

Toward an Overall Analytical Framework for the Integrated Sustainability Assessment of the Production and Supply of Raw Materials and Primary Energy Carriers

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Toward an Overall Analytical Framework for the Integrated Sustainability Assessment of the Production and Supply of Raw Materials and Primary Energy Carriers

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Summary

The sustainable production and supply of raw materials ("nonenergy raw materials") and primary energy carriers ("energy raw materials") is a core element of many policies. The natural resource base for their production and supply, and the access thereto, are limited. Moreover, raw material supply is high on environmental and social impact agendas as well. A broad, quantitative framework that supports decision makers is recommended so as to make use of raw materials and primary energy carriers more sustainably. First, this article proposes a holistic classification of raw materials and primary energy carriers. This is an essential prerequisite for developing an integrated sustainability assessment framework (ISAF). Indeed, frequently, only a subset of raw materials and primary energy carriers are considered in terms of their source, sector, or final application. Here, 85 raw materials and 30 primary energy carriers overall are identified and grouped into seven and five subgroups, respectively. Next, this article proposes a quantitative ISAF for the production and supply of raw materials and primary energy carriers, covering all the sustainability pillars. With the goal of comprehensiveness, the proposed ISAF integrates sustainability issues that have been covered and modeled in quite different quantitative frameworks: ecosystem services; classical life cycle assessment (LCA); social LCA; resource criticality assessment; and particular international concerns (e.g., conflict minerals assessment). The resulting four areas of concerns (i.e., environmental, technical, economic, and social/societal) are grouped into ten specific sustainability concerns. Finally, these concerns are quantified through 15 indicators, enabling the quantitative sustainability assessment of the production and supply of raw materials and primary energy carriers.

Introduction

With a growing world population, society and policy makers are becoming more and more aware of the essential role raw

materials play in the functioning of our modern societies. This is exemplified by the Raw Materials Initiative of the European Commission (EC) in 2008 and the Critical Materials Strategy of the U.S. Department of Energy in 2011. In the latter strategy,

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emphasis is put on the role that particular rare earth elements and other key raw materials play in specific sectors and applications, such as clean energy technologies (e.g., wind turbines, electric vehicles, solar cells, and energy-efficient lighting). Several clean energy technologies use materials with a high risk of supply disruptions in the short term, with risks generally decreasing in the medium and long terms. In the recent report on critical raw materials of the EC, 20 materials have been identified to be critical for the European Union (EU), including platinum group metals and rare earths, among others (EC 2014a).

Natural resources play a key role in fulfilling functions that enable meeting the physical needs of humans, but also are part of the natural environment and hence can also play a role in ecosystems functioning. Hence, it is of utmost importance to supply and use natural resources in a sustainable way, given their availability constraints and the social and environmental consequences of their extraction. Natural resources have been defined quite differently. Some consider them as an asset in nature, from where economic production and consumption start (Organization for Economic Cooperation and Development; OECD). Others consider both their source and sink functions, thus adding an ecosystem services perspective component to the commodity perspective (EC 2005). The same heterogeneity in the definition of raw materials can be identified. Sometimes raw materials are considered as they occur in the natural environment, that is, being part of the natural resource base next to, for example, flow resources (EC 2005). Others consider them to be (partially) processed natural resources (e.g., chemical, high-tech raw materials: so-called primary raw materials) or even processed waste (e.g., scrap: so-called secondary raw materials) (EC 2008). Clearly, there is a need for a more consolidated classification and broader consensus on what we exactly mean with “natural resources” and “raw materials” as well as the relations of one term to the other.

Building on an enhanced understanding and classification of raw materials, this article addresses a second issue concerning raw materials, namely, how to assess their sustainable production and supply in an integrated, holistic way. Many methods have been developed to assess the sustainability of the production and supply of raw materials (Jeswani et al. 2010; Sala et al. 2013). However, most methods have grown historically to address specific sustainability concerns. For example, classical life cycle assessment (cLCA) is generally presented in an environmental context, whereas social life cycle assessment (sLCA) methods have been developed somewhat independently, with a focus more on social issues. As a result, sustainability assessment addressing multiple sustainability concerns simultaneously is not common practice; however, comprehensive assessment, based upon the integration of existing methods, would be both feasible and useful.

This article proposes an integrated sustainability assessment framework (ISAF) for assessing the production and supply of raw materials and primary energy carriers. To do so, the article starts

with a systematic analysis of the production and consumption value chains to clearly distinguish between natural resources and raw materials, among others. At the same time, it presents a systematic overview of raw materials and primary energy carriers. The overview is not limited to a particular natural resource base, nor to a particular sector or to a particular application, but rather aims at providing a holistic picture. This is essential if the goal is to create a generic ISAF to assess the sustainability of production and supply of raw materials and primary energy carriers. In a subsequent section, the article identifies sustainability concerns across the production, supply, and use of raw materials and primary energy carriers. Sustainability concerns covered include not only environmental ones, but also technical, social, and economic issues. Following this identification, a comprehensive set of quantitative indicators is proposed that should enable quantitative depiction of the sustainability of the production and supply of raw materials and primary energy carriers.

Raw Materials and Primary Energy Carriers: Where Are They Positioned in the Life Cycle of Products and How to Structure Them?

The Supply Chain: From Natural Resources at the Cradle to Products and Services at the End User

Different stages can be identified along the life cycle of a product, starting from the asset of natural resources in the environment, through to the production of products and services bringing functionality to fulfill human needs, followed by end-of-life (EOL) waste management. A simplified life cycle scheme is illustrated in figure 1, where we identify the asset of natural resources in the natural environment, supplying natural resources to the primary production sector. This primary production sector transforms natural resources into raw materials and primary energy carriers to feed the manufacturing sector. The latter sector produces goods and services for the end users. Finally, products end up in waste. At the so-called EOL phase, eventually energy and/or materials can be recovered, for example, through incineration with heat and electricity production, and recycling, respectively.

In the following subsections, we describe, in more detail, the flow of the natural resources in their different forms as they move through the natural and human industrial environment. Figure 2 illustrates this in more detail.

