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Potential of life cycle assessment for supporting the management of critical raw materials

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Abstract

Purpose The security of the supply of resources is a key policy and business concern. This concern has been increasingly addressed by bodies such as the European Commission to help identify materials of potential concern in terms of economic importance and supply risks. Equally, tools such as life cycle assessment (LCA) systematically compile inventories of the resources attributable to the supply of goods and services. Such well-established tools, hence, provide an important opportunity for business and governments for strategic management and for identifying improvement options that reduce reliance on so-called critical raw materials (CRMs). This paper explores current practice and the potential of LCA to help business and governments more systematically assess their supply chains.

Methods Raw materials of concern to business and governments in relation to security of supply are denoted as *critical*. This paper highlights how such CRMs are identified in the existing methodologies. It then focuses on LCA methodology and explores its potential in providing information on CRMs at different levels: considering the flows of CRMs at inventory level, including criticality criteria in the impact assessment, and analyzing the flows of CRMs associated with the consumption of goods and services at macroeconomic scale.

Results and discussion Consideration of resource security can be specifically addressed in LCA starting from the goal and scope definition. These CRMs may otherwise be neglected due to cut-off criteria based, e.g., on quantity. If systematically addressed, LCA can provide such CRM information routinely at inventory level. Inclusion of further indicators under the Area of Protection (AoP) "Resources" in LCA may also ensure such assessments more systematically address issues such as criticality. In strategic analysis, as those at macroeconomic scale, LCA results at the inventory (e.g., amounts of CRMs domestically extracted and those used for producing imported and exported intermediate products) and at impact assessment level can better support decision making.

Conclusions At both microscale and macroscale, LCA might have more potential in capturing hot spots and improvement opportunities of raw materials of concern, not only in terms of scarcity. This paper highlights that LCA is well positioned for providing information on resource-related issues of concern to business and governments such as the criticality of raw materials used in the supply chains. The paper outlines the methodological developments that could enhance LCA potential to further support resource assessments to help more systematically meet such business and governmental interests.

Keywords Critical raw materials · Impact assessment · Life cycle assessment · Life cycle indicators · Resource depletion · Resource security

1 Introduction

The availability of natural resources is crucial to human societies and is the cause of a number of sustainability challenges, including a key contributing factor to many historical conflicts. Over the past 40 years, the concern related to overexploitation of resources has been increasing (e.g., Dittrich et al. 2012; UNEP 2011). This is often manifested in the consideration of the scarcity of a resource and environmental consequences associated with extraction activities. At the same time, commodity price fluctuations have been further heightening awareness and concerns associated with reliance on

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specific materials and sources of these materials. Communities such as the European Union are equally aware of their high reliance on imported materials included in semi-finished and finished goods. Associated concerns relate both to the risks associated with supply and with ethical issues (EC 2010c; EC 2014a).

Several national strategies have been implemented in the last years to help identify concerns and related policy options (see, e.g., Federal Ministry of Economics and Technology 2010; DEFRA and BIS 2012). These strategies are increasingly adopted in resource-dependent economies with the aim of ensuring an undistorted access to raw materials. As a first step toward targeted and prioritized policy actions, most strategies define a list of “critical raw materials” (CRMs). In developing and resource-rich countries, however, resource policies can be motivated by the need of developing the economy and diversifying the production from the primary economic sector. In various cases, protectionist measures have been implemented in order to restrict export of raw materials and use them to foster a domestic downstream industry (Ramdoo 2011; Wübbeke 2013).

Resource security is therefore mainly an economic and geopolitical issue, related to the resource risk faced by enterprises, economy competitiveness and trade relationships between countries. Therefore, the concept of resource criticality is referred to a certain economic or political entity (e.g., enterprise, sector, region, state) and cannot be assessed in absolute sense or at global level. Resource efficiency and scarcity, instead, have been commonly addressed in environmental policies, even though they have relevant economic implications for industries.

International initiatives, e.g., the Resource Panel of the United Nations Environment Program, have been launched with the objective of supporting policy with scientific assessments to facilitate a more sustainable use of resources (UNEP 2012). The need of a coordinated action for resource efficiency has been put forward in several contexts. For example, in the European Union a more efficient use of resources is at the core of an overarching policy, the “EU 2020 strategy” (EC 2010a). Resource security is part of the associated European Flagship Initiative on Resource Efficiency (EC 2011a). The necessity for secure access to resources is addressed within a *communication* on commodity markets (EC 2011b).

EU resource efficiency policies stress that “in order to make the right choices […] we need to consider the whole life-cycle of the way we use resources, including the value chain, and the trade-offs between different priorities” (EC 2011a), and with regard to minerals and metals efficiency, it will be improved “through measures to take life-cycle impacts more into account, to avoid waste, reuse and recycle more […]” (EC 2011c).

Various complementary tools exist to help assess resource use and to identify improvement opportunities. These include material flow analysis (Adriaanse et al. 1997; Matthews et al. 2000; OECD 2008), energy analysis (Haberl 2001), exergy analysis (Dewulf et al. 2007), environmentally extended input-output tables (EEIOT) (Leontief 1970; Tukker et al. 2006; Eurostat 2008; Miller and Blair 2009), and life cycle assessment (LCA) (ISO 14044 2006).

This paper focuses on LCA; LCA being a tool that helps to systematically analyze the use of raw materials in relation to the supply chain, use phase, and end-of-life waste management of specific goods and services. By modeling processes in the life cycle and how resources are used at each stage, LCA provides in-depth analysis of hot spots and improvement opportunities. It is also a key tool to help identify some of the trade-offs between product options, including between health, environment, and resource-related considerations.

While appearing to be a very relevant tool for assessing resource-related issues of concern to business and governments, the potential of LCA to be exploited in this context remains limited. This is partly driven by several factors that are explored in this paper, including perceptions about the predominantly environmental context in which LCA should be used, the associated scope of such assessments, the influence of only considering materials used in large quantities, as well as the historical basis of resource-related indicators in LCA.

This paper investigates how resource security considerations can be integrated into LCA, in order to facilitate the management of CRMs in supply chains, their use phase and of waste. It also highlights possible synergies between LCA and methodologies used for the identification of CRMs. We focus the discussion on the European context, where a cross-cutting policy has been implemented for resource efficiency and for CRMs, and where LCA has a potential for further supporting science-based decision making. Nevertheless, we note the analogous situation in other economies such as the USA and Japan in terms of needs, policies, and methods. Similarly, even though the “criticality” concept could be applied to all kinds of natural resources and analogous considerations, the discussion in this paper focuses on the example of integration of resource security in LCA.

