COMBI

Calculating and Operationalising
the Multiple Benefits of
Energy Efficiency in Europe

WP4 Resources

Literature review on resource benefits

D4.1 report

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1 Background

1.1 Project outline

Within the call EE-12 of the Horizon 2020 programme, the EU funds several projects on "Energy Efficiency Research and Innovation". The COMBI project aims at quantifying the multiple non-energy benefits of energy efficiency together with the research partners University of Antwerp, University of Manchester, Copenhagen Economics and ABUD/Advanced Buildings and Urban Design, and is coordinated by the Wuppertal Institute for Climate, Environment and Energy.

The multiple benefits of energy efficiency are gaining relevance in the research and the current policy discourse, but scientific evidence is yet scarce and scattered. Therefore, this project will gather existing approaches and evidence from the EU area, develop modelling approaches and come up with consolidated data on different benefits such as emissions (effects on health, ecosystems, crops, built environment), resources (biotic/abiotic, metals and non-metals), social welfare (disposable income, comfort, health), macro economy (labour market, public finance, GDP), and the energy system (grid, supply-side, energy security).

All project outcomes will be available at an open-source online database and be analysable via a graphic online-visualisation tool for personalising the findings as to their geographic location and selected benefits. To this end, the development of an aggregation methodology is of central importance to avoid double-counting and presenting the various benefits on their various dimensions. Finally, insights for policy relevance will be derived and policy recommendations will be elaborated to facilitate the communication of the non-energy benefits in the relevant policy areas. In addition, the project is in touch with on-going processes of how to include multiple energy efficiency benefits into policy evaluation.

1.2 Paper outline

This paper contributes to the COMBI literature review on benefits of energy efficiency improvements focussing on material and resource savings. First it elaborates on the relevance of the benefit and its evaluation in literature (section 1). Section 2 presents key methods and indicators as well as existing quantified impact values, while section 3 discusses methodological challenges. The paper also attempts to provide first insights for the required resource benefit methodology later in the project, which are summarized in section 4.

1.3 Relevance and importance of resource benefits

The efficient use of resources is a prominent scheme to reduce environmental impacts (Behrens, Kovanda, Giljum, & Niza, 2007). Besides, resource savings can also lead to cost savings and lower the dependency on resource imports.

Resources in terms of fossil fuels as well as raw materials (material resources) - for an energy related-technology and its corresponding services and products - are directly linked to energy efficiency. A reduction in overall energy use or energy demand saves natural resources, which otherwise would have to be extracted and beneficiated. This effect can be cumulative, because the provision of scarce resources or resources with a high market demand is often difficult: Suppliers are increasingly confronted with lower ore contents or have to rely on alternative sources for their provision (such as oil sands or shale gas).

Facing this, the following aspects for the intended measurement of resource benefits are focused in the literature review:

- Estimation of the overall environmental burden attributed to material flows in the global economy,
- Quantifying cost savings associated with material efficiency or material substitutions

1.3.1 Environmental burden of global resource extraction and conversion

The extraction and energetic conversion of fossil fuels (energetic resources) for energy production causes considerable emissions polluting air, water and soil along the whole value chain. Avoidance of these emissions, where possible, requires additional investments and energy. As to the relevance of resource extraction there are a number of studies analysing the increased global resource extraction and their environmental impacts. A 2011 study by the International Resource Panel (UNEP) (Fischer-Kowalski & Swilling, 2011, p. 10) reports that the "total material extraction[1] increased over" the period 1900 to 2005 "by a factor of 8". While the strongest increase is observed for construction materials (factor 34), ores and industrial minerals still increased by a factor of 27 and energy carriers by a factor of 12. In the same period global GDP increased by a factor of 23, implying that decoupling of economic activity and resource use has taken place for at least biomass (factor 3.6) and energy carriers. The authors further observe that although the overall resource productivity (added value per resource use) has increased and some countries achieve high incomes per capita at low resource use, other countries display very high resource consumption without a corresponding rise in incomes per year. These differences can mainly be attributed to the shift of manufacturing and mining industry from industrialised countries into emerging markets and developing countries, which goes hand in hand with shifting a major part of environmental burden and resource extraction.

The extraction of abiotic or inorganic resources (mining and beneficiation[2]) is often associated to the environmental impacts by acid mining drainage (AMD). AMD is generally characterized by a "[...] high concentration of heavy metals, sulphate and low PH [...]" and is a "unavoidable by-product of [...] mining" (Akcil & Koldas, 2006, p. 955) and especially its extend waste rock. Due to the fact that AMD occurs even after the mining is ceased and contains non-degradable heavy metals, it is a unique pollutant and "a serious threat to human health and ecological systems" (Kumari, Udayabhanu, & Prasad, 2010, p. 956). Although literature suggests that AMD occurrence can be mitigated and even avoided by e.g. neutralization and water covers (Akcil & Koldas, 2006), the extent waste rock of "coal, copper, gold and uranium [mining] [...] has increased dramatically since the mid-twentieth century" and is probable to increase even further.

The extraction or rather conversion of biotic resources on the other hand is often associated to issues of land use and conversion as well as local declines in biodiversity. Bringezu et al. (2009) for

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[1] The Total Material Extraction "accounts not only for the resources used in economic processes, but also for the total material mobilized during the extraction process" (Fischer-Kowalski & Swilling, 2011, p. 7).

[2] Benefication is a term in extractive metallurgy, describing the removal of non-wanted minerals from a ore in order to producer a higher ore grade product.

example analysed whether an increase in biofuel demand in Germany from 2006 to 2030 would result in an increased land use in foreign countries. The authors conclude that "Germany would significantly contribute to increasing the pressure to expand the global area under cultivation and the associated environmental impacts such as GHG emissions and loss of biodiversity" (Bringezu et al., 2009, p. 565). Theses expanded production areas abroad could lead to "a net effect [of GHG emissions] of 23 - 37 Mt", taking GHG mitigation potentials (14 - 17 Mt) already into account (Bringezu et al., 2009, p. 565).

1.3.2 Costs of resource extraction and conversion

Resource costs are directly linked to the costs for energetic and non-energetic raw materials. While the costs for energy carriers have been of importance to economies since the beginning of industrialization and mobilization, non-energetic raw materials and their associated costs are a more recent concern. Non-energetic raw materials are a necessity in the European industries, since "everything is made from material [.] and sectors [...] rely on these materials as direct inputs" (European Commission, 2014, p. 7). "Securing a sustainable supply of raw materials is [therefore] a key priority for the EU"[3]. While some non-energetic raw materials can be recycled or produced from European sources such as mass steels and bulk plastics, there are a number of materials, which are deemed to be crucial (or rather critical) for the European economy due to their economic importance and in light of their supply risk (see Figure 1). The supply risk can have many reasons such as scarcity, degrading ore content, availability, regional concentration, current production rates or import restrictions.

In addition, some raw materials are co-products and their prices often depend on the extraction rates of other elements. Rare earth elements (REE) for example, although being fairly common in the earth crust on a global scale, show a high price volatility due to their regional concentration, the co-element extraction and the increasing demand for permanent magnets. A recent study by the Massachusetts Institute of Technology (MIT) forecasts an increase in neodymium and dysprosium demand of 700 % and 2,600 % over the next 25 years, if "the present needs in automotive and wind appliances are representative of future needs" (Alonso et al., 2012, p. 3406). Another example would be Lithium, which is more common than lead, but faces a shortage in the future due to current reserves, mining capacity and forecasted demand according to a study by the Queen´s University in Ontario, Canada (Sonoc & Jeswiet, 2014). Both element groups are relevant to so called green technologies: REE are used in direct-drive permanent excited wind turbine generators and Lithium in batteries for electrical vehicles.

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[3] See http://ec.europa.eu/growth/sectors/raw-materials/index_en.htm

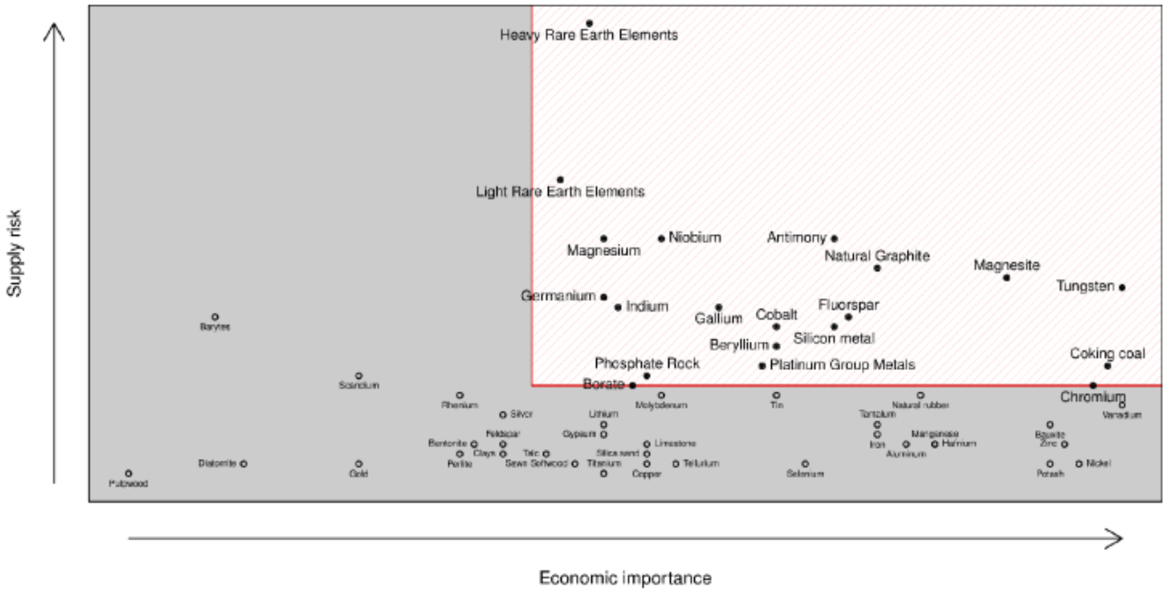

Figure 1: Updated criticality assessment for the EU for 2013

Source: European Commission, 2014, p. 24

Resource costs are also related to the conversion of raw materials into higher quality materials or wrought material compositions. Silica for example is one of the most common elements in the earth crust (25 % at 16 km), easy to come by and usually cheap. However, converted into electronic grade silicon for photovoltaic cells with purities up to 99.5 %, its production is comparable expensive (30 - 45 $/kg compared to 1.5 - 2.5 $/kg for metallurgical grade silicon) and faces a limited availability in the future (Woditsch & Koch, 2002, pp. 12 – 13). This is mainly caused by the high energy needs (120 kWh/kg) for its production (Pizzini, 2010) and the increased market demand. Similar observations can be made for aluminium from bauxite or high-speed steels made from tungsten or vanadium alloying elements. These costs occur at different stages in the value chain and can therefore be disaggregated or attributed to life cycle phases.

