Knowledge is limited.
Imagination encircles the world.
Albert Einstein

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Analysis and development of indicators for a sustainable use of natural resources in a life cycle perspective

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Nederlandse vertaling:

Analyse en ontwikkeling van indicatoren voor een duurzaam gebruik van natuurlijke grondstoffen in een levenscyclusperspectief.

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Table of Contents

List of abbrevations

ABS = Acrylonitrile Butadiene Styrene
ADP = Abiotic Depletion Potential
AU = Australia
B = Benefits
CED = Cumulative Energy Demand
CEENE = Cumulative Exergy Extracted from the Natural Environment
CExC = Cumulative Exergy Consumption
CExD = Cumulative Exergy Demand
CML = Centrum voor Milieuwetenschappen Leiden
CRM = Critical Raw Materials
CumDP = Cumulative Degree of Perfection
DE = Germany
DMC = Domestic Material Consumption
EC = European Commission
ECEC = Ecological Cumulative Exergy Consumption
EEIOA= Environmentally Extended Input-Output Analysis
ELU = Environmental Load Unit
EM = Emissions
EMC = Environmentally weighted Material Consumption
EM-FL = Emission Efficiency at Flow Level
EM-IMP= Emission Efficiency at Impact Level
ENV = Natural environment
EP = Endpoint impact level
EPS = Environmental Priority Strategies
EU = European Union
EU25 = European Union 25 member states
EU27 = European Union 27 member states
FAO = Food and Agriculture Organization
GDP = Gross Domestic Product
GHG = Greenhouse Gas
GPI = Genuine Progress Indicator
GWP = Global Warming Potential
HDI = Human Development Index
HH = Human Health
HHV = Higher Heating Value
ICEC = Industrial Cumulative Exergy Consumption
IEA = International Energy Agency
ILCD = International reference Life Cycle Data system
IN = India
IO(A)= Input-Output (Analysis)

IPCC = Intergovernmental Panel on Climate Change
IR = Industrial Resources
ISO = International Organization for Standardization
JRC = Joint Research Centre
LCA= Life Cycle Assessment
LCI = Life Cycle Inventory
LCIA = Life Cycle Impact Assessment
LHV = Lower Heating Value
MC = Moisture Content
MIPS = Material Input per Service unit
MP = Midpoint impact level
NG = Natural Gas
NGL = Natural Gas Liquids
NR = Natural Resources
OE-IMP = Overall Efficiency at Impact Level
PE = Polyethylene
PEF = Product Environmental Footprint
PET = Polyethylene Terephthalate
PP = Polypropylene
PPS = Purchasing Power Standard
PS = Polystyrene
RAM = Resource Accounting Methods
RBR = Recyclability Benefit Rate
RCR = Recycling Rate
RE-FL = Resource Efficiency at Flow Level
RE-IMP = Resource Efficiency at Impact Level
RMC = Raw Material Consumption
RO = Romania
ROW = Rest Of the World
RRR = reuse/recycling/recovery
RRR*= reusability/recyclability/recoverability
SED = Solar Energy Demand
SERI = Sustainable Europe Research Institute
SS = Single Score impact
TMC = Total Material Consumption
UNSTAT = United Nations Statistics Division
US(A) = United States of America
USGS = United States Geological Survey
WMD = World Mining Database
WR = Waste-as-Resources
WTP = Willingness to pay

Summary

To monitor the transition towards a more sustainable society in terms of natural resource consumption, a wide variety of indicators has been developed over the years, generating confusion. The overall aim of this thesis was to analyze and further develop indicators for a sustainable use of natural resources. Two major types of indicators were identified: footprint indicators and efficiency indicators.

First, the exergy concept was introduced in *chapter 2*, as this is a common theme throughout all the chapters. Exergy is a strong thermodynamic tool that can be used in sustainability analysis of natural resource consumption.