The paper is organized as follows: Sect. 2 presents the specific policy framework for resources in the EU, followed by Sect. 3 where we provide an overview of the methodologies for CRM identification. Section 4 focuses on the potential capability of LCA to support and integrate the management of critical resources, taking into account (i) the information on CRM flows at inventory level and (ii) the inclusion of resource security at impact assessment level. In Sect. 5, while LCAs have the power to facilitate in-depth analysis for specific goods and services, the macroscale analysis of CRM flows associated with supply chains is also analyzed within the framework of the life cycle-based indicators. Discussion on the synergies between CRM identification methodologies and LCA and an outlook for the integration of security of supply considerations in LCA are then provided in the last section.

2 Resource policy in EU: toward an integrated framework

In the EU, a more efficient use of resources is at the core of policy aimed at promoting sustainable growth for the next decade, the EU 2020 strategy. A secure access to resources, is also an objective in two flagship initiatives encompassed in the EU 2020 strategy:

- “Resource Efficient Europe” (EC 2011a), addressing all the types of natural resources (minerals and metals, water, air, land and soil, marine resources), and advocating more efficient use of resources for ensuring the security of supply, decoupling economic growth from resource use; and reducing the environmental pressure related to resource extraction and use
- “An Integrated Industrial Policy for the Globalization Era—Putting Competitiveness and Sustainability at Centre Stage” (EC - European Commission 2010b), underlining the importance of establishing secure access to raw materials for the European economy and for achieving industrial competitiveness, employment, and innovation

Earlier, resource security has been the objective of the raw material initiative (RMI) (EC 2008). This policy action—focusing on non-energy raw materials—re-iterated the importance of establishing secure access to raw materials for the European economy and for achieving industrial competitiveness, employment, and innovation.

The communication 25 (2011) (EC 2011b) “Tackling the challenges in commodity markets and on raw materials,” an initiative foreseen under the Resource Efficient Flagship, refers to and updates the RMI. This communication presents a set of 14 CRMs identified by an ad hoc working group as being highly relevant for the European economy and as having a high risk of supply shortage in the next 10 years (EC 2010c). A draft Communication “On the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative” was published in 2014 with the updated list of CRMs.

Figure 1 presents an overview on the EU policies on resources, linked to the categories of resources they address.

3 Critical raw materials and methodologies for their identification

According to Oxford dictionary,[1] “critical” means “having a decisive or crucial importance in the success, failure, or existence of something,” but also “having the potential to become disastrous; at a point of crisis”. In the existing literature and policy documents on CRMs, these concepts are embodied in the risk of supply disruption and the related consequences, which are the main issues behind the concept of resource criticality.

The concern for resource security is a recurrent issue over history and is closely related to economic and geopolitical factors that can affect the access to resources, e.g., import dependence, diplomatic relationships, political stability of producing countries, unbalanced bargaining power (Buijs and Sievers 2011; Buijs et al. 2012). Until 2008, EU resource security policies focused mainly on energy, due to the high import dependence of the EU and the role of energy resources for fostering economic growth (EC 2000).

Price surges and fluctuations intensified in the last years (Dobbs et al. 2011; The World Bank 2013) increasing the policy concern on security of supply of raw materials especially in consuming countries with high import dependence. This is the case of the EU, having a high reliance on imports for some metals (EC 2008). The production of these elements is often concentrated in few countries with emerging economies and low political stability.

Rare earth elements (REEs) are examples of materials that have started to be perceived as critical in recent years, in spite of their relative geological abundance (USGS 2013). REEs are used, e.g., for permanent magnets, chemical catalysts, alloys, and polishing and glass, thus are essential for electronics, environmental and energy technology, metallurgy, military technology, and many other fields. The worry about REE security of supply has increased since China—which produces 95 % of the world REE—applied a restriction of the export quota (which passed from 48,010 t in 2005 to 30,996 t in 2012 (Tse 2011)). The major REE consumer states (EU, Japan, and USA) requested a consultation within the World Trade Organization (WTO) in March 2012 (WTO 2012), arguing that this protectionist measure fails to comply with the General Agreement on Tariffs and Trade (GATT). The main concern for the consuming countries is that China and other producing countries can use the control over natural resources for geopolitical reasons. However, other narratives identify the environmental protection and resource conservation as main reasons to reduce the REE export. According to Wübbeke (2013), export controls can also be motived by an economic development strategy aiming at fostering the downstream industries (e.g., the high-tech manufacturing), having higher added value and lower environmental impact than the extractive industry.

From an EU perspective, other raw materials have similar constraints as REE and are perceived as unsecure. Table 1 provides an overview of the metals having the highest share of net import over apparent consumption (more than 50 %) in

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[1] http://www.oxforddictionaries.com/

