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Toward a systematized framework for resource efficiency indicators

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ABSTRACT

The transition toward resource efficient production and consumption patterns is currently one of the main challenges in engineering, environmental science and especially in governmental policies. This transition has led to a proliferation of meanings related to the resource efficiency concept, resulting in a wide variety of indicators. In this paper, we propose a systematized framework in which resource efficiency indicators can be structured and comprehensively positioned. The aim is to provide a proper understanding of the scope and limitations of particular existing resource efficiency indicators in order to assist policy makers and the scientific community in the application and further development of indicators. This framework covers all different resource use-related aspects evaluated in existing approaches, including simple accounting of resource extraction and use; environmental impact assessment due to resource extraction and use; accounting and environmental impact assessment of specific processes and of full supply chains; analyses at micro-scale and macro-scale; and analysis of both natural resources versus waste-as-resources. To illustrate the potential application of the framework, a set of currently used indicators was selected, whereupon these indicators were structured and evaluated within the framework.

1. Introduction

In the last years, policy awareness has grown about the increasing competition for natural resources and its possible consequences for economies, human well-being and the environment.

International initiatives, e.g. the Resource Panel of the United Nations Environment Program, have been launched to support policies with scientific assessments in order to achieve a more sustainable use of resources (UNEP, 2014). Japan has been promoting resource efficiency since the 1990s through policies focusing on resource productivity and waste management: the fundamental law for establishing a sound material-cycle society promotes the "3R (reduce, reuse, recycle)" principle and the cascading use of resources (Takiguchi and Takemoto, 2008). US policies have instead focused more on energy efficiency through the Energy Star program, which is a voluntary labeling scheme for the identification and promotion of energy-efficient products to reduce greenhouse gas emissions, introduced in 1992 (Brown et al., 2002). At European level, the challenges related to natural resources are a main part of the 2020 growth strategy (EC, 2010a) and are addressed in the Flagship Initiative "Resource Efficient Europe" (EC, 2011a). In this context, using natural resources more efficiently is deemed as a necessary step to avoid scarcities and achieve environmental targets, e.g. reducing climate change and preserving ecological assets, but also as an opportunity for economic competitiveness. Natural resources have become a high priority theme also in the EU industrial policy and from a resource security perspective. For example, the access to resources and the security of supply of raw materials have been addressed first in the Raw Materials Initiative and in the context of the Resource Efficiency Initiative (EC, 2008). In order to prioritize the policy actions and avoid supply shortages, a first list of materials facing the highest supply risk with respect to the whole EU economy (i.e. Critical Raw Materials, CRM) has been published in 2010 and will be updated every three years (EC, 2010b, 2014).

The transition toward more resource efficient economies implies the need for quantitative indicators, capable to trace resource consumption and associated impacts with production and consumption systems. Such indicators have historically been developed both in a policy and scientific context, based on

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different theoretical and conceptual frameworks. However, this leads to a diversity of resource-related indicators that are not univocally defined, generating confusion on the real meaning of adopted indicators.

Indeed, indicators have been developed for systems situated at different levels of economic activity: from the micro-scale of specific processes and products, e.g. the energy efficiency of an ethanol-producing system (Liao et al., 2011), to the meso- and macro-scale of sectors and countries, e.g. the energy efficiency of the Norwegian society (Ertesvag, 2005). At micro-scale, some indicators analyze products and processes in a gate-to-gate perspective, while others consider a full life cycle perspective. The same difference is present at macro-scale: some indicators evaluate resource efficiency in a national or regional perspective, while others consider a more global perspective by including resources that are embodied in imported products (BIO-SEC-SERI, 2012). Another point of attention is the provenience of resources: some studies refer to resources extracted from nature, e.g. the inland water consumption (BIO-SEC-SERI, 2012) while in others waste is also considered as a resource, e.g. the resources obtained from recycling waste of electric and electronics equipment (Ardente and Mathieux, 2012). Further, some indicators refer to the amount of resource consumption, e.g. the ratio of the Gross Domestic Product (GDP) over the domestic material consumption (DMC) as applied in the roadmap to a Resource Efficient Europe (EC, 2011a), while others are based on environmental impacts, e.g. the GDP over the Environmentally Weighted Material Consumption (EMC) as established by Van der Voet et al. (2005).

With the current increasing awareness of the role of natural resources and the current multiplication of resource efficiency indicators, a clear systematization of these indicators is needed, in order to increase their capability of giving insight into efficiency issues and to promote their proper use among the broad range of applications for ‘resource efficiency’: from technical indicators in engineering to macro-scale indicators in governmental policies.

The objective of this paper is hence to propose a systematized framework in which resource efficiency indicators can be structured and critically analyzed. The aims are: (1) to provide a proper understanding of the theoretical foundation of existing resource efficiency indicators highlighting scope and limitations, allowing more consistency and comprehensiveness; (2) to support a meaningful application of indicators in environmental policies and (3) to pave the way for the further development of indicators, either by improving existing indicators or by creating new indicators where no indicators are available. The article is organized as follows: Section 2 describes how the systematized framework was established. In Section 3, potential applications are illustrated by structuring several key indicators in practice today according to the framework. In Section 4, some pending challenges are presented.

2. Establishing a systematized framework

So far, a generally accepted definition for ‘resource efficiency’ does not exist yet. The resource efficiency platform of the European Commission describes resource efficiency as “using the Earth’s limited resources in a sustainable manner while minimizing impacts on the environment” (EC-OREP, 2014). To be able to establish a systematized framework in which resource efficiency indicators can be classified, several terms and concepts need to be clarified.

2.1. Defining resources

First, it is important to have a clear definition of what resources are. The Earth’s resources are natural resources, defined by Udo de Haes et al., 2002 as “objects of nature which are extracted by man from nature and taken as useful input to man-controlled processes, mostly economic processes”. Different categorizations are possible, splitting natural resources differently, as mentioned in the International Reference Life Cycle Data System (ILCD) handbook (EC-JRC, 2011). We will here refer to the categorization of Dewulf et al. (2007): fossil fuels, minerals, metals, nuclear energy, water resources, land resources (biomass and occupation), abiotic renewable energy (including hydropower, wind, tidal, wave and geothermal energy) and atmospheric resources. Apart from these natural resources, also industrial resources and waste-as-resources should be considered. This is further explained in Section 2.3.

2.2. Defining efficiency

Second, it is essential to have a clear view on how efficiency can be defined. In literature, two types of metrics are being used to characterize efficiency, here referred to as level 1 and level 2 efficiencies.