Chapter 3 was focused on footprint indicators. These indicators are a combination of inventory methodologies, which sum up the resources consumed by a system, with resource accounting impact methodologies, which provide results in single units. The two main inventory methodologies are Life Cycle Inventory Analysis (LCI) and environmentally extended input-output analysis (EEIOA), going from systems at microscale (products, processes) to systems at meso/macroscale (industrial sectors, countries). The aim was to develop an overall resource footprint, integrating all natural resource types in one single indicator. Therefore, the Cumulative Exergy Extraction of the Natural Environment (CEENE) was selected as resource accounting method. This exergy-based method accounts for fossil fuels, metals, minerals, nuclear resources, land resources, water resources and abiotic renewable resources. So far, the CEENE had only been combined with LCI through the Ecoinvent database, resulting in a resource footprint for systems at microscale. In chapter 3, we developed a resource footprint for systems at macroscale ('IO-CEENE') by combining CEENE with the Exiobase IO-database. By using this world IO-database, natural resources embodied in imports could be included, providing a global perspective.

In *chapter 4*, a systematized framework for resource efficiency indicators was developed, since these indicators are not univocally defined. Many different aspects are considered in this framework: from the simple accounting of resources to environmental impact assessment; from the microscale of products and processes to the macroscale of regions and countries; from a gate-to-gate perspective to a life cycle perspective or from a national perspective to a global perspective. Also the provenience of resources (natural resources or waste-as-resources) and the quantification metrics (monetary or physical)

are considered. Within this framework, resource efficiency indicators can be critically evaluated, identifying possibilities for the further development of targets and policies.

Chapter 5 illustrated the use of the newly developed resource footprint. The case study is based on a report of the European Commission's Joint Research Centre (JRC), in which they calculated the environmental impacts associated with the consumption per capita in the European Union through Life Cycle Assessment (LCA). The aim of chapter 5 was to calculate these impacts through EEIOA, using the Exiobase database. Next to the classic environmental impacts that are mainly focused on emissions, the overall resource footprint IO-CEENE was also calculated, making it possible to account for natural resource use in a more consistent way. Nonetheless, the CEENE method cannot assess the depletion of metals and minerals. Instead, resource depletion methods like the ADP (Abiotic Depletion Potential) would have to be used. However, it is difficult to integrate such methods with IO-databases, as the flows for metals and minerals are too aggregated to perform an adequate impact assessment.

Chapter 6 further elaborated the recyclability benefit rate (RBR), which is a resource efficiency indicator developed by JRC. The RBR is defined as the ratio of the potential environmental savings that can be achieved from recycling over the environmental burdens related to virgin production and disposal. These savings and burdens are expressed in terms of environmental impacts, here quantified by the CEENE method. The indicator was used in two cases of plastic waste treatment in Flanders: closed-loop recycling (case A) and open-loop recycling (case B). Case A considers plastics extracted from electronic waste, and case B considers plastics from household waste. The recycled plastic in case B is only useable for low-grade products, e.g. street benches, in which it substitutes other materials, e.g. wood. Hence, the indicator had to be adapted for open-loop recycling. The results indicated that recycling of these two waste streams is more resource efficient than incineration or landfill, and that closed-loop recycling has a higher RBR (58%) than open-loop recycling (13%). These results may be useful for policy makers, for example in legislation on taxes and subsidies.

Overall, it can be concluded that resource sustainability indicators require further development. This dissertation tries to address this matter by proposing an overall resource footprint indicator at macroscale, and a systematized framework for resource efficiency indicators. Nonetheless, there are still opportunities for future research, which are discussed in *chapter 7*.

Samenvatting

Om de transitie naar een meer duurzame samenleving op te volgen, verscheen er de laatste jaren een brede waaier aan grondstof-gerelateerde indicatoren. Dit leidde tot verwarring over de precieze betekenis van deze indicatoren. Bijgevolg is het doel van deze thesis het analyseren en verder ontwikkelen van indicatoren voor een duurzaam gebruik van natuurlijke grondstoffen. Er werden twee types geïdentificeerd: voetafdruk indicatoren en efficiëntie indicatoren.

Eerst werd het begrip exergie geïntroduceerd in *hoofdstuk 2*, aangezien dit de rode draad is doorheen de thesis. Exergie is een thermodynamische eenheid die gebruikt wordt in duurzaamheidsanalyses van natuurlijk grondstoffengebruik.