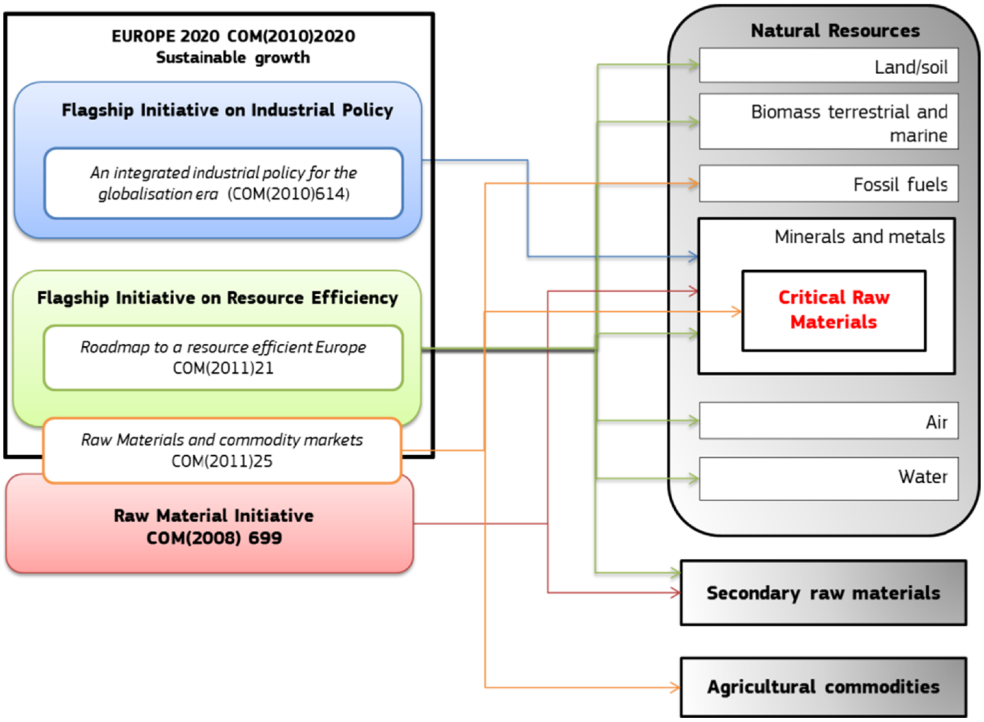

Fig. 1 The framework of the EU policies addressing critical raw materials and other typologies of resources

EU-27. It also shows the high market concentration and the application of export quotas.

Governments and institutions have started to plan resource security strategies, which include the identification of the materials that are more critical, i.e., facing a higher risk of supply disruption. The assessment of CRMs allows setting priorities in policy making focusing efforts where the major risks are foreseen, and raising awareness on the importance of raw materials.

Criticality can be assessed by taking into account different factors affecting availability and access to resources (geopolitical, economic, social, environmental). It can be performed at governmental level (e.g., CCMI CER and NRC 2008; EC 2010c), as well as at sectorial and business levels, similarly to a risk assessment (e.g., Moss et al. 2013). Some of these frameworks for the identification of criticality have been developed in scientific and academic contexts (e.g., Graedel et al. 2012). Others have been endorsed by institutions and governments with their results used to support and prioritize policy decisions (e.g., EC 2010c). Table 2 presents the main features of some methodologies used for the identification of CRMs.

Indium and REEs result as critical in four out of the six methodologies as shown in Table 2 (excluding the methodology by Graedel, which has been applied to elements of the geological copper family only). Antimony and platinum group metals (PGMs) turned out as critical in three of the six methodologies.

Aspects that are commonly considered are the material substitutability, the supply concentration (both at company and country level and in terms of reserves), and governance of producing countries.

Resource scarcity and/or availability are also taken into account in most of the methodologies, in terms of depletion time and ratio between reserves and production. Environmental implications are treated differently in the methodologies: in Graedel et al. (2012), this dimension refers to the environmental burden of the material, that is, assessed through LCA in terms of damages to human health and ecosystems; in Morley and Eatherley (2008), global warming potential, total material requirement, and climate change vulnerability are taken into account. In the methodology developed for the EU, the Environmental Performance Index (EPI) of the producing country was included in the first assessment on CRM (2010), while in the 2014 update the EPI indicator was not considered relevant enough for the assessment (EC - European Commission 2014b).

The methodologies of EU and by Graedel et al. (2012) are summarised in the following sections.

3.1 Critical raw materials for the EU

The EU study on CRM (EC 2010c, 2014b) adopts a “pragmatic approach” to the identification of materials that could be subjected to supply restriction in the near future. This study considered a time horizon of 10 years, and the evaluation took into consideration the relative criticality of materials, defining a CRM as one for which “the risks of supply shortage and their impacts on the economy are higher than for most of the other raw materials” (ibidem).

The criticality concept applied in this study does not consider the geological scarcity of resources, since this is not

Table 1 Metal concentrates and ores, EU-27 net imports, major producing countries, and application of export quota

Metal	Net import as % of apparent consumption[a]	Major producers (proportion of world production %)[a]	Export quota (2010)[b]
Antimony	100 %	China (87 %)	57,500 t
Cobalt	100 %	Congo (36 %)	
		Australia (11 %)	
		Canada (11 %)	
Molybdenum	100 %	USA (34 %)	
		China (23 %)	25,500 t
Niobium	100 %	Brazil (90 %)	
Platinum	100 %	South Africa (77 %)	
Rare earths elements	100 %	China (95 %)	Dysprosium: full export ban Lanthanum: c.a. 9,000 t (e) Neodymium: c.a. 5,000 t (e)
Tantalum	100 %	Australia (60 %)	
Titanium minerals	100 %	Australia (42 %)	
		South Africa (18 %)	
Vanadium	100 %	South Africa (45 %)	
		China (38 %)	Unknown amount
Manganese ore	90 %	China (21 %)	
		Gabon (20 %)	
		Australia (16 %)	
Iron ore	86 %	Brazil (22 %)	
		Australia (21 %)	
		China (15 %)	
Bauxite	82 %	Australia (34 %)	
		Brazil (22 %)	
Tin	82 %	China (40 %)	21,000 t
		Indonesia (28 %)	
Zinc	66 %	China (28 %)	
		Australia (13 %)	
		Peru (11 %)	
Chromium	55 %	South Africa (41 %)	
		Kazakhstan (27 %)	

e estimate

[a] Commission staff working document accompanying the Communication from the Commission to the European Parliament and the Council: The raw materials initiative—meeting our critical needs for growth and jobs in Europe (EC 2008)

[b] Scarcity of minerals—a strategic security issue (Kooroshy et al. 2009)

considered an issue in the time horizon of the study. Two aggregated indicators are calculated for 54 materials:

- Economic importance, assessed on the basis of the *added value* of the economic sector using the raw material as an input.
- Supply risk due to poor governance, which encompasses four sub-components: level of concentration of worldwide production of raw materials (using the *Herfindahl-Hirschman Index* (HII)); political and economic stability of the producing countries (measured with the World Bank indicator *Worldwide Governance Indicator* (WGI)); potential of substitution of the raw materials (based on a *substitutability index* estimated through experts' opinion) and recycling rate, considering the share of EU consumption of raw materials addressed through secondary materials. The aggregation of the four elements listed above has been performed using the following equation:

$$\mathrm{SR}_i = \sigma(1-\rho_i)\,\mathrm{HHI}_{\mathrm{WGI}}$$

where

SR = supply risk

$$\sigma = \text{substitutability} = \sum_s A_{is}\,\sigma_{is}$$

Table 2 General features and criteria adopted in some methodologies for criticality determination

