minerals policy framework	Marta Iglesias and Gara Villalba (UAB)	Policy perception index and Investment Attractiveness Index	%	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Exploration Extraction	Framework conditions for mining	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
	Public acceptance (of mining)	Marta Iglesias and Gara Villalba (UAB)	Public perception of the various types of company to behave responsibly towards society	%	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Exploration Extraction	Framework conditions for mining	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	
	Material flows in the circular economy	Marta Iglesias and Gara Villalba (UAB)	Circular use of raw materials in the EU economy (supply from recycled materials)	million tonnes	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Recycling	Circular economy and recycling	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
	Recycling's contribution to meeting materials demand	Marta Iglesias and Gara Villalba (UAB)	EoL recycling input rate (EoL-RIR)	%	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Collection Recycling	Circular economy and recycling	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	no	no	no	no	no	no	
	WEEE management	Marta Iglesias and Gara Villalba (UAB)	Collection, reuse and recycling of WEEE	kg per capita	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Collection Recycling	Circular economy and recycling	no	no	no	no	no	no	no	no	no	yes	yes (EU countries)	yes (EoL of WEEE)	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
	Trade in secondary raw materials	Marta Iglesias and Gara Villalba (UAB)	Net exports of secondary raw materials	million tonnes million €	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Collection Recycling	Circular economy and recycling	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	Covers only the legal exports of waste materials (but amount of illegally exported waste is significant)
	Air emissions	Marta Iglesias and Gara Villalba (UAB)	Emissions of greenhouse gases and other air pollutant emissions from the production of raw materials in the EU	million tonnes CO2 eq million tonnes TOFP eq	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Extraction Processing	Environmental and social sustainability	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but emissions are correlated with energy use	yes, with the emissions the environmental impacts can be calculated	no	
	Water	Marta Iglesias and Gara Villalba (UAB)	Water use from the production of raw materials in the EU		European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Extraction Processing	Environmental and social sustainability	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	yes, with the water use the water footprint can be calculated	no	No suitable data are readily available
	Extractive waste management	Marta Iglesias and Gara Villalba (UAB)	Waste from the extraction and processing of minerals	million tonnes	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Extraction Processing	Environmental and social sustainability	yes (size of extractive waste)	yes	no, but it is related to the extraction efficiency	no, but it is related to the extraction efficiency	yes, where extractive waste is generated	no	no	no	no	no	no	no, in this case, interesting to determine the recycling from extractive waste	yes (if it is known the composition of the metal in the extractive waste)	yes (if it is known the composition of the metal in the extractive waste)	no	no	no	no, but energy use during extraction is correlated with extractive waste	yes, related to generation of waste, toxic substances, …	no	Insufficient data for a comprehensive and accurate analysis of extractive waste generation and its environmental and economic implications. Potential data sources are EU projects ProSUM and SmartGround.
	Sustainable wood supply	Marta Iglesias and Gara Villalba (UAB)			European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Extraction Processing	Environmental and social sustainability	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no mineral indicator
	Occupational safety	Marta Iglesias and Gara Villalba (UAB)	Incidence rate of non-fatal accidents of the raw materials sector	Accidents per 100.000 employees	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Extraction Processing	Environmental and social sustainability	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	
	Sustainability reporting	Marta Iglesias and Gara Villalba (UAB)	Raw materials companies publishing GRI reports	Number of companies	European Union (2016) Raw Materials Scoreboard. https://bookshop.europa.eu/en/raw-materials-scoreboard-pbET0416759/	Extraction Processing	Environmental and social sustainability	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	
	Material Consumption	Marta Iglesias and Gara Villalba (UAB)	Amount of raw materials that are consumed per year in a process	tonnes	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13696	Processing Manufacture of end-products	Material flows	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
	Material Input per Service Unit	Marta Iglesias and Gara Villalba (UAB)	Amount of materials used to produce a product taking into account its whole life cycle	tonnes / tonnes	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13697	Processing Manufacture of end-products	Material flows	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	It can be applied at national and corporate level. It is not vey spread in the EU industry, and remains of marginal use. It can be used as a resource efficiency measurement to compare products or services.
	Recycled Content	Marta Iglesias and Gara Villalba (UAB)	Proportion of recycled/reused materials that are incorporated into the product or production chain and helps quantify the reduction in the use of new materials.	%	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13698	Processing Manufacture of end-products	Material flows	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
	Specific Consumption	Marta Iglesias and Gara Villalba (UAB)	Use of a particular material in a process.	tonnes / tonnes	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13699	Processing Manufacture of end-products	Material flows	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
	Embodied Energy and Cumulative Energy Demand	Marta Iglesias and Gara Villalba (UAB)	Energy needed to manufacture a product using the Life Cycle Approach.	J or KWh	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13700	Processing Manufacture of end-products	Energy use	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	
	Exergy Indicators (Exergy, Exergy Accounting and Cumulative Exergy Consumption)	Marta Iglesias and Gara Villalba (UAB)	Measurement of quality of any resource. These indicators help detect inefficiencies and irreversibilities in processes.	J	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13701	Processing Manufacture of end-products	Energy use	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	
	Energy Intensity Factor	Marta Iglesias and Gara Villalba (UAB)	Ratio of the energy used to a finantial value, such as business turnover, value added, GDP, etc. Secondary energy should be converted to the primary energy content.	GJ/€ Turnover	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13702	Processing Manufacture of end-products	Energy use	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	