Efficiency at level 1 originates from thermodynamics-assisted engineering (Heijungs, 2007). It is defined as the ratio between the useful outputs (or benefits) and the inventoried flows (Eq. (1)).

$$\text{efficiency at level1} = \frac{\text{benefits}}{\text{inventoried flows}} \tag{1}$$

Efficiency at level 2 is derived from the original eco-efficiency concept (Heijungs, 2007). In the first definition by Schaltegger et al., 1990), eco-efficiency is defined as the ratio between the intended effects (or benefits) and environmental impacts, assessed through specific impact assessment models (Eq. (2)):

$$\text{efficiency at level2} = \frac{\text{benefits}}{\text{environmental impacts}} \tag{2}$$

2.3. Defining benefits, flows and impacts

The inventoried flows in Eq. (1) can be natural resources, industrial resources, waste-as-resources or emissions. These flows are schematically presented in Figure 1. When natural resources are extracted from the natural environment, they enter the industrial system, consisting of a production and consumption part. Within the production system, natural resources are transformed into industrial resources (IR) (e.g. energy carriers, semi-finished products, chemical building blocks . . .), used further on in the primary, secondary and tertiary economic sectors. The output of the production system consists of products and services that are supplied to the consumption system. These products and services are thus the useful outputs or benefits (B) of the production system. Both the production and consumption system generate emissions (EM) and waste materials. Emissions are released to the environment, while waste materials can be transferred to the waste treatment sector. From this sector, waste materials can be utilized as waste-as-resources (WR) and supplied to the production system. If not, they are disposed without any recovery. These flows and benefits can be expressed in biophysical metrics (e.g. mass, volume, energy or occupation) or in monetarian metrics (e.g. euros, dollars). These quantification metrics are given in Table 1. As this study rather focuses on an environmental than an economic context, the emphasis will be mainly on biophysical metrics further on.

To allow a better interpretation of what these flows exactly mean, several attempts are made by environmental scientists and policy makers to relate these flows to potential benefits and impacts (Eq. (2)). A commonly used methodology that converts the inventoried flows that are directly exchanged with the environment, i.e. natural resources and emissions, to environmental impacts is Life Cycle Assessment (LCA) (ISO, 2006). To evaluate the environmental impact of these flows, characterization factors can be applied

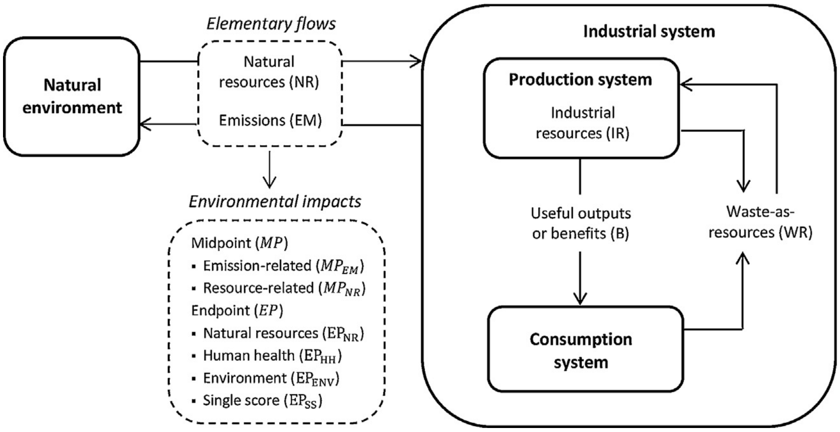

Fig. 1. Flows and impacts related to resource use. NR = natural resources, IR = industrial resources, WR = waste-as-resources, B = useful outputs or benefits, *MP* = midpoint impact level, MP_{EM} = emission-related midpoint impacts, MP_{NR} = resource-related midpoint impacts, *EP* = endpoint impact level, EP_{HH} = endpoint impacts to human health, EP_{NR} = endpoint impacts to natural resources, EP_{ENV} = endpoint impacts to the environment, EP_{SS} = endpoint single score impact.

to convert the flows to common units and aggregate them within environmental impact categories (e.g. acidification, eutrophication etc.) (ISO, 2006). Traditionally, two points are taken in the cause-effect chain of flow-to-impact modeling. At the so-called midpoint impact level (*MP*) (Figure 1), the impact categories include several environmental aspects, such as eutrophication and eco-toxicity. They can be subdivided into impact categories with the focus on emissions (MP_{EM}), e.g. climate change, and on natural resources (MP_{NR}), e.g. abiotic resource depletion. On the other hand, endpoint impact categories (*EP*) usually aggregate midpoint impact categories into three areas of protection: human health (EP_{HH}), natural environment (EP_{ENV}) and natural resources (EP_{NR}). At single score endpoint impact level (EP_{SS}) (Figure 1), all areas of protection are covered by one single indicator (Goedkoop et al., 2009). Environmental impacts are quantified by characterization factors (Table 1), e.g. the abiotic depletion potential is expressed in kg antimony equivalent per year for minerals mining to express their contribution to depletion.

In case of waste-as-resources, environmental impacts can also be used to quantify the benefits. Indeed, the concept of 'waste-as-resources' is based on two paradigms (Directive 2008): (a) waste prevention implies the reduction of the use of resources and (b) the recovery of waste and the use of recovered materials implies the reduction of the use of natural resources. Therefore, level 2 efficiencies are usually expressed by comparing the environmental benefits related to the amount of avoided or reused/recycled/recovered waste, to the environmental impacts of the considered system. These benefits are generally 'credited' to the considered product as avoided impacts otherwise produced by other production systems (Allacker et al., 2014). This is based on the assumption that avoided or reused/recycled/recovered materials will imply a reduced use of natural resources, and consequently a reduction of environmental impacts (Ekvall and Finnveden, 2001).

2.4. Systematized framework

The proposed systematized framework in which resource efficiency indicators can be classified is presented in Table 2. This table also includes some general examples to illustrate each family of indicators.

The framework reflects developments in scientific literature and in practice of resource-related indicators. Firstly, we assess the elements affecting the system boundary of the analysis. In fact, historically (Baster, 1972), resources have been inventoried in terms of mass consumed in a specific process (gate-to-gate perspective) (Ciriacy-Wantrup and Parsons, 1967) and subsequently in a supply chain (life cycle perspective) (Hart, 1995). Based on the different purpose of the analysis, analysis of resource flows has been performed at the micro-scale (processes, products) and at the macro-scale (industrial sectors, economies) (Vanek, 1963). Secondly, we assess the evolution of performance indicators: from the mere mass accounting to performance in terms of comparing resources against a benefit e.g. money (Solow, 1974) and, more recently, to impact indicators attributing different impacts to each resource (Brown and Field, 1979). This evolved from reporting only the consumed resources to reporting also the associated emissions, and subsequently the impacts related to these emissions.