General features	EC 2010b	Morley and Eatherley 2008	CCMI CER and NRC 2008	US Department of Energy 2010	Erdmann et al. 2011	Moss et al. 2011	Graedel et al. 2012
Reference subject	EU economy	UK economy	US society	Clean energy economy	German economy	Six low carbon energy technologies	Variable
Level of analysis	Over-national (European Union)	National	National	Sector-based	National	Sector-based	Corporate, national, and global
Time horizon	10 years	Not specified	Short, medium, and long term	Short term (0–5 years) and medium term (5–15 years)	Short, medium, and long term	20 years	1–5 years at corporate level; 5–10 years at national; 10–100 years at global level
Main dimensions	Economic importance; supply risk; environmental risk	Material risk; supply risk	Supply risk; impact of supply restrictions	Importance to clean energy; supply risk	Vulnerability; supply risk	Likelihood of a rapid demand growth limitation to expand production capacity concentration of supply political risk	Supply risk; vulnerability to supply restriction; environmental implication
Indicators related to:							
Consumption and demand		Consumption at global level	Consumption at national level Emerging uses	Demand for clean energy Competing technologies demand	Share of national consumption Change in the share of national consumption in world consumption Demand from emerging technologies	Likelihood of a rapid demand growth	
Substitutability	Substitutability	Lack of substitutability	Substitutability	Substitutability	Substitutability		Substitute performance Substitute availability
Import			Import dependence		Change in import		Net import reliance Net import reliance ratio
Resource scarcity and availability		Physical scarcity	Ratio of world reserve to production Ratio of world reserve base to production	Basic availability	Ratio of world reserve to production		Depletion time of reserves
Recycling, by-products, co-products, companion, and scraps	Recycling rate		World by-product production compared with total primary production Secondary production from scraps compared with consumption	Co-dependence on other markets	World by-product production compared with total primary production Recycling rate		Companion metal fractions
Supply concentration	Concentration of supply at country level	Monopoly supply		Producer diversity	Concentration of reserves Company concentration	Concentration of supply at country level	Concentration of supply at country level
Environment	Environmental country risk[a]	Life cycle based assessment of global warming potential					Environmental impact ratio (LC based assessment of impact on human health and ecosystems)

Table 2 (continued)

General features	EC 2010b	Morley and Eatherley 2008	CCMI CER and NRC 2008	US Department of Energy 2010	Erdmann et al. 2011	Moss et al. 2011	Graedel et al. 2012
		Total material requirement Climate change vulnerability					
Geopolitical issues and governance	Worldwide Governance Indicator (WGI)	Political instability		Political, regulatory, and social factors	Country risk of producing countries Governance of countries selling to Germany (including also export restrictions)	Political risk	WGI Human Development Index (HDI) Potential Policy Index (PPI)
Economic importance	Value added of end-use sector						National economic importance Percentage of population utilizing
Other aspects					Sensitivity of value chain	Limitation to expand production capacity	Global Innovation Index (GII)
Resulting CRM	Antimony, beryllium, cobalt, fluorspar, gallium, germanium, graphite, indium, magnesium, niobium, platinum group metals (PGMs), REEs, tantalum, tungsten	Gold, rhodium, platinum, strontium, silver, antimony, tin	PGMs, REES, indium, manganese, and niobium	REEs (terbium, neodymium, dysprosium, yttrium, europium), indium	Highest criticality: germanium, rhenium, antimony	REEs (neodymium and dysprosium), indium, tellurium, and gallium	Arsenic has the highest criticality at global level; gold and arsenic at national level[b]

[a] "The risk that measures can be taken by countries with the intention of protecting the environment and doing so endangering the supply of raw materials to the European Union" (EC 2010c). This indicators was used in the 2010 assessment only

[b] Results from Nassar et al. (2011), where the methodology has been applied to elements of the geological copper family (Cu, As, Se, Ag, Te, and Au)

A = share ofa raw material consumption in a given end use sector

i = raw material

s = end use sector

ρ = recycling rate

= ratio of recycling from old scrap to EU consumption

HHI = Herfindahl-Hirschman Index

WGI = Worldwide Governance Index

The resulting list of CRMs is derived considering the materials with a relatively high supply risk and economic importance, setting thresholds for the two dimensions and selecting the group having relatively higher scores for both the dimensions. The original list of CRM in 2010 included the following: antimony, beryllium, cobalt, fluorspar, gallium, germanium, graphite, indium, magnesium, niobium, PGMs, REEs, tantalum, and tungsten. The 2014 updated list contains also borates, chromium, coking coal, magnesite, phosphate rock and silicon metal, while tantalum is not considered critical anymore (EC -European Commission 2014b)

3.2 Methodology of metal criticality determination (Graedel et al. 2012)

The Center for Industrial Ecology of Yale University developed a framework for identifying critical metals at corporate, national, and global levels (Graedel et al. 2012). Based on the preliminary study of the US National Research Council (National Research Council 2008), the methodology takes into account three key dimensions: supply risk (SR), environmental implications (EI), and vulnerability to supply restrictions (VSR).

The SR is assessed on a medium (5–10 years) and long-term (few decades) basis considering different components and measured through indicators:

- Geological, technological, and economic component, including two equally weighted indicators: the *depletion time* and the *companion metal fraction*, which is the percentage of the metal mined as a companion
- Social and regulatory component, assessed by the *Policy Potential Index* and the *Human Development Index*
- Geopolitical component, measured through the WGI and the *global supply concentration* implemented with the HII index.

The EI refer to the environmental burden of materials, i.e., their toxicity, the use of energy and water in processing, and the emissions to air, water, or land. They are assessed with LCA using Ecoinvent database and according the ReCiPe endpoint methodology (Goedkoop and De Schryver 2009), with “world” normalization and “hierarchist” weighting.

The VSR is appraised at business level (considering the importance of the material, its substitutability and the ability to innovate), national level (taking into account the economic importance and the percentage of population utilizing a certain material, its substitutability and susceptibility[2]), and global level (in which the importance is assessed as percentage of population utilizing the material and the materials’ substitutability is assessed on the base of substitute’s performance, availability, and environmental impact ratio).