Indicator	Person preparing this information	Description	Units	Reference	Life Cycle Stage	ion / Cluster (according to t	economic, reserv	(economic, reso	n rates of main	n rate of by-prod	extraction takes	action rate deve	tes in-use urban	cation of in-use	re demand deve	stimates EoL sto	es location of Ec	EoL recycling rat	ctive waste, pro	extractive waste,	npurities, non-fu	on of Output from	iticality Assessme	Energy use	vironmental impa	Social impacts	Comments
Odex index	Marta Iglesias and Gara Villalba (UAB)	Measures the energy efficiency progress by main sector and for the whole economy.	%	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13703	Processing Manufacture of end-products	Energy use	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	
Use of contact cooling water	Marta Iglesias and Gara Villalba (UAB)		Volume/period of time	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13704	Processing Manufacture of end-products	Water use	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	
Use of non-contact cooling water	Marta Iglesias and Gara Villalba (UAB)		Volume/period of time	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13705	Processing Manufacture of end-products	Water use	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	
Water footprint of products	Marta Iglesias and Gara Villalba (UAB)	Water used, evaporated, incorporated into a product or polluted by a product, process, company or economy activity. It measures the total volume of global freshwater that an entity consumes, including the water used to produce the goods used as inputs to the process, considering their entire life cycle from raw material extraction to consumption.	Volume/year; volume/ton; volume/unit produced	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13706	All life cycle stages	Water use	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	yes	no	
Water recycled or reused	Marta Iglesias and Gara Villalba (UAB)	Amount of water that has been previously discharged as wastewater and is being used.	%	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13707	All life cycle stages	Water use	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	yes	no	
Generation of hazardous waste	Marta Iglesias and Gara Villalba (UAB)	Amount of hazardous waste in mass units produced per year by waste generating activities.	Unit of weight; Unit of weight per unit of GDP	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13708	All life cycle stages	Waste generation and management	no	no	no	no	no	no	no	no	no	no	no	no	yes (if it is known the composition of the metal in the extractive waste)	yes (if it is known the composition of the metal in the extractive waste)	no	no	no	no	yes	no	
Generation of waste	Marta Iglesias and Gara Villalba (UAB)	All types of waste including hazardous and non-hazardous wastes produced by industries and different sectors of the economy.	Unit of weight; weight per capita; weight per economic value	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13709	All life cycle stages	Waste generation and management	no	no	no	no	no	no	no	no	no	no	no	no	yes (if it is known the composition of the metal in the extractive waste)	yes (if it is known the composition of the metal in the extractive waste)	no	no	no	no, but energy requirements can be calculated	yes	no	
Share of waste treatment and disposal	Marta Iglesias and Gara Villalba (UAB)	Measures in percentage, the amount of waste that is recycled, composted, incinerated and land filled, over the total waste generated.	%	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13710	All life cycle stages	Waste generation and management	no	no	no	no	no	no	no	no	no	no	no	yes, it can be calculated with the amount recycled	no	no	no	no	no, but the recycled amount of an element influences the criticality	no	yes	no	
Abiotic depletion potential (CML)	Marta Iglesias and Gara Villalba (UAB)	Extraction rate of a substance in relation to the total existing resources (or reserves) of this substance	kg of antimony equivalent	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13711	All life cycle stages	Abiotic depletion	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Abiotic depletion potential - elements (CML)	Marta Iglesias and Gara Villalba (UAB)	Extraction rate of chemical elements in relation to the total existing resources (reserves) of these elements	kg of antimony equivalent	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13712	All life cycle stages	Abiotic depletion	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Abiotic depletion potential - fossil fuels (CML)	Marta Iglesias and Gara Villalba (UAB)	Sum of fossil resources used in the life cycle of a product	MJ	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13713	All life cycle stages	Abiotic depletion	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Mineral Depletion Potential (endpoint) (ReCiPe)	Marta Iglesias and Gara Villalba (UAB)	Indicator based on the marginal cost increase (additional efforts society has to pay) as a result of mineral extraction.	Dollars	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13714	All life cycle stages	Abiotic depletion	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Fossil Depletion Potential (endpoint) (ReCiPe)	Marta Iglesias and Gara Villalba (UAB)	Indicator based on the marginal cost increase (additional efforts society has to pay) as a result of fossil fuels extraction.	Dollars	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13715	All life cycle stages	Abiotic depletion	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
CO2 emissions	Marta Iglesias and Gara Villalba (UAB)	Refers to the anthropogenic emissions of carbon dioxide produced by a process.	Unit of weight of CO2	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13717	All life cycle stages	GHG emissions	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
GHG emissions	Marta Iglesias and Gara Villalba (UAB)	Measures all GHG emissions under the Kyoto Protocol from anthropogenic sources.	Unit of weight of CO2 equivalent	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13718	All life cycle stages	GHG emissions	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Indirect GHG emissions	Marta Iglesias and Gara Villalba (UAB)		Metric tonnes of CO2 equivalent	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13719	All life cycle stages	GHG emissions	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Carbon Footprint of products	Marta Iglesias and Gara Villalba (UAB)	GHG emissions that are directly and indirectly produced by an activity or that are accumulated during the life stages of goods and services.	kg of CO2 or kg CO2 equivalent	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13720	All life cycle stages	GHG emissions	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Eco-efficiency indicator	Marta Iglesias and Gara Villalba (UAB)	Compares the value and environmental impacts of a product against benchmark product in its category	Dimensionless	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13721	All life cycle stages	Other environmental impacts	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Ozone depletion potential (EDIP)	Marta Iglesias and Gara Villalba (UAB)	Destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances (ODS).	g CFC11 eq	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13722	All life cycle stages	Other environmental impacts	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Human toxicity, cancer effects (USEtox)	Marta Iglesias and Gara Villalba (UAB)	Carcinogenic effects on humans related to a chemical's fate in the environment, human exposure, and differences in toxicological response.	Comparative toxic unit for humans (CTUh)	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13723	All life cycle stages	Other environmental impacts	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Human toxicity, non-cancer effects (USEtox)	Marta Iglesias and Gara Villalba (UAB)	Toxic (non-carcinogenic) effects on humans related to a chemical's fate in the environment, human exposure, and differences in toxicological response.	Comparative toxic unit for humans (CTUh)	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13724	All life cycle stages	Other environmental impacts	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Particulate matter / respiratory inorganics (RiskPoll)	Marta Iglesias and Gara Villalba (UAB)	Ambient concentrations of particulate matter (PM) are elevated by emissions of primary and secondary particulates. The mechanism for the creation of secondary emissions involves emissions of sulphur dioxide and nitrogen oxides that create sulphate and nitrate aerosols.	kg PM2.5 eq	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13725	All life cycle stages	Other environmental impacts	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Photochemical ozone formation (ReCiPe)	Marta Iglesias and Gara Villalba (UAB)	The negative impacts from the photochemically generated pollutants are due to their reactive nature which enables them to oxidise organic molecules on the surface they expose.	kg C2H4 eq	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13726	All life cycle stages	Other environmental impacts	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Acidification (Accumulated Exceedance - AE)	Marta Iglesias and Gara Villalba (UAB)	Processes that increase the acidity of water and soil systems by hydrogen ion concentration. It is caused by atmospheric deposition of acifiying substances generated largely from emissions of NOx, SO2, and ammonia (NH3).	mole H+ eq - accumulated exceedance	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13727	All life cycle stages	Other environmental impacts	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Eutrophication, terrestrial (Accumulated Exceedance - AE)	Marta Iglesias and Gara Villalba (UAB)	In terrestrial systems, the addition of nutrients may change the species composition of the vegetation by favouring those species which benefit from higher levels of nutrients to grow faster than more nutrient efficient plants. It is caused by deposition of airborne emissions of nitrogen compounds.	mole N eq - accumulated exceedance	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13728	All life cycle stages	Other environmental impacts	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Eutrophication, aquatic (ReCiPe)	Marta Iglesias and Gara Villalba (UAB)	In aquatic systems (freshwater and marine), the addition of nutrients has a number of consequences: species composition of the plant community changes to more nutrient-demanding species, …	kg P eq - Fraction of nutrients reaching freshwater end compartment	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13729	All life cycle stages	Other environmental impacts	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Ecotoxicity (freshwater) (USEtox)	Marta Iglesias and Gara Villalba (UAB)	Factors for toxicity effects on the environment are based on models that account for a chemical's fate in the enviroment, species exposure, and differences in toxicological response.	Comparative toxic unit for ecosystems (CTUe)	Benchmarking of current sectorial tools and indicators (2014) TOP-REF. http://toprefproject.eu/?p=13730	All life cycle stages	Other environmental impacts	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Thermodynamic rarity	Marta Iglesias and Gara Villalba (UAB)	Actual amount of exergy resources needed to obtain a mineral commodity from Thanatia (a completely degraded state) to the market conditions using the current best available technologies.	kJ, MJ	Valero, A., Valero, A. (2015) Thermodynamic Rarity and the Loss of Mineral Wealth. Energies (2015) 8, 821-836; doi:10.3390/en8020821 Valero, A., & Valero, A. (2014). Thanatia, the destiny of the Earth's mineral resources. http://www.worldscientific.com/worldscibooks/10.1142/7323#t=toc	Extraction Processing		no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes (the higher the termodynamic rarity of the element, the scarcer is the element, or more costly to obtain)	yes, but it is calculated through exergy values	yes (related to abiotic depletion)	no	
Reserves in EU	Marta Iglesias and Gara Villalba (UAB)	Quantity of the element in the EU reserves	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Exploration	Parameters representing physical flows and stocks of materials	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
Reserves in ROW	Marta Iglesias and Gara Villalba (UAB)	Quantity of the element in the rest of the world (ROW) reserves	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Exploration	Parameters representing physical flows and stocks of materials	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
Resources in EU	Marta Iglesias and Gara Villalba (UAB)	Quantity of the element in the EU resources	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Exploration	Parameters relating to future supply and demand change	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	

Indicator	Person preparing this information	Description	Units	Reference	Life Cycle Stage	ion / Cluster (according to t	economic, reserv	(economic, reso	n rates of main	n rate of by-prod	extraction takes	action rate deve	tes in-use urban	cation of in-use	re demand deve	timates EoL sto	es location of Eo	EoL recycling rat	ctive waste, pro	extractive waste,	npurities, non-fu	n of Output from	ticality Assessme	Energy use	vironmental impa	Social impacts	Comments
Resources in ROW	Marta Iglesias and Gara Villalba (UAB)	Quantity of the element in the rest of world (ROW) resources	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Exploration	Parameters relating to future supply and demand change	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
Investment in exploration	Marta Iglesias and Gara Villalba (UAB)	Current and planned investment in exploration	million € / $	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Exploration	Parameters relating to future supply and demand change	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
Production of primary materials as main product in EU sent to processing in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the production of primary material as main product in EU sent to processing in EU Primary material refers to products at the gate of the mine, pit or quarry (ore or concentrate after a preliminary processing step in situ).	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Production of primary materials as by product in EU sent to processing in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the production of primary material as by-product in EU sent to processing in EU Primary material refers to products at the gate of the mine, pit or quarry (ore or concentrate after a preliminary processing step made in situ).	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters representing physical flows and stocks of materials	no	no	no	yes	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Exports from EU of primary material	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the exports from EU of primary material (as main product or by-product) Primary material refers to products at the gate of the mine, pit or quarry (ore or concentrate after a preliminary processing step made in situ).	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Extraction waste disposed in situ/tailings in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the extraction waste disposed in situ in EU Extraction waste disposed in situ refers to tailings (waste from extraction and if applicable preliminary step of processing made in situ)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no	no, but with material and energy requirements it can be calculated	no	
Stock in tailings in EU	Marta Iglesias and Gara Villalba (UAB)	Quantity of the element in tailings in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no	no, but with material and energy requirements it can be calculated	no	
Country concentration	Marta Iglesias and Gara Villalba (UAB)	Index highlighting the concentration of the countries involved in the extraction of the element. Use the Herfindahl-Hirschman-Index (HHI), given by the sum of the squared market shares of the countries extracting the element.	Dimensionless	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	no	
Governance risk supply (extraction)	Marta Iglesias and Gara Villalba (UAB)	Index highlighting the concentration of the countries involved in the extraction of the element with regard to their governance stability. Use the modified Herfindahl-Hirschman-Index (HHI), given by the sum of the squared market shares of the countries extracting the element multiplied by their score in the World Governance Index. The result is then weighted by the Substitutability Index and the Recycling Input Rate at world level.	Dimensionless	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	yes	
Production of primary materials as main product in ROW	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the production of primary material as main product in rest of the world (ROW)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters relating to policy objectives	no	no	yes	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Production of primary materials as by product in ROW	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the production of primary material as by product in rest of the world (ROW)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters relating to policy objectives	no	no	yes	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Industry structure in EU (extraction)	Marta Iglesias and Gara Villalba (UAB)	SME ratio of companies involved in extraction	%	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
Future supply (extraction)	Marta Iglesias and Gara Villalba (UAB)	Published projections of future extraction	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters relating to future supply and demand change	no	no	no	no	yes	yes	no	no	no	no	no	no	no	no	no	no	yes	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Typical time required for production of primary material in EU	Marta Iglesias and Gara Villalba (UAB)	Past typical time range to obtain necessary permits and to begin the production of primary material in the mine, pit or quarry in EU, including a sub-distinction between 2 timeframes: - The average timeframe for the completion of the administrative process: From the submission by the operator of all the necessary documents to the competent authorities to the formal and official reply of the competent authorities (i.e. permit(s) granted or refused); - The average timeframe to open the mine once the necessary permits have been obtained, including the average timeframe lost because of court proceeding.	Years	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters relating to future supply and demand change	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
Typical time required for production of primary material in ROW	Marta Iglesias and Gara Villalba (UAB)	Past typical time range to obtain necessary permits and to begin the production of primary material in the mine, pit or quarry in the rest of the world (ROW), including a sub-distinction between 2 timeframes: - The average timeframe for the completion of the administrative process: From the submission by the operator of all the necessary documents to the competent authorities to the formal and official reply of the competent authorities (i.e. permit(s) granted or refused); - The average timeframe to open the mine once the necessary permits have been obtained, including the average timeframe lost because of court proceedings.	Years	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Extraction	Parameters relating to future supply and demand change	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	