Following the first rationale, the framework was divided in different perspectives: a gate-to-gate perspective versus a life cycle perspective for systems at micro-scale, and a domestic (national)

Table 1
Quantification of flows and impacts relevant for establishing efficiency metrics.

Flow or impact		Type	Metrics	Quantity
EM	Emissions	Elementary flow	Biophysical	Mass, volume, energy, etc.
NR	Natural resources	Elementary flow	Biophysical Monetarian	Mass, volume, energy, etc. Monetary value (e.g. euro)
B IR WR	Benefits Industrial resources Waste-as-resources	Industrial flow	Biophysical Monetarian	Mass, volume, energy, etc. Monetary value (e.g. euro)
MP	Midpoint impact	Specific impact	Biophysical	Toxicity (equivalents), etc.
EP	Endpoint impact	Impact on a particular area of protection	Biophysical Monetarian	Species lost, etc. Monetary value, etc.
EP_{SS}	Single score endpoint	Impact on all areas of protection	Relative	Single score (e.g. ecopoints)

Table 2
Systematized framework with some general examples.

		Level 1		Level 2 (Eco-efficiency)		
Fields of study: **environmental science and engineering or environmental policy**		**Resource efficiency at flow level (RE-FL)** Benefits over resource flows (natural, waste or industrial)	**Emission efficiency at flow level (EM-FL)** Benefits over emission flows (often the reciprocal is used)	**Resource efficiency at impact level (RE-IMP)** Benefits over impacts derived from the resource flows	**Emission efficiency at impact level (EM-IMP)** Benefits over impacts derived from the emission flows	**Overall efficiency at impact level (OE-IMP)** Benefits over impacts from both resource and emission flows
Micro-scale ↓ **Macro-scale**	**Gate-to-gate perspective**	*benefits over (kg) resources*	*benefits over (kg) emissions*	*benefits over (ADP) impact*	*benefits over (GWP) impact*	*benefits over single score impact*
	Life cycle Perspective	*benefits over (kg) resources in life cycle*	*benefits over (kg) emissions in life cycle*	*benefits over (ADP) impact in life cycle*	*benefits over (GWP) impact in life cycle*	*benefits over single score impact in life cycle*
	Domestic perspective	*GDP over (kg) domestic extracted resources*	*GDP over (kg) domestic emissions*	*GDP over domestic (ADP) impact*	*GDP over domestic (GWP) impact*	*GDP over domestic single score impact*
	Global Perspective	*GDP over (kg) global extracted resources*	*GDP over (kg) global emissions*	*GDP over global (ADP) impact*	*GDP over global (GWP) impact*	*GDP over global single score impact*

GDP = gross domestic product, ADP = abiotic depletion potential, GWP = global warming potential. The white columns (RE-FL, RE-IMP) are 'resource efficiency indicators in *sensu stricto*', the dotted column (OE-IMP) are 'resource efficiency indicators *in sensu lato*', the arced gray columns (EM-FL, EM-IMP) are in this study not considered as resource efficiency indicators. For the sake of completeness, they are also presented to clearly accentuate the difference with the other efficiencies.

perspective versus a global perspective for systems at macro-scale. In a gate-to-gate perspective, only direct inputs to the studied system are taken into account. These inputs can be natural resources, industrial resources or waste-as-resources. In a life cycle perspective, all the natural resources embodied in the industrial resources are also taken into account. At macro-scale, the studied system is typically a country or region. In a domestic perspective, only direct inputs to the country are considered, which can be natural resources, extracted within the country, and industrial resources, being imported products. In a global perspective, natural resources embodied in these imported products are also taken into account.

Following the second rationale, the framework was divided in two levels, based on the two efficiencies in Section 2.2. At level 1, the benefits are divided by the flows, and at level 2 (eco-efficiency), the benefits are divided by the environmental impacts. As mentioned earlier, resource efficiency indicators evolved from reporting only the consumed resources to reporting also the associated emissions and impacts. Therefore, there are two possibilities at level 1: (1) the benefits can be divided by the resource flows, called 'resource efficiency at flow level' (RE-FL); (2) the benefits can be divided by the emission flows, called 'emission efficiency at flow level' (EM-FL). At level 2, there are three possibilities: (1) when the impact in the denominator is derived from resource flows, the resulting efficiency is called 'resource efficiency at impact level' (RE-IMP); (2) when the impact in the denominator is derived from emission flows, the resulting efficiency is called 'emission efficiency at impact level' (EM-IMP); (3) when the denominator represents an overall impact, derived from both the resource flows and the emission flows, the resulting efficiency is called 'overall efficiency at impact level' (OE-IMP).

The efficiencies that are solely based on associated emissions (EM-FL, EM-IMP) are used by some authors in a resource efficiency context in the most broad sense of the term, e.g. in the Roadmap to a Resource Efficient Europe (EC, 2011a), although they are basically emission efficiency indicators. For the sake of completeness, they are also presented in the framework, to clearly accentuate the difference with the other efficiencies. The efficiencies that are solely based in resource flows (RE-FL, RE-IMP) can be considered as 'resource efficiency indicators in sensu stricto' (in strict sense). The efficiencies that are based on both resource flows and emission flows (OE-IMP) can be considered as 'resource efficiency indicators in sensu lato' (in broad sense).

Finally, it is important to emphasize that the way of calculating and interpreting resource efficiency indicators largely depends on the considered resource type (natural, industrial or waste-as-resources) and the field of study (environmental science and engineering or environmental policy). By environmental policy, we understand governmental policy mechanisms concerning environmental issues. By environmental science and engineering, we mean scientific journal papers, research at universities, decision tools at manufacturing plants, etc. This field relies on biological, chemical, physical sciences and engineering to solve environmental problems like resource efficiency. These aspects were also included in the multidimensional framework.

2.5. Potential applications of the framework

Having developed a systematized framework, it is possible to situate properly resource efficiency indicators. By structuring these indicators, they can be analyzed within the context of the framework, providing better insights in what exactly is indicated: the considered resource type (natural, industrial, waste-as-resources); the type of efficiency (at flow level or at environmental impact level), the considered perspective (gate-to-gate or life cycle perspective, national or global perspective); the economic scale (micro, meso or macro); the completeness at resource level (which and how many natural resource types are taken into account); the used quantification metrics (physical units, monetary units etc.) and the type of environmental impact method (emission-related, resource-related, midpoint, endpoint). These insights may serve as a basis for resource efficiency management, showing which indicators are properly selected for their particular purposes and why, in function of their application. This way, the framework can assist in the selection of relevant indicators and in the further development and improvement of indicators. In the next section, the framework is illustrated by using several resource efficiency indicators in practice today as an example.