1.4 Scope of resource assessment

The objective of work package 4 is the incorporation of resource benefits in a manner that is relevant to the research object (energy efficiency actions) and consistent to the framework of co-benefits. In general, there is a very broad understanding of the term resources and the quantification of resources. The following chapters describe how resources and the evaluation perspective are defined within the project context.

1.4.1 Definition of resource benefits

For the purpose of resource benefit quantification a further and more comprehensive classification of resource benefits is necessary. According to the German Resource Efficiency Programme (ProgRess) on behalf of the Federal Government of Germany (BMU, 2015, p. 4), natural resources can be disaggregated in up to five categories: water, air, land/soil, biodiversity and raw materials. Based on the classifications in this 2015 study and against the background of the project (focus on raw materials), the authors classify resource benefits into two raw material categories (abiotic and biotic material as in inorganic and organic[4]), with five functionalities provided by these raw materials, and six final types of raw materials.

Figure 2 shows the final scope of the benefits on resources. The energetic abiotic and biotic raw materials *fossil fuels* and *biofuels* feature strong direct links to energy efficiency measures. *Ores*, *minerals* (including unused extraction and overburden), *food/feed* and *other material* could also become relevant at different stages in the project, at least on a technological scope (indirect cause-effects by introduction or adaption of energy efficiency technologies). Regarding the relevance of raw materials for EE actions taking place in different sectors, fossil fuels are highly relevant for all sectors, but especially non-energetic abiotic raw materials can become important for industrial, commercial and residential applications.

Not included in the scope are output flows back into nature, as they are characterised or adressed by other co-benefits or are no resources from nature in a narrow sense (such as waste). Although these flows are not part of the resource benefit scope, they are to be discussed later on in the development of the resource benefit methodology, which will also address issues of allocation and recycling.

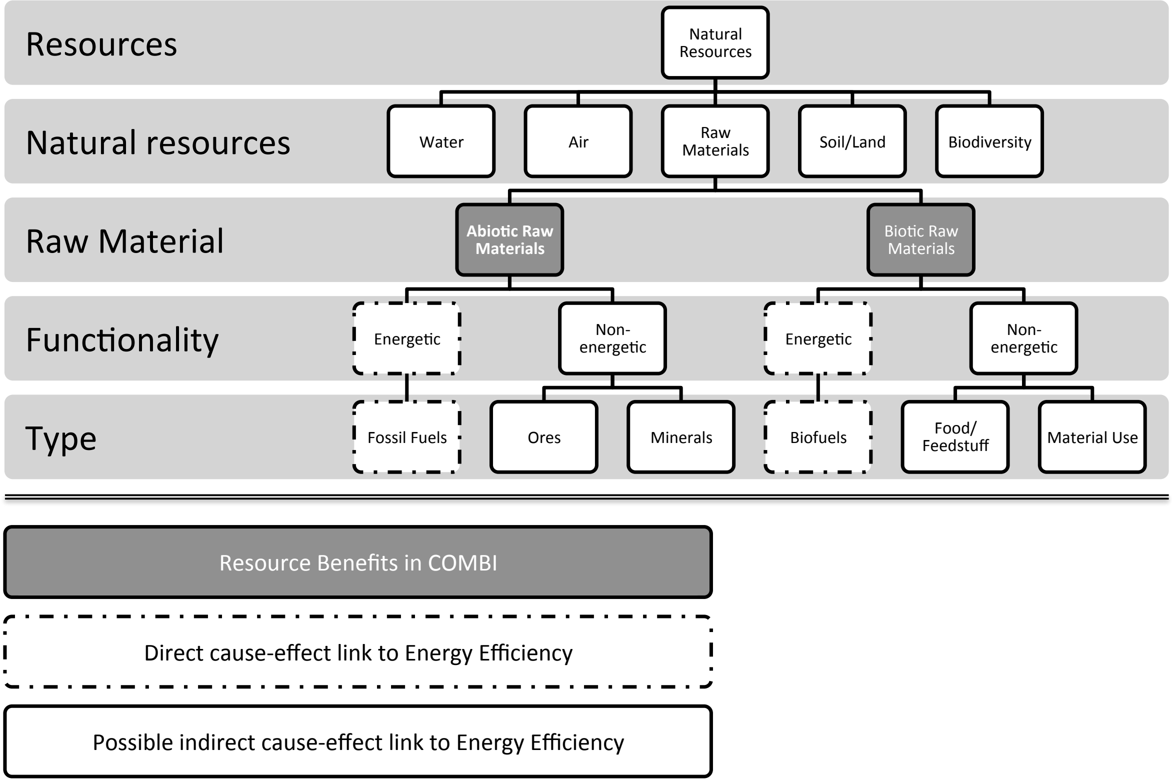

Figure 2: Scope for resource benefits in COMBI

Source: Wuppertal Institute based on BMU, 2015, p. 4

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[4] The terms inorganic and organic were replaced in favour of biotic and abiotic, since the former suggest a misleading proximity to chemistry terms: plastics for example are considered to be organic compounds in chemistry, but inorganic resources in environmental sciences.

1.4.2 Evaluation perspectives

The evaluation methods for resource benefits can be macroeconomic (as in total resource extraction or material flow conversion in economies) or microeconomic based (e.g. benefits through material efficiency in a certain production process). The end-user perspective is usually chosen, if resource benefits are quantified by life cycle assessment methods (e.g. a producer of a EE action technology). The latter can be connected to macro- or microeconomic evaluation methods and vice versa (e.g. by a bottom-up end-user evaluation method with a microeconomic basis).

Direct resource benefits to society (as in societal perspective) have, to the knowledge of the authors, not been quantified yet. It is possible though to link or relate resource extraction savings for example to life quality, poverty, income and expenses of households or the GDP per country or cap. The indicators in most of these cases are *reactive*, meaning that resource use is seldom an end to itself, but rather an outcome or condition of other economic activities. For the same reason it is uncommon to quantify resource benefits from a public budget perspective. Both perspectives however are applicable for resource benefits, if the multi-benefits of e.g. policies are to be quantified and monetized (e.g. resource cost savings in subsidized housing programmes).

With regard to societal and public budget perspectives, the European Union published a short list of critical raw materials in the EU in 2011 (European Commission, 2010) and further updated the list in May 2014 (European Commission, 2014). The evaluation approach consists of a ranking of raw materials between the two axes economic importance and supply risk. While the approach is considered to be "pragmatic" (European Commission, 2010, p. 21), "it is independent of both market size and price of the individual raw materials" (European Commission, 2010, p. 21).

(Bringezu, 2015) recently suggested three targets for the global resource use (societal perspective) in line with a Sustainable Development Goal proposition by the International Resource Panel which aims towards an "efficient use of natural resources in an equitable and environmentally benign manner for human well-being and future generations" (IRP-International Resource Panel, 2014, p. 8). The "10-2-5 target"[5] is meant to be an orientation for policies and its values are quantified in tons per person.

(Lettenmeier, Liedtke, & Rohn, 2014) on the other hand suggest a sustainable resource cap target for households (8 t/person in Finland) based on a microeconomic approach. The chosen indicator Material Footprint (Liedtke et al., 2014) is thereby attributed to six different components of the household system such as nutrition, mobility or leisure activities. This approach allows for a close examination of consumption patterns and an evaluation of the complexity and probability for resource reductions.

In "The Material Footprint of nations" (Wiedmann et al., 2015) the authors examine to what extent other variables (gross domestic product, domestic extraction and population density) influence changes in the consumption of materials by countries. The macroeconomic indicator is based on their final demand for goods and services as well as multiplier for global upstream material

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[5] 6 - 12 t/person of Total Material abiotic resource Consumption (abiotic TMC), a maximum of 2 t/person of Total Material biotic resource Consumption and a Raw Material Consumption (RMC) of used biotic and abiotic materials ranging from 3 to 6 t/person until 2050 (Bringezu, 2015, p. 48).

requirements. While population density "seems to have a lesser and mixed influence on resource use indicators", the authors find that variations in the Material Footprint[6] of nations are mostly explained by variations in the GDP/cap [...]" (Wiedmann et al., 2015, p. 6274): "41 % (29 Gt) of total global resource extraction was associated with international trade flows in 2008, [but] only one-third of these materials actually crossed national borders [...]" (Wiedmann et al., 2015, p. 6275). These results are confirmed by other literature: Schandl & West (2010) analysed the resource use of the Asia-Pacific region and conclude that rising incomes per capita contributed more strongly to growing material use than population growth. They also found that Asia-Pacific has become the single largest user of resources globally and its decreasing resource efficiency from 1970 - 2005 has lead to a decrease in the overall global resource efficiency. The authors of another macroeconomic study (Behrens, Kovanda, et al., 2007) - while observing relative decoupling between global resource extraction and global GDP - find that global extraction of natural resources has expanded in absolute terms. "This indicates that the scale effect dominates structural and technology effects and that anthropogenic pressures associated with resource extraction continue to increase" (Behrens, Kovanda, et al., 2007, p. 451).

Regarding the evaluation perspective, resource benefits are also quantified on a microeconomic scale, drawing conclusions on resource impacts by modelling single market stakeholders (households, companies), technologies or markets. Wiesen, Teubler, & Rohn (2013) for example quantified the resource use of onshore and offshore wind power plants based on the MIPS approach (Liedtke et al., 2014). The evaluation method is engineer-based and service related. The authors compare the resource use per kWh at grid connection point of three wind energy plants to the German and European electricity mix.

In comparison Yellishetty, Mudd, & Ranjith (2011) analysed the steel industry and the availability of its resources, employing the LCIA impact abiotic depletion potential (adp) (Guinée & Heijungs, 1995). Although the authors focused on one industrial sector, the interpretation of results is drawn on a global scale. The authors find "that reserves are commonly greater over time, [but] production is also significantly higher. When considering the long-term future, it is clear that abiotic depletion is indeed a problem [...]" (Yellishetty et al., 2011, p. 89).

2 Methods

The quantification of resource benefits is challenging. There are differences in the nature of resources and their functionality (e.g. energy carriers fulfil a different purpose than ores and minerals), the related impacts (while the conversion of biotic resources into food/feed in agriculture is relevant to indicators such as acidification, the energetic conversion is usually associated with high levels of greenhouse gas emissions), and the perspective of the cause-effect relationships (thermal energy can be perceived as the output of a material resource conversion or as a resource itself).