4 Life cycle assessment for the management of critical materials

LCA entails the analysis of flows exchanged between a product system and the environment, resources consumed, and emissions in its supply, use, and end-of-life. The impact assessment in LCA of resources is generally limited to the depletion potential of abiotic resources. However, also other aspects related to resources can be useful in eco-design contexts and in policy making, e.g., the material efficiency of alternative products as well as the use and recovery of critical resources. This latter information would support and guide the minimization of use of critical resources, recovery in waste management, and/or their substitution. A further potential use of LCA consists in the evaluation of the environmental performance of possible substitutes of CRMs. Considering the criticality of materials within the LCA may require, however, a methodological advancement that could include both a better definition of the meaning of the resource impact category and the analysis of potential mismatching or inconsistencies that could exist between LCA and criticality assessments.

The potential of LCA in integrating considerations related to resource security is explored here in terms of the following:

- Availability of information on CRM flows used in the supply chain, at inventory level
- Suitability of the current LC impact assessment methods for including criticality criteria (i.e., aspects like supply risk, substitution and recycling potential, etc.) within the

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[2] The susceptibility is expressed as the *net import reliance* and the INSEAD’s country-level global innovation index (INSEAD. Global Innovation Index 2009/2010; Fontainebleau, France 2010)

current conceptual definition of the "natural resources" area of protection
- Potential to analyze the flows of CRM at macroeconomic scale and at sectorial level within the framework of resource life cycle indicators

In each section, the main research gaps and open issues regarding the role of LCA in supporting a resource policy are addressed.

4.1 Inventory

Life cycle inventory (LCI) analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system (its supply, use, and end-of-life). In principle, LCI should include all relevant flows related to unit processes within the system boundaries. This refers to all kind of resources, including CRMs. However, LCI is performed in line with the goal definition and meeting the requirements derived in the scope phase (EC 2010d). Some flows could be not accounted due to applied cutoff rules or allocation rules and system boundary definition. This could be the case of critical materials, which are usually used in very small amounts in a product's life cycle. This may result in a lack of information on the issue of resource criticality.

Therefore, criticality should be specifically addressed during the goal and scope definition, at least for those products belonging to sectors where such materials are relevant. Relevance of sectors is related to geopolitical, economic, social, and environmental considerations. EU relevant sectors have been recently identified by the European Commission (EC 2010c, Annex V) (see Table 3). These sectors cannot be considered a general priority and might differ from market to market.

LCI data quality is related to completeness, which is usually evaluated against selected impact categories (EC 2010e). Current resource depletion impact assessment methods do not consider several criticality aspects and could therefore not capture CRM-related flows that are relevant. Having a clear impact category related to such issues, hence requiring explicit consideration of CRMs when assessing product life cycles, would ensure CRMs to be considered while evaluating data quality and completeness.

A further issue to take into account when analyzing the use of critical resources in supply chains is the nature of criticality indicators. In the EU study, the "supply risk" aggregated indicator includes country-dependent indexes, i.e., HII and WGI (see Sect. 3.1). This suggests the need for a spatially differentiated LCI, unless just listed totals of critical raw material inventory irrespective of their origin.

The concept of spatial differentiated resources inventory has been already introduced (e.g., Strauss et al. 2006; Gao et al. 2009), but only a very limited number of examples can be found in literature at this time. Although only at a country resolution and assuming this would be the appropriate resolution where no more detailed supplier insights exist, spatially differentiating resources inventory could increase drastically both the number of flows to be accounted and LCI database management and update operations. For foreground data, such information may be more readily available and result in no additional burden. For background data, this may be more complex and reliance may have to be on the total inventory of CRMs irrespective of their source/supplier.

The European Commission has developed methodologies and tools for spreading the life cycle thinking (LCT) and facilitating a broad application of LCA. The European Platform on LCA (http://eplca.jrc.ec.europa.eu/) has been created with the aim of improving the quality and reliability of life cycle data and assessment, increasing the availability of quality ensured data and facilitating the knowledge exchange. This has facilitated the development of the European Life Cycle Database (ELCD), the International Reference Life Cycle Data System (ILCD) handbook, and the Life Cycle Data Network amongst other outputs.

The ELCD provides reference data on life cycle inventories of selected processes of material production, energy carriers and technologies, transport services, systems like packaging and construction, end-of-life treatments. As far as currently feasible, these reference data are aligned with the entry-level criteria of the Life Cycle Data Network. These criteria include a format and nomenclature developed as part of the ILCD handbook.

CRMs are currently listed as elementary flows in the ILCD reference nomenclature list. REE and PGM flows are not aggregated, and inventory of single resources is required. The ILCD data format allows running spatial differentiated LCI for the CRM resources.

The ELCD datasets provide an insight on the use of CRMs within the supply chains of some products widely taken into account in LCAs, both as production inputs and as by-products/emissions/waste. Displaying the amounts of materials used in products and processes, these datasets can expedite the implementation of resource efficiency strategies focused on the use of CRMs, within or in parallel with the LC practice. Table 3 summarizes the availability of information on CRMs in the ELCD database, with reference to the main end-use markets and mega-sectors, as defined by the EU study on CRMs (EC 2010b).

4.2 Impact assessment

There is a lack of consensus on how resources should be addressed in LCA. The existing impact category refers to resource depletion or scarcity only; security of supply is so far not explicitly included in the impact assessment methodologies.

Table 3 Availability of ELCD datasets CRM (2010) are traced and related end-use markets and megasectors

CRM	Main end-use markets	Megasectors	Availability in the ELCD
Antimony	Flame retardants, glass	Rubber, plastic, and glass	X
Beryllium	Electronic equipment, domestic appliances	Electronic equipment and domestic appliances	
	Mechanical equipment	Mechanical equipment	
Cobalt	Batteries, pigments	Chemicals	
	Superalloys and magnets, hardmetals	Metals	X
Fluorspar	Hydrofluoric acid	Chemicals	
	Steel, aluminum	Metals	X
Gallium	Integrated circuits, laser diodes, and LED	Electronics % ICT	
	Alloys	Research and development	X
Germanium	Fiber optic, electrical, and solar equipment	Electronics % ICT	
Graphite	Steel industry, crucible production	Metals	
	Electrical applications	Electronics % ICT	
Indium	Flat display panels	Electronics % ICT	
	Low melting point alloys	Metals	
	Architectural glass, windscreen	Rubber, plastic, and glass	
Lithium	Glass and ceramics	Rubber, plastic, and glass	X
	Batteries	Electronics % ICT	
	Lubricating grease	Refining	X
Magnesium	Casting alloys (mainly car parts)	Road transport	X
	Al-alloys (packaging)	Beverage	X
	Al-alloys (transport)	Metals	X
Niobium	Ferroniobium for steel, alloys	Metals	X
	Ferroniobium for construction	Construction material	
Platinum group metal	autocatalysis	Road transport	
	Jewellery	Consumer goods	
	Electronics and electrics	Electronics and ICT	
Rare earths	Catalysts, batteries	Chemicals	
	Magnets	Electrical equipment, domestic appliances	
	Glass	Rubber, plastic, and glass	X
	Iron and steel	Metals	X
Tantalum	Capacitors	Electronics and ICT	
	Cemented carbides	Mechanical equipment	
	Aerospace and automobile	Road transport	
Tungsten	Cemented carbides, alloy steels	Mechanical equipment	
	Fabricated products	Electrical equipment, domestic appliances	