3. Illustrating the use of the framework

It is not our ambition to cover all existing resource efficiency indicators exhaustively, but to select typical indicators in practice today and use them as an example. In Sections 3.1 and 3.2, the indicators are shortly described and situated within the framework. In Sections 3.3 and 3.4, they are critically analyzed within the context of the framework.

3.1. Structuring natural/industrial resource efficiency indicators

Indicators for natural/industrial resources have a broad range of users, going from environmental science and engineering to environmental policy. Several examples indicators have been structured within the framework, see Table 3, together with references of case studies.

3.1.1. In environmental science and engineering

The process-efficiencies are typical indicators from process engineering. They are situated at level 1 in a gate-to-gate perspective, e.g. in (Liao et al., 2011; Peirò et al., 2008). These indicators trace back to the origin of the efficiency concept, which is based on the laws of thermodynamics (Heijungs, 2007). Whereas the first law states that in every process mass and energy are conserved, the second law states that every process generates entropy, meaning that the quality of the energy decreases. This quality is called the ‘useful energy’ or exergy (Dewulf et al., 2008). Hence, efficiency is defined as the ratio between output and input flows, both quantified by either their mass, energy or exergy content (Kotas, 1985). Only resources entering the system directly are considered, which can be both natural resources and industrial resources.

The other indicators in this field consider a life cycle perspective, both at level 1 and at level 2. A well-known level 1 indicator is MIPS. MIPS stands for the Material Input Per Service Unit (Schmidt-Bleek, 1994). It relates the accounted resources (minerals, fossil fuels, biomass, water, air and soil movements) in terms of mass to a service unit. MIPS expresses the ‘material intensity’ of a product through a metric that is the reciprocal of the one commonly used to express resource efficiency (Mancini et al., 2012; Samus et al., 2013).

At level two, a typical indicator is the CumDP (Cumulative Degree of Perfection). The CumDP defines resource efficiency as the ratio of the energy or exergy contained in the useful output to the cumulative energy or exergy consumption (Bakshi and Baral, 2010; Lucas et al., 2012). The cumulative consumption can be calculated with cumulative energy or exergy consumption methods. These methods sum up all energy or exergy contained in all natural resources required along the life cycle, per unit output under consideration (Szargut and Morris, 1987). Both the natural resources entering the system directly and the natural resources embodied in industrial resources are taken into account. These cumulative consumption methods are considered as environmental impact methods (Swart et al., 2014). One could namely subdivide the impact pathway related to resource use into three steps: step 1 gives answers to questions of environmental sustainability by consistently accounting for resource use at midpoint level, while step 2 and 3 evaluate the resource scarcity at midpoint and endpoint level (Swart et al., 2014). The cumulative consumption methods are situated at the first step in the impact pathway, in the sense that they go beyond the classic resource inventory (in kg, m^3, . . .), providing results in single units (energy or exergy). Six operationalized cumulative consumption methods exist (Swart et al., 2014): two based on energy, i.e. the Cumulative Energy Demand (CED) and the Solar Energy Demand (SED), and four based on exergy, i.e. the Cumulative Exergy Demand (CExD), the Industrial Cumulative Exergy Consumption (ICEC), the Cumulative Exergy Extraction from the Natural Environment (CEENE), and the Ecological Cumulative Exergy Consumption (ECEC). Because some materials have low energy value, e.g. water and minerals, energy-based methods do not achieve a high completeness at resource level. Exergy-based methods on the other hand, considering both the quantity and the quality of resources, can provide a more complete resource range. ECEC and SED go one step further than the other methods in the sense that they account also for some ecosystem services that were needed to produce the natural resources. As this approach goes beyond the definition of natural resources from Udo de Haes et al., 2002, these methodologies might be questioned as natural resource efficiency indicators.

Other level 2 indicators evaluate resource efficiency within an eco-efficiency context, namely as the monetary output (e.g. in euros) over environmental impacts, calculated from the inventoried resource flows, e.g. in Suh et al. (2005). These impacts are usually situated at the second and third step in the impact pathway, in which resource depletion is evaluated. However, resource-related environmental impact methods are not yet as mature as emission-related environmental impact methods. Hence, due to lack of properly quantified resource-related impacts, authors often replaced the environmental impact in the denominator of Eq. (2) by the inventoried resource flows, e.g. in Van Caneghem et al. (2010): the denominator represents the water use of a steel company. Similar examples are mentioned in Shonnard et al. (2003) and Gomez-Limona et al. (2011), all basically using an efficiency ratio conceived as in Eq. (1). Although all authors refer them to as eco-efficiency (level 2), these particular indicators should be classified at level 1.

3.1.2. In environmental policies

In policies, typical level 1 indicators represent ‘resource productivity’, which is defined as the ratio of the Gross Domestic Product (GDP) of an economy over national accounts (materials, energy,

Table 3
Typical indicators for natural/industrial resources.

Indicator	Field of application	Level: flow (1) or impact (2)	Perspective	Example reference
Process efficiency	Env. Sc. & Eng.	Flow (1)	G-to-G	Liao et al. (2011)
MIPS	Env. Sc. & Eng.	Flow (1)	Life cycle	Mancini et al. (2012)
CUMDP	Env. Sc. & Eng.	Impact (2)	Life cycle	Bakshi and Baral (2010)
Eco-efficiencies	Env. Sc. & Eng.	Impact (2)	Life cycle	Suh et al. (2005)
GDP/national accounts	Env. Policy	Flow (1)	Domestic	EC (2011a)
GDP/global accounts	Env. Policy	Flow (1)	Global	BIO-SEC-SERI (2012)
GDP/EMC	Env. Policy	Impact (2)	Domestic	Van der Voet et al. (2005)
GDP/overall impact	Env. Policy	Impact (2)	Global	EC-JRC (2012)

MIPS = material input per service unit; CumDP = cumulative degree of perfection; GDP = gross domestic product; EMC = environmentally weighted material consumption; Env. Sc & Eng. = environmental science and engineering; Env. Policy = environmental policy; G-to-G = gate-to-gate perspective.

water or land use) in a domestic perspective, or as the GDP over global accounts (materials, energy, water or land use) in a global perspective (EC, 2011a; BIO-SEC-SERI, 2012).