Natural Resources at the Cradle. Resources occur in the natural environment (at the cradle), that is, at the location where humans extract or harvest them. Removal deprives them from the environment and ecosystems (or excludes others from using them).

Many subgroups have been proposed to classify natural resources in the environment by many researchers and governmental bodies (e.g., EC 2005). Based on a recent review (Swart et al. 2014), we can differentiate:

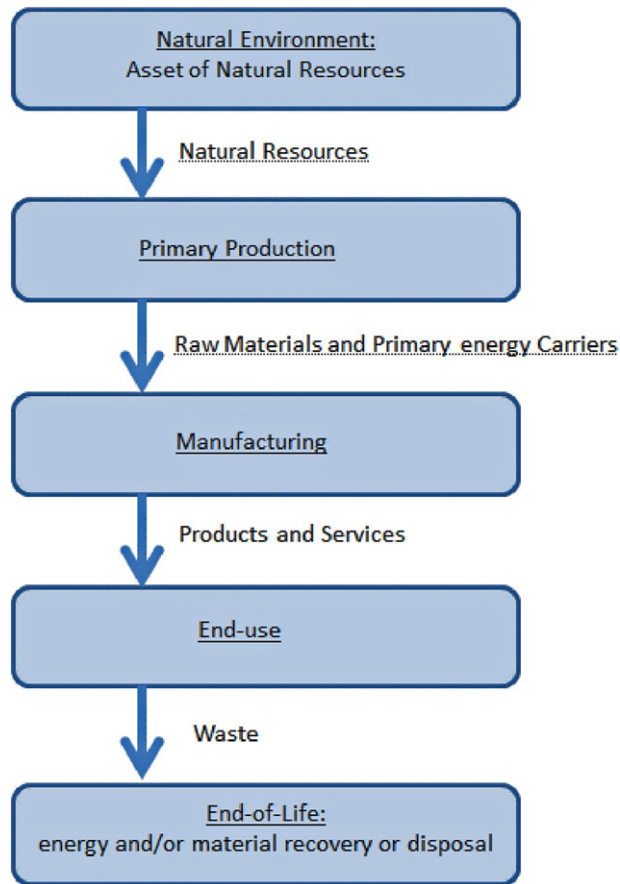


Figure 1 Simplified life cycle of products and services derived from natural resources, with positioning of raw materials and primary energy carriers as intermediates.

- Land area
- Sea area
- Flow energy resources (solar irradiation, water, wind, and tidal currents)
- Water
- Metallic ores
- Minerals (for industrial and construction applications: so-called industrial minerals and construction materials)
- Fossil fuels (FFs)
- Nuclear ores
- Atmosphere/air
- Natural biomass (natural flora and fauna)

The first two listed can be grouped as “space” (EC 2005). The other are repositories of energy and/or materials, including atmosphere/air, for example, for sourcing noble gases. Similarly, waste produced in the anthroposphere can also be seen as a resource that originally has been derived from natural resources. It is typically not considered in the set of natural resources as such, being distinguished as a secondary, as opposed to primary, resource.

Natural resources can be classified in several ways (Dewulf et al. 2007; EC-JRC 2010a; Klinglmaier et al. 2014; Swart

et al. 2014). Some researchers divide them into renewable and nonrenewable, into biotic and abiotic, and others into exhaustible and inexhaustible. Typically, flow energy resources, metallic ores, minerals, FFs, and nuclear ores are considered as abiotic resources. Natural biomass represents the biomass generated from, and renewed by, natural biotic processes performed by ecosystems without human intervention for their production, as distinct from biomass produced by agricultural systems.

Based on their key characteristics, another valuable type of classification is according to: stocks versus funds versus flows (Swart et al. 2014). Stocks are deposits of minerals and metals generated by long-term geological processes: They are nonrenewable. Organic stocks, such as coal, are similarly exhaustible. Funds are naturally occurring materials (e.g., fish). They are renewable, but exhaustible, when exploited beyond their regeneration capacity. Flows are solar, water, wind, or geothermal energy streams that are renewed and considered nonexhaustible given that they are generated continuously with a long time perspective, although they are not unlimited.

The aforementioned classifications typically reflect the function of usage by humans, albeit that they are part of the natural ecosystem and may have some functions there as well. However, this latter perspective is out of the focus in this framework.

It must be said that natural resources are quite broadly defined here. They are the source for materials with a material application (e.g., ores such as natural resource for copper as a raw material). Equally, they are the source for materials that can have both a material and an energy application (e.g., crude oil as natural resource for manufacturing chemicals and for producing fuels). They are also the source for energy applications only (e.g., wind currents as a natural resource to produce wind power electricity as a primary energy carrier). During the application, the material can be used up or just used, which may have significant consequences afterward.

Natural Resources at Primary Production. The primary production sector transforms natural resources through its typical operations: growing, harvesting, mining, and/or refining. Primary production sectors include biomass-producing sectors (agriculture, forestry, and fisheries), the mining sector, and the primary energy production sector.

In the primary production sector, natural resources at the cradle are transformed into base products, typically the first market commodities. These we have named (primary [nonenergy]) raw materials or primary energy carriers (or [primary] energy raw materials), depending on their further applications. Raw materials will have, in the end, mainly material functions (e.g., refined metal). Primary energy carriers (e.g., natural gas [NG]) are mainly used as a utility for heating, cooling, pressurizing, transportation, and so on. Primary energy carriers are basically the first marketable element in energy supply chains. They are the first traded energy form owing to the fact that the primary production sector typically transforms the natural resources into a form that can be supplied to further use elsewhere after trade.