Indicator	Person preparing this information	Description	Units	Reference	Life Cycle Stage	ion / Cluster (according to t	economic, reserv	(economic, reso	n rates of main	n rate of by-prod	extraction takes	action rate deve	tes in-use urban	cation of in-use	re demand deve	stimates EoL stoc	es location of Ec	EoL recycling rat	ctive waste, pro	extractive waste,	npurities, non-fu	on of Output from	iticality Assessme	Energy use	vironmental impa	Social impacts	Comments
Production of processed material in EU sent to manufacture in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the production of processed material in EU sent to manufacture in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Processing	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Exports from EU of processed material	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the exports from EU of processed material	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Processing	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Imports to EU of primary material	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the imports to EU of primary material (as main product or by-product) Primary material refers to products at the gate of the mine, pit or quarry (ore or concentrate after a preliminary processing step made in situ).	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Processing	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Imports to EU of secondary material	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the imports to EU of secondary material	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Processing	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Processing waste in EU sent for disposal in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the processing waste in EU sent for disposal in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Processing	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	no	yes	yes	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Exports from EU of processing waste	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the exports from EU of processing waste	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Processing	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	no	yes	yes	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Output from the value chain at the processing step	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element exiting the value chain (as impurities, non functional by-product, dissipation…)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Processing	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Country concentration (processing)	Marta Iglesias and Gara Villalba (UAB)	Index highlighting the concentration of the countries involved in the processing of the element. Use the Herfindahl-Hirschman-Index (HHI), given by the sum of the squared market shares of the countries processing the element.	Dimensionless	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Processing	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	no	
Governance risk supply (processing)	Marta Iglesias and Gara Villalba (UAB)	Index highlighting the concentration of the countries involved in the processing of the element with regard to their governance stability. Use the modified Herfindahl-Hirschman-Index (HHI), given by the sum of the squared market shares of the countries processing the element multiplied by their score in the World Governance Index. The result is then weighted by the Substitutability Index and the Recycling Input Rate at world level.	Dimensionless	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Processing	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	yes	
Industry structure in EU (processing)	Marta Iglesias and Gara Villalba (UAB)	SME-ratio of companies involved in processing	%	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Processing	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes (related to economic importance for EU; EU megasector value)	no	no	no	
Future demand (processing)	Marta Iglesias and Gara Villalba (UAB)	Published projections of future demand of processed material	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Processing	Parameters relating to future supply and demand change	no	no	no	no	no	no	no	no	yes	no	no	no	no	no	no	no	yes	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Production of manufactured products in EU sent to use in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the production of manufactured products in EU sent to use in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	yes	yes	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Exports from EU of manufactured products	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the exports from EU of manufactured products	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	yes	yes	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Imports to EU of processed material	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the imports to EU of processed material	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Manufacture waste in EU sent for disposal in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the manufacture waste in EU sent for disposal in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Manufacture waste in EU sent for reprocessing in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the manufacture waste in EU sent for reprocessing in EU = Annual quantity of the element in the processing inputs of secondary material from manufacture from EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	

Annex 2: MinFuture - Deliverable 3.2 (Work Package 3)

Indicator	Person preparing this information	Description	Units	Reference	Life Cycle Stage	ion / Cluster (according to t	economic, reserv	(economic, rese	n rates of main	n rate of by-prod	extraction takes	action rate deve	tes in-use urban	cation of in-use	re demand deve	stimates EoL sto	es location of Eo	EoL recycling rat	ctive waste, pro	extractive waste,	npurities, non-fu	on of Output from	iticality Assessme	Energy use	vironmental impa	Social impacts	Comments
Exports from EU of manufacture waste	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the exports from EU of manufacture waste	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Output from the value chain at the manufacturing step	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element exiting the value chain (as impurities, non-functional by-product, dissipation…)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Main uses	Marta Iglesias and Gara Villalba (UAB)	Main applications	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters relating to policy objectives	no	no	no	no	no	no	yes	yes	yes (if future projections of main uses are considered)	no	no	no	no	no	no	no	yes (related to economic importance for EU; applications)	no	no	no	
Substitutability index	Marta Iglesias and Gara Villalba (UAB)	Substitutability Index at world level This parameter takes over the results in the Report on Critical Raw Materials for the EU (2014, European Commission)		BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes (a factor of supply risk)	no	no	no	
Economic importance	Marta Iglesias and Gara Villalba (UAB)	Economic importance of megasectors (ratio of GVA on EU 's GDP) This parameter is calculated based on the methodology described in the Report on Critical Raw Materials for the EU (2014, European Commission) and on updated data gathered within this project		BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	no	
Industry structure in EU (manufacturing)	Marta Iglesias and Gara Villalba (UAB)	SME-ratio of companies involved in manufacture.	%	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes (related to economic importance for EU; EU megasector value)	no	no	no	
Future supply (manufacturing)	Marta Iglesias and Gara Villalba (UAB)	Published projections of future demand of manufactured products, Evolution of megasectors, Opportunities and impacts of new technologies and policies	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Manufacture of end-products	Parameters relating to future supply and demand change	no	no	no	no	no	no	no	no	yes	no	no	no	no	no	no	no	yes	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Stock of manufactured products in use in EU	Marta Iglesias and Gara Villalba (UAB)	Quantity of the element in the stock of manufactured products in use in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Use	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	yes	yes	no	yes (considering the life cycle of the products in use, it gives potential future secondary supply)	yes (considering the life cycle of the products in use, it gives potential future secondary supply)	no	no	no	no	no	no	no	no	no	
Stock of manufactured products at end of life in EU	Marta Iglesias and Gara Villalba (UAB)	Quantity of the element in the stock of manufactured products at end of life that are kept by users in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Use	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no	no	no	no	no	no	
Exports from EU of manufactured products for reuse	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the exports from EU of manufactured products for reuse (products for reuse not considered as waste)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Use	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Imports to EU of manufactured products	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the imports to EU of manufactured products	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Use	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	yes	yes	no	no	no	no	yes (considering the life cycle of the products in use, it gives potential future secondary supply)	yes (considering the life cycle of the products in use, it gives potential future secondary supply)	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
In use dissipation in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element lost by in use dissipation in EU In use dissipation refers for example to: a loss of zinc due to corrosion of zinc coating on steel, a loss of copper due to spread of copper sulphate as a fungicide (based on UNEP definition)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Use	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Products at end of life in EU collected for treatment	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the manufactured products at end of life (waste) in EU collected for treatment	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Use	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Annual Addition to in-use stock of manufactured products in EU	Marta Iglesias and Gara Villalba (UAB)	Quantity of the element that is annually added to the stock of manufactured products in use in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Use	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	yes	yes	no	yes (considering the life cycle of the products in use, it gives potential future secondary supply)	yes (considering the life cycle of the products in use, it gives potential future secondary supply)	no	no	no	no	no	no	no	no	no	
Annual addition to end-of-life stock of manufactured products in EU	Marta Iglesias and Gara Villalba (UAB)	Quantity of the element that is annually added to the stock of manufactured products at end of life that are kept by users in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Use	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no	no	no	no	no	no	
Exports from EU of manufactured products at end of life	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the exports from EU of manufactured products at end of life (waste for treatment)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Collection	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes (potential secondary supply that is lost for EU)	yes (potential secondary supply that is lost for EU)	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	