In *hoofdstuk 3* lag de focus op grondstofvoetafdruk indicatoren. Deze combineren inventarisatie methoden met 'resource accounting' methoden, die de inventarisatie in 1 enkele eenheid uitdrukken. De twee voornaamste inventarisatie methoden zijn 'Life Cycle Inventory analysis' (LCI) en 'Environmentally extended Input-Output analysis' (EEIOA). LCI situeert zich op het microniveau (processen, producten), terwijl EEIOA zich situeert op het meso/macroniveau (sectoren, landen). Het doel van hoofdstuk 3 was de ontwikkeling van een complete grondstofvoetafdruk indicator, die alle types natuurlijke grondstoffen in beschouwing neemt. Om dit te doen selecteerden we de Cumulative Exergy Extraction from the Natural Environment (CEENE) als 'resource accounting' methode. Deze exergie-gebaseerde methode omvat fossiele brandstoffen, metalen, mineralen, nucleaire grondstoffen, land, water en abiotisch hernieuwbare grondstoffen. Tot nu toe was CEENE enkel gekoppeld met LCI via de Ecoinvent database. Dit geeft een grondstofvoetafdruk voor het microniveau. In hoofdstuk 3 werd een grondstofvoetafdruk ontworpen voor het macroniveau, door CEENE te koppelen met de Exiobase database ('IO-CEENE'). Door deze wereld IO-database te gebruiken was het mogelijk om grondstoffen die vervat zitten in geïmporteerde producten ook in rekening te brengen.

In *hoofdstuk 4* werd een classificatieschema ontworpen voor grondstofefficiëntie indicatoren, vermits deze niet eenduidig gedefinieerd zijn. Verschillende aspecten komen hierbij aan bod: van het eenvoudigweg optellen van grondstoffen tot de berekening van milieu-impacten; van het microniveau van producten en processen tot het macroniveau van regio's en landen; van een nationaal perspectief tot een globaal perspectief. Daarnaast worden ook de gebruikte eenheden (monetair of fysisch) en het

type grondstof (natuurlijk, industrieel of afval) beschreven. Dit classificatieschema maakt het mogelijk om grondstofefficiëntie indicatoren kritisch te evalueren, zodat men het beleid kan verbeteren.

Hoofdstuk 5 illustreert het gebruik van de nieuwe grondstofvoetafdruk indicator, IO-CEENE. De case studie is gebaseerd op een rapport van het Joint Research Centre (JRC), waarin de milieu-impact gerelateerd aan de consumptie van een gemiddelde inwoner van de Europese Unie (EU) berekend werd via levencyclusanalyse (LCA). In hoofdstuk 5 werden deze milieu-impacten berekend via EEIOA. Hierbij werd opnieuw gebruikt gemaakt van de Exiobase database. Naast de klassieke milieu-impacten die voornamelijk gebaseerd zijn op emissies, hebben we ook de grondstofvoetafdruk IO-CEENE berekend. Zo kan het gebruik van natuurlijke grondstoffen op een consistente manier in rekening gebracht worden. Het nadeel is dat de uitputting van metalen en minerals niet gemeten kan worden met IO-CEENE. Hiervoor moeten methoden zoals ADP (Abiotic Depletion Potential) gebruikt worden, maar deze zijn moeilijk te combineren met EEIOA, aangezien IO-databases te geaggregeerd zijn.