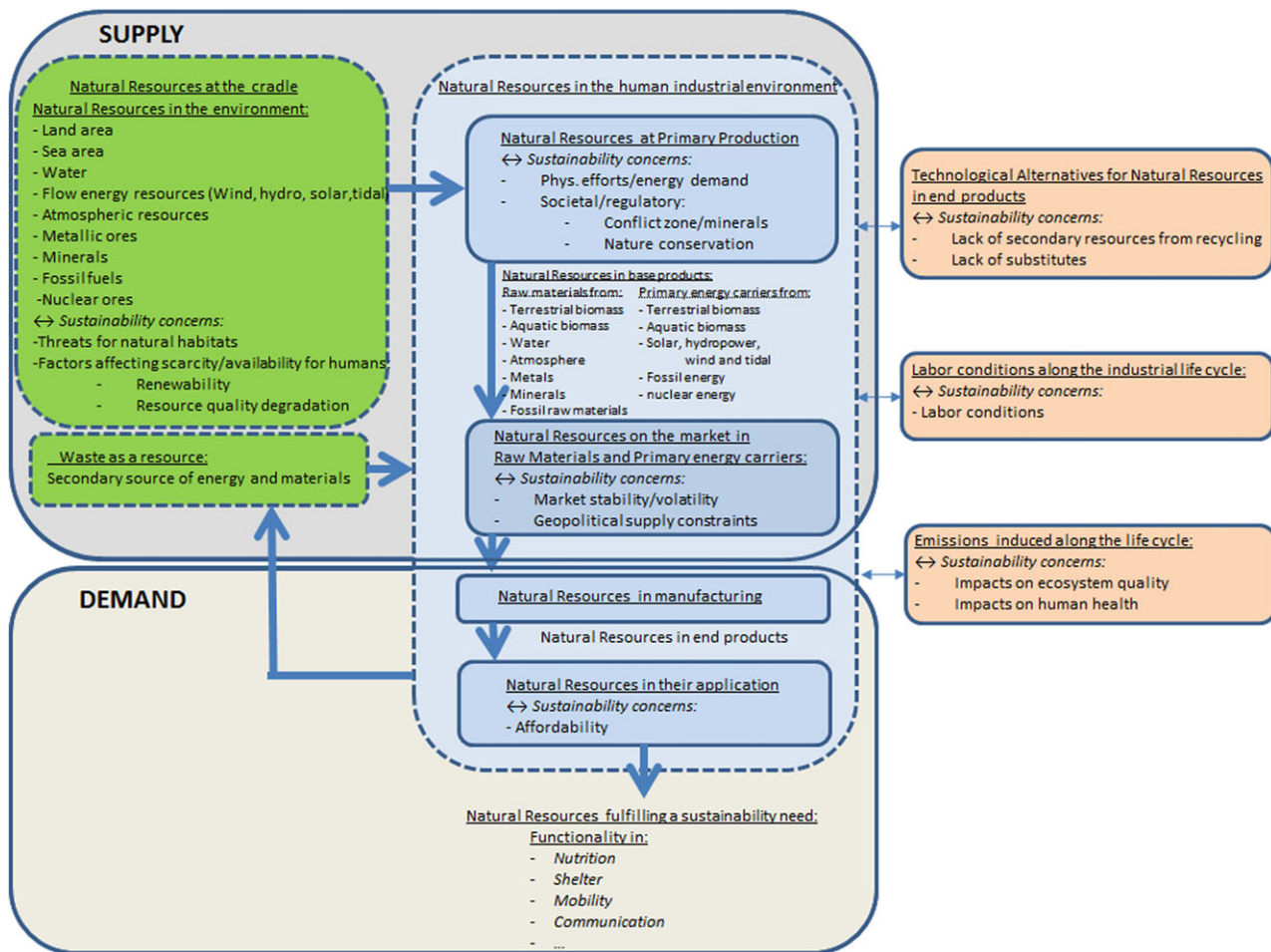


Figure 2 Natural resources: their flow from the cradle to the final application with indication of sustainability concerns. Phys. = physical.

In the case of fossil energy carriers (basically hydrocarbons), often international conventions apply. For example, NG can be distributed from so-called hubs as starting points of distribution networks (e.g., Henry hub in Erath, Louisiana). Alternatively, fractions can be derived from primary fossil energy resources as raw materials or energy carriers (e.g., naphta) to downstream industries. On the other hand, in the case of renewable energy derived from wind as an example, the first traded energy carrier after primary production is the electricity.

We can distinguish a number of raw materials groups:

- Terrestrial biomass for food and material applications
- Aquatic biomass for food and material applications
- Raw materials derived from water bodies
- Raw materials derived from the atmosphere
- Metals
- Minerals and mineral materials (Industrial minerals and construction materials)
- Raw materials from fossils

Similarly, we can identify the following types of primary energy carriers:

- Terrestrial biomass for energy applications
- Aquatic biomass for energy applications

- Renewable energy from flow resources: solar, hydropower, wind, and tidal (electricity or heat)
- Fuels from fossils
- Nuclear energy

We prefer to not use raw materials as a term for the full asset of energy and material raw materials, because this terminology may be interpreted to exclude flow resources (e.g., solar, hydropower, and so on). These latter resources are essentially not materials.

The set of raw materials can be subdivided according to their function, that is, their biotic/abiotic and/or renewable/nonrenewable nature. The biotic subgroup consists of terrestrial and aquatic biomass for food, material, and energy applications. This biomass is grouped with renewable energy from flow resources in the group renewable raw materials and primary energy carriers. However, both biomass and renewable energy from flow resources may rely partially on nonrenewable and finite natural resources for their primary production (e.g., FFs, fertilizer minerals, and land in the production of terrestrial biomass for energy applications).

The systematization presented here provides a holistic view of primary raw materials and energy carriers, clarifying their origin and their further application. At the same time, it reflects the nature in terms of biotic versus abiotic and renewable versus

nonrenewable; this is relevant in terms of some specific sustainability concerns. Additionally, this systematization is the base for structuring and further detailing the products supplied by the primary production: This will be done in the next section and in table 1.

Manufacturing. After primary production, the processed natural resources are used as raw materials or primary energy carriers into manufacturing, that is, incorporation of the natural resource into a final product. The manufacturing sector can also use recovered energy and materials embodied in by-product and waste streams, so-called secondary materials, substituting for and saving raw materials and primary energy carriers derived from virgin natural resources.

Use Phase. Natural resources are subsequently available to the consumer/user, that is, embodied in final products suitable for consumer use.

End-of-Life Phase. Finally, at the end of their use, natural resources embodied into a product can be a source of so-called secondary materials or of energy. This is achieved through, for example, recycling and incineration with energy recovery. If not, the resources may be a direct source of emission and pollution, which is typically the case for materials in energy applications through their combustion and for products disposed into landfills.