Material accounts are derived from Economy-Wide Material Flow Analysis (EW-MFA), which is an accounting methodology describing the material throughput (i.e. biomass, fossil fuels, metal ores and minerals) in a national economy, as well as considering imported and exported goods, all expressed in tons (Bringezu et al., 2003). As a national account, the Domestic Material Consumption (DMC) is usually applied, e.g. in (Eurostat, 2010). This DMC equals the sum of the domestically extracted materials, which are natural resources, plus the imports minus the exports, which are both industrial resources. In the global accounts, natural resources embodied in these imports and exports are also considered. Two often used global material accounts are the Raw Material Consumption (RMC), accounting only for the used material extraction, and the Total Material Consumption (TMC), accounting also for the unused material extraction, e.g. overburden from mining (Kovanda and Weinzettel, 2013). The other resource accounts (energy, water, land use) are based on the same principle as the material accounts: they describe the energy, land or water use by an economy, either in a domestic or a global perspective. More detailed information can be found in the review of Hoekstra and Wiedmann (2014).

Level 2 policy indicators are typically defined as the ratio of the GDP of an economy over an overall environmental impact. A first attempt to consider the environmental impacts of the DMC was performed through the Environmentally weighted Material Consumption (EMC) by Van der Voet et al. (2005). In this EMC, 13 environmental impact categories were aggregated, based on an equal weighting, to one overall environmental impact. Later on, life cycle-based indicators, expressed as the ratio of the GDP over the overall environmental impact, have been advanced by the European Commission Joint Research Centre (EC-JRC, 2012). The approach used for these indicators goes beyond the one used to calculate the EMC. They provide a more global perspective by including impacts that happen outside Europe but are linked to European consumption via import. Further, a more complete resource range is considered by using not only the material accounts, but also other resource accounts (energy, water and land).

3.2. *Structuring waste-as-resource efficiency indicators*

Several examples of waste-as-resource indicators have been structured within the framework, see Table 4, together with references of case studies. Two types of indicators were identified: those situated entirely in the field of environmental science and engineering, and those intertwined between the latter and the field of environmental policy.

Typical level 1 indicators are the process efficiencies, the reuse/recycling/recovery (RRR) rates, the reusability/recyclability/recoverability (RRR*) rates and the recycled content. The process-efficiencies, e.g. as applied by (Ignatenko et al., 2007), are situated entirely in the field of environmental science and engineering, as already described for natural/industrial resources. The other indicators can be situated in both the fields of environmental science and engineering, and environmental policy. The reuse/recycling/recovery (RRR) rates refer to the percentage of the mass of a product that is effectively reused/recycled/recovered (Choi et al., 2006; Directive 2012), while the reusability/recyclability/recoverability (RRR*) rates refer to the percentage of the mass of a product that is expected to be reused/recycled/recovered at the end-of-life (IEC, 2012; ISO, 2002). These RRR* rates are generally used for ecodesign purposes (Mathieux et al., 2008), but there are examples of applications in wider context, as for example in product policies (Ardente and Mathieux, 2014). Both indicators also exist in macro-scale applications, in which they evaluate an economy or a region. An analogous indicator is the ‘reused/recycled content’ of a product, defined as the amount of reused/recycled materials used for the manufacturing of a product (Ardente et al., 2009; EC, 2011b).

Typical level 2 indicators are the CumDP, the environmentally weighted RRR* rates, the recycled content benefit and the product environmental footprint. These indicators move further from the accounting of waste flows to the assessment of the potentially related life cycle environmental benefits. The CumDP (Cumulative Degree of Perfection) defines resource efficiency as the ratio of the energy/exergy content of the recovered product to the cumulative energy/exergy consumption, including the input waste, e.g. as applied by Dewulf and Van Langenhove, 2002 and Amini et al. (2007). It can be calculated as described for natural/industrial resources. This CumDP indicator is situated entirely in the field of environmental science, while the other level 2 indicators are rather intertwined between environmental science and environmental policy.

In the environmentally weighted RRR* rates (Huisman et al., 2003; Ardente and Mathieux, 2014) and the recycled content benefit (Ardente and Mathieux, 2014), the environmental benefits related to the reused/recycled/recovered waste are compared to the life cycle impacts of the product. Similar indicators have also been developed based on economic values, e.g. the economic recoverability indicator, accounting for the overall economic benefits of the recovery of a product at the end of its life (Mathieux et al., 2008). Another example of a comprehensive approach for the accounting of impacts in a product's life cycle (including reuse, recycled content, recyclability and energy recovery) is the Product Environmental Footprint, developed by the European Commission (EC, 2013a; Allacker et al., 2014).

3.3. *Analysis of natural/industrial resource efficiency indicators*

Having structured the selected indicators, they can now be analyzed within the context of the framework. Depending on the field of study, large differences could be noticed. Hence, the indicators

Table 4
Typical indicators for waste-as-resources.

Indicator	Field of application	Level: flow(1) or impact (2)	Perspective	Example reference
Process efficiency	Env. Sc. & Eng.	Flow (1)	G-to-G	Ignatenko et al. (2007)
CUMDP	Env. Sc. & Eng	Impact (2)	Life cycle	Dewulf and Van Langenhove (2002), Amini et al. (2007)
Recycled content	Env. Sc. & Eng Env. Policy	Flow (1)	G-to-G	Ardente et al. (2009), EC (2011b)
RRR rates	Env. Sc. & Eng Env. Policy	Flow (1)	G-to-G	Choi et al. (2006), Directive (2012)
RRR* rates	Env. Sc. & Eng Env. Policy	Flow (1)	G-to-G	Mathieux et al. (2008), ISO (2002)
Recycled content benefit	Env. Sc. & Eng Env. Policy	Impact (2)	Life cycle	Ardente and Mathieux (2014)
Environ. weighted RRR*	Env. Sc. & Eng Env. Policy	Impact (2)	Life cycle	Huisman et al. (2003), Ardente and Mathieux (2014)
Product Env. Footprint	Env. Sc. & Eng Env. Policy	Impact (2)	Life cycle	EC (2013a)

CumDP = cumulative degree of perfection; RRR = reuse, recycling, recovery, RRR* = reusability, recyclability, recoverability. Env. Sc & Eng. = environmental science and engineering; Env. Policy = environmental policy; G-to-G = gate-to-gate perspective.

are analyzed by comparing environmental policies with environmental science and engineering.

In environmental policies, typical level 1 indicators are expressed as the GDP over national accounts or global accounts. However, the national accounts (e.g. the DMC) are based on an equal weighting of natural resources and industrial resources, i.e. imported products. In global accounts, this is avoided by considering also natural resources embodied in imports. As extensively acknowledged in the literature, e.g. in (Behrens et al., 2007), burden shifting due to international trade is growing and is particularly relevant in resource importing regions. Limiting environmental monitoring to a national level is likely to provide misleading information to policy makers. Therefore, we would recommend the use of global accounts over national accounts. Further, all the resource accounts should be used when evaluating resource efficiency to achieve a more complete and satisfactory resource range, instead of using only material accounts like the DMC.