Considering criticality of raw materials in LC impact assessment (LCIA) entails the inclusion of aspects that can constrain the access to resources. These aspects have different natures: political (e.g., the stability of producing countries), economic (e.g., concentration of supply, demand dynamics, or trade barriers), and regulatory (e.g., the level of environmental legislation in the producing countries). The meaning of an impact category for resources and its inclusion in the LCA framework are, however, still open issues.

The debate whether or not natural resources should be considered an area of protection in the context of LCA started in at least the 1990s and is still unresolved (Weidema et al. 2005). Resource use is appraised in LCA with an anthropocentric approach, according to which the assessment focus on the impacts on human welfare derived by reduced resource availability. The conceptual definition of the natural resources area of protection is, however, unclear: in the assessment of the impacts related to resource depletion, many doubts rise concerning the boundaries between environmental and socio-economic spheres. Indeed, a considerable range of methodologies for assessing resource depletion in LCA have been proposed, with different theoretical underpinnings (Klinglmair et al. 2013). Currently, in most of the LCIA methods, use of resources is accounted, at midpoint level, in the impact category “resource depletion,” taking into account the decreased availability caused by the resource use both for abiotic and biotic resources.

Presently, LCIA methods have as their modeling basis different definitions of the depletion problem (Steen 2006), that could be summarized as follows: (1) assuming that mining cost will be a limiting factor, (2) assuming that collecting metals or other substances from low-grade sources is mainly an issue of energy, (3) assuming that scarcity is a major threat, and (4) assuming that environmental impacts from mining and processing of mineral resources are the main problem.

These four problem definitions reflect mainly a socioeconomic orientation in the resource depletion assessment. In all the four problem definitions, extraction of a resource from the natural environment leads to a decrease in its future availability for human use. This, in turn, is expressed either in relation to the available amount of a resource at a given point in time (e.g., ore deposits or fossil fuel reserves) or the future consequences (e.g., higher economic and/or energetic costs) of the extraction of a certain amount of a resource in the present. Environmental and human health impacts related to extraction or use, such as toxic emissions, are taken into account under separate environmental impact categories, and scarcity or criticality impacting directly ecosystem health is not taken into account.

Focusing on abiotic resources, many impact assessment methodologies exist. These are based on the property of the materials (e.g., exergy), the resource scarcity (thus considering use/extraction and availability), or at an endpoint level, the consequences of resource depletion for society. The different methodologies provide very diverse estimations and different coverage of CRMs (Table 4), while there is no consensus on the basis underpinning this impact category.

Currently, the methods for impact assessment in LCA recommended by the ILCD handbook (EC 2011d) cover only scarcity-related issues and not all CRMs. The selected method for midpoint is the abiotic depletion potential (ADP) (Guinée 2002), which assesses fossil fuels and mineral resources in terms of resource scarcity by including the extraction rate and its reserve. Instead, none of the endpoint methods were considered robust at the time of the related analysis, hence were not recommended.

The consideration of aspects that can constrain the access to resources (in addition to the geological availability) in the impact assessment of resources is currently debated, and some methods have been developed with this aim.

In the context of the European project LC impact, a stakeholder consultation has been organized on the impact assessment of resources. The conclusion of this process was that an indicator for mineral resource depletion in a short-term perspective should be based on political factors limiting resource availability (Vieira et al. 2011). In Schneider et al. (2011, 2013) factors, e.g., concentration of supply (at country and company levels), availability of secondary production and substitutes, trade barriers, and anthropogenic reserves have been included in an “economic resource scarcity potential (ESP)” indicator.

The consideration of aspects related to supply risk in the impact assessment of resources faces, however, methodological hurdles. Some open issues have to be addressed before implementing such development, e.g.,

- How to bring in a characterization model indicators and/or concepts used for assessing criticality?
- Since CRMs result from a relative ranking and their assessment has some degree of subjectivity (given by, e.g., the setting of thresholds), how could they be considered in the LCIA, which is based on measured and absolute figures?
- How to deal with the fact that CRMs are assessed relatively to a certain country/region and do not have an absolute validity?
- How to differentiate the geographic origin (and the risk related to different geographic areas) of resource supply in the LCIA?
- Should the aspect related to supply risk be taken into account in the environmental LCA or in the social LCA?

Addressing the abovementioned questions implies, however, a common understanding of the resource category and also of the whole LCA methodology. We advocate that the assessment of impacts related to resource use should take into account both environmental, social, and economic issues and that a common understanding of the area of protection Natural

Table 4 Number of natural resources and CRMs (2010) covered per impact assessment method

	Exergy	AADP	CML 2002	Eco-indicator 99	EcoPoints 2006	EDIP 97	EPS 2000	IMPACT 2002+	ReCiPe 2008
Abiotic, mineral	57	10	48	12	1	29	67	13	19
Abiotic, fossil fuels	6	–	4	4	4	4	3	5	4
Abiotic, nuclear fuels	1	–	1	–	1	1	1	1	1
Biotic	5	–	–	–	1	–	2	1	–
CRMs	0	2	13	1	0	8	28	1	7

Resources is needed. Moreover, LCA should not be considered only an environmental assessment methodology since it already has a broader scope, e.g., in the assessment of resource depletion. Rather more, other socioeconomic and geopolitical issues, e.g., supply risk, could be taken into account. As stated by Schneider et al. (2013), the consideration of economic and social dimensions related to resources could complement existing scarcity-based models and would represent a contribution toward life cycle sustainability assessment (LCSA) (UNEP 2011).