Indicator	Person preparing this information	Description	Units	Reference	Life Cycle Stage	ion / Cluster (according to t	economic, reserv	(economic, reso	n rates of main	n rate of by-prod	extraction takes	action rate deve	ates in-use urban	cation of in-use	re demand deve	stimates EoL stoc	es location of Eo	EoL recycling rat	ctive waste, pro	extractive waste,	npurities, non-fu	on of Output from	ticality Assessme	Energy use	vironmental impa	Social impacts	Comments
Imports to EU of manufactured products at end of life	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the imports to EU of manufactured products at end of life (waste for treatment)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Collection	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Manufactured products at end of life in EU sent for disposal in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the manufactured products at end of life (waste) in EU sent for disposal in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Collection	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Manufactured products at end of life in EU sent for recycling in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the manufactured products at end of life in EU sent for recycling in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Collection	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Stock in landfill in EU	Marta Iglesias and Gara Villalba (UAB)	Quantity of the element in landfill in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Collection	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	no	yes	yes	no	no	no	no	no	no	
Annual addition to stock in landfill in EU	Marta Iglesias and Gara Villalba (UAB)	Quantity of the element that is annually added to landfill in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Collection	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	no	yes	yes	no	no	no	no	no	no	
Production of secondary material from post-consumer functional recycling (old scrap) in EU sent to processing in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the production of secondary material from post-consumer functional recycling (old scrap) in EU sent to processing in EU Functional recycling refers to recycling in which the element in a discarded product is separated and sorted to obtain secondary material displacing same primary material (based on UNEP definition)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Recycling	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	yes	no	no	no	no	yes	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Production of secondary material from post-consumer functional recycling (old scrap) in EU sent to manufacture in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the production of secondary material from post-consumer functional recycling (old scrap) in EU sent to manufacture in EU. Functional recycling refers to recycling in which the element in a discarded product is separated and sorted to obtain secondary material displacing same primary material (based on UNEP definition)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Recycling	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	yes	no	no	no	no	yes	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Exports from EU of secondary material from post-consumer recycling	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the exports from EU of secondary material from post-consumer functional and non-functional recycling	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Recycling	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes (potential secondary supply that is lost for EU)	yes (potential secondary supply that is lost for EU)	yes	no	no	no	no	yes	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Production of secondary material from post-consumer non-functional recycling in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the production of secondary material from post-consumer non-functional recycling in EU. Non-functional recycling refers to recycling in which the element in a discarded product is collected and incorporated in a associated large magnitude material stream. This represents the loss of its function as it is generally impossible to recover it from the large magnitude stream (based on UNEP definition)	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Recycling	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	yes	yes	yes	yes (potential secondary supply that is lost because of non-functional recycling)	yes (potential secondary supply that is lost because of non-functional recycling)	yes	yes	yes	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Recycling waste in EU sent for disposal in EU	Marta Iglesias and Gara Villalba (UAB)	Annual quantity of the element in the recycling waste in EU sent for disposal in EU	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Recycling	Parameters representing physical flows and stocks of materials	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
European Functional Recycling rate	Marta Iglesias and Gara Villalba (UAB)	Functional Recycling rate including collection rate and recycling process efficiency rate at EU level. The definition of this parameter is presented in section 5.5, and it is different from that of the parameter "End-of-life Recycling Input Rate" used in the Report on Critical Raw Materials for the EU (2014, European Commission).	%	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Recycling	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no	no	yes	no	no	no	
European Non Functional Recycling rate	Marta Iglesias and Gara Villalba (UAB)	Non Functional Recycling rate including collection rate and recycling process efficiency rate at EU level. The definition of this parameter is presented in section 5.5, and it is different from that of the parameter "End-of-life Recycling Input Rate" used in the Report on Critical Raw Materials for the EU (2014, European Commission).	%	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Recycling	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	yes	no	yes	no	no	no	
Industry structure in EU (Recycling)	Marta Iglesias and Gara Villalba (UAB)	SME-ratio of companies involved in recycling.	%	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Recycling	Parameters relating to policy objectives	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes (related to economic importance)	no	no	no	
Future supply (Recycling)	Marta Iglesias and Gara Villalba (UAB)	Published projections of future supply of secondary material from post-consumer recycling. Model data of anthropogenic stocks	Unit of weight	BIO by Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Prepared for the European Commission, DG GROW. http://c.ymcdn.com/sites/www.intlmag.org/resource/resmgr/docs/membership_central/newsletter/2016/February/MSA_Final_Report_02.pdf	Recycling	Parameters relating to future supply and demand change	no	no	no	no	no	no	no	no	no	no	no	no	yes	yes	no	no	yes	no, but energy requirements can be calculated	no, but with material and energy requirements it can be calculated	no	
Domestic extraction (DE)	Kovanda, Jan (CUNI)	Extraction of raw materials and biomass harvest from domestic territory	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction																						EW-MFA indicator
Physical imports (IM)	Kovanda, Jan (CUNI)	Imports of raw materials and manufactured products	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products																						EW-MFA indicator
Physical exports (EX)	Kovanda, Jan (CUNI)	Exports of raw materials and manufactured products	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products																						EW-MFA indicator
Physical trade balance (PTB)	Kovanda, Jan (CUNI)	IM minus EX	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products																						EW-MFA indicator
Direct material input (DMI)	Kovanda, Jan (CUNI)	Sum of DE and IM	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products																						EW-MFA indicator