Nevertheless, these level 1 policy indicators still do not yet capture resources in a complete, comprehensive and mutually exclusive way: first, each resource type is also equally weighted, e.g. no distinction is made between 1 kg mineral and 1 kg biomass. Second, several resources are counted twice, e.g. crude oil is accounted for its energy properties in the energy accounts and for its mass properties in the material accounts. Third, the GDP is not entirely satisfactory to evaluate the output, since it is solely based on economic values.

To overcome the equal weighting of different resource types, some environmental policies use level 2 indicators, relying on the concept that different resources have different environmental impacts. These level 2 indicators are the GDP over the EMC (Van der Voet et al., 2005) and the GDP over the overall environmental impact (EC-JRC, 2012). As earlier mentioned, the latter is more mature than the former, because of its more complete resource range and more global perspective.

Although equal weighting is avoided at level 2, the benefits are still measured by monetary values (GDP). In this sense, environmental policies could benefit from the insights gained in environmental science and engineering. The process efficiencies and CumDP do not evaluate the output by its monetary value, but by its energy or exergy content. Also MIPS does not use monetary values. The concept of using other values than the economic GDP has also been introduced in the 'Beyond GDP' program of the European Commission (EC, 2013b). This program includes for example the Human Development Index (HDI), merging the GDP with indices on health and education. Another alternative for the GDP is the Genuine Progress Indicator (GPI). While GDP is a measure of the current economic production, GPI is a measure of the generated economic welfare (Kubiszewski et al., 2013).

Another difference could be observed between level 2 indicators from environmental policies (GDP over overall impact) and level 2 indicators from environmental science and engineering (CumDP and eco-efficiencies). While environmental policy indicators usually evaluate '*resource efficiency in sensu lato*' by considering overall impacts, indicators in environmental science and engineering evaluate '*resource efficiency in sensu stricto*': CumDP indicators consider only resource-related impacts through cumulative energy or exergy methods, while eco-efficiency indicators usually present resource-related impacts like abiotic resource depletion next to emission-related impacts like the global warming potential.

Evaluating resource efficiency both in *sensu lato* and *sensu stricto* could be interesting, because this may lead to different conclusions. Disaggregation can sometimes be necessary to link resource consumption closer to specific environmental impacts, making a more thorough interpretation possible (Giljum et al., 2011). In this sense, CumDP indicators are closer related to resource consumption than most of the eco-efficiency indicators, because they evaluate the first step in the impact pathway (answering questions of sustainability by consistently accounting for resource use), while eco-efficiency indicators usually evaluate the second and third step in the impact pathway (evaluating resource scarcity at midpoint and endpoint level). Further, the cumulative exergy methods can provide a more complete resource range than other impact methodologies.

3.4. Analysis of waste-as-resource efficiency indicators

One of the main observations for level 1 indicators situated in both the fields of environmental policy and environmental science and engineering (i.e. the RRR rates, RRR* rates and Recycled Content), is that they are mainly based on mass flows. However, recycling materials causes quality loss, which cannot be evaluated by simple mass measures.

In this sense, the exergy-based indicators (i.e. the CUMDP and process-efficiencies) provide an advantage over mass-based indicators, because they can also evaluate the quality of materials. Another option is the use of downcycling factors next to mass-based indicators. Downcycling factors can refer to the loss of value of recycled materials compare to primary ones (Villalba et al., 2002), or the loss of quality in physical terms due to e.g. reduced mechanical performance or the content of tramp elements in metals (EC, 2013a).

As an overall observation, micro-scale applications seem to be more developed than macro-scale applications. To improve macro-scale indicators, one could for example explore the global perspective by considering also waste resources embodied in exported products.

In addition, indicators for waste-as-resources could be also expressed in terms of avoided amount of waste. Although benefits related to avoided waste are generically discussed (e.g. within policy documents as the Directive 2008/98/EC) there are no evidences of specific indicators developed for the purposes. In this case the framework proposed in the present article can be useful to theorize new potential indicators for resource efficiency.

4. Concluding perspectives

The proposed systematized framework makes it possible to structure and critically analyze resource efficiency indicators, providing insights in what exactly one likes to indicate: progress in terms of resource flows or in terms of environmental impacts; natural resources or industrial resources; a global or domestic perspective; etc. These insights can assist governmental policies and the scientific community in effective implementation and further development of indicators for quantitative assessment of resource efficiency and eco-efficiency. The framework could for example be used as a basis for decision-making models, making it possible to select relevant indicators for specific needs. Such models could take additional aspects into account, e.g. the calculation time, budget, data availability, etc.

A potential application of the framework was illustrated in Section 3. Several key indicators in practice today were structured and analyzed within the framework's context. One of the main observations was that policies may benefit from insights gained in environmental science and engineering, e.g. higher completeness at resource level and the use of other metrics than monetary values to evaluate the outputs.

In general, the integration of resource efficiency with the life-cycle impact methodology, either at micro-scale or macro-scale, is still in its infancy (Mancini et al., 2014). Concerning life cycle impact assessment, the ILCD handbook (EC-JRC, 2011) provides recommendations on which impact categories to consider for the comprehensive assessment of environmental impact. So far, resource-related environmental impact methods are not yet as mature as emission-related impacts methods (Klinglmaier et al., 2013). Ideally, level 2 indicators should reflect the wider spectrum of potential impacts in a consistent, transparent and reproducible way, which remains a challenge (Sala et al., 2012).

The system boundaries definition will also need attention in the future. The framework presented is based on a clear system boundary between the natural environment and the industrial society. In the future, it may be that this system boundary gets more vague (Alvarenga et al., 2013; Schaubroeck et al., 2013). Indeed, the environment is typically considered natural as long as there is no human intervention in the (natural) resource production, e.g. wild fish capture. This might get difficult as human intervention grows, e.g. with integrated production systems.

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References

Allacker K, Mathieux F, Manfredi S, Pelletier N, De Camillis C, Ardente F, Pant R. Allocation solutions for secondary material production and end of life recovery: proposals for product policy initiatives. Resour Conserv Recycl 2014;88:1–12.

Alvarenga RAF, Dewulf J, Van Langenhove H, Huijbregts MAJ. Exergy-based accounting for land as a natural resource in life cycle assessment. Int J Life Cycle Assess 2013;18(5):939–47.

Amini SH, Remmerswaal JAM, Castro MB, Reuter MA. Quantifying the quality loss and resource efficiency of recycling by means of exergy analysis. J Clean Prod 2007;15:907–13.