5 Analysis of CRMs' consumption at macroeconomic scale: the Life cycle indicators framework

The life cycle indicators framework The overall consumption of biotic and abiotic resources, as well as overall impacts related to emissions of pollutants in the European Union, was recently assessed in the context of the *life cycle indicators framework* developed by the European Commission Joint Research Centre (EC 2012a, 2012b, 2012c, 2012d).[3] These indicators were developed in the context of the increased policy support accounting for life cycle thinking[4] with the aim of helping to monitor the burdens associated with European production and consumption. They support different policy areas, as outlined in Table 5. This includes providing a response to the current policy needs for the indicators that capture also impacts from trade as expressed in the Roadmap to a resource efficient Europe (EC 2011d) developed under the flagship initiative "A resource-efficient Europe" of the Europe 2020 Strategy (EC 2010a).

All the life cycle indicator sets (*resource efficiency*, *basket of products*, and *waste management*) are designed to provide information on the potential burdens of domestic European consumption and production, including the impacts that happen outside Europe but are linked to European consumption (imports). The burdens are assessed according to the life cycle assessment methodology, following the ILCD recommendations (EC 2011c). This means that the burdens are expressed predominantly in terms of impact categories (e.g., climate change and acidification). Therefore, these figures can be used also as normalization values at EU-27 level (Benini et al. 2014).

The *resource efficiency indicators* (EC 2012b)—apart from providing information about environmental impact—can be used to inform policy and business on the flows of CRMs within the EU economy and associated burdens. The underlying dataset is suitable for assessing direct and indirect flows of CRMs in the EU economy, including imports, exports, and EU consumption and waste management. The dataset is composed of territorial statistics on resources extracted as well as of estimations based on life cycle inventories of imports and exports for representative products (see EC 2012b). In particular, these data allow accounting for the following:

- The amounts of CRMs domestically extracted in the European Union
- The amounts of CRMs extracted and used for producing imported and exported intermediate products
- The resource depletion related to the consumption of CRMs
- The efficiency of the CRM use, indicating the amount used in relation to the economic performance

The data underlying the basket of product indicators can provide useful information on the withdrawals of CRM driven by the consumption of European citizens. The basket of products indicators are aimed to account for the burdens of the final consumption of an average citizen of EU-27 (or member states), reflecting the entire life cycle[5] of associated goods and services.

The calculations of the basket of products are based on the combination of expenditure and consumption statistics with life cycle inventories of final products for a set of goods and services that are representative of selected demand categories,[6] adopting a cradle-to-grave perspective. The selection of representative products for each category is based on the magnitude of their environmental impact and their market penetration (EC 2012c). As reported in the life cycle indicators framework (EC 2012a), this indicators' datasets differ substantially from the resource efficiency indicators for several reasons. The most important is the focus of the analysis. Whereas the resource efficiency indicators aim at accounting for the impacts associated to the entire economic activities of the EU by modeling imports and exports by product groups along with territorial statistics, the basket of products indicators include only a subset of final products and services consumed by the citizens. The impacts associated to the domestic production for export are thus not accounted for in the basket of products indicators, as the focus of the analysis is on domestic consumption rather than on the whole economy as in the case of the resource efficiency indicators. The data underlying the basket of product indicators can provide useful information on the consumption of CRM directly driven by the consumption patterns of goods and services by the

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[3] http://eplca.jrc.ec.europa.eu/

[4] Integrated product policy (EC 2003), thematic strategy on the sustainable use of natural resources (EC 2005a), and thematic strategy on the prevention and recycling of waste (EC 2005b).

[5] Production, use, and end-of-life

[6] The demand categories covered by the basket of products are nutrition, shelter/private housing, consumer goods, mobility, and service.

Table 5 Scope and policies addressed by life cycle indicators

Indicators	Scope	Policy
Resource efficiency indicators	•Assessing the environmental impacts of the EU-27 and of each member state linked to the resource consumption and related emissions to the environment •Assessing the efficiency of the use of natural resources •Assessing the degree of decoupling of environmental impacts from economic growth	•Thematic strategy on the sustainable use of natural resources (EC 2005a) •A resource-efficient Europe—flagship initiative of the Europe 2020 strategy (EC 2011a) •Roadmap to a resource efficient Europe (EC 2011b)
Basket of products indicators	Assessing the environmental impacts related to the consumption of goods and services by an average EU (and MS) citizen	Integrated product policy (EC 2003)
Waste management indicators	Assessing the environmental impacts related to the management of the waste streams in EU and in each MS.	Thematic strategy on the prevention and recycling of waste (EC 2005b)

From: EC (2012a, b, c, d)

European Union's citizens, as well as providing useful information for monitoring the resource efficiency and resource security strategies.

The coverage of CRMs in the dataset currently available within the life cycle indicators framework is reported in Table 6.

Within the basket of products indicators, the set of products modeled within demand categories is partial by definition (EC 2012c) as the estimation is meant to cover broad demand categories with a relatively small number of representative goods. This assumption can lead to potential misrepresentation of some resource flows, especially those being very specific of production products with low market penetration and elevated inputs of CRM, thus potentially leading to high impacts in resource depletion. In the context of CRM, this can be an important issue, as critical raw materials can be used for products which might not have been captured yet in the resource efficiency indicators or in the basket of products indicators.

A possible approach to address such data gaps could consist of the inclusion of an additional set of products to the original modeled datasets, either for the resource efficiency indicators and the basket of products indicators datasets. Such additional products should be selected among the goods that entail the largest inputs of CRMs in their production, so to identify where CRMs are used and to capture their flows within the EU economy. In this respect, the set of products shown in Table 1 can represent a relevant starting point from which to develop a set of representative goods. Similarly to what is already done in the life cycle indicators framework, the inventory calculated on the basis of representative products can be combined with production statistics and then up-scaled to estimate economic sectors or end-use categories. By so doing, a better representation of the overall inputs of CRMs to the EU economy, as well as of the consumption driven by EU citizens, can be drawn.

Additionally, it is relevant to note that also the environmentally extended input-output tables, as well as their joint use with LCA data, could further support the assessment of CRM consumption. In fact, as reported by EC (2013), EEIOT combine economic information from monetary input-output (IO) tables (Leontief 1970) with environmental data (Tukker et al. 2006); Eurostat 2008; Miller and Blair 2009; Wiedmann et al. 2011) to assess the impacts associated with a given sector or product group. Such a methodology has been applied to the assessment of the environmental impact of products, at EU-25 scale, in the context of, e.g., the EIPRO study (EC 2006). The authors, through the means of a hybrid approach between EEIOT and LCA, assessed eight environmental impact indicators[7] also including for the indicators of depletion of abiotic resources (Guinée 2002). Despite the intrinsic limits of the methodology (EC 2010f), developing such an assessment by extending the list of resources covered to include CRMs could lead to a better understanding of the relevance of such resources at sectorial and product group scales, as well as providing a basis for comparison with the life cycle indicators framework outputs.