Detailing the Full Asset of Raw Materials and Primary Energy Carriers: A Proposal for Classification

Natural resources, raw materials, primary energy carriers, semifinished products, and end products are all interconnected. Yet, they are inventoried in databases with quite different scopes and purposes. For instance, they are inventoried in life cycle assessment (LCA) databases (see the European Platform on LCA Resource Directory), in macroeconomic databases (e.g., by Eurostat for the EU economy), but also in sector-specific statistics (e.g., by the Food and Agriculture Organization for agriculture sector and by the U.S. Geological Survey for mining sector). Similarly, in policy contexts, for example, in the assessment of the criticality of raw materials or in terms of conflict minerals, alternative specific groupings are utilized. In some approaches, different products along the same value chain are considered in the same analysis (e.g., bauxite and aluminum). However, none of the currently available classifications can be regarded as sufficiently comprehensive, complete, and systematically structured to perform a sustainability assessment for the supply of raw materials and primary energy carriers.

Here, we propose a classification anchored to the output of the primary production sector (figures 1 and 2): raw materials and primary energy carriers. The idea is that primary production mainly relies on natural resources at the cradle and it is the first step to make available primary products (first market commodities) for the economy through its typical core operations: growing, harvesting, mining, and refining. Based on this approach, a list has been proposed (see table 1). This list is the synthesis result of a detailed study of various sources of infor-

mation. It integrates lists used by the life cycle community, lists made by governmental statistical bodies, and lists from particular national and international sectorial organizations or institutes. The list contains 85 raw materials, subdivided into seven groups according to their origin. In a similar way, 30 primary energy carriers are listed into five groups. For the sake of completeness, important materials and energy carriers are supplied as by-products or wastes originating from other sectors than the primary production sector; for example, household waste can be an important source of precious metals derived from electronic waste and a source of energy generated from organic waste.

Table 1 is intended to be as comprehensive as possible, mainly in function to have a systematic list of raw materials and primary energy carriers that can be subjected to a sustainability assessment with respect to their production and supply. At the same time, it illustrates the diversity of raw materials and primary energy carriers. It raises awareness about the challenge to provide a complete picture of sustainability concerns that need to be addressed when developing a sustainability assessment.

Sustainability Concerns for the Production and Supply of Raw Materials and Primary Energy Carriers

Identification of Sustainability Concerns in the Overall Life Cycle

In the use phase of a product, we find mainly the benefit of the full chain for humans by the services they obtain from the natural resources embedded in a product. But the preceding stages can be associated with a risk, an impact, a critical element, a threat, a concern, or a constraint for both the sustainable supply and use of natural resources, as well as for human and ecosystem health. In the following selected examples, we use the wording concerns or constraints. From figure 2, we can identify constraints at the different life cycle stages:

Cradle. Sustainability concerns are multifaceted. Before being extracted (i.e. “at the cradle”), natural resources may have, for example, an ecological function. For example, they can have a key role in a natural habitat such as a forest. Second, from an anthropocentric point of view, access to natural resources can become more and more difficult because of (increasing) technical constraints. Such technical constraints and the potential for physical scarcity are influenced by (lack of) renewability and resource quality deterioration.

Primary Production. At the primary production stage, sustainability concerns are the (increasing) physical efforts (e.g., need for more energy or auxiliaries) required to produce raw materials and primary energy carriers. Further on, social/societal impacts can be identified. Some of these issues are expressed by, for example, international regulations discouraging the use of resources that play a key role in conflict zones, so-called conflict minerals. These minerals can contribute to, and their provision can benefit from, serious violations of human rights, violations of international humanitarian law, or violations amounting to

Table 1 Structuring raw materials and primary energy supplied by the primary production sector, on the basis of their origin in nature^a

<i>Origin of raw materials</i>	<i>Raw material group</i>	<i>No.</i>	<i>Raw materials</i>
Terrestrial biomass (for material applications)	Agricultural raw materials	8	Cereals (wheat, maize, rice, sorghum, barley, rye, oats, millets, others) Vegetables and melons (leafy and stem vegetable, fruit-bearing vegetable) Fruit and nuts (tropical and subtropical fruits, citrus fruits, grapes, berries, pome and stone fruits, nuts, other fruits) Oilseed crops (soya, groundnuts, other temporary oilseed crops, permanent oilseed crops) Root crops (potatoes, sweet potatoes, cassava, yams, others) Beverage crops (beverage crops, spice crops) Leguminous crops Other crops (grasses and fodder crops, fiber crops, medicinal/aromatic/pesticidal/similar crops, rubber, flowers, tobacco, aromatic/drug/pharmaceutical crops, etc.)
	Forestry raw materials	12	Wood in the rough Residues of wood processing Recoverable wood products Wood chips and particles Wood simply worked or processed Wood sawn lengthwise Veneer sheets Wood-based panels Pulp of wood and similar Paper and paperboard Waste paper Raw/semiprocessed/worked cork
Aquatic biomass for food and material applications	Aquaculture raw materials	2	Wild fishing products Aquaculture products
Water (components)	Freshwater raw materials	3	Groundwater Surface water Rainwater
	Raw materials from seawater	3	Raw seawater Deionized seawater Salts (from seawater) (sodium, iodine, chlorine, etc.)
Atmosphere	Raw materials from atmosphere	3	Nitrogen gas Oxygen gas Noble gases (Ne, Ar, Kr, Xe)
Fossil fuels (for material applications)	Petroleum raw materials	5	Petroleum gases as chemical building block (ethane, propane, etc.) Lubricating oils Paraffins Asphalt and tar

(Continued)