In *hoofdstuk 6* werd de recyclability benefit rate (RBR), een grondstofefficiëntie indicator van JRC, verder uitgewerkt via een case studie. De RBR is gedefinieerd als de verhouding van de milieukundige voordelen gerelateerd aan recyclage ten opzichte van de milieukundige nadelen gerelateerd aan productie uit nieuwe grondstoffen gevolgd door storten of verbranding. Deze milieukundige voordelen en nadelen worden uitgedrukt in milieu-impacten. In dit hoofdstuk werd de Cumulative Exergy Extraction from the Natural Environment (CEENE) gebruikt. De indicator werd toegepast op twee types van kunststoffenrecyclage in Vlaanderen: gesloten-kring recyclage (type 1) en open-kring recyclage (type 2). Type 1 verwerkt kunststoffen die afkomstig zijn van elektronisch afval. Het recyclaat kan gebruikt worden in dezelfde producten als voorheen. Type 2 verwerkt kunststoffen die afkomstig zijn van huishoudelijk afval, uitgezonderd PMD. Het recyclaat is van mindere kwaliteit en kan enkel gebruikt worden in laagwaardige toepassingen, bv. stadsbanken, waarin het andere materialen vervangt, bv. hardhout. De indicator moest bijgevolg aangepast worden aan dit type recyclage. Uit de resultaten kon afgeleid worden dat recyclage van deze twee afvalstromen meer grondstoffen-efficiënt is dan storten of verbranding, en dat gesloten-kring recyclage een hogere RBR (58%) heeft dan open-kring recyclage (13%). Deze resultaten kunnen relevant zijn voor beleidsmakers, bijvoorbeeld in wetgeving omtrent heffingen en subsidies.

In het algemeen kan er besloten worden dat indicatoren voor een duurzaam gebruik van natuurlijke grondstoffen nog veel verbetering vragen. Deze doctoraatsthesis zet een eerste stap in de juiste richting door zowel een complete grondstofvoetafdruk indicator als een gesystematiseerd kader voor grondstofefficiëntie indicatoren te ontwikkelen. Uiteraard zijn er nog vele mogelijkheden voor verder onderzoek. Deze worden uitgebreid besproken in hoofdstuk 7.

Chapter 1
Introduction

1.1 A diversity of resource-related indicators

Our whole civilization depends on the use of natural resources. Natural resources are defined by Udo de haes et al. [1] 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 [2]. This thesis refers to the categorization of Dewulf et al. [3]: 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.

Nonetheless, resources are not always managed in a sustainable way, causing worldwide environmental problems. These are both indirect problems, e.g. emission-related climate change through amongst others combustion of fossil fuels [4], and direct problems, e.g. the depletion of non-renewable resources [5, 6], see Figure 1. Depletion of a resource means that its amount on earth is being reduced [7]. In the last few years, this awareness has caused increasing attention to resource use, next to the focus on emission control. 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.

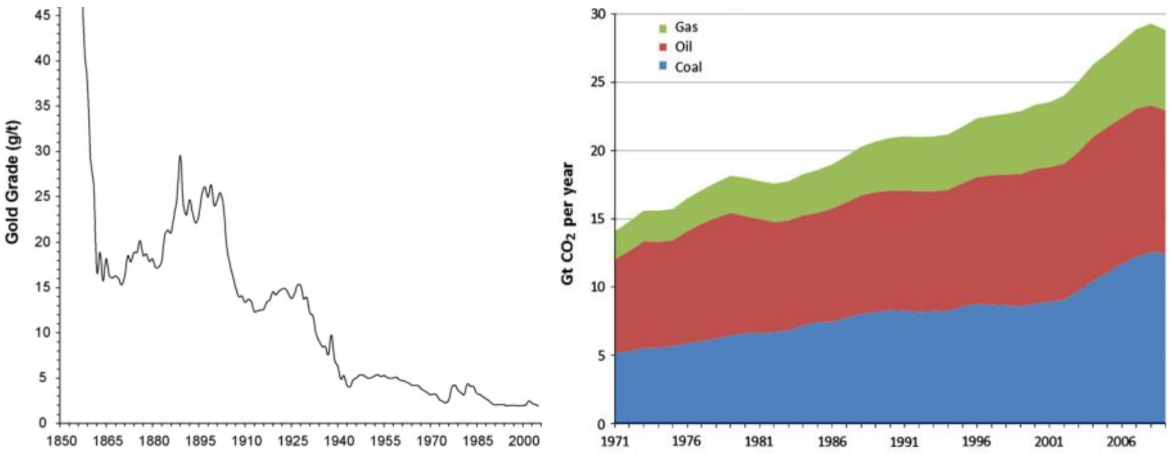

Figure 1: Left: Decreasing gold ore grade over time in Australia, extracted from Mudd [6]. Right: CO_2 emission trends from 1971 to 2009 by fuel type, extracted from Höök and Tang [4].