Ardente F, Mathieux F. Application of the project's methods to three product groups. Luxembourg: European Commission-Joint Research Centre, Institute for Environment and Sustainability/Publications Office of the European Union; 2012, Available from http://bookshop.europa.eu/it/integration-of-resource-efficiency-and-waste-management-criteria-in-european-product-policies-second-phase-pbLBNA25667/ [cited September 2014].

Ardente F, Mathieux F. Identification and assessment of product's measures to improve resource efficiency of products: the case-study of an energy using product. J Clean Prod 2014;83(15):126–41.

Ardente F, Cellura M, Lo Brano V, Mistretta M. Life cycle assessment-driven selection of industrial ecology strategies. Integr Environ Assess Manag 2009;6(1):52–60.

Bakshi RB, Baral A. Thermodynamic metrics for aggregation of natural resources in life cycle analysis: insight via application to some transportation fuels. Environ Sci Technol 2010;44(2):800–7.

Baster N. Development indicators: an introduction. J Dev Stud 1972;8(3):1–20.

Behrens A, Giljum S, Kovanda J, Niza S. The material basis of the global economy worldwide patterns of natural resource extraction and their implications for sustainable resource use policies. Ecol Econ 2007;64(2):444–53.

BIO-SEC-SERI (BIO Intelligence Service, Institute for Social Ecology and Sustainable Europe Research Institute). Assessment of resource efficiency indicators and targets. Final report prepared for the European Commission, DG Environment; 2012, Paris, available from: http://ec.europa.eu/environment/enveco/resource_efficiency/pdf/report.pdf [cited October 2013].

Bringezu S, Schütz H, Moll S. Rationale for and Interpretation of economy-wide materials flow analysis and derived indicators. J Ind Ecol 2003;7(2):43–64.

Brown GM, Field B. The adequacy of measures for signalling the scarcity of natural resources. In: Scarcity and growth reconsidered. New York: Resources for the Future; 1979.

Brown R, Webber C, Koomey JG. Status and future directions of the energy star program. Energy 2002;27(5):505–20.

Choi B, Shin HS, Lee SY, Hur T. Life cycle assessment of a personal computer and its effective recycling rate. Int J Life Cycle Assess 2006;11(2):122–8.

Ciriacy-Wantrup SV, Parsons JJ. Natural resources: quality and quantity. University of California Press; 1967.

Dewulf J, Van Langenhove H. Quantitative assessment of solid waste treatment systems in the industrial ecology perspective by exergy analysis. Environ Sci Technol 2002;36(5):1130–5.

Dewulf J, Bösch ME, De Meester B, Van Der Vorst G, Van Langenhove H, Hellweg S, Huijbregts MAJ. Cumulative exergy extraction from the natural environment (CEENE): a comprehensive life cycle impact assessment method for resource accounting. Environ Sci Technol 2007;41(24):8477–83.

Dewulf J, Van langenhove H, Muys B, Bruers S, Bakshi BR, Grubb GF, Paulus DM, Sciubba E. Exergy: its potential and limitations in environmental science and technology. Environ Sci Technol 2008;42(7):2221–32.

Directive 2008/98/EC of European parliament and of the council of 19 November 2008 on waste and repealing certain Directives; 2008, Available from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do? uri=OJ:L:2008:312: 0003: 0030:en:PDF [cited November 2013].

Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE); 2012, Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ. do?uri=OJ:L:2012:197:0038:0071:en:PDF [cited November 2013].

EC – European Commission, Communication from the Commission to the European Parliament, the Council. The raw materials initiative – meeting our critical needs for growth and jobs in Europe; 2008, Brussels, available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0699:FIN:en:PDF [cited December 2013].

EC – European Commission, Communication from the Commission to the European Parliament, the Council. Europe 2020 – A strategy for a smart, sustainable and inclusive growth; 2010a, Brussels, available from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:2020:FIN:EN:PDF [cited December 2013].

EC – European Commission, Ad-Hoc Working Group on Defining Critical Raw Materials. Critical raw materials for the EU; 2010b, Brussels, available from http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/report-b_en.pdf [cited December 2013].

EC – European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A resource-efficient Europe – flagship initiative under the Europe 2020 strategy; 2011a, Brussels, available from: http://ec.europa. eu/resource-efficient-europe/pdf/resource_efficient_europe_en.pdf [cited December 2013].

EC – European Commission. Commission Decision 2011/337/EU on establishing the ecological criteria for the award of the EU Ecolabel for personal computers. Off J Eur Union 2011b, Available from: http://eur-lex.europa.eu [cited December 2012].

EC – European Commission. Commission recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. Off J Eur Union 2013a, Available from: http://eur-lex.europa.eu [cited December 2013].

EC – European Commission. Commission staff working document: Progress on 'GDP and beyond' actions; 2013b, Brussels, available from: http://ec.europa.eu/environment/enveco/pdf/SWD_2013_303.pdf [cited December 2013].

EC – European Commission. Study on critical raw materials at EU level, final report; 2014, Brussels, available from: http://ec.europa.eu/enterprise/newsroom/cf/itemdetail.cfm?item_id=5830 [cited March 2014].

EC-JRC (European Commission – Joint Research Centre). International Reference Life Cycle Data System (ILCD) Handbook – Recommendations for Life Cycle Assessment in the European context. Luxembourg: Publications Office of the European Union; 2011, Available from: http://lct.jrc.ec.europa.eu/ [cited October 2013].

EC-JRC (European Commission – Joint Research Centre). Life cycle indicators framework: development of life cycle based macro-level monitoring indicators for resources, products and waste for the EU-27. Luxembourg: Publications Office of the European Union; 2012, Available from: http://lct.jrc.ec.europa.eu/pdf-directory/LBNA25466ENN.pdf [cited October 2013].

EC-OREP (European Commission Online Resource Efficiency Platform). Available from: http://ec.europa.eu/environment/resource_efficiency/ [cited March 2014].

Ekvall T, Finnveden G. Allocation in ISO 14041—a critical review. J Clean Prod 2001;9(3):197–208.

Ertesvag IS. Energy, exergy, and extended-exergy analysis of the Norwegian society 2000. Energy 2005;30(5):649–75.

Eurostat. Environmental statistics and accounts in Europe 2010. Luxembourg: Publications Office of the European Union; 2010, Available from http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-32-10-283/EN/KS-32-10-283-EN.PDF [cited November 2013].

Giljum S, Burger E, Hinterberger F, Lutter S, Bruckner MA. Comprehensive set of resource use indicators from the micro to the macro level. Resour Conserv Recycl 2011;55:300–8.

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R. ReCiPe 2008 – A life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level – Report I: Characterization. Dutch Ministry of Housing, Spatial Planning and Environment; 2009, Available from http://lcia-recipe.net [cited November 2013].