Indicator	Person preparing this information	Description	Units	Reference	Life Cycle Stage	ion / Cluster (according to t	economic, reserv	(economic, reso	n rates of main	n rate of by-prod	extraction takes	action rate deve	tes in-use urban	cation of in-use	re demand deve	timates EoL sto	es location of Eo	EoL recycling rat	ctive waste, pro	extractive waste,	npurities, non-fu	n of Output from	iticality Assessme	Energy use	vironmental impa	Social impacts	Comments
Domestic material consumption (DMC)	Kovanda, Jan (CUNI)	DMI minus EX	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products																						EW-MFA indicator
Unused domestic extraction (UDE)	Kovanda, Jan (CUNI)	Materials extracted or otherwise moved on a nation's territory on purpose and by means of technology which are not fit or intended for use.	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Construction activities																						EW-MFA indicator
Indirect flows of imports (IFIM)	Kovanda, Jan (CUNI)	The up-stream material input flows that are associated to imports but are not physically imported.	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products, Construction activities																						EW-MFA indicator
Indirect flows of exports (IFEX)	Kovanda, Jan (CUNI)	The upstream material input flows that are associated to exports but are not physically exported.	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products, Construction activities																						EW-MFA indicator
Total material requirement (TMR)	Kovanda, Jan (CUNI)	Sum of DMI, UDE and IFIM	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products, Construction activities																						EW-MFA indicator
Total material consumption (TMC)	Kovanda, Jan (CUNI)	TMR minus EX and IFEX	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products, Construction activities																						EW-MFA indicator
Raw material equivalents (RME) of imports	Kovanda, Jan (CUNI)	DE that was needed worldwide to manufacture imported commodities	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products																						EW-MFA indicator
Raw material equivalents (RME) of exports	Kovanda, Jan (CUNI)	DE that was needed worldwide to manufacture exported commodities	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products																						EW-MFA indicator
Raw material input (RMI)	Kovanda, Jan (CUNI)	Sum of DE and RME of imports	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products																						EW-MFA indicator
Raw material consumption (RMC)	Kovanda, Jan (CUNI)	RMI minus RME of exports	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products																						EW-MFA indicator
Domestic processed output (DPO)	Kovanda, Jan (CUNI)	Sum of emissions to air, emissions to water, landfilled waste, dissipative uses of products and dissipative losses	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products																						EW-MFA indicator
Total domestic output (TDO)	Kovanda, Jan (CUNI)	Sum of DPO and UDE	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products, Construction activities																						EW-MFA indicator
Net additions to stock (NAS)	Kovanda, Jan (CUNI)	The weight of new construction materials used in buildings and other infrastructure, and materials incorporated into new durable goods such as cars, industrial machinery, and household appliances.	Unit of weight	Eurostat. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxembourg: Eurostat; 2001.	Extraction, Processing, Manufacturing of end-products, Construction activities																						EW-MFA indicator
Raw material consumption (RMC) of the EU	Dittrich, Monika (IFEU)	Raw material use indicator calculated by Eurostat with the EU RME model (hybrid input-output model with an adapted domestic technology assumption)	Weight in RME (raw material equivalents)	Schoer, K., Dittrich, M., Kovanda, J. Weinzettel, J., Ewers, B., Moll, S. Bouwmeester, M. (2016): Eurostat Documentation of Eurostat's RME model. Heidelberg/Wiesbaden/ Prag/Luxembourg, URL: http://ec.europa.eu/eurostat/documents/1798247/6191533/Documentation-EU-RME-model/.	Use	?	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but the inclusion is possibe	no	no	
Raw material input (RMI) of the EU	Dittrich, Monika (IFEU)	Raw material use indicator calculated by Eurostat with the EU RME model (hybrid input-output model with an adapted domestic technology assumption)	Weight in RME (raw material equivalents)	Schoer, K., Dittrich, M., Kovanda, J. Weinzettel, J., Ewers, B., Moll, S. Bouwmeester, M. (2016): Eurostat Documentation of Eurostat's RME model. Heidelberg/Wiesbaden/ Prag/Luxembourg, URL: http://ec.europa.eu/eurostat/documents/1798247/6191533/Documentation-EU-RME-model/.	Use	?	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but the inclusion is possibe	no	no	
RME of imports of the EU	Dittrich, Monika (IFEU)	Raw material use indicator calculated by Eurostat with the EU RME model (hybrid input-output model with an adapted domestic technology assumption)	Weight in RME (raw material equivalents)	Schoer, K., Dittrich, M., Kovanda, J. Weinzettel, J., Ewers, B., Moll, S. Bouwmeester, M. (2016): Eurostat Documentation of th EU RME model. Heidelberg/Wiesbaden/ Prag/Luxembourg, URL: http://ec.europa.eu/eurostat/documents/1798247/6191533/Documentation-EU-RME-model/.	Use	?	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but the inclusion is possibe	no	no	
RME of Exports of the EU	Dittrich, Monika (IFEU)	Raw material use indicator calculated by Eurostat with the EU RME model (hybrid input-output model with an adapted domestic technology assumption)	Weight in RME (raw material equivalents)	Schoer, K., Dittrich, M., Kovanda, J. Weinzettel, J., Ewers, B., Moll, S. Bouwmeester, M. (2016): Eurostat Documentation of the EU RME model. Heidelberg/Wiesbaden/ Prag/Luxembourg, URL: http://ec.europa.eu/eurostat/documents/1798247/6191533/Documentation-EU-RME-model/.	Use	?	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no, but the inclusion is possibe	no	no	
Statistical entropy	Helmut Rechberger and Astrid Allesch (TU Wien)	statistical entropy, which quantifies the distribution pattern of a substance (e.g. copper) caused by a system (e.g. political economy).	%	11.) Rechberger, H. and Graedel, T. E. (2002): The contemporary European copper cycle: statistical entropy analysis. Ecological Economics 42: 1–2 59-72.	All life cycle stages		no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	The entropy approach improves our understanding of industrial metabolism and is a useful decision support and design tool, since complex systems can thereby be quantified by a single metric per substance.
P Import dependency	Helmut Rechberger and Astrid Allesch (TU Wien)	Import dependency, as the name suggests,measures how dependent the country is fromimported P and was first put forward as indicator of national P management under the name "Net imports" by Cooper and Carliell-Marquet (2013).	tP y−1	Zoboli, O.; Zessner, M.; Rechberger, H. (2016) "Supporting phosphorus management in Austria: Potential, priorities and limitations", Science of the Total Environment, Vol. 565, p. 313-323. dx.doi.org/10.1016/j.scitotenv.2016.04.171,	Import		no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
Consumption of fossil-P fertilizers and	Helmut Rechberger and Astrid Allesch (TU Wien)	It is also worth distinguishing between fossil P used to produce mineral fertilizers and other goods. Therefore, the specific contribution to Consumption of fossil-P fertilizers is also assessed.	tP y−1	Zoboli, O.; Zessner, M.; Rechberger, H. (2016) "Supporting phosphorus management in Austria: Potential, priorities and limitations", Science of the Total Environment, Vol. 565, p. 313-323. dx.doi.org/10.1016/j.scitotenv.2016.04.171,	Use/Consumption		no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	
P Emissions to water bodies.	Helmut Rechberger and Astrid Allesch (TU Wien)	The main reason to evaluate separately the effect on Emissions to water bodies is that this indicator addresses the management of P seen as a pollutant, whereas the other two regard P as a critical resource.	tP y−1	Zoboli, O.; Zessner, M.; Rechberger, H. (2016) "Supporting phosphorus management in Austria: Potential, priorities and limitations", Science of the Total Environment, Vol. 565, p. 313-323. dx.doi.org/10.1016/j.scitotenv.2016.04.171,	Emission		no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	
Circularity Index (CI)	Jonathan Cullen (Ucam)	CI = α×β, where α is a ratio which describes the combined effects of material stock dynamics and dissipative losses, and β is the ratio between the energy needed for material recovery and the energy required for primary material production from virgin ore.		J.M. Cullen (2017) "Circular Economy - Theoretical Benchmark or Perpetual Motion Machine?", Journal of Industrial Ecology, DOI: 10.1111/jiec.12599	Recycling		no	no	no	no	no	no	no	no	no	no	no	It is related	no	no	no	no	no	no	no	no	
Byproduct fraction	Xinkai Fu and Elsa Olivetti (MIT)	The fraction of a metal extracted as a byproduct of another metal in its total annual global production (primary production only). This fraction is based on one pair of metals.	%	Fu, X., Polli, A., Olivetti E. (2017) "High-resolution insight into materials criticality: Quantifying risk for byproduct metals", under review at Environmental Science and Technology	Extraction		no	no	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	no	
Value ratio of byproduct/carrier	Xinkai Fu and Elsa Olivetti (MIT)	The global average ratio between the monetary value of a byproduct metal B and a carrier metal C in all the mines which produce B as byproduct of C.	%	Fu, X., Polli, A., Olivetti E. (2017) "High-resolution insight into materials criticality: Quantifying risk for byproduct metals", under review at Environmental Science and Technology	Extraction		no	no	yes	yes	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	no	
Price elasticity of supply/demand	Xinkai Fu and Elsa Olivetti (MIT)	The responsiveness of the quantity supplied/demanded to a change in its price, calculated through econometric models.	Dimensionless	Fu, X., Polli, A., Olivetti E. (2017) "High-resolution insight into materials criticality: Quantifying risk for byproduct metals", under review at Environmental Science and Technology	Extraction		no	no	yes	yes	no	yes	nno	no	yes	no	no	no	no	no	no	no	yes	no	no	no	
Gibbs free energy of mineral	Xinkai Fu and Elsa Olivetti (MIT)	Gibbs free energy of formation for the main mineral form of an element, which represents the lower thermodynamic boundary of separating pure metal from mineral compounds.	Unit of energy	Phillips, W. G. B., and D. P. Edwards. "Metal prices as a function of ore grade." *Resources policy* 2.3 (1976): 167-178.	All life cycle stages		no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	yes	no	no	
Ore grade	Xinkai Fu and Elsa Olivetti (MIT)	Average grade of metal in the mineral	% or ppm	Phillips, W. G. B., and D. P. Edwards. "Metal prices as a function of ore grade." *Resources policy* 2.3 (1976): 167-178.	Extraction		no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	

Annex 3. Case Studies

Annex 3A

Table 1: Compilation of critical materials used in passenger car vehicles (in g) with the exception of Al, Cast Iron, Cu and Steel which are in kg.

Material	Authors compilation									
	[1]	[2]		[3]		[4]		[5]	[6]	[7]
	ICE	ICE[1]	PHEV[2]	PHEV	BEV[3]	ICE	BEV	ICE	ICE	PHEV
Aluminum (kg)						50	200	88.45		
Cast Iron (kg)						50	20			
Cerium	81	12.91	0.31							
Cobalt										
Copper (kg)		27	60			25	150			67.5
Dysprosium	27.45	1.96	129.66	210	336					
Erbium		0	0.18							
Europium	0.45	<0.01	<0.01							
Gadolinium	0.36	<0.01	<0.01							
Gallium		0.42	0.57	1.05	1.68					
Germanium				0.05	0.08					
Gold				0.2	0.32					
Indium		0.38	0.08	0.05	0.08					
Lanthanum	8.1	0	6.68							
Lithium		1.36	6,256.55							
Molybdenum										
Neodymium	297	27.6	531.88	360	576					
Niobium		89.81	109.14							
Palladium		1.24	1.81		0.12					
Platinum		7.85	5.51							
Praseodymium	30.6	2.47	4.01	120	192					
Rhodium		<0.01	<0.01							
Samarium	3.24	0.73	1.4							
Scandium	1.13									
Silver		17,5	50	6	9.6					
Steel (kg)						730	790		975.22	
Strontium										
Tantalum		6.99	10.83							
Terbium	0	0	19.86	21	34					
Ytterbium	0	0	0.16							
Yttrium	0.59	0.02	0.23							

[1] [1]
[2] [3]
[3] [5]
[4] (González Palencia et al, 2015)
[5] [2]
[6] [4]
[7] (García-Olivares et al, 2012)

[1] With medium equipment level.
[2] With medium equipment level.
[3] Original values are published for a 50 kW motor. In the present study, values are adapted for 50 kW and 80 kW motors in PHEV and BEV, respectively.