Unfortunately, there are no aggregated and well documented indicators for the environmental impacts of global resource use in comparison to e.g. greenhouse gas emissions and economic

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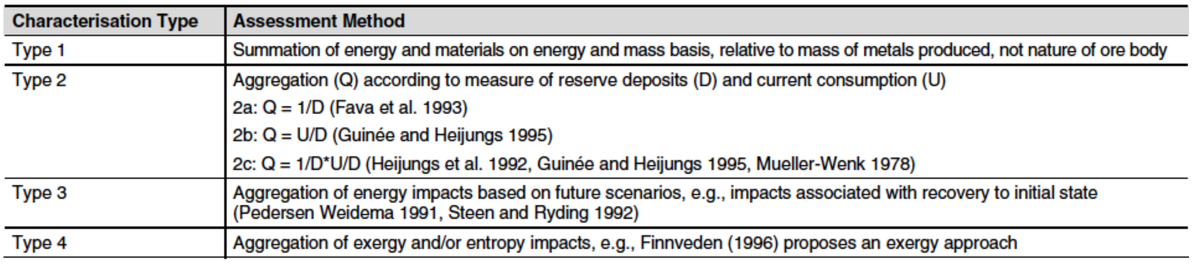
[6] The Material Footprint indicator in Wiedmann et al. (2015) is different from the Material Footprint in (Lettenmeier, Liedtke, & Rohn, 2014), although both rely on material flows and their masses (type 1 according to (Stewart & Weidema, 2005)).

activity (Fischer-Kowalski & Swilling, 2011). Resource use indicators like the abiotic depletion potential (adp) usually stem from life cycle assessment and material flow accounting methods on the scale of products, processes and services or on the scale of economies and sectors. Some methods allow for an attribution and allocation of other environmental impacts (e.g. emissions) to the extraction phase of raw materials or the manufacturing of products. Moreover, resulting positive and negative resource impacts are also often directly linked to a material perspective. Many metals for example display high emissions in their extraction state as ores due to the high energy demand and requirement for fossil fuel conversion in this phase (Hertwich, 2010, p. 65).

There are basically three types of methods for the quantification and qualification of resource benefits:

1. Life Cycle Assessment (LCA) methods (e.g. the indicator abiotic depletion potential)
2. Input-/Output and material flow accounting (MFA) methods (e.g. the indicator Total Material Requirement)
3. Multi-Criteria-Analysis methods (e.g. raw material criticality assessment by the European Commission)

According to Stewart and Weidema (2005), who developed a resource impact framework focusing on resource functionality, the underlying assessment methods can further be characterized by up to four types (see Figure 3) such as the summation on energy and mass basis (type 1), the relation of deposits and consumption (type 2), energy impacts based on future scenarios (type 3), and the aggregation of exergy and/or entropy impacts (type 4).



Characterisation Type	Assessment Method
Type 1	Summation of energy and materials on energy and mass basis, relative to mass of metals produced, not nature of ore body
Type 2	Aggregation (Q) according to measure of reserve deposits (D) and current consumption (U) 2a: Q = 1/D (Fava et al. 1993) 2b: Q = U/D (Guinée and Heijungs 1995) 2c: Q = 1/D*U/D (Heijungs et al. 1992, Guinée and Heijungs 1995, Mueller-Wenk 1978)
Type 3	Aggregation of energy impacts based on future scenarios, e.g., impacts associated with recovery to initial state (Pedersen Weidema 1991, Steen and Ryding 1992)
Type 4	Aggregation of exergy and/or entropy impacts, e.g., Finnveden (1996) proposes an exergy approach

Figure 3: Synthesis of methodologies for assessing impacts of resource use

Source: Stewart & Weidema, 2005, p. 240

While this framework is suitable to issues of scarcity and to the economic value of raw materials, it does not fully cover the common resource benefit indicators. Most LCA methods, for example, are applicable to both ex post and ex ante evaluation, while the "nature of an ore body" is not restricted to its reserve deposits and current consumption but also related to the indirect environmental impacts of mining.

In the following subchapter, possible criteria for indicator selection and suitable methods are described. Second, the results of the literature screening for environmental impacts and monetisation are shown.

2.1 Method of indicator selection

The aim of the project is to quantify and monetise multiple benefits in the scope of energy efficiency (EE) actions in countries throughout the European Union. These actions range from efficiency improvements of technologies (e.g. of heating systems) and market implementation of new technologies (e.g. green IT appliances) to the market diffusion of already existing technologies (e.g. deep retrofit of buildings) in different sectors. The necessary raw materials and their functionality are therefore highly heterogeneous and studies with focus on characterization by weighting are deemed to be not suitable. In addition, many important material characteristics, like the CO_2 characterisation factors of materials, are already included in the quantification of other benefits. Resource scarcity on the other hand, while indirectly reflected by monetisation, is influenced by many external factors, which are non-specific to certain technologies such as import restrictions and future demands of competing technologies.

Against this background, resource benefit indicators should be EE action-specific, have little or no relations to other multi-benefits and be quantifiable along two lines:

1. Estimation of additional environmental impacts of natural resource extraction
2. Quantification of cost savings

The following sections will discuss the applicability of these methods for resource benefits in COMBI: Life Cycle Assessment, Material Flow Accounting and monetisation methods mainly building on MFA or LCA. Criticality assessments are, like most MCAs, semi-quantitative assessments[7] and therefore not suited for the quantification and monetisation of resource benefits in a multi-benefit assessment. However, they are often the starting point for quantitative assessments of critical material stocks and possible future bottle-necks, as shown by Klötzke et al. (2015) or Viebahn et al. (2014) for critical material restraints in electro mobility or energy systems.

2.2 Estimation of additional environmental impacts of natural resource extraction

This subchapter describes the result of the literature review for methods and indicators assessing the environmental impacts of natural resources extraction related with EE actions. An overview of methods identified is given in Table 1.

2.2.1 Life Cycle Assessment (LCA) methods

Life Cycle Analysis (LCA) is a widely accepted approach for environmental assessment at product level. The LCA framework allows quantifying specific environmental impacts of goods and services related to the so-called functional unit. The requirements of how to conduct a Life Cycle Assessment (LCA) are set in the guidelines ISO 14040/44 (Finkbeiner, Inaba, Tan, Christiansen, & Klüppel, 2006; ISO, 1997, 2006) . Based on these guidelines, a handbook (Hiederer, European Commission, Joint Research Centre, & Institute for Environment and Sustainability, 2011) describing the basis for assuring quality and consistency of life cycle data, methods and assessments is provided by the European Union. The framework consists of four parts, which are

a) The goal and scope definition phase (setting the system boundaries),

b) The inventory analysis phase (data gathering for life cycle inventory),

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[7] Even if single criteria of criticality assessments are based on quantitative literature, a weighting takes place and impacts are often evaluated by expert assignment, not measure or calculation.

c) The impact assessment phase, and

d) The interpretation phase.

Goal and scope definition depends on the specific analysis. The ISO 14040/44 does not provide many specifications for defining the scope. At the beginning of the analysis the functional unit has to be defined in a way that is measurable and system borders have to be set. All life cycle stages should be included as long as they are relevant for the results of the analysis. Cut-off criteria (specification for material or energy flows to be excludes from a study) for the life cycle inventory (LCI) and assumptions have to be described and their influcence on the outcome of the study assessed. A Cut-off criterion could for example be a defined percentage of mass flows to the overall mass input or alternatively energy flows as percentage of the overall energy inputs. Also, the environmental significance - as a defined amount of the overall environmental impact of the functional unit - can be used as a cut-off criterion.

One outcome of the analysis phase is the Life Cycle Inventory (LCI), which specifies the flows crossing the system borders for every process. The LCI builds the starting point for the life cycle impact assessment (LCIA). The LCIA consist of three mandatory elements (ISO, 2006):

- Selection of impact categories, category identification and characterization models,
- Assignment of LCI results to the selected impact categories, and
- Calculation of category indicator results (characterization).

There are various LCIA methods to calculate different indicators. They link different types of LCI results and cover different impact categories and characterization models. Common impact categories are climate change, human and eco-toxicity, acidification, eutrophication and resource depletion. The indicators of the specific impact categories can point to midpoint or endpoints. A midpoint impact for the impact category climate change is for example kg CO_2-equivalents/kg gas; a referring endpoint impact could be the impact on nature (as rise of sea level or global average temperature). While endpoint indicators enable to clarify concrete environmental impacts, their calculation is associated with higher uncertainties than midpoint indicators. Some methodologies derive a final score out of the impact indicators.

Besides ISO 14040/44 there are other specific assessment frameworks for greenhouse gases on product level such as ISO 14067: Carbon Footprint of Product (ISO, 2013), French Environmental Footprint (BPX 30-323) (French Standardization, 2009), or UK's Product Carbon footprint guidelines PAS 2050 (Sinden, 2009). They all employ the LCA approach as common basis from the ISO 14040/44 standard.

For the work within the COMBI project, the ISO 14040/44 framework gives a good orientation for calculation rules and impact assessment, but is in many points not sufficiently well specified: While the system borders for each EE action would have to be set individually, specification is needed e.g. for questions of open loop allocation, as system expansion would require an additional expansion for other benefits as well.

In addition, there is a high variability in the results of different LCA resource impact indicators. Klinglmair, Sala, & Brandão (2014) compared the characterisation factors of eight methods for seven materials and normalized the results. They showed (see Figure 4) that the LCA characterization factors for individual substances differ by several orders of magnitude. For example, while the cumulative exergy demand of copper is about 100 times higher than of iron, its extended abiotic depletion potential (aadp) is nearly a 1000 times higher. Applying LCA indicators related to resource depletion would therefore raise controversy on the suitability of the chosen indicator and the implication of its selection in opposition to other resource indicators.