Gomez-Limona JA, Picazo-Tadeo AJ, Reig-Martinez E. Eco-efficiency assessment of olive farms in Andalusia. Land Use Policy 2011;29(2):395–406.

Hart SL. A natural-resource-based view of the firm. Acad Manag Rev 1995;20(4):986–1014.

Heijungs R. From thermodynamic efficiency to eco-efficiency. In: Huppes G, Ishikawa M, editors. Quantified eco-efficiency, eco-efficiency in industry and science. Netherlands: Springer; 2007. p. 79–103.

Huisman J, Boks CB, Stevels A. Quotes for environmentally weighted recyclability (QWERTY): the concept of describing product recyclability in terms of environmental value. Int J Prod Res 2003;41(16):3649–65.

Hoekstra A, Wiedmann T. Humanity's unsustainable environmental footprint. Science 2014;344(6188):1114–7.

IEC – International Electrotechnical Commission. Guidelines for end of life information provision from manufacturers and recyclers, and for recyclability rate calculation of electrical and electronic equipment. Technical Report IEC/TR 62635; 2012, Available from: http://webstore.iec.ch/ [cited October 2013].

Ignatenko O, Van Schaik A, Reuter MA. Exergy as a tool for evaluation of the resource efficiency of recycling systems. Miner Eng 2007;20(9):862–74.

ISO 22628. Road vehicles – recyclability and recoverability – calculation method. Geneva: International Organization for Standardization; 2002.

ISO 14040/14044. Environmental management – life cycle assessment – principles and framework. Generva: International Organization for Standardization; 2006.

Klinglmaier M, Sala S, Brandao M. Assessing resource depletion in LCA: a review of methods and methodological issues. Int J Life Cycle Assess 2013;19(3): 580–92.

Kotas TJ. The exergy method of thermal plant analysis. Malabar, FL: Krieger Publishing Company; 1985.

Kovanda J, Weinzettel J. The importance of raw material equivalents in economy-wide material flow accounting and its policy dimension. Environ Sci Policy 2013;29:71–80.

Kubiszewski I, Costanza R, Franco C, Lawn P, Talberth J, Jackson T, Aylmer C. Beyond GDP: measuring and achieving global genuine progress. Ecol Econ 2013;93:57–68.

Liao W, Heijungs R, Huppes G. Is bioethanol a sustainable energy source? An energy-, exergy-, and emergy-based thermodynamic system analysis. Renew Energy 2011;36(12):3479–87.

Lucas A, Silva CA, Neto RC. Life cycle analysis of energy supply infrastructure for conventional and electric vehicles. Energy Policy 2012;41:537–47.

Mancini L, Lettenmeierb M, Rohnb H, Liedtke C. Application of the MIPS method for assessing the sustainability of production–consumption systems of food. J Econ Behav Organ 2012;81(3):779–93.

Mancini L, Benini L, Goralczyk M, Recchioni R, Sala S, Pennington DW. The potential of life cycle assessment for managing critical raw materials and supporting resource policy. Int J Life Cycle Assess 2014 [in press].

Mathieux F, Froelich D, Moszkowicz P. ReSICLED: a new recovery-conscious design method for complex products based on a multicriteria assessment of the recoverability. J Clean Prod 2008;16(3):277–98.

Peirò LT, Mendez GV, Durany XG. Exergy analysis of integrated waste management in the recovery and recycling of used cooking oils. Environ Sci Technol 2008;42(13):4977–81.

Sala S, Pant R, Hauschild M, Pennington D. Research needs and challenges from science to decision support. Lesson learnt from the development of the international reference life cycle data system (ILCD) recommendations for life cycle impact assessment. Sustainability 2012;4(7):1412–25.

Samus T, Lang B, Rohn H. Assessing the natural resource use and the resource efficiency potential of the Desertec concept. Sol Energy 2013;87:176–83.

Schaltegger S, Sturm A. Ökologische Rationalität. Die Unternehmung; 1990.

Schaubroeck T, Alvarenga RAF, Verheyen K, Muys B, Dewulf J. Quantifying the environmental impact of an integrated human/industrial-natural system using life cycle assessment: a case study on a forest and wood processing chain. Environ Sci Technol 2013;47(23):13578–86.

Schmidt-Bleek F. Wieviel Umwelt braucht der Mensch? MIPS – Das Mass für ökologisches Wirtschaften. Berlin: Birkhauser; 1994.

Shonnard DR, Kicherer A, Saling P. Industrial applications using BASF eco-efficiency analysis: perspectives on green engineering principles. Environ Sci Technol 2003;37(23):5340–8.

Solow RM. The economics of resources or the resources of economics. Am Econ Rev 1974;64(2):1–14.

Suh S, Lee KM, Ha S. Eco-efficiency for pollution prevention in small to medium-sized enterprises. J Ind Ecol 2005;9(4):223–40.

Swart P, Alvarenga RAF, Dewulf J. Abiotic resource use. In: Hauschild M, Huijbregts MAJ, editors. Encyclopedia of LCA, Volume IV: life cycle impact assessment. Springer Press; 2014 [submitted for publication].

Szargut J, Morris DR. Cumulative exergy consumption and cumulative degree of perfection of chemical processes. Energy Res 1987;11(2):245–61.

Takiguchi H, Takemoto K. Japanese 3R policies based on material flow analysis. J Ind Ecol 2008;12(5–6):792–8.

Udo de Haes HA, Finnveden G, Goedkoop M, Hertwich E, Hofstetter P, Klöpffer W, Krewitt W, Lindeijer E. Life-cycle impact assessment: striving towards best practice. Florida: SETAC Press; 2002.

UNEP (United Nations Environment Programme). International Resource Panel; 2014, Available from: http://www.unep.org/resourcepanel/ [cited September 2014].

Van Caneghem J, Block C, Crammc P, Mortier R, Vandecasteele C. Improving eco-efficiency in the steel industry: The ArcelorMittal gent case. J Clean Prod 2010;18(8):807–14.

Van der Voet E, Moll S, Schütz H, Bringezu S, De Bruyn S, Sevenster M, Van Oers L. Policy review on decoupling: development of indicators to assess decoupling of economic development and environmental pressure in the EU-25 and AC-3 countries [Internet]. European Commission DG Environment; 2005, Available from: http://ec.europa.eu/environment/natres/pdf/fin_rep_natres.pdf [cited November 2013].

Vanek J. The natural resource content of United States foreign trade 1870–1955. Cambridge: MIT press; 1963.

Villalba G, Segarra M, Fernandez AI, Chimenos JM, Espiell F. A proposal for quantifying the recyclability of materials. Resour Conserv Recycl 2002;37(1):39–53.