Table 7 summarizes the potential of LCA for managing CRM at inventory and impact assessment level and through the macroscale life cycle indicators and lists the methodological development needed.

6 Concluding remarks and outlook

Resource security is a policy priority. At EU level, for example, this objective is integrated in overarching policy on resource efficiency. The aim is sustainable use of natural resources and secure access. LCA is a well-established methodology for the appraisal of burdens along the supply chains of goods and services related to resource use and emissions. However, in spite of the potential of LCA, the consideration of resource-related aspects in LCA are inadequate to respond policy and business needs.

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[7] Abiotic depletion, acidification, ecotoxicity, global warming, eutrophication, human toxicity, ozone layer depletion, photochemical oxidation

Table 6 CRM data (2010)availability in the LC indicators database

	Basket of products	Resource efficiency			Life cycle impact assessment	
	EU citizen average consumption[a]	Domestic[b]	Import[c]	Export[d]	Resource depletion[e] (kg Sb eq.)	Resource depletion[f] (person reserve)
Antimony	X	0[n.m.]	x	x	n.e.	x
Beryllium	n.q.	0[n.m.]	n.q.	n.q.	n.e.	n.e.
Cobalt	X	0[n.m.]	x	n.q.	x	x
Fluorspar	X	x	x	x	n.e.	n.e.
Gallium	X	0[n.m.]	n.q.	n.q.	x	n.e.
Germanium	n.q.	0[n.m.]	n.q.	n.q.	n.e.	n.e.
Graphite	n.q.	x	n.q.	n.q.	n.e.	n.e.
Indium	X	0[n.m.]	n.q.	n.q.	n.e.	n.e.
Magnesium	n.q.	x	x	x	n.e.	n.e.
Niobium	n.q.	0[n.m.]	n.q.	n.q.	n.e.	n.e.
PGMs[g]	x(1)	0[n.m.]	x(1)	x(1)	x(3)	x(3)
REEs[h]	x(2)	0[n.m.]	x(2)	x(2)	n.e.	n.e.
Tantalum	X	0[n.m.]	n.q.	n.q.	n.e.	x
Tungsten	X	x	x	x	x	x

The current availability of CRM (as listed by the EU report) data within the life cycle indicators refers to the period 2004–2006 for EU-27 and a pilot member state (Germany). Only palladium, platinum, and rhodium (1); only lanthanum and neodymium (2); only palladium and platinum (3)

n.q. not quantified because of the limitations in the methodology, *n.e.* not existing characterization factors, *n.m.* missing characterization factors

[a] Amount of materials consumed by an average EU citizen in 1 year (disaggregated by life cycle phase)

[b] Extracted within EU-27 (or member state) territory

[c] Import of intermediate products (representative subset)

[d] Export of intermediate products (representative subset)

[e] Resource depletion of materials (CML methodology; Guinee 2002)

[f] Resource depletion of materials (EDIP 2003 methodology, Hauschild and Wenzel 1998—updated in 2004)

[g] Platinum group metals (PGMs): platinum, palladium, iridium, rhodium, ruthenium and osmium; [h] Rare Earths: yttrium, scandium, lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium

[h] REEs: yttrium, scandium, lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium

Table 7 Resuming table on the potential of LCA for managing CRM and supporting resource policies and required methodological developments

LCA step	Potential of LCA in the management of CRMs and for a resource security policy	Required methodological developments of LCA
Life cycle inventory	The existence of inventory data for thousands of processes may help the identification of the presence of CRMs within the supply chain related to a product and to a sector.	Enlarging the coverage of CRM flows in LC inventories; Expanding availability of datasets for CRMs. The concept of spatial differentiated resource inventory could be particularly interesting for managing CRMs in supply chains.
Life cycle impact assessment	LCA can be used in the methodologies for the identification of CRM in order to assess the environmental risk related to raw materials; LCA can be used to evaluate environmental performance of potential CRM substitutes.	Redesign of the resource depletion impact category; Integration of quantitative metrics with relative and qualitative assessments.
Normalization and macroeconomic based LC indicators	Data on normalization, referring to actual rate of resource consumption, may be used to evaluate CRMs supply and demand trends.	Expansion of data availability for CRM in the LC indicators databases.

Sources: Mancini et al. (2013); Guinee (2002); Nassar et al. (2011)

In this paper, we analyzed the potential of LCA in the context of supporting the management of critical raw materials.

At inventory level in LCA, input and output flows represent a relevant source of information for the management of raw materials in supply chains. Issues such as criticality could be specifically addressed. This needs to be highlighted during the goal and scope definition for certain product groups in order to avoid loss of relevant information due to, e.g., cutoff criteria. A knowledge of the origin of resources used could enhance such assessments, being likely more straightforward in relation to foreground than background data.

At impact assessment level in LCAs, current methods in the Area of Protection "Resources" already focus on socio-economic issues. This is primarily in the context of scarcity in current practice. Security of supply could be taken into account, as could other analogous issues such as "conflict minerals." Unless using standard lists of materials identified as critical, such analyses would require information on the origin of the materials.

At macroeconomic scale, such as for the EU, the framework of life cycle-based indicators provides data that can be used to inform decision makers on the flows of CRMs into, within, and out of the economy. Relevant indicators from a revised LCA framework could be incorporated to further enhance the relevance of the resource-related information in a policy and business context.

We highlighted in this paper that the assessment of natural resources in LCA—that has environmental, social and economic implications—should be more comprehensive. A redesign of the resource depletion impact category and how resource use information are used is needed to be more business and policy relevant.

Equally, methods for the identification of critical raw materials can build on LCA.

For example, LCA can be used to help assess the environmental implications of CRMs, and therefore provide indicators to be used for CRM identification from the environmental perspective. Similarly, life cycle data for critical raw materials as well as for certain associated product groups can provide valuable insights into the options for management and the fate of these materials at the end of their life, complementary, or as an input to, material flow analysis.

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