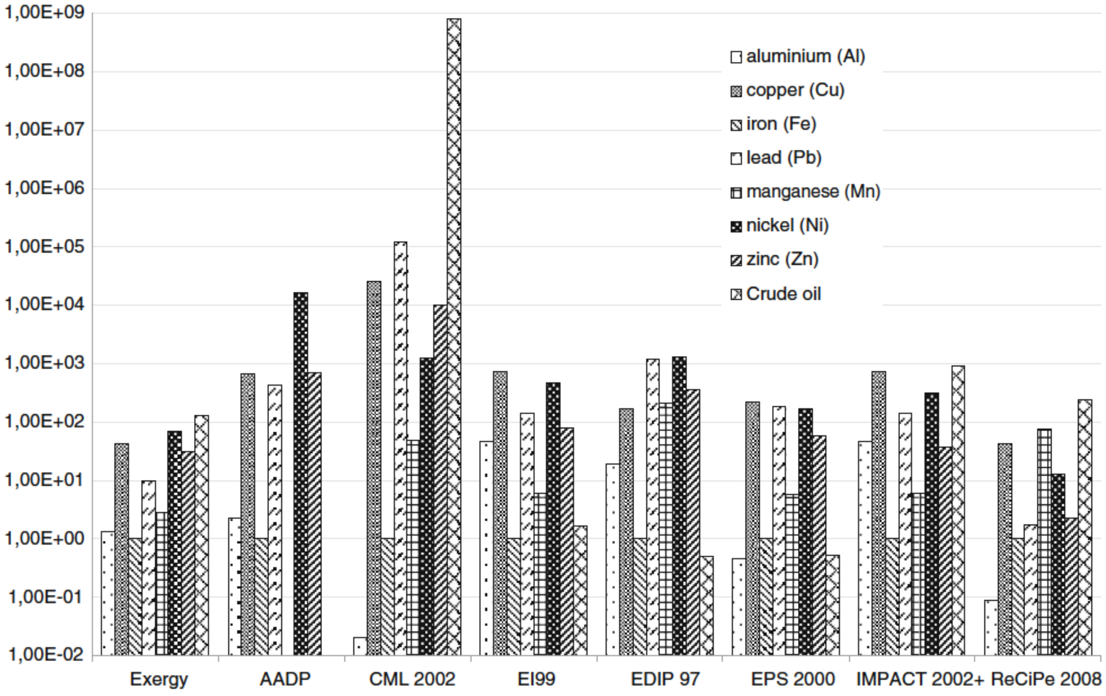


Figure 4: Characterisation (at midpoint) of selected resources, normalized over iron

Source: Klinglmair et al., 2014, p. 589

2.2.2 Material Flow Accounting (MFA) methods

The MFA approach is a model, in which the economy is a subsystem of the environment. It depends on the throughput of materials and energy. Raw materials, water and air are extracted from nature as inputs, transformed in the technosphere (e.g. into products) and re-enter the nature as outputs (e.g. in form of emissions). The corresponding terms for this process are *industrial* (Ayres, 1989) and *societal* (Fischer-Kowalski & Hüttler, 1998) *metabolism*.

Hinterberger, Giljum, & Hammer (2003) describe the basic model as shown in Figure 5, while accounting and methodological guidelines have been set by EUROSTAT (European Commission (2001)) and Weisz et al. (2007). While all of the following explanations hold true to Economy Wide-Material Flow Accounting (EW-MFA), other methods such as MIPS, apply similar, but not the same model definitions and rely on different system boundaries.

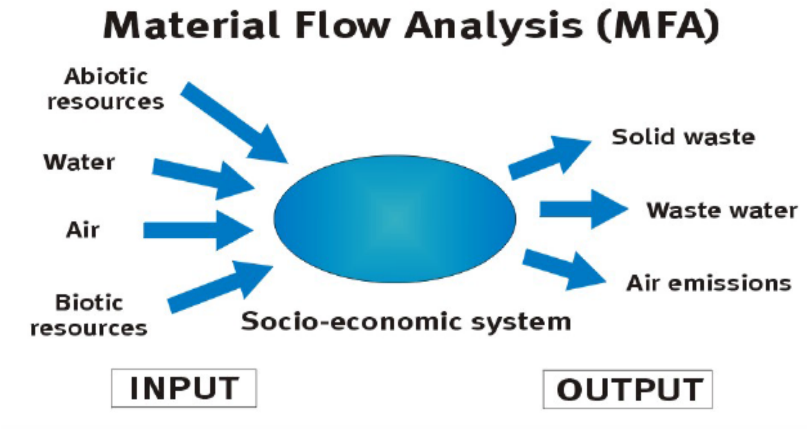


Figure 5: The basic model of material flow accounting and analysis (MFA)

Source: Hinterberger et al., 2003, p. 4

According to Hinterberger et al. (2003, p. 4) the total inputs always equal the total outputs plus the net accumulation in any system and its subsystems. In order to account all material flows of e.g. a nation, the boundaries between environment and economy have to be set in such a manner, that national accounting systems such as the "System of National Accounts" (SNA) cover the main economic activities production, consumption and stock exchange. This is defined to be the first barrier of a national MFA. The second barrier is between nations, therefore accounting all imports and exports crossing it.

For the accounting itself three types of flows can be distinguished according to the European Commission (2001, p. 20):

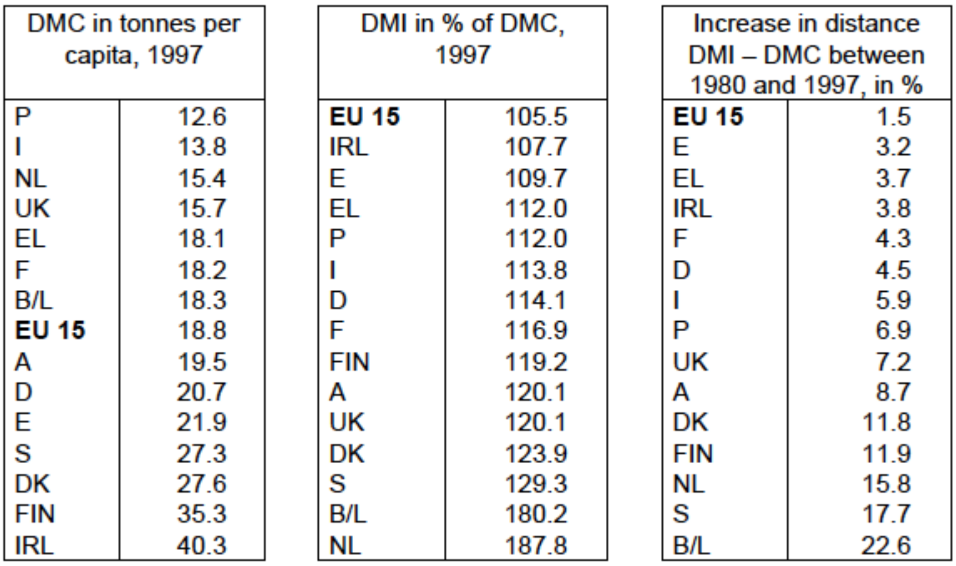
- *domestic* versus *rest of the world*,
- *direct* versus *indirect*, and
- *used* versus *unused*.

The terms domestic and rest of the world are required to clarify origin and destination of flows, while direct and indirect flows can either be observed directly or require additional calculations for upstreams. Used flows are inputs that are of a use to an economy, like raw materials for products. In general: "all *direct flows* are also *used flows*, but not all *used flows* are *direct flows*" (European Commission, 2001, p. 20).

The resource use indicators derive from the material flow balance on the input and output side. EW-MFA distinguishes between seven input flow indicators:

1. Domestic Extraction (DE) for direct used domestic flows such as fossil fuels, minerals and biomass
2. Direct Material Input (DMI) for DE plus imports
3. Unused Domestic Extraction (UDE) for unused domestic flows from mining, harvest and soil excavation
4. Total Material Input (TMI) for UDE and DMI
5. Total Material Requirement (TMR) for TMI plus indirect flows associated to imports
6. Domestic Material Consumption (TMC) for DE plus imports minus exports
7. Total Material Consumption (TMC) for TMR plus imports (including indirect flows) minus exports (including indirect flows)

These resource flows can be interpreted in relation to other economic indicators. Resource productivity for example is measured as GDP at constant prices generated per tonne of material consumption (TMC and DMC). Another example is the relation between input and consumption (see Figure 6), whereas the distance between DMI and DMC has increased over time for all EU 15 countries.



DMC in tonnes per capita, 1997	
P	12.6
I	13.8
NL	15.4
UK	15.7
EL	18.1
F	18.2
B/L	18.3
EU 15	18.8
A	19.5
D	20.7
E	21.9
S	27.3
DK	27.6
FIN	35.3
IRL	40.3

DMI in % of DMC, 1997	
EU 15	105.5
IRL	107.7
E	109.7
EL	112.0
P	112.0
I	113.8
D	114.1
F	116.9
FIN	119.2
A	120.1
UK	120.1
DK	123.9
S	129.3
B/L	180.2
NL	187.8

Increase in distance DMI – DMC between 1980 and 1997, in %	
EU 15	1.5
E	3.2
EL	3.7
IRL	3.8
F	4.3
D	4.5
I	5.9
P	6.9
UK	7.2
A	8.7
DK	11.8
FIN	11.9
NL	15.8
S	17.7
B/L	22.6

Figure 6: Comparison of DMI and DMC for the EU 15

Source: European Commission, 2001, p. 39

In the context of the COMBI project, EW-MFA is suitable for two reasons: First, the resource indicators have got strong cause-effect links between resources from nature and raw materials in economy, thus giving a good proxy of the related environmental burden for resource extraction. Secondly, this and similar methods (e.g. Material Footprint of nations) are in accordance with national accounting systems, ensuring high data consistency and quality. On the other hand, these very accounting systems are also highly aggregated on national and sector-wide levels, which could impede the quantification of resource benefits on the level of EE actions. In addition, there is a probability of double-counting regarding macroeconomic indicators.

As indicated above, the Material Input per Service (MIPS) method applies a similar model, but is very similar to the ISO 14040/14044 LCA in terms of scope and system boundaries. The MIPS concept, for the first time described in Schmidt-Bleek (1998) and further developed in Schmidt-Bleek & Wuppertal Institut für Klima, Umwelt, Energie (1998) and Liedtke et al. (2014), accounts for all material inputs (MI) from nature in up to five categories (see Figure 7), and relates those inputs to a service.