Table I Continued

<i>Origin of raw materials</i>	<i>Raw material group</i>	<i>No.</i>	<i>Raw materials</i>
			Sulfur (from petroleum)
	Raw materials from natural gas	3	Natural gas hydrocarbons as chemical building block (ethane, propane, etc.) Sulfur (from natural gas) Helium (from natural gas)
	Raw materials from nonconventional fossil fuels (shale gas, oil sands, methane hydrates, coal bed methane, etc.)	3	Natural gas hydrocarbons as chemical building block (ethane, propane, etc.) Sulfur (from shale gas) Helium (from shale gas)
Metallic ores	Ferrous metals raw materials	8	Pig iron Cobalt Molybdenum Nickel Chromium Manganese Vanadium Tungsten
	Nonferrous bulk/traditional metal raw materials	6	Aluminium Copper Zinc Lead Titanium Tin
	Nonferrous rare metal raw materials	5	Cadmium Mercury Niobium and tantalum Metalloids (silicium, germanium, arsenic, antimony, tellurium, polonium) Post-transition metals (indium, bismuth, gallium)
	Nonferrous precious/high-tech metal raw materials	5	Gold Silver Beryllium Platinum group metals (Ru, Rh, Pd, Os, Ir, Pt) Rare earth elements (Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu)
	Alkali metal raw materials	3	Lithium salts Lithium minerals Potassium minerals
Natural deposits of industrial minerals and construction materials	Construction minerals and mineral materials	4	Aggregates (sand, gravel, crushed rock) Common clays (for construction) Ornamental stones (marble, granite, sandstone, slate, basalt, etc.) Minerals for cement production

(Continued)

Table I Continued

<i>Origin of raw materials</i>	<i>Raw material group</i>	<i>No.</i>	<i>Raw materials</i>
	Industrial minerals and mineral materials	11	Phosphate rocks Silicates (mica, asbestos, perlite, vermiculite, zeolites, etc.) Limestone and talc Clays (kaoline, ball clay, fuller earths, etc.) Bentonite Graphite Diatomite Gypsum Magnesite Barite Halogen-containing deposits (fluorine: fluorspar, fluorapatite, cryolite, etc./chlorine: halite, sylvite, carnallite, etc./bromine salts/Iodine: caliche, etc.)
	Other	1	Gemstones, including diamond
<i>Origin of primary energy carriers</i>	<i>Primary energy carrier group</i>		<i>Primary energy carrier</i>
Terrestrial biomass (for energy applications)	Energy crops	4	Starch crops (corn) Grass crops (miscantus, etc.) Oilseed energy crops (canola oil) Other energy crops
	Forestry products (for energy)	1	Firewood
	Soil products	1	Peat
Aquatic biomass (for energy applications)	Aquaculture energy products	1	Algae
Flow resources (solar, water, wind, and geothermal)	Solar-based energy carriers	3	Photovoltaic electricity Concentrating solar power energy Solar thermal heat
	Hydropower-based energy carriers	2	Gravitational electrical hydropower (electricity) Osmotic hydropower (electricity)
	Wind-energy-based energy carriers	2	Onshore wind electricity Offshore wind electricity
	Tidal-energy-based energy carriers	1	Tidal electricity
	Geothermal-based energy carriers	1	Geothermal heat
Fossils for energy applications	Coal and lignite energy carriers	3	Anthracite/hard coal Bituminous coal Lignite
	Petroleum-based energy carriers	7	Liquified petroleum gas

(Continued)

Table I Continued

<i>Origin of raw materials</i>	<i>Raw material group</i>	<i>No.</i>	<i>Raw materials</i>
			Gasoline Naphtha Kerosene Diesel Fuel oils Petroleum coke
	Natural-gas-based energy carriers	1	Natural gas as fuel
	Nonconventional fossil-based energy carriers (shale gas)	1	Shale gas as fuel
Nuclear energy metal ores	Nuclear-energy-based energy carriers	2	Nuclear fission energy (electricity and heat) Nuclear fission energy (electricity and heat)

^aA key step in developing a generic integrated sustainability assessment framework for raw materials and primary energy carriers.

Ne = neon; Ar = argon; Kr = krypton; Xe = xenon; Ru = ruthenium; Rh = rhodium; Pd = palladium; Os = osmium; Ir = iridium; Pt = platinum; Sc = scandium; Y = yttrium; La = lanthanum; Ce = cerium; Pr = praseodymium; Nd = neodymium; Sm = samarium; Eu = europium; Gd = Gadolinium; Tb = Terbium; Dy = dysprosium; Ho = holmium; Er = erbium; Tm = thulium; Yb = ytterbium; Lu = lutetium.

crimes under international law (Global Witness 2011). Next to regulated constraints, particular social impacts need consideration, for example, labor conditions (child labor, forced labor, excessive working hours, and injuries and fatalities) in the primary production sector.

(International) Market of Raw Materials and Primary Energy Carriers. Once the natural resources are transformed into raw materials and primary energy carriers, they become tradable goods on the commodities markets and are often traded internationally. Their sustainable production by the primary production sector and their supply to the downstream users can be threatened by market instability (volatility). Additionally, the application of protectionist measures and other forms of resource nationalism by the producing countries can increase the risk of supply disruptions. These considerations are taken into account in resource criticality assessments, for example.

Manufacturing. Through the international market, the processed natural resources become available as raw materials and primary energy carriers for the manufacturing. Here, the raw materials and primary energy carriers are further transformed into products and services for the end users. Again, working conditions may be relevant from a sustainability point of view.

Use Phase. Finally, the natural resources embedded into final products reach their application, where affordability from the end-user perspective may be of concern. Affordability and access depend on the societal organization. These may not be seen as a key constraint from the supply point of view; these use-phase considerations will not be further considered. However, the role of end users and the waste management sector is relevant in terms of recovering and recycling materials and en-

ergy from EOL products. They can provide a secondary source of energy and materials and can feed either the primary production or the manufacturing sector.

Entire Chain. Along the entire chain, including the EOL phase, one should be aware of key interactions that are interlinked. First, there are the vulnerability and dependency of the envisaged application on the particular virgin raw material. They can be partially the result of insufficient recovery of the materials after their use through recycling and of a lack of alternatives or substitutes, offered by innovation. Further on, throughout the life cycle, emissions are generated that may impact both ecosystems and human health through cause-and-effect chains.

Limiting the Concerns to the Production and Supply of Raw Materials and Primary Energy Carriers

Given that the overall life cycle of natural resources can be quite complex, one may need to distinguish and specify particular phases in the life cycle. Here, we make a distinction between production and supply of raw materials and of primary energy versus demand. As long as the natural resources are not incorporated in (semifinished) products, we can consider the stages as part of the production and supply. The manufacturing industry and its downstream users (including the individual end consumers) can be seen as the demand side.