Table 2. Studied materials in vehicles, contribution in mass (g) per unit of vehicle analyzed

Material	Type of vehicle			
	ICEV	**PHEV NiMH**	**PHEV Li:ion**	**BEV**
Ag	17.5	28.0	28.0	29.8
Al	110,544	115,544	141,370	200,000
Au	0	0.20	0.20	0.32
Ce	46.95	2,127	49.67	0.15
Co	0	8,313	2,712	9,330
Cr	6,510	6,510	6,510	6,031
Cu	28,500	43,481.92	59,166	150,000
Dy	14.70	165.72	165.72	224.63
Er	0	0.18	0.18	0.18
Eu	0.23	0.23	0.23	0.23
Fe	806,144	853,826	806,144	746,945
Ga	0.42	0.81	0.81	1.12
Gd	0.18	0.17	0.17	0.17
Ge	0	0.05	0.05	0.08
In	0.38	0.38	0.38	0.38
La	4.04	14,555	7.38	7.38
Li	1.36	1.36	2,242	7,709
Mn	5,968	5,968	5,968	5,530
Mo	260	260	260	260
Nb	426.30	426.30	426.30	426.30
Nd	162	2,631	552.79	749.30
Ni	1,780	82,832	16,049	55,724
Pb	5,850	5,850	5,850	5,850
Pd	1.24	0.94	0.94	0
Pr	16.53	2,129	51.48	98.00
Pt	7.85	5.51	5.51	0
Rh	0.01	0.01	0.01	0
Sm	1.98	2.32	2.32	3.15
Ta	6.99	10.83	10.83	10.83
Tb	0	13.62	13.62	26.93
V	852.61	852.61	852.61	790
Yb	0	0.08	0.08	0.16
Y	0.41	0.41	0.41	0.41
weight	967	1,145	1,048	1,190
weight analyzed	82.5 %	84,7 %	80 %	74.7 %
others[4] (kg)	206.1	206.1	263.1	402.4
total weight	1,173	1,351	1,311	1,592

[4] Others includes rubbers, plastics, glasses and fluids content in vehicle and in battery.

Table 3. Mass and Rarity approach in an ICEV.

ICEV							
Mass approach				Exergy approach			
Element	**Mass (gr)**	**Share**	**Cumulative share**	**Element**	**Rarity (kJ)**	**Share**	**Cumulative share**
Fe	806,144.17	83.86%	83.86%	Al	73,140,332.16	43.52%	43.52%
Al	110,544	11.50%	95.36%	Pt	37,549,334.40	22.35%	65.87%
Cu	28,500	2.96%	98.33%	Fe	25,675,691.92	15.28%	81.15%
Cr	6,510	0.68%	9900%	Pd	11,862,720.75	7.06%	88.21%
Mn	5,968	0.62%	99.63%	Cu	9,929,400.00	5.91%	94.12%
Ni	1,780	0.19%	99.81%	Ta	3,396,516.49	2.02%	96.14%
V	852	0.09%	99.90%	Nb	2,038,709.20	1.21%	97.35%
Nb	426	0.04%	99.94%	Ni	1,349,941.32	0.80%	98.16%
Mo	260	0.03%	99.97%	V	1,340,305.28	0.80%	98.95%
Nd	162	0.02%	99.99%	Mn	437,116.86	0.26%	99.21%
Ce	46.96	< 0.01%	99.99%	Ga	317,027.76	0.19%	99.40%
Ag	17.50	< 0.01%	99.99%	Mo	274,536.60	0.16%	99.57%
Pr	16.54	< 0.01%	100 %	Cr	266,519.40	0.16%	99.72%
Dy	14.71	< 0.01%	100 %	Ag	156,401.00	0.09%	99.82%
Pt	7085	< 0.01%	100 %	In	138,288.73	0.08%	99.90%
Ta	6099	< 0.01%	100 %	Nd	108,760.48	0.06%	99.96%
La	4.04	< 0.01%	100 %	Ce	29,125.72	0.02%	99.98%
Sa	1.99	< 0.01%	100 %	Pr	14,441.34	0.01%	99.99%
Li	1.36	< 0.01%	100 %	Dy	10,764.06	0.01%	100 %
Pd	1.24	< 0.01%	100 %	Sa	1,453.02	< 0.01%	100 %
Ga	0.42	< 0.01%	100 %	La	1,358.81	< 0.01%	100 %
Y	0.41	< 0.01%	100 %	Li	1,330.53	< 0.01%	100 %
In	0.38	< 0.01%	100 %	Rh	1,030.88	< 0.01%	100 %
Eu	0.23	< 0.01%	100 %	Gd	746.60	< 0.01%	100 %
Gd	0.18	< 0.01%	100 %	Y	562.26	< 0.01%	100 %

ICEV							
Mass approach				Exergy approach			
Element	Mass (gr)	Share	Cumulative share	Element	Rarity (kJ)	Share	Cumulative share
Rh	0.01	< 0.01%	100 %	Eu	168.36	< 0.01%	100 %
Tb	0.01	< 0.01%	100 %	Tb	4.04	< 0.01%	100 %
Yb	< 0.01	< 0.01%	100 %	Yb	0.63	< 0.01%	100 %
Au	< 0.01	< 0.01%	100 %	Au	< 0.01	< 0.01%	100 %
Er	< 0.01	< 0.01%	100 %	Er	< 0.01	< 0.01%	100 %
Ge	< 0.01	< 0.01%	100 %	Ge	< 0.01	< 0.01%	100 %

Table 4. Mass and Rarity approach in a PHEV.

PHEV							
Mass approach				Exergy approach			
Element	Mass (gr)	Share	Cumulative share	Element	Rarity (kJ)	Share	Cumulative share
Fe	806,026.24	82.10%	82.10%	Al	76.448.532.16	46.23%	46.23%
Al	115,544.00	11.77%	93.87%	Pt	26.356.284.40	15.94%	62.17%
Cu	43,481.92	4.43%	98.30%	Fe	25.671.935.84	15.53%	77.70%
Cr	6,510	0.66%	98.96%	Cu	15.149.102.53	9.16%	86.86%
Mn	5,968	0.61%	99.57%	Pd	9.040.541.21	5.47%	92.33%
Ni	1,780	0.18%	99.75%	Ta	5.262.413.96	3.18%	95.51%
V	852	0.09%	99.84%	Nb	2.038.709.20	1.23%	96.74%
Nd	552	0.06%	99.90%	Ni	1.349.941.32	0.82%	97.56%
Nb	426	0.04%	99.94%	V	1.340.305.28	0.81%	98.37%
Mo	260	0.03%	99.97%	Ga	611.410.68	0.37%	98.74%
Dy	165.72	0.02%	99.98%	Mn	437.116.86	0.26%	99.00%
Pr	51.49	0.01%	99.99%	Nd	370.437.87	0.22%	99.23%
Ce	49.68	0.01%	99.99%	Mo	274.536.60	0.17%	99.39%
Ag	28.00	< 0.01%	100 %	Cr	266.519.40	0.16%	99.55%
Tb	13.62	< 0.01%	100 %	Ag	250.241.60	0.15%	99.71%
Ta	10.83	< 0.01%	100 %	In	138.288.73	0.08%	99.79%

PHEV							
Mass approach				Exergy approach			
Element	Mass (gr)	Share	Cumulative share	Element	Rarity (kJ)	Share	Cumulative share
La	7.38	< 0.01%	100 %	Au	130.936.60	0.08%	99.87%
Pt	5.51	< 0.01%	100 %	Dy	121.307.04	0.07%	99.94%
Sa	2.33	< 0.01%	100 %	Pr	44.967.42	0.03%	99.97%
Li	1.36	< 0.01%	100 %	Ce	30.813.94	0.02%	99.99%
Pd	0.95	< 0.01%	100 %	Tb	9.970.09	0.01%	99.99%
Ga	0.81	< 0.01%	100 %	La	2.481.48	< 0.01%	100 %
Y	0.41	< 0.01%	100 %	Sa	1.703.73	< 0.01%	100 %
In	0.38	< 0.01%	100 %	Li	1.330.53	< 0.01%	100 %
Eu	0.24	< 0.01%	100 %	Ge	1.212.35	< 0.01%	100 %
Au	0.20	< 0.01%	100 %	Rh	1.030.88	< 0.01%	100 %
Er	0.18	< 0.01%	100 %	Gd	728.21	< 0.01%	100 %
Gd	0.18	< 0.01%	100 %	Y	562.26	< 0.01%	100 %
Yb	0.08	< 0.01%	100 %	Eu	172.75	< 0.01%	100 %
Ge	0.05	< 0.01%	100 %	Er	131.76	< 0.01%	100 %
Rh	0.01	< 0.01%	100 %	Yb	59.17	< 0.01%	100 %

Table 5. Mass and Rarity approach in a BEV

BEV							
Mass approach				Exergy approach			
Element	Mass (gr)	Share	Cumulative share	Element	Rarity (kJ)	Share	Cumulative share
Fe	746,539.32	76.60%	76.60%	Al	73,545,229.52	49.85%	49.85%
Al	111,155.96	11.41%	88.01%	Cu	33,461,899.36	22.68%	72.53%
Cu	96,044.49	9.86%	97.86%	Fe	23,777,277.32	16.12%	88.65%
Ni	6,637.54	0.68%	98.54%	Ta	5,262,413.96	3.57%	92.21%
Cr	6,031.94	0.62%	99.16%	Ni	5,033,868.92	3.41%	95.63%
Mn	5,530.00	0.57%	99.73%	Nb	2,038,709.20	1.38%	97.01%
V	790.00	0.08%	99.81%	V	1,241,880.00	0.84%	97.85%