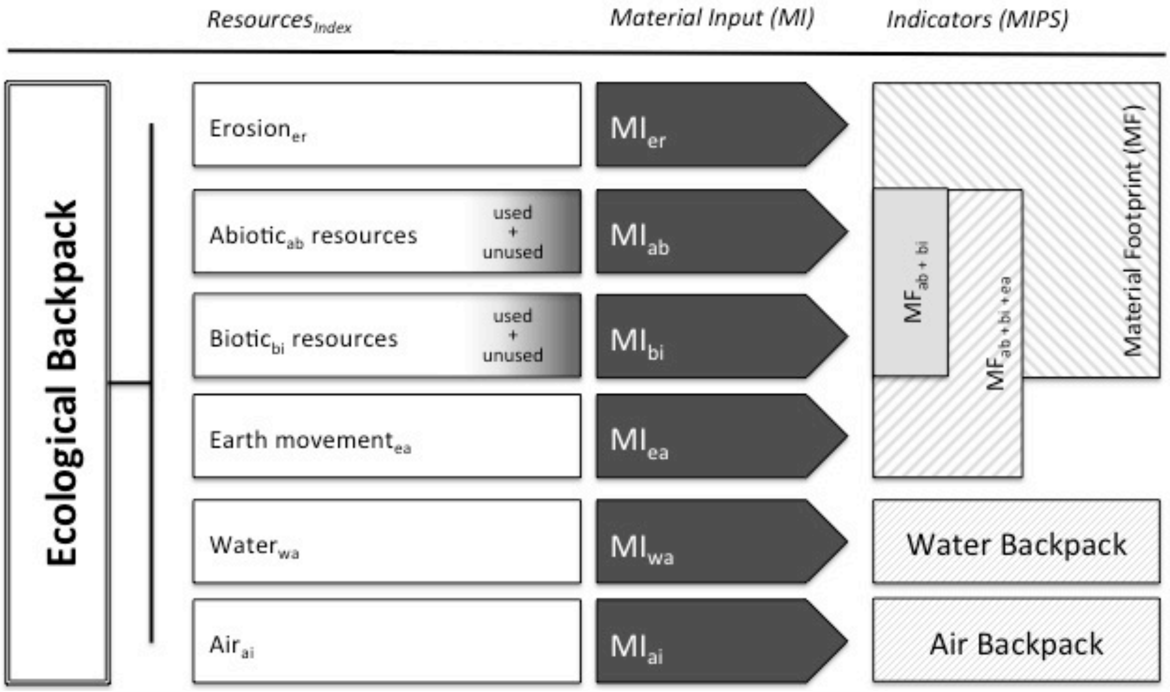


Figure 7: Resource categories, Material Input (MI), and Material Footprint (MF)

Source: Liedtke et al., 2014, p. 550

Its subindicator for raw material resources, Material Footprint (MF), allows for the estimation of environmental impacts of technologies, because it measures all raw material resources from nature including the overburden of mining. "[The MIPS concept] is based on the idea of the ecological backpack, which is a metaphor for the burden of natural resources every object carries in addition to the materials it contains directly" (Liedtke et al., 2014, p. 547) and "[It] has been developed to provide a proxy for ecological measures" (Liedtke et al., 2014, p. 546). The scope and system boundaries of a MIPS analysis are set in accordance with the analysis objective and follow the principles of an ISO 14040/14044 LCA. The service unit in this case fulfils the same function as the functional unit. {Citation}

While MIPS measures removed or translocated resources in up to five categories, the Material Footprint sums up only abiotic and biotic raw material resources and is in compliance with the scope in section 1.4. MF is easy quantifiable (summing up of kg of extracted raw material resources), already operationalized on the level of Life Cycle Inventories (LCI), compatible with LCI databases (Saurat & Ritthoff, 2013) and suited for bottom-up calculations. Since it is an input-indicator, its cause-effect relationships to other benefits are minimal. On the other hand, data quality and availability is highly dependent on the extent and quality of literature for the EE actions as well as the level of detail in EE action descriptions and assumptions.

Table 1: Overview on approaches/methods

Type of method (name)	Short description	Key description literature	Key review literature	Quantification metric used	Method strengths	Method limitations
CML 2002: adp / aadp	abiotic depletion potential: extraction rates in relation to ultimate reserves	Guinée & Heijungs (1995) Schneider, Berger, & Finkbeiner (2011)	Klinglmair et al. (2014) Schneider et al. (2011) Stewart & Weidema (2005)	non-monetary	• midpoint indicator • mass-based • includes economic reserves (aadp)	• no impacts of mining • limited to a restricted number of abiotic resources • no biotic resources • ultimate reserves (earthcrust) instead of economic reserves (adp) • no inclusion of social and economic impacts • no consideration of loss in functionality • no unused extraction
ReCiPe: mineral resource depletion	Monetizes surplus energy demand for future resource extraction efforts	Goedkoop et al. (2009)	Klinglmair et al. (2014)	monetary	• cost-based • ex-ante perspective	• no impacts of mining • limited to a restricted number of abiotic resources • no biotic resources • no inclusion of social impacts • no unused extraction
MFA: EW-MFA	Economy-wide material flow accounting: accounts for all material flows within and between economies	(Fischer-Kowalski et al. (2011)	Giljum, Burger, Hinterberger, Lutter, & Bruckner (2011)	non-monetary	• mass based • reliable and robust data • includes all biotic and abiotic resources • includes economic stocks • can be linked to socio-economic data • includes unused extraction	• high levels of aggregation • no inclusion of social impacts • no consideration of loss in functionality
MIPS	Material Input per Service: sum of resources from nature including hidden and unused flows	Liedtke et al. (2014)	Giljum et al. (2011), Stewart & Weidema (2005)	non-monetary	• mass based • midpoint indicator • includes all biotic and abiotic resources • includes mining impacts • includes unused extraction	• no consideration of loss in functionality • no inclusion of social and economic impacts

2.3 Quantification and Monetisation

Monetisation is a well-known method in the research field of environmental economy (Knorring, 1995) aiming at quantifying environmental problems from an economical perspective. The basic idea of monetisation is to translate the physical pressure on the environment into an economically expressed pressure: An environmental problem is converted into costs for society. Monetisation reflects the following key aspects of 1) which cost types for whom? 2) How to assess the cost? and 3) What is the impact of those costs?

The main environmental cost[8] types (1) damage costs and (2) abatement costs are addressed. (1) *Damage costs* describe the "(...) cost incurred by repercussions (effects) of direct environmental impacts (...) such as the degradation of land or human-made structures and health effects" (OECD, 2007, p. 170). (2) In contrast *abatement costs* describe the economic compensation to avoid an environmental problem and thus to avoid the damage costs (Knorring, 1995; OECD, 2007, p. 8; UN, COM, IMF, OECD, & WB, 2003, pp. 391–399). Due to Knorring (1995) both cost types also reflect whether an ex-post (costs incurred) or an ex-ante evaluation (costs might incur in future) is performed.

Monetisation methods build on MFA or LCA. Results of the literature screening are described in the following, and Table 2 presents an overview of methodologies and approaches for the quantification of environmental problems by monetisation of resource costs at the macro and micro level.

Walter & Staub (2009) describe key approaches based on the MFA (see section 2.2.2). They have in common the combination of environmental (physical) and economic accounts on the macro economy level. Key applications of MFA at macro level are National Accounts (NA), Environmental Accounts (EA), and the System of Economic und Environmental Accounts (SEEA). They provide material flow (accounts) and cost accounting results.

National and Environmental Accounts are available in continuing time series at EUROSTAT database under the topics "Environment and Energy", "Economy and Finance", and "Industry, Trade and Services" (see: http://ec.europa.eu/eurostat/data/database). The database includes material flow accounts presented in the indicators domestic material consumption (DMC), resource productivity and raw material consumption (RMC). Cost related issues are expressed in the following indicators (selection from database "Environment and Energy"[9]):

- environmental tax (energy, transport, pollution, resource)
- environmental protection expenditure (following CEPA - Classification of Classification of Environmental Protection Activities)
- environmental goods and services sector (data on the producers' output of these products measured in monetary values, gross value added, employment linked with this production)

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[8] "Environmental costs are costs connected with the actual or potential deterioration of natural assets due to economic activities." (OECD, 2007, p. 255)

[9] See Eurostat for the variety of "Economy and Finance" indicators e.g. GDP, financial and non financial transactions, gross investment to GDP ratio as well as the variety of ""Industry, Trade and Services" indicators e.g. Inquiry on Investments in the Iron and Steel Industry (in Thousands of euros), Production value, Value added.

broken down by economic activity, environmental protection following CEPA, and resource management following CrEMA - Classification of Resource Management Activities

Some of these indicators are used to reflect the on-going process of e.g. EU 2020 Strategy or the Sustainable Development Strategy (e.g. resource efficiency indicators such as resource productivity or energy taxes).

The System of Economic und Environmental Accounts (SEEA) "describes physical flows from the environment to the economy". SEEA Central Framework (2012) (2014a) is a revision of SEEA (2003) accounting all natural resources and ecosystem inputs "under the heading of natural inputs, which (...) are divided into natural resource inputs, inputs of energy from renewable sources, and other natural inputs (including inputs from soil and inputs from air)" (United Nations & Committee of Experts on Environmental-Economic Accounting, 2014). However, the above-described accounts might only serve as a knowledge framework for monetization of resource benefits at action level, because their data is mostly limited to the national or sectoral level (excl. the PRODCOM and NACE databases).

Further, there is a virulent scientific and political discussion on assessment of environmental costs focusing on the society's well being (e.g. Green GDP, Adjusted Net Saving/Genuine Net Saving, GPI Genuine Progress Indicator, Peskin-Model and ENRAP-Project). They result in aggregated monetised welfare indicators, which are based on a variety of assumptions and thus results of high insecurity and low validity (Walter & Staub, 2009).

Approaches at the micro level (company, products, processes) are the Material Flow Cost Accounting, Environmental Life-Cycle Costing and the combined approach Resource Efficiency Accounting.

The approach of Material Flow Cost Accounting (MFCA) aims at identification and monetary valuation of inefficiencies in material use. Material flows are assessed quantitatively and monetarily. In principle, MFCA is applicable at product, company, and regional level (Sygulla, Götze, & Bierer, 2014). General MFCA principles were published as ISO standard 14051. "It considers the production of goods as a system of movements of materials—the material flows—which are assessed quantitatively and monetarily. Additionally, the flows are distinguished in desired material flows (movements of production’s input raw materials, operating supplies, intermediates, products, etc.) and in undesired material flows which represent the movements of processes’ unintended material outputs such as clippings, rejects or used lubricants."

The Environmental Life-Cycle Costing (E-LCC) is an internationally discussed approach pointing out the necessity to link (environmental) LCA and LCC approaches. "It is needed since there are many LCC approaches, with often very different results when applied, and LCC is usually applied not in LCA-context" (Ciroth et al., 2011). Thus, a Code of Practice has been developed by an Expert Group at SETAC (Swarr et al., 2011). Ciroth et al. (2011) point out that further guidance on data collection, quality assurance, and review is needed.

Busch et al. (2006) suggest the method of Resource Efficiency Accounting (REA) based on life-cycle wide assessment of environmental impacts at physical scales aiming at an integrated monetary and environmental accounting at several levels (company, products, and processes). REA combines ecological and cost data, where the ecological dimension is based on material intensity analysis. Cost accounting can be based on company's cost and activity accounting. REA thus contributes to measure resource cost savings at companies e.g. focus on assessing their value creation by "(1) savings through the more efficient use of materials and energy, (2) reduced costs through less end-of-pipe remediation, (3) proactive and voluntary actions that make costly retrofits redundant, and (4) new business opportunities which are made possible by responsible corporate governance and good reputation" (Busch et al., 2006, p. 111).