Looking at the scheme in figure 2, the supply includes the following stages: natural resources in the environment; natural resources at primary production; and natural resources on the market in the form of raw materials and primary energy products. In terms of sustainability concerns of supply specific to

the cradle, primary production and the market of raw materials and primary energy carriers are to be taken into account. Additionally, the issues relevant for the overall supply and demand chain (i.e., technological alternatives, labor conditions, and emissions) allocated to the supply stages need to be addressed as well.

Toward an Integrated Framework

Establishing an Integrated Framework

Before developing an ISAF, it is worth looking at existing frameworks. In fact, these are quite diverse in terms of their focus, level, and sustainability dimensions, as discussed in the options to broaden and deepen LCA by Jeswani and colleagues (2010). The researchers distinguish procedural methods, typically used *ex ante* to support decision making in projects or policy, with methods such as environmental impact assessment, strategic environmental assessment, sustainability assessment, or multicriteria decision analysis. These methods can incorporate environmental, social, and economic dimensions. However, for the sustainability assessment of the production and supply of raw materials and primary energy carriers, the so-called analytical methods are a better base. Indeed, they are used to identify and analyze sustainability impacts related not only to policies and projects, but also to products and substances (Jeswani et al. 2010). A series of frameworks have to be mentioned: material flow analysis (MFA); substance flow analysis (SFA); energy analysis; exergy analysis; environmentally extended input-output analysis (EEIOA); (hybrid) LCA; risk analysis; life cycle costing (LCC); cost-benefit analysis; eco-efficiency analysis; and sLCA. These frameworks can rely on quite different sources of information; for example, LCC starts from economic accounting. Frameworks such as MFA, SFA, and energy analysis start from energy and material inventories and balances. Process-based LCA adds cause-and-effect chains onto these energy and material inventories and balances. EEIOA starts from economic figures at sector level and adds sectorial environmental pressure information. sLCA can start from the working hours spent in particular sectors and particular countries with assignment of some risk level for humans, while different quantitative and qualitative methodologies are emerging.

On top of the aforementioned frameworks listed by Jeswani and colleagues (2010), other relevant approaches for the sustainability assessment of raw materials and primary energy carriers can be mentioned. The ecosystem services framework looks to the broader role of natural resources in an overall perspective, that is, not only from a provisioning point of view, but also in relation to their role in habitats, in regulation and cultural functions (Maes et al. 2013). Business and governments can look at the role of resources and materials in relation to sourcing from conflict zones (EC 2014b). Finally, criticality assessment accounts for socioeconomic vulnerabilities that can be considered as factors of risk of supply and consequences, for example, because of reliance on a limited number of sources, lack of sub-

stitutes, or poor recycling rates (e.g., Erdmann and Graedel [2011]; EC Memo on critical raw materials [Memo/14/377; 26 May 2014]).

Despite their differences in scope, there is overlap and complementarity in these frameworks. We therefore identified a comprehensive set of sustainability concerns in the many frameworks with the aim to: (1) cover different and mutually exclusive sustainability concerns, as holistically as possible; (2) propose a quantitative assessment of impacts on sustainability related to the use and supply of raw material and primary energy with a surveyable set of indicators; and (3) provide specific sustainability indicators for the respective sustainability concerns, from the different existing frameworks.

For the sake of comprehensiveness, we organize the sustainability concerns into the following areas of concern (AoCs):

- Environmental
- Economic
- Social/societal
- Technical/technological

In accord with the classical triple-bottom-line approach of sustainability (Elkington 1997), we start with environmental, economic, and social concerns. We then give emphasis to engineering solutions to sustainable development challenges by introducing a fourth area of concern focused on the technology involved in the production and supply of raw materials. This expanded approach can help toward integrating an engineering process into an ISAF (Shields et al. 2011) for the production and supply of raw materials and primary energy carriers (figure 3).

Environmental Concerns. With respect to the environmental AoC, concerns are twofold. First, at the withdrawal of the natural resources at their “cradle,” operations can affect the functioning and services of ecosystems, in particular, at the withdrawal site of the natural resources, mainly by affecting the land or sea surface area that has a key role in natural habitats. Second, along the life cycle, emissions that impact the natural ecosystem also need to be considered.

Technical Concerns. The technical AoC includes both (change in) physical availability in the natural environment and (change in) technological capabilities. Physical availability is determined by the (lack of) renewability of the natural resources and (the decrease in) the physical resource quality in the natural environment (e.g., ore grades of minerals). It must be mentioned that also some renewable resources (i.e., funds) can be subjected to an increased scarcity. At the same time, the technological efforts required to grow, harvest, mine, and/or refine the natural resources, which can be expressed in, for example, energy or exergy (= useful energy) requirements, should be envisaged. If significant technical improvement is achieved through, for example, innovation, it may eliminate some of the concern associated with reduced accessibility to natural resources in terms of, for example, location or grade. Similarly, a lack of alternatives for the raw materials for particular applications can be another technical concern. This lack of