BEV							
Mass approach				Exergy approach			
Element	Mass (gr)	Share	Cumulative share	Element	Rarity (kJ)	Share	Cumulative share
Nd	749.30	0.08%	99.89%	Ga	849,181.50	0.58%	98.43%
Nb	426.31	0.04%	99.93%	Nd	502,120.92	0.34%	98.77%
Mo	260.00	0.03%	99.96%	Mn	405,017.20	0.27%	99.04%
Dy	224.63	0.02%	99.98%	Mo	274,536.60	0.19%	99.23%
Pr	98.01	0.01%	99.99%	Ag	266,328.56	0.18%	99.41%
Ag	29.80	< 0.01%	99.99%	Cr	246,947.56	0.17%	99.57%
Tb	26.93	< 0.01%	100 %	Au	209,498.56	0.14%	99.72%
Ta	10.83	< 0.01%	100 %	Dy	164,429.20	0.11%	99.83%
La	7.38	< 0.01%	100 %	In	138,288.73	0.09%	99.92%
Sa	3.15	< 0.01%	100 %	Pr	85,595.61	0.06%	99.98%
Li	1.36	< 0.01%	100 %	Tb	19,712.76	0.01%	99.99%
Ga	1.13	< 0.01%	100 %	La	2,481.48	< 0.01%	99.99%
Y	0.41	< 0.01%	100 %	Sa	2,309.37	< 0.01%	100 %
In	0.38	< 0.01%	100 %	Ge	1,939.76	< 0.01%	100 %
Au	0.32	< 0.01%	100 %	Li	1,330.53	< 0.01%	100 %
Eu	0.24	< 0.01%	100 %	Gd	728.21	< 0.01%	100 %
Er	0.18	< 0.01%	100 %	Y	562.26	< 0.01%	100 %
Gd	0.18	< 0.01%	100 %	Rh	515.44	< 0.01%	100 %
Yb	0.16	< 0.01%	100 %	Eu	172.75	< 0.01%	100 %
Ce	0.16	< 0.01%	100 %	Er	131.76	< 0.01%	100 %
Ge	0.08	< 0.01%	100 %	Yb	117.12	< 0.01%	100 %
Rh	0.01	< 0.01%	100 %	Ce	96.14	< 0.01%	100 %

Table 6. Mass and Rarity approaches in a Lead based battery

	Lead based technology						
	Mass (gr)	Share	Cumulative share		Rarity (KJ)	Share	Cumulative share
Pb	5,850	100%	100%	Pb	238,797	100%	100%

Table 7. Mass and Rarity approaches in a Lithium based battery with an autonomy of 200 km

	Lithium based technology						
	Mass (gr)	Share	Share Cumulative		Rarity (KJ)	Share	Share Cumulative
Al	88,840	42%	42%	Co	102,725,166	46%	46%
Cu	53,960	26%	68%	Al	58,780,098	26%	72%
Ni	49,090	23%	92%	Ni	37,229,561	17%	88%
Co	9,330	4%	96%	Cu	18,799,664	8%	97%
Li	7,710	4%	100%	Li	7,542,924	3%	100%
Fe	410	0%	100%	Fe	13,059	0%	100%

Table 8. Mass and Rarity approaches in a Lithium based battery with an autonomy of 50 km

	Lithium based technology						
	Mass (gr)	Share	Share Cumulative		Rarity (KJ)	Share	Share Cumulative
Al	22,210	42%	42%	Co	25,681,291	46%	46%
Cu	13,490	26%	68%	Al	14,695,024	26%	72%
Ni	12,272	23%	92%	Ni	9,307,390	17%	88%
Co	2,332	4%	96%	Cu	4,699,916	8%	97%
Li	1,927	4%	100%	Li	1,885,731	3%	100%
Fe	102	0%	100%	Fe	3,274	0%	100%

Table 9. Mass and Rarity approaches in a Nickel based battery with an autonomy of 50 km

NiMH based technology							
	Mass (gr)	**Share**	**Cumulative share**		**Rarity (KJ)**	**Share**	**Cumulative share**
Ni	81,052	51%	51%	Co	91,528,271	56%	56%
Fe	47,800	30%	82%	Ni	61,469,482	38%	93%
La	14,548	9%	91%	La	4,889,961	3%	96%
Co	8,313	5%	96%	Pr	1,815,111	1%	97%
Ce	2,078	1%	97%	Fe	1,522,430	1%	98%
Nd	2,078	1%	99%	Nd	1,392,684	1%	99%
Pr	2,078	1%	100%	Ce	1,289,124	1%	100%

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Annex 3. Case Studies

Annex 3B

Table 1: List of parameters included in the MSA. White = required parameter; Grey = optional parameter

Life cycle stage	Type of parameter	Parameter	Description of the parameter
A. Exploration	**1 - Parameters representing physical flows and stocks of materials**	A.1.1 Reserves in EU	*Quantity of the element in the EU reserves*
		A.1.2 Reserves in ROW	*Quantity of the element in the rest of the world (ROW) reserves*
	3 - Parameters relating to future supply and demand change	A.3.1 Resources in EU	*Quantity of the element in the EU resources*
		A.3.2 Resources in ROW	*Quantity of the element in the rest of world (ROW) resources*
		A.3.3 Investment in exploration	*Current and planned investment in exploration*
B. Extraction	**1 - Parameters representing physical flows and stocks of materials**	B.1.1 Production of primary material as main product in EU sent to processing in EU	*Annual quantity of the element in the production of primary material as main product in EU sent to processing in EU* *Primary material refers to products at the gate of the mine, pit or quarry (ore or concentrate after a preliminary processing step in situ).*
		B.1.2 Production of primary material as by product in EU sent to processing in EU	*Annual quantity of the element in the production of primary material as by-product in EU sent to processing in EU* *Primary material refers to products at the gate of the mine, pit or quarry (ore or concentrate after a preliminary processing step made in situ).*
		B.1.3 Exports from EU of primary material	*Annual quantity of the element in the exports from EU of primary material (as main product or by-product)* *Primary material refers to products at the gate of the mine, pit or quarry (ore or concentrate after a preliminary processing step made in situ).*
		B.1.4 Extraction waste disposed in situ /tailings in EU	*Annual quantity of the element in the extraction waste disposed in situ in EU* *Extraction waste disposed in situ refers to tailings (waste from extraction and if applicable preliminary step of processing made in situ)*
		B.1.5 Stock in tailings in EU	*Quantity of the element in tailings in EU*
	2 - Parameters relating to policy objectives	B.2.1 Country concentration	*Index highlighting the concentration of the countries involved in the extraction of the element. Use the Herfindahl-Hirschman-Index (HHI), given by the sum of the squared market shares of the countries extracting the element.* *This parameter is calculated based on the methodology described in the Report on Critical Raw Materials for the EU (2014, European Commission) and on updated data*

Life cycle stage	Type of parameter	Parameter	Description of the parameter
			gathered within this project.
		B.2.2 Governance risk supply	*Index highlighting the concentration of the countries involved in the extraction of the element with regard to their governance stability. Use the modified Herfindahl-Hirschman-Index (HHI), given by the sum of the squared market shares of the countries extracting the element multiplied by their score in the World Governance Index. The result is then weighted by the Substitutability Index and the Recycling Input Rate at world level.* *This parameter is calculated based on the methodology described in the Report on Critical Raw Materials for the EU (2014, European Commission) and on updated data gathered within this project*
		B.2.3 Production of primary material as main product in ROW	*Annual quantity of the element in the production of primary material as main product in rest of the world (ROW)*
		B.2.4 Production of primary material as by product in ROW	*Annual quantity of the element in the production of primary material as by product in rest of the world (ROW)*
		B.2.5 Industry structure in EU	*SME ratio of companies involved in extraction*
	3 - Parameters relating to future supply and demand change	B.3.1 Future supply	*Published projections of future extraction*
		B.3.2 Typical time required for production of primary material in EU	*Past typical time range to obtain necessary permits and to begin the production of primary material in the mine, pit or quarry in EU, including a sub-distinction between 2 timeframes:* *- The average timeframe for the completion of the administrative process: From the submission by the operator of all the necessary documents to the competent authorities to the formal and official reply of the competent authorities (i.e. permit(s) granted or refused);* *- The average timeframe to open the mine once the necessary permits have been obtained, including the average timeframe lost because of court proceeding.*
		B.3.3 Typical time required for production of primary material in ROW	*Past typical time range to obtain necessary permits and to begin the production of primary material in the mine, pit or quarry in the rest of the world (ROW), including a sub-distinction between 2 timeframes:* *- The average timeframe for the completion of the administrative process: From the submission by the operator of all the necessary documents to the competent authorities to the formal and official reply of the competent authorities (i.e. permit(s)*