Table 2: Overview of methods and applications for monetisation of resource cost savings

Method	Evaluation perspective	Application	Short description	Source
National Accounts (NA)	Society,	Supra-/National level e.g. EU, Germany, Austria, Swiss	Based on international standard (System of National Accounts: SNA); NA provide physical and monetary accounts; Physical flow accounts are based on MFA; Monetary accounts display direct financial impact of implemented policies; Application for monitoring or decision-making processes in cost-benefit analysis; "SNA does not record externalities that arise through economic or other human activity, whether they are positive externalities (e.g., the ecosystem service of flood protection) or negative externalities (e.g., the degradation of river systems through pollution)."	Walter & Staub (2009), United Nations & Committee of Experts on Environmental-Economic Accounting (2014b, p. 106)
Environmental Accounts (EA)	Society	EU, National level	EA provide cost data (e.g. environmental protection expenditure and energy taxes) as well as resource data (material flows) based on SEEA 2003	Walter & Staub (2009), EEA (1999)
System of Economic und Environmental Accounts (SEEA)	Society	European Commission and Eurostat use SEEA 2003 in Environmental Accounts; cooperation of UNSD, EU, IWF, OECD, World Bank	Extension of System of National Accounts (SNA) by the integration of environmental satellite accounts assessing the cost of environmental protection separately to production processes (e.g. satellite account: Environmental Protection Expenditure Accounts - EPEA); Material inputs and product outputs are classified by industry NACE codes but are not divided into into raw-, auxiliary and operating materials; In the SEEA (...) the values reflected in the accounts are (...) based on the current transaction prices or market prices for the associated goods, services or assets that are exchanged (2008 SNA, para. 3.118). Records of market prices: "In practice, prices are generally impacted by taxes, subsidies and the costs of distributing products to consumers (reflected in transport, wholesale and retail margins). The SNA therefore defines a number of different prices—basic prices, producer prices and purchasers' prices—in terms of different treatments of taxes, subsidies and margins. The distinctions between these different prices should be considered in valuation exercises". Further transaction costs are given (monetary and non-monetary transactions);	Walter & Staub (2009), United Nations & Committee of Experts on Environmental-Economic Accounting (2014b, p. 112), Jasch (2010)
Millennium Ecosystem Assessment (MEA)	Society	UNO	Systematic approach of Ecosystem Services (provisioning, regulating, cultural and supporting services); MEA focuses on economic, ecologic, and social drivers of human well-being; MEA is not based on quantitative accounts at macro economic level;	Walter & Staub (2009)
Land and Ecosystem Accounts (LEAC)	Society	EEA and Eurostat	LEAC are based on SEEA Accounts and MEA approach; Ecosystem Services are addressed by marketed Ecosystem Services (Euro) and non-market end use (physical units, Euro);	Walter & Staub (2009)

Inclusive Domestic Product (IDP) / Full Costs of Goods and Services (FCGS)	Society	EEA (concept)	Monetization of Ecosystem Services (Ecosystem Accounts) based on GDP; Analysis of damage costs of national economy within the country and of imported goods;	Walter & Staub (2009)
Final Ecosystem Services (FES)	Society		Boyd/Banzhaf (2007) discuss a definition of accounting units for «Final Ecosystem Services» to assess the "Green GDP". The approach assesses the welfare contribution of goods and environmental performance.	Walter & Staub (2009)
Material Flow Cost Accounting (MFCA)	Society, End-user	ISO 14051; based on development by German 'Institut für Management und Umwelt'	MFCAs general principles were published as ISO standard 14051. "MFCA is a specialized accounting method which aims at the identification and monetary valuation of inefficiencies in material use. Generally, it can be applied to a wide range of systems—single companies, value chains or even geographic regions." "It considers the production of goods as a system of movements of materials—the material flows—which are assessed quantitatively and monetarily. Additionally, the flows are distinguished in desired material flows (movements of production's input raw materials, operating supplies, intermediates, products, etc.) and in undesired material flows which represent the movements of processes' unintended material outputs such as clippings, rejects or used lubricants." Costs defined are: material costs, energy costs, waste management costs, and system costs; Currently limited implementation;	Sygulla et al. (2014)
Cost-Benefit Analysis (CBA)	Society, End-user		Analysis of specific policy scenarios and alternatives, in the evaluation of specific projects; The assessments "of costs and benefits take into account the impacts not only on various individual enterprises and households but also on the broader community and, in the context of ecosystems, the broader environment." Most commonly "the focus is on welfare economic values and the use of welfare analysis, since it is the impacts of various policy choices on economic outcomes that are of common interest." "All impacts are measured in both physical and monetary values"; Estimation of monetary values of environmental effects (for those without market mechanism price); Assessment of positive and negative impacts will be summed up into one monetary figure (net present value); "Net Present Value is a method that uses discounted cash flows, which means that the method considers time value of money. The initial investment is compared with future cash flows discounted to today's value. If the NPV is positive the investment should be realized."	United Nations & Committee of Experts on Environmental-Economic Accounting (2014b, p. 106, 111), Fatta, Moll, Tsotsos, & European Environment Agency (2003, p. 53) Larsson & Qviberg (2004, p. 98)
Total Economic Value (TEV)			"in the estimation of prices for non-market goods and services, it is relevant to consider the determinants of consumers' willingness to pay. One model that is commonly used in this regard is the total economic value (TEV) framework. In the TEV framework, the value of a good or service encompasses four key dimensions: direct and indirect use value, option value, non-use value"	United Nations & Committee of Experts on Environmental-Economic Accounting (2014b, p. 110)

Environmental Life-Cycle Costing (Environmental LCC)	End-user	"A method designed to be used in parallel with (environmental) LCA efficiently and consistently." "It is needed since there are many LCC approaches, with often very different results when applied, and LCC is usually applied not in LCA-context" "Life Cycle Costing summarizes all costs associated within the life cycle of a product that are directly covered by one, or more, of the actors in the product life cycle (e.g. supplier, producer, user/consumer, End-of-Life actor). Costs are the monetary value of goods and services that producers and consumers purchase (real money flows) "	Ciroth et al. (2011), Swarr et al. (2011a)

2.3.1 Review of methods for the quantification of resource benefits

As there are very different types of issues related to resource and raw material consumption, there is also a wide range of methods quantifying or "dealing" with these issues. Table 1 lists the most important methods and captures some of their strengths and limitations in the context of COMBI. While none of the methods quantifies direct social impacts, they differ in their comprehensiveness (all or selected input materials), data reliability, basis for quantification (mass, energy or monetary based indicators) and the consideration of the economic or ecological impacts of resource extraction (e.g. by in- or exclusion of unused extracted resources).

In the LCA methodology scarcity and the depletion of resources is perceived to be most important impact of resource benefits. The corresponding characterisation factors, such as abiotic depletion potential (adp) in CML 2002 or the anthropogenic stock extended abiotic depletion potential (aadp), relate extracted materials to ultimate or extractable reserves. Since reserves can only be estimated for the present in a robust manner and the depletion of a resource by itself is no direct environmental impact, these methods do not fully cover the impacts of especially resource extraction: higher ore grades, increased energy consumption of mining or the absolute magnitude of mining for bulk materials. The ReCiPe[10] method (applicable to LCAs as well) covers some of these issues by quantifying the marginal costs, resulting from increased energy consumption for low-grade ores. However, like adp and aadp, it does not include the unused extraction of resources and is restricted to a limited number of raw materials. All three methods also offer no or very few characterization factors for biotic raw materials.

Material flow accounting methods, like the Economy-wide Material Flow Accounting (EW-MFA) use mass based indicators in order to quantify the magnitude of resource extraction. The EW-MFA is based on national and international statistics (see section 2.2.2). The economic impacts of resource extraction are derived by relating the material flows of economies to socio-economic variables like GDP or the average income. It is but restricted to the aggregation levels in the statistics, impeding the quantification of resource benefits on high detail levels. The Material Input per Service (MIPS) on the other hand can be used for resource quantifications on company or product level, but faces difficulties regarding data variability and robustness like all life cycle methods. Both methods allow for a distinction of extracted, consumed, used and unused resources and can be related to monetary variables (e.g. resource productivity).

Monetization methods, like Life-Cycle Costing, Cost-Benefit Analysis, Material Flow Cost Accounting (MFCA) might be in general applicable to assess resource cost savings. The existing Accounts and Frameworks (e.g. National and Environmental Accounts) provide good guidelines and databases at the macro level. However, there are limitations due to data availability and aggregation level of monetary indicators in the same way as above described (see EW-MFA).

Sygulla, Bierer, & Götze (2011) conclude that "traditional cost accounting methods seem not to be suited very well (...). [M]ost of the material cost are considered to be direct cost (and therefore, are assigned directly to products). This entails, that traditional cost accounting provides only insufficient knowledge about the internal use of materials and energy as well as the manufacturing's material

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[10] The acronym represents the main contributors to the development of the method: RIVM and Radboud University, CML, and PRé Consultants.

and energy losses". The method MFCA addresses these limitations by focusing on material losses (non product outputs) and related cost savings (reducing material losses and disposal costs). On the other hand MFCA is not considering external effects and costs (e.g. damage costs by mining). If further costs (e.g. taxes, other environmental costs) are included in e.g. CBA double counting might occur (e.g. emission trading scheme costs).

2.3.2 Case Studies on resource benefits

Table 3 shows a number of selected studies, which quantified or monetized resource benefits in different contexts.

Table 3: Overview on Multiple Impact (MI) values

Source (reference)	Case description	Method used	Magnitude of the MI, absolute terms	Unit	Magnitude of the MI, relative terms
(Saiz, Kennedy, Bass, & Pressnail (2006)	adp of Standard and 'green' roofed buildings	LCA (adp)	Standard: 103,000 Green: 98,000	kg Sb equiv. / building	4.9 % savings in adp
Notter et al. (2010)	adp internal combustion (ICEV) electrical battery (BEV) cars	LCA (adp)	ICEV: 261 BEV: 163	kg Sb equiv. / km	37,5 % less adp for BEV
(Santoyo-Castelazo, Gujba, & Azapagic (2011)	adp of electricity production in Mexico	LCA (adp)	4.24	kg Sb equiv. / MWh	36 % for natural gas extraction, 32 % for crude oil extraction and 25 % for coal mining
Behrens, Giljum, Kovanda, & Niza (2007)	Domestic resource extraction (DE) in different countries and regions	MFA (DE)	about 1.0 (Europe) to 6.5 (Africa)	tons per 1,000 US $ GDP	25 % less material input per unit of GDP in 2002 compared to 1980
Wang, Yue, Lu, Schuetz, & Bringezu (2013)	Total material requirement (TMR) of China and other countries	MFA (TMR)	China (2008): 42.9 China (2000): 33.0 China (1995): 27.0 Finland (1999): 95.0 Germany (2000): 68.0 Netherlands (1993): 50.0 UK (1999): 39.4 EU-15 (1997): 46.3 USA (1994): 71.4 Japan (1994): 44.7	tons TMR per capita	48,5 % TMR/cap in China (2000) compared to Germany (2000), but increase of 59 % TMR from 1995 to 2008 (China)
(Wiesen, Teubler, & Rohn, 2013b)	MIPS of wind energy	MFA (MIPS)	Abiotic: 90 to 162 Water: 837 to 948 Air: 8 to 9	kg of resource per MWh	European electricity mix up to 76.3 (water), 52.5 (air), 17.5 (abiotic) times higher than wind power plants
Samus, Lang, & Rohn (2013)	MIPS of collector solar plants	MFA (MIPS)	Abiotic: 122 to 216 Water: 4,871 to 8,921 Air: 9 to 16	kg of resource per MWh	not applicable