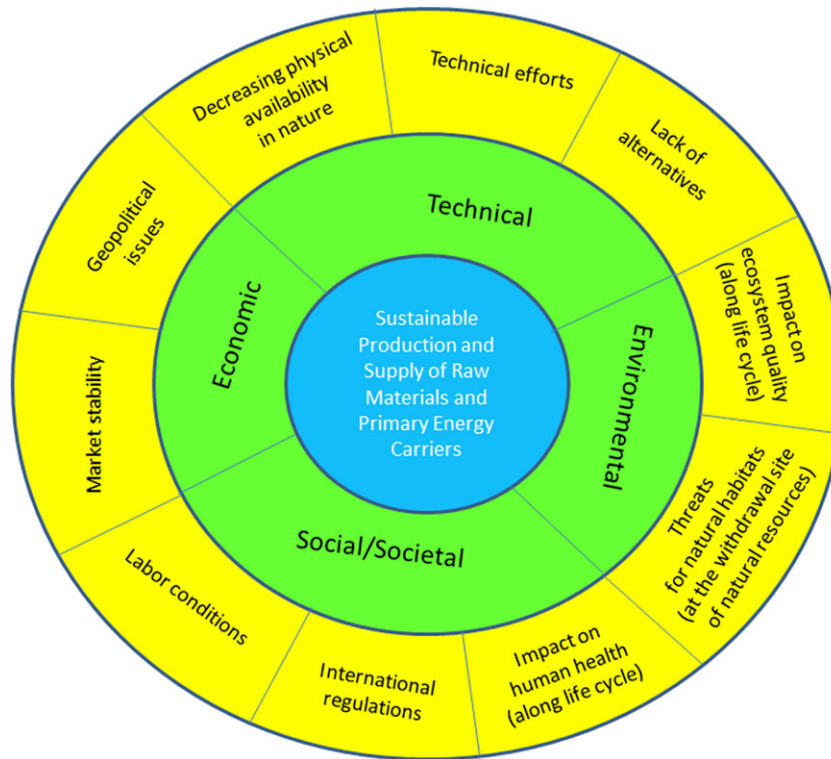


Figure 3 Sustainable production and supply of raw materials and primary energy carriers: areas of concern (inner) and specific sustainability concerns (outer).

alternatives may be overcome by innovation, directly through substitution by other natural resources or through enhanced recovery of the natural resources embodied in EOL products, or, for example, by finding alternative products that meet social needs.

Economic Concerns. As the natural resources move into the manufacturing as raw materials and primary energy carriers, economic issues play a role as an AoC. First, the stability or volatility of the prices can result in security concerns related to supply, next to eventual geopolitical issues. In particular, resource-dependent countries can face the risk of supply disruption when the production of raw materials is concentrated in few countries with low political stability and poor governance. The application of protectionist measures and export restrictions may also be motivated by an increasing internal demand for raw materials and economic development strategies, further contributing to security-of-supply concerns of other countries.

Social and Societal Concerns. Well-accepted societal concerns, endorsed by regulation, with a key example of conflict minerals, are relevant when it comes to supply constraints. Similarly, working conditions in the primary production (child labor, forced labor, excessive working hours, and injuries and fatalities) are social sustainability concerns. Bad conditions hence impact the sustainability of production and supply at the level of the involved labor. Finally, emissions at the different stages in supply chains can affect human health, including those in

the stages of the production and supply of raw materials and primary energy carriers.

From an Integrated Framework Toward Indicators

Prerequisites for Selecting Indicators

The proposed four AoCs and the associated sustainability concerns for the supply of raw materials and primary energy carriers need further substantiation. This can be done by, for example, proposing a set of indicators, ideally with a one-to-one match in between concerns and indicators. However, before proposing a set of indicators, five prerequisites need to be addressed.

First, the indicators must match with the intended scope of the sustainability assessment. Basically, the set of indicators should cover the issues of sustainability as defined by the Brundlandt commission (WCED 1987). Its report has been the ground to develop the areas of concern in the previous section: environmental, social/societal, economic, and technical.

Second, the perspective to establish the indicators needs to be defined. The perspective can be an individual, a community, a company, a region, a country, and so on. Given that raw materials and primary energy carriers are often traded internationally, a somewhat macroeconomic-scale perspective may be appropriate. In this sense a national or even a supranational level can be an appropriate perspective to develop indicators.

Third, operationalization into indicators requires well-established and accepted indicators. Indeed, the

mentioned constraints with their specific concerns need to be quantified properly by robust indicators in order to support policy and decision making for a sustainable supply of raw materials and primary energy carriers. Such quantitative indicators need to be properly defined with units and eventually scaled or normalized.

A fourth key element for the operationalization is data availability. From a pragmatic point of view, existing specific frameworks that are already provided with their specific data sets should be used as far as possible.

Finally, the proposed indicators are to be generic: They should be ideally applicable, or adaptable, to all elements listed in table 1.

Selection of Indicators

Based on the aforementioned AoCs, table 2 presents a selection of indicators. The indicators rely on the following existing frameworks: cLCA; ecosystem services (ES); criticality (CRIT); sLCA; and regulation (conflict minerals assessment).

Environmental Areas of Concern. With respect to the environmental AoCs, threats at the cradle for the ecosystem are quantified in ES in terms of monetary values. These values reflect the habitat services that can be deprived owing to exploitation of natural resources (de Groot et al. 2002). This is especially related to the surface area that is deprived or occupied. For the impact of emissions along the life cycle (supply section) onto ecosystem quality, the LCA framework offers a quantification of emissions and provides a weighted pressure-based indicator. Distinction is not generally made between impacts, relative severity, and pressures that may, or may not, result in any consequence (EC-JRC 2010b). This indicator can be expressed in terms of species lost as an end-point indicator (e.g., de Haes et al. 2002; Goedkoop et al. 2009). Neither ES nor cLCA clearly account for resource carrying capacity (Sala et al. 2013). This consideration should be the object of future efforts in the identification of specific indicators.

Technical Areas of Concern. With respect to the technical AoCs, first the (change in) availability or scarcity in nature is to be indicated. Two characteristics of natural resources can be envisaged to quantify this. First, renewability can be considered. The quantification of renewability can be simplified as 0% for nonrenewable and 100% for renewable resources. The indicator quantifies the relative contribution of renewable resources to the total resource consumption (Baral and Bakshi 2010). With respect to stock resources (e.g., minerals and mineral materials, ores, and fossils), the availability, in terms of decreasing quality, can be considered. It is known that humans exploit typically first the easiest ones, at least locally, as covered in, for example, LCA (de Haes et al. 2002). The models here account for the quantity of natural resources extracted (mass, energy, exergy, and land). Alternatively, they can relate this accounting to what is already identified (reserves) and not yet extracted (reserves-to-production rates), or they quantify the expected changes in future efforts humans will need to invest to obtain the same natural resources (Klingmaier et al. 2014; Swart et al. 2014; Rohrbech 2014). Additionally, methods that reflect the

changing required ore quantities per amount of metal have been recently developed (Vieira et al. 2012; Swart and Dewulf 2013). The ore requirement indicator (ORI) may be a promising indicator here (Swart and Dewulf 2013), expressing the relative annual increase of ore that has to be processed to obtain the same amount of metal. In principle, other finite resources, such as FFs and land area, might also be modeled from this decreasing quality perspective (e.g., decrease in soil fertility).