Life cycle stage	Type of parameter	Parameter	Description of the parameter
			granted or refused); *- The average timeframe to open the mine once the necessary permits have been obtained, including the average timeframe lost because of court proceedings.*
C. Processing	**1 - Parameters representing physical flows and stocks of materials**	C.1.1 Production of processed material in EU sent to manufacture in EU	*Annual quantity of the element in the production of processed material in EU sent to manufacture in EU*
		C.1.2 Exports from EU of processed material	*Annual quantity of the element in the exports from EU of processed material*
		C.1.3 Imports to EU of primary material	*Annual quantity of the element in the imports to EU of primary material (as main product or by-product)* *Primary material refers to products at the gate of the mine, pit or quarry (ore or concentrate after a preliminary processing step made in situ).*
		C.1.4 Imports to EU of secondary material	*Annual quantity of the element in the imports to EU of secondary material*
		C.1.5 Processing waste in EU sent for disposal in EU	*Annual quantity of the element in the processing waste in EU sent for disposal in EU*
		C.1.6 Exports from EU of processing waste	*Annual quantity of the element in the exports from EU of processing waste*
		C.1.7 Output from the value chain at the processing step	*Annual quantity of the element exiting the value chain (as impurities, non functional by-product, dissipation…)*
	2 - Parameters relating to policy objectives	C.2.1 Country concentration	*Index highlighting the concentration of the countries involved in the processing of the element. Use the Herfindahl-Hirschman-Index (HHI), given by the sum of the squared market shares of the countries processing the element.* *This parameter is calculated based on the methodology described in the Report on Critical Raw Materials for the EU (2014, European Commission) and on updated data gathered within this project*
		C.2.2 Governance risk supply	*Index highlighting the concentration of the countries involved in the processing of the element with regard to their governance stability. Use the modified Herfindahl-Hirschman-Index (HHI), given by the sum of the squared market shares of the countries processing the element multiplied by their score in the World Governance Index. The result is then weighted by the Substitutability Index and the Recycling*

Life cycle stage	Type of parameter	Parameter	Description of the parameter
			Input Rate at world level. *This parameter is calculated based on the methodology described in the Report on Critical Raw Materials for the EU (2014, European Commission) and on updated data gathered within this project*
		C.2.3 Industry structure in EU	*SME-ratio of companies involved in processing*
	3 - Parameters relating to future supply and demand change	C.3.1 Future demand	*Published projections of future demand of processed material*
D. Manufacture of end-products	**1 - Parameters representing physical flows and stocks of materials**	D.1.1 Production of manufactured products in EU sent to use in EU	*Annual quantity of the element in the production of manufactured products in EU sent to use in EU*
		D.1.2 Exports from EU of manufactured products	*Annual quantity of the element in the exports from EU of manufactured products*
		D.1.3 Imports to EU of processed material	*Annual quantity of the element in the imports to EU of processed material*
		D.1.4 Manufacture waste in EU sent for disposal in EU	*Annual quantity of the element in the manufacture waste in EU sent for disposal in EU*
		D.1.5 Manufacture waste in EU sent for reprocessing in EU	*Annual quantity of the element in the manufacture waste in EU sent for reprocessing in EU = Annual quantity of the element in the processing inputs of secondary material from manufacture from EU*
		D.1.6 Exports from EU of manufacture waste	*Annual quantity of the element in the exports from EU of manufacture waste*
		C.1.7 Output from the value chain at the manufacturing step	*Annual quantity of the element exiting the value chain (as impurities, non-functional by-product, dissipation…)*
	2 - Parameters relating to policy objectives	D.2.1 Main uses	*Main applications*
		D.2.2 Substitutability index	*Substitutability Index at world level* *This parameter takes over the results in the Report on Critical Raw Materials for the EU (2014, European Commission)*

Life cycle stage	Type of parameter	Parameter	Description of the parameter
		D.2.3 Economic importance	*Economic importance of megasectors (ratio of GVA on EU 's GDP)* *This parameter is calculated based on the methodology described in the Report on Critical Raw Materials for the EU (2014, European Commission) and on updated data gathered within this project*
		D.2.4 Industry structure in EU	*SME-ratio of companies involved in manufacture,*
	3 - Parameters relating to future supply and demand change	D.3.1 Future supply	*Published projections of future demand of manufactured products, Evolution of megasectors, Opportunities and impacts of new technologies and policies*
E. Use	**1 - Parameters representing physical flows and stocks of materials**	E.1.1 Stock of manufactured products in use in EU	*Quantity of the element in the stock of manufactured products in use in EU*
		E.1.2 Stock of manufactured products at end of life in EU	*Quantity of the element in the stock of manufactured products at end of life that are kept by users in EU*
		E.1.3 Exports from EU of manufactured products for reuse	*Annual quantity of the element in the exports from EU of manufactured products for reuse (products for reuse not considered as waste)*
		E.1.4 Imports to EU of manufactured products	*Annual quantity of the element in the imports to EU of manufactured products*
		E.1.5 In use dissipation in EU	*Annual quantity of the element lost by in use dissipation in EU* *In use dissipation refers for example to: a loss of zinc due to corrosion of zinc coating on steel, a loss of copper due to spread of copper sulphate as a fungicide (based on UNEP definition)*
		E.1.6 Products at end of life in EU collected for treatment	*Annual quantity of the element in the manufactured products at end of life (waste) in EU collected for treatment*
		E.1.7 Annual Addition to in-use stock of manufactured products in EU	*Quantity of the element that is annually added to the stock of manufactured products in use in EU*
		E.1.8 Annual addition to end-of-life stock of manufactured products in EU	*Quantity of the element that is annually added to the stock of manufactured products at end of life that are kept by users in EU*

Life cycle stage	Type of parameter	Parameter	Description of the parameter
F. Collection	**1 - Parameters representing physical flows and stocks of materials**	F.1.1 Exports from EU of manufactured products at end of life	*Annual quantity of the element in the exports from EU of manufactured products at end of life (waste for treatment)*
		F.1.2 Imports to EU of manufactured products at end of life	*Annual quantity of the element in the imports to EU of manufactured products at end of life (waste for treatment)*
		F.1.3 Manufactured products at end of life in EU sent for disposal in EU	*Annual quantity of the element in the manufactured products at end of life (waste) in EU sent for disposal in EU*
		F.1.4 Manufactured products at end of life in EU sent for recycling in EU	*Annual quantity of the element in the manufactured products at end of life in EU sent for recycling in EU*
		F.1.5 Stock in landfill in EU	*Quantity of the element in landfill in EU*
		F.1.6 Annual addition to stock in landfill in EU	*Quantity of the element that is annually added to landfill in EU*
G. Recycling	**1 - Parameters representing physical flows and stocks of materials**	G.1.1 Production of secondary material from post-consumer functional recycling (old scrap) in EU sent to processing in EU	*Annual quantity of the element in the production of secondary material from post-consumer functional recycling (old scrap) in EU sent to processing in EU* *Functional recycling refers to recycling in which the element in a discarded product is separated and sorted to obtain secondary material displacing same primary material (based on UNEP definition)*
		G.1.2 Production of secondary material from post-consumer functional recycling (old scrap) in EU sent to manufacture in EU	*Annual quantity of the element in the production of secondary material from post-consumer functional recycling (old scrap) in EU sent to manufacture in EU* *Functional recycling refers to recycling in which the element in a discarded product is separated and sorted to obtain secondary material displacing same primary material (based on UNEP definition)*
		G.1.3 Exports from EU of secondary material from post-consumer recycling	*Annual quantity of the element in the exports from EU of secondary material from post-consumer functional and non-functional recycling*
		G.1.4 Production of secondary material from post-consumer non-functional recycling in EU	*Annual quantity of the element in the production of secondary material from post-consumer non-functional recycling in EU* *Non-functional recycling refers to recycling in which the element in a discarded product is collected and incorporated in a associated large magnitude material stream. This represents the loss of its function as it is generally impossible to recover*

Life cycle stage	Type of parameter	Parameter	Description of the parameter
			it from the large magnitude stream (based on UNEP definition)
		G.1.5 Recycling waste in EU sent for disposal in EU	*Annual quantity of the element in the recycling waste in EU sent for disposal in EU*
	2 - Parameters relating to policy objectives	G.2.1 European Functional Recycling rate	*Functional Recycling rate including collection rate and recycling process efficiency rate for EU.* *The definition of this parameter is presented in section* ***Fehler! Verweisquelle konnte nicht gefunden werden.****, and it is different from that of the parameter "End-of-life Recycling Input Rate" used in the Report on Critical Raw Materials for the EU (2014, European Commission).*
		G.2.2 European Non Functional Recycling rate	*Non Functional Recycling rate including collection rate and recycling process efficiency rate at EU level.* *The definition of this parameter is presented in section* ***Fehler! Verweisquelle konnte nicht gefunden werden.****, and it is different from that of the parameter "End-of-life Recycling Input Rate" used in the Report on Critical Raw Materials for the EU (2014, European Commission).*
		G.2.3 Industry structure in EU	*SME-ratio of companies involved in recycling,*
	3 - Parameters relating to future supply and demand change	G.3.1 Future supply	*Published projections of future supply of secondary material from post-consumer recycling* *Model data of anthropogenic stocks*