De Meester, Dewulf, Verbeke, Janssens, & Van Langenhove (2009)	Cumulative exergy demand of 65 optimized Belgian dwellings	LCA (ELCA)	65	GJ exergy/year	non-renewable inputs are responsible for 62 % (wooden frames) to 86 % (cavity wall and external insulation) of total exergy
Burchart-Korol (2012)	Cumulative exergy demand (CExD) of blast furnace technologies	LCA (CExD)	20.6 to 32.5	GJ per ton of liquid steel	not applicable
Hydraulic Institute, Europump, & U.S. Department of Energy's Office of Industrial Technologies (2001)	LCC of pumping systems (comparison of control valve systems)	LCC (present LCC value)	Option B (trim impeller): 59,481 Option D (repair control valve): 113,930	EURO or USD	comparison of four different control valve systems identified best option B having 50% of the LCC value of the worst option D
ICDA, Euro Inox, & SASSDA (2005)	LCC of stainless and carbon steel application in bus underframe	LCC (Total LCC)	stainless steel: 23,130 carbon steel: 26,160	no unit given	bus underframe from stainless steel has about 12 % lower life costs than carbon steel underframe (although initial costs are higher, but maintenance cost are lower)
Moussatche & Languell (2001)	LCC of flooring materials	LCC (Total Costs in Net present worth NWP)	ceramic tile, mortar: 15.56 bamboo flooring: 294.40	USD per square foot	the best hard flooring system (ceramic tile, mortar) is 83 % better than the best soft flooring system (carpet tile, hard back) and 87 % better than the best resilient flooring system (linoleum, adhesive)
Stripple (2013)	LCC of Rockdrain and standard drainage system	LCC (Costs in Euro per m2 drainage)	Rockdrain: 201.4 Standard: 449.6	Euro per m2 drainage	cost reduction of 55.2 % when switching from a conventional drainage system to Rockdrain

3 Methodological challenges

3.1 Lifecycle approach

A full lifecycle ranges from biosphere to technosphere, from extraction to utilization or rather from cradle-to-grave (including upstream processes outside the EU) and cradle-to-cradle. This raises two major methodological challenges for resource benefits in COMBI:

- Defining End-of-Life allocation and discounting rules
- Defining robust use phase parameters.

First and from the point of an EE action, end-of-life (EoL) of EE actions are highly uncertain and subjected to assumptions. Whether a product or its waste materials are recycled, re-used or utilized energetically depends on a number of external parameters usually not included in system boundaries:

- the existence of markets and utilities for each type of EoL treatment,
- the state-of-art of utilization technologies,
- the costs of utilization technologies,
- the capacities of utilization technologies,
- the current prices for secondary and primary materials, and
- regulatory requirements.

These variables are different for sectors and even technologies within these sectors, can depend on the specific life time duration in case of goods, and therefore cannot be generalized. LCA guidelines leave such decisions usually to the analysts of a study in accordance to the study objectives. While some general assumptions *could be made* (e.g. allocation relations of waste to energetic combustion and recycling), they would either not reflect the current state of the EE action or possibly lead to an inconsistent quantification of multi-benefits.

In regard to the outcome of EoL decisions in LCAs Nicholson et al. (2009) analysed five different EoL allocation methods for different materials and against a baseline material: cut-off, loss of quality, closed loop, 50/50 allocation and substitution. The authors observe that " [...] cumulative environmental impact results differ according to EOL allocation method [and] [...] the results change across methods at a different rate for different materials [...]" (Nicholson et al., 2009, p. 7). Further, Saner et al. (2012), studying end-of-life and waste management in LCAs, state that "in order to make fair and consistent environmental assessments of waste treatment alternatives, differences in scope definitions, low data quality, and subjective weighting in the impact assessment have to be minimized. Waste prevention, the first pillar of the waste hierarchy, is often not considered in EoL-LCA [...]" (Saner et al., 2012, p. 509).

Against this background and due to the high variability of results for certain EE actions (esp. buildings), it is recommended to exclude EoL related life cycle phases from the resource benefit quantification. Recycled content (ex post) should and can be considered though. This will reduce the amount of resources in most cases (compared to primary raw material), but not necessarily the raw material costs.

Another challenge are assumptions in the use phase. Nearly all benefits based on a life-cycle-approach, such as impacts in a LCA or the Material Footprint in MIPS, show direct cause-effect links to use phase parameters. The ecological performance of an energetic refurbished building for example, is directly related to the lifetime of the building and its envelope components as well as the climate and the heating behaviour of its inhabitants. And the ecological efficiency of an improved steel production process also depends on the throughput and the economy of scale. However, the decisive parameters are few and have to be set anyway, if the specific or overall energy efficiency potentials is to be quantified. Wherever benefits do not overlap, the inclusion of (additional) use phase parameters is therefore preferable and possible for resource benefits in COMBI.

3.2 Additionality and baseline issues

The base case for the quantification of resource benefits in EE actions is usually a technology. This technology or the product of this technology is compared to a best-available-technology (BAT), which is either an alternative product or the same product without energy efficiency improvements. The BAT can be drawn from the proposed list of EE actions.

The baseline for the resource benefit of an EE action in COMBI could be an attributional average retrospective LCA or MFA with cradle-to-gate system boundaries, comparing alternative A to alternative B. Attributional retrospective LCAs (ALCA) model flows within a time window in the past (in opposition to flows dependent on decisions), whereas average refers to generic data.

Any direct or indirect energy savings by EE actions would therefore also save resources due to the direct cause-effect between energetic raw materials and energy. Additional resource benefits occur from hidden flows in extraction, mining and beneficiation of all involved raw materials including the cradle-to-gate flows of energetic raw materials.

On the other hand, additional environmental impacts of resource provision could occur because of the market implementation of energy efficiency technologies. These "negative" benefits can mainly be attributed to the extraction and beneficiation of scarce, precious or energy related raw materials, such as

- the electrical production of primary aluminium e.g. for the light-weight build of fuel efficient vehicles,
- the impacts of crude oil extraction for EPS, XPS and PU plastics in improved building envelopes,
- the environmental side-effects of primary gold and silver extraction e.g. for electronics in control, measure and automation
- or the provision of heat-resistant alloying elements for improved combined heat and power plants or energy storage.

Literature suggests that these and other "resource rebounds" are usually noticeable lower than the positive benefits. Gillingham et al. (2013) for example conclude that "in sum, rebound effects are small and are therefore no excuse for inaction. People may drive fuel-efficient cars more and they may buy other goods, but on balance more-efficient cars will save energy" (Institute of Electrical and Electronics Engineers, 2009, p. 476). Nonetheless, "negative" resource benefits ought to be considered for quantification in COMBI.

3.3 Distributional aspects & context dependencies

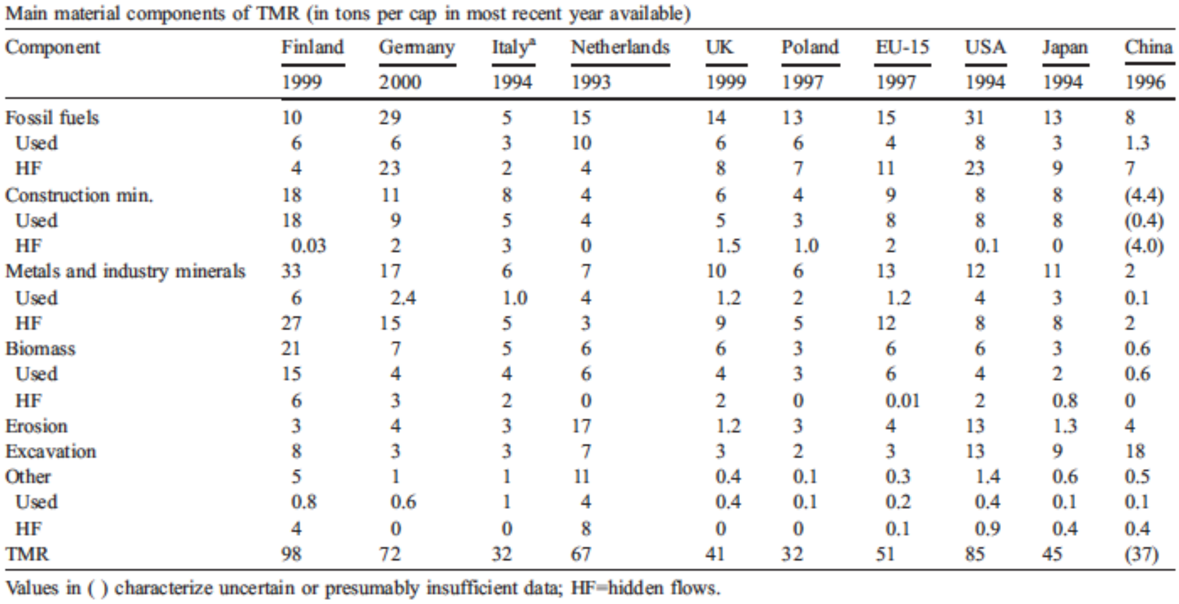
A consistent multi-benefit analysis disallows for double-counting, as far as the interrelation of benefits is concerned. For resource benefits, most benefits accounted are based on material or energy flows, which also potentially cause other interacting benefits (e.g. by material-energy conversion; see section 3.4). More fundamental double-counting problems arise from variability in space and time between methods, but also from the accounting principle itself: What benefits are accounted at what location and to whom? It is crucial for COMBI to harmonize the accounting principle, because multi-benefits in COMBI are not quantified within one methodology (yet), but accounting is based on different models.

This issue is not novel to environmental accounting, which mainly differentiates between the producer and consumer principle (Wiling & Vringer, 2007). The first considers all pressures in a country's territory ("polluters pay"), its production and the second allocates pressures to consumption including imports from other countries. National policies usually apply a producer principle for defining e.g. emissions targets. Footprint evaluation methods (like the ecological or the carbon Footprint) are mostly based on consumer principles. Accounting values for countries based on consumer principles are normally higher for high GDP countries and lower for developing countries compared to quantifications based on territorial production. In Environmental accounting, LCA methods in general (like CML 2002 and ReCiPe 2008) tend to apply a consumer principle. Most MFA methods are capable of both, but current research focuses on frameworks for consumer approaches (Wiling & Vringer, 2007) or approaches which share responsibility for environmental pressure (see Lenzen et al. (2007) or Bastianoni et al. (2004)).