Additionally, there are the technical efforts that are required to process the natural resources in the primary production to end up with raw materials or primary energy carriers. These can be quantified by the technical potential embodied in all the feedstock, auxiliaries, and utilities used. This technical potential is captured by thermodynamics as exergy (exploitable fraction of energy). The cumulative exergy demand (CExD) has been studied in LCA, and one can rely on CExD (Bösch et al. 2007) or CEENE (cumulative exergy extracted from the natural environment) as an indicator (Dewulf et al. 2007).

A third technical concern is the lack of alternatives for the natural resources for their particular applications. Two sources of alternatives can be offered. First, other raw materials (or primary energy carriers) could substitute the particular material, which is quantified by the substitutability in CRIT (EC 2014a). Another source of alternatives comes from recycling the material itself after its application, which is quantified by the recycling rate in CRIT (EC 2014a).

Economic Area of Concern. With respect to this AoC, price volatility is a major concern for both suppliers and users; it is covered in CRIT by the price volatility indicator (EC 2014a). Another concern for securing the supply of raw materials (and primary energy carriers) can be geopolitical constraints, which is also covered in the CRIT framework (EC 2014a). To account for these geopolitical constraints, the Herfindahl-Hirschmann Index for country concentration (the HHI_{WGI} indicator) takes into account both the country concentration of the primary producing countries and their level of governance.

Social/Societal Areas of Concern. In terms of the social/societal AoCs, labor conditions in the primary production sector and the manufacturing sector need to be assessed. From the sLCA framework, we identify the workers in the production and supply as the stakeholders potentially impacted directly. Child labor, forced labor, excessive working hours, and injuries and fatalities can be considered. They can be quantified in terms of, for example, medium-risk hours equivalents per working hour (Pelletier et al. 2013).

Similarly, constraints imposed by international regulations can be addressed—for example, the sourcing of raw materials from conflict-affected areas. This is specifically covered in policies related to conflict minerals, for example, in the EU by proposal for a regulation (EC 2014b). In order to support such regulations, the EC recently proposed a quantification for conflict risks based on two variables: conflict intensity and projected risk of conflict (EC-JRC 2015).

Additionally, emissions are generated along the supply chain that may affect human health. Human health is considered in

Table 2 From areas of concerns toward specific indicators

Area of concern	Specific concern	Related framework	Proposed indicator(s)	Symbol	Unit
Environmental	Threats for natural habitats (at the withdrawal site of natural resources)	Ecosystem services	Habitat services lost	HSL	€/yr/ha
	Impact of emissions on ecosystem quality (along the life cycle)	Life cycle assessment	Species lost	SPL	Species/yr
Technical	Decreasing physical availability in nature	Life cycle assessment	Renewability	REN	%
			Ore grade indicator	ORI	yr ⁻¹
	Technical efforts	Life cycle assessment	Cumulative exergy demand	CEENE	MJ _{exergy}
	Lack of alternatives	Criticality	Substitutability	SUBST	%
Recycling rate			RECYC	%	
Economic	Market stability/volatility	Criticality	Price volatility index	HPV	—
	Geopolitical issues	Criticality	Herfindahl-Hirschmann Index for country concentration	HHI _{WGI}	—
Social/societal	International regulations	Conflict minerals assessment	OECD supply chain due diligence initiative (red flag)	CONFL	%
	Labor conditions	Social life cycle assessment	Child labor risk	CLR	mrh _{equiv} /wh
			Forced Labor risk	FLR	mrh _{equiv} /wh
			Excessive working hours risk	EWR	mrh _{equiv} /wh
			Injuries and fatalities risk	IFR	mrh _{equiv} /wh
	Impact of emissions on human health (along the life cycle)	Life cycle assessment	Disability-adjusted life years	DALY	yr

Note: The areas of concern are grouped into four separate subgroups. Nevertheless, some specific concerns in one subgroup may also have a role in another subgroup; for example, threats for natural habitats is for certain an environmental concern, but, in the long term, these threats may also have consequences for society or for the economy. Another example is impact of emissions: Water pollution can affect human health, but it may, in the worst case, affect also the physical availability of suitable water sources from a technical point of view.

OECD = Organization for Economic Cooperation and Development; €/yr/ha = Euros per year per hectare; MJ = megajoule; mrh_{equiv}/wh = medium-risk hours equivalents per working hour.

sLCA and cLCA. Here, we propose to express the impact on human health by disability-adjusted life years (DALY), typically used as an end-point indicator in LCA, capturing health effects that may be caused by toxic effects of compounds, radiation, tropospheric ozone, particulate matter, and stratospheric ozone depletion (de Haes et al. 2002; Goedkoop et al. 2009).

The supporting information on the Journal's website presents a further elaboration of the indicators.

Conclusions and Perspectives

This article identified many issues that are to be taken into account in an integrated sustainability assessment framework,

with a focus on the production and supply of raw materials and primary energy carriers. These are essential commodities in between the natural resource base and the downstream users. In order to develop a quantitative ISAF, it proved essential to propose a complete and consistent set of raw materials and primary energy carriers, given that many studies typically focus on a subgroup of them.

Connecting the envisaged full asset of raw materials and primary energy carriers (table 1) with the sustainability concerns of the ISAF (figure 3) quantified with specific indicators (table 2), further implementation could result in visual representation of sustainability per particular raw material or primary energy carrier. The visualization could result, for example, in a spider web version of figure 3, where the quantified impacts are represented along the axes in the spider web, eventually normalized based on the results of the full asset of raw materials and primary energy carriers.

A next step for the proposed quantitative ISAF would be a demonstration for a set of raw materials. The perspective will have to be chosen (e.g., European, Japanese, or U.S.), given that the supply chains with their specific social and environmental impacts and their vulnerability of disruptions are specific. Further on, expertise and data from quite different fields will be essential: Economic, environmental, and social impact expertise, including associated models, software, and data, will be indispensable. Nevertheless, if society and its policy makers strive for sustainability, this challenge is to be taken given that it may result in a compass for meeting their objective.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information elaborates environmental indicators, technical indicators, economic indicators, social/society indicators.