The domestic material consumptions of European countries for example (producer principle) shows the highest shares for biomass and construction minerals throughout the EU-15, with only few countries having also comparable high shares for fossil fuels (Weisz et al., 2006, p. 681). Their total material requirement however is often more influenced by the resource extraction associated with the supply of imports (Bringezu, Schütz, Steger, & Baudisch, 2004, p. 102). As shown in Table 4 these hidden flows (HF) often exceed the directly used material consumption, especially for fossil fuels, metals and industry minerals.

Resource benefits in COMBI, as defined by the scope in section 1.4, therefore could be attributed not only to direct material flows but also to the extraction of raw materials for imported wrought materials (hidden flows). In this context, applying the producer principle would exclude all raw material flows outside of the European Union, concealing the actual mining impacts of e.g. gold for electronics.

Table 4: Used and hidden flows of different European Countries, the EU-15, USA, Japan and China



Main material components of TMR (in tons per cap in most recent year available)

Component	Finland	Gemany	Italy[a]	Netherlands	UK	Poland	EU-15	USA	Japan	China
	1999	2000	1994	1993	1999	1997	1997	1994	1994	1996
Fossil fuels	10	29	5	15	14	13	15	31	13	8
Used	6	6	3	10	6	6	4	8	3	1.3
HF	4	23	2	4	8	7	11	23	9	7
Construction min.	18	11	8	4	6	4	9	8	8	(4.4)
Used	18	9	5	4	5	3	8	8	8	(0.4)
HF	0.03	2	3	0	1.5	1.0	2	0.1	0	(4.0)
Metals and industry minerals	33	17	6	7	10	6	13	12	11	2
Used	6	2.4	1.0	4	1.2	2	1.2	4	3	0.1
HF	27	15	5	3	9	5	12	8	8	2
Biomass	21	7	5	6	6	3	6	6	3	0.6
Used	15	4	4	6	4	3	6	4	2	0.6
HF	6	3	2	0	2	0	0.01	2	0.8	0
Erosion	3	4	3	17	1.2	3	4	13	1.3	4
Excavation	8	3	3	7	3	2	3	13	9	18
Other	5	1	1	11	0.4	0.1	0.3	1.4	0.6	0.5
Used	0.8	0.6	1	4	0.4	0.1	0.2	0.4	0.1	0.1
HF	4	0	0	8	0	0	0.1	0.9	0.4	0.4
TMR	98	72	32	67	41	32	51	85	45	(37)

Values in ( ) characterize uncertain or presumably insufficient data; HF=hidden flows.

Source: Bringezu et al., 2004, p. 102

The quantification of resource benefits and its interrelation with other benefits also depends on the design of EE actions and their context. From a national point of view, it can become highly relevant where specific materials are imported from, while a producer or provider of an EE technology will focus on matters of material costs and efficiencies. For national policy makers, resource benefits should be quantified based on the actual import conditions (down to specific extraction rates from certain mines), while global average extraction values (generic data) allow for a comparison of different EE actions in relation to the potential technical energy savings.

In the resource benefit literature (see Table 5), studies with a focus on generic data in the extraction phase are usually LCA based methods and analyse or compare technologies on a service related scale (physical relation). Resource benefit studies with policy relevance apply EW-MFA or input-output models, in order to capture the global environmental pressure by resource use. As they are based on national accounting and trade statistics, regional specifics are accounted for and benefits are usually related to other contexts, such as the GDP/capita. However, these models have difficulties to disaggregate resource benefits down to level of single actions, as the underlying statistics are highly aggregated. In addition, material and energy flows of EE actions are located in different sectors and different countries, occur on different time lines and are part of reuse and recycling cycles. For example: Flat glass is used in vehicles, but also in photovoltaics. Upstream material flows for its production can take place in a variety of countries and consist of primary as well as secondary materials from different sources. And the material flows would have to be allocated to different products by an allocation model consistent with the other benefits (e.g. value added), in order to avoid double-counting.

For the accounting of resource benefits in COMBI it is therefore suggested to apply a more basic service-related (energy saved by action) method with generic data whereever possible. This resource benefit and the resource benefit of other actions can then be added up to the appropriate scale (national level, EU level) with help of Bottom-up calculations. In addition, and because resource benefits mainly depend on the import and export situation of countries, it is not recommendable to allocate resource benefits to different actors (e.g. income groups) or areas (e.g. urban vs. rural) in an uneven way.

Table 5: Context dependencies

Source (reference)	Actions analysed	Contexts analysed
Wang et al. **(2013)**	Material requirement of China 1995 - 2008	Influential factors for changes in TMR of China such as shares of domestic extraction, amount of excavation and shifts in materials
Wiedmann et al. **(2015)**	Natural resource use of 186 countries	Resource use versus GDP or in the context of population density
Van Caneghem **(2010)**	Steel production in a Belgian steelwork	Comparison of five different methods for abiotic depletion calculation (CML-, CExD-, EPS-, Eco-indicator 99- and mass and energy methods)
De Meester et al. **(2009)**	Life cycle of low-energy input buildings	Distribution of non-renewable and renewable inputs to the cumulative exergy demand by walls, external insulation and construction
Thiers & Peuportier (2012)	Life cycle of high energy performance buildings	Passive houses versus renovated buildings, inclusion of renewable energy production, choice and sizing of heating systems
(Wiesen et al., 2013b)	Electricity production of wind farms	Comparison of the resource consumption of wind farms and the German electricity mix
Schmidt et al. (2004)	Recycle, recovery and light weight vehicle design options	Impacts of production phase versus savings/benefits by recycling or fuel reduction by light weight design
Bartolozzi, Rizzi, & Frey (2013)	Hydrogen production chains from renewable sources for use as automotive fuel	Comparison of seven scenarios with different energy sources (three electric and three fuel cell vehicles and one internal combustion engine)

3.4 Interrelations of multiple benefits

There are few interrelations of resource benefits to other benefits in COMBI. Regarding natural resources, only the benefit crops could be affected if this benefit is – in any way – related to the amount of biotic raw materials. Additional, but not quantifiable relations are those between resource extraction in mining and its impacts on the ecosystem and the health of the mining workers.

Within resource benefits energy resources can be both inorganic or organic natural resources. In order to avoid double-counting, energy resources are not considered a single resource category. Instead abiotic and biotic resources can either be non-energetic or energetic (see scope in section 1.4).

All other possible interrelations of multi-benefits are related to costs of raw materials for energy conversion and wrought materials for the provision of action related technologies. Double-counting could occur wherever material flows are related to materials costs within the benefits public budget, GDP and energy costs. It is recommended to account only for additional material costs, therefore excluding energetic raw materials, wrought materials for energy systems and publicly funded material purchases from the quantification of material costs and cost savings. Table 6 summarizes the potential multi-benefit interactions.

Table 6: Interaction of resource benefits with other MIs

MI Resources		Type of interaction
Pollution	Health	Emissions from mining
	Eco-system	Reduction or Change of ecosystems by resource extraction
	Crops	Biotic resources for biotic raw materials
	Built environment	
Resources	Organic resources	see energy resources
	Non-organic resources	see energy resources
	Energy resources	Energy resources can be organic and inorganic
Social welfare/ commercial productivity	Disposable income/fuel poverty reduction	
	Improved comfort	
	Health	
	Productivity in commercial buildings	
Macro	Employment	
	GDP	GDP reduction from reduced mining activities in fossil fuel producing countries
	Public budget	Costs for wrought materials in technologies or action related products
Energy system/security	Energy system costs	Costs for non-energetic wrought materials (energy system technologies) and energetic raw materials (organic and inorganic)
	Energy security	

4 First insights for a resource benefit methodology within COMBI

The aim of this review was to find out in what way resource benefits are accounted for in literature and what methods are suitable for quantification in COMBI. It showed that the global environmental impacts of material resource use and extraction, although being perceived to be an issue, have not been directly quantified yet. Instead, resource benefit research is usually concerned with the overall amount of raw material extraction and conversion, exergy losses in the future or the depletion of certain economic important materials. In regard to actions for higher energy efficiency and the aspired quantification of multiple benefits in COMBI, a mass-based raw material approach seems more in line with the objectives for the following reasons:

1. Quantification and monetisation affects all material flows on the input side of the model and indirectly by conversion also all material flows on the output side.
2. Monetization and quantification can be conducted based on the same (consistent) material and energy flows.
3. The conversion of materials into energy and the savings of materials by savings in energy use are operationalizable and well defined by literature. Thus, direct double-counting can be avoided.
4. The amount of raw material consumption is a characteristicum of a EE action, while depletion depends on a number of parameters outside the modelling of EE actions.

The proposed scope of resource benefits therefore focuses on raw materials, which are classified by their functionality (energetic and non-energetic) and origin in nature (abiotic or biotic resources), while the original scope in the proposal did not account for raw materials which could be both energy resources and abiotic or biotic resources.

Of the reviewed methodologies (LCA, MFA and LCC), material flow accounting methods showed the highest applicability for COMBI. They account for all raw materials (including economically unused but nonetheless extracted resources impacting nature), allow for a qualification of environmental issues closest to a full impact assessment, can be directly related to energy savings by EE actions and permit the disaggregation of material flows in order to avoid double counting. Although data availability could become an issue in some cases, they can be linked to LCI databases or national statistics.

For monetization assessing direct material costs by raw material market prizes might be a suitable approach. This approach is quite narrow as it is not taking life cycle costs into consideration, but is a consistent approach for the assessment of non-monetary resource benefits as it avoids double counting with other benefits (e.g. pollution, social).

The identified methodology challenges for resource benefit accounting range from life cycle applicability and baseline issues to context dependencies and interrelations with other benefits. While a full implementation of an LCA approach was deemed to be not feasible, cradle-to-gate is possible, particularly if parameters of the use phase are well defined within the proposed EE actions. For baseline and comparison of benefits, EE technologies, the related products and their alternatives (before and after implementation) are proposed. Additional negative benefits from EE action implementation should at least be considered and discussed. While interrelations with other benefits are low as far as one can tell this early in the project, a multi-benefit consistent distribution of the accounted resource benefits throughout countries or the EU can become challenging. Although literature showed a high variety of studies within different geographic and economic boarders, most studies focus on single technologies and sectors by a consumer principle. It will probably become necessary to conduct bottom-up assessments in order to quantify resource benefits on e.g. a national scale. This would decrease comparability to other benefits, which are quantified by top-down approaches or more complex models. In regard to the context, literature in the area of the proposed EE actions mainly links benefits to engineer-based metrics or to the assessed products itself. Still, while a direct societal context could not be found, some studies relate resource benefit indicators to economic metrics such as the GDP.

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