Japan for example has been promoting policies focusing on resource productivity and waste management since the 1990s: the fundamental law for establishing a sound material-cycle society promotes the 'Reduce, Reuse, Recycle' principle and the cascading use of resources [8]. 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 [9].

At European level, the challenges related to natural resources are a main part of the 2020 growth strategy [10] and are addressed in the Flagship Initiative 'Resource Efficient Europe' [11]. In this context, using natural resources more efficiently is deemed as a necessary step to avoid resource scarcity, i.e. when the amount of a resource available for use is, or will soon be, insufficient [7]. But is also seen as a necessary step to achieve environmental targets, e.g. reducing climate change and preserving ecological assets, and as an opportunity for economic competitiveness. Further, the critical access to raw materials been addressed in the Raw Materials Initiative and in the Resource Efficiency Initiative [12]. Criticality of a resource means that it is scarce and at the same time essential for the present society. In addition to environmental aspects, criticality assessment often also considers economic, social, and geopolitical issues. A first list of critical raw materials with respect to the EU economy has been published in 2010 and will be updated every three years [13, 14], see Figure 2. The EU methodology used to assess criticality combines two components: economic importance and supply risk. The latter is assumed to be influenced by countries with a poor governance, because the supply may be interrupted e.g. through political unrest. A material is defined as critical if it exceeds both the threshold for economic importance and the supply risk [13].

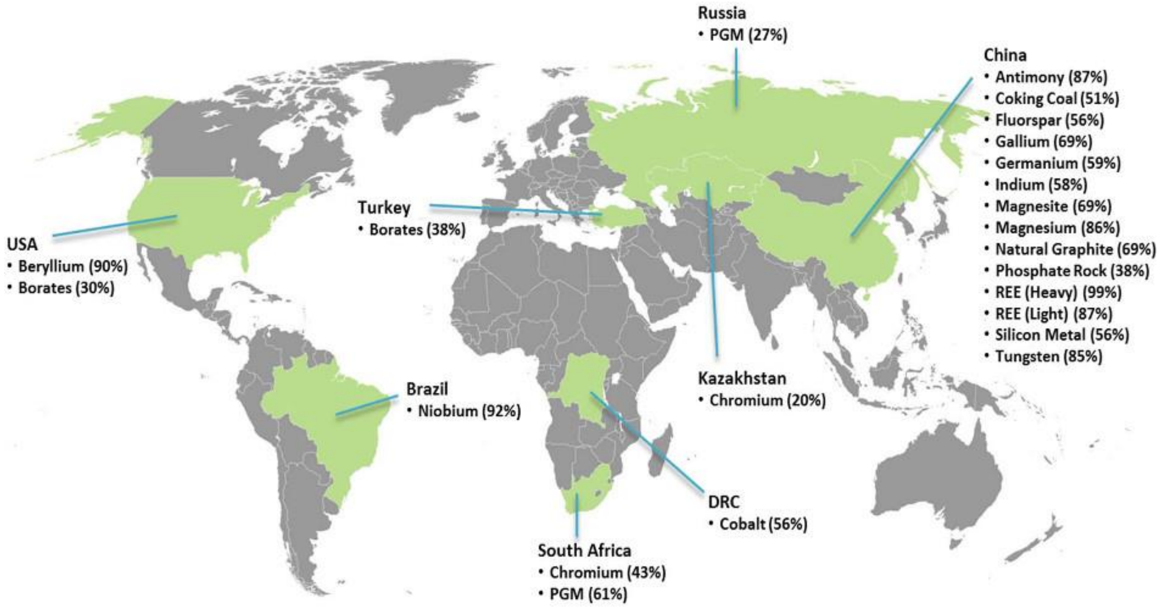

Figure 2: Countries with dominant supplies of critical raw materials, extracted from the report on critical raw materials for the EU [13].

The transition towards more sustainable economies in terms of resource use implies the need for quantitative indicators. Such indicators have historically been developed both in a policy and scientific context, based on different theoretical and conceptual frameworks. The ISO 14001 [15] defines an indicator as 'a measurable representation' to indicate the status or condition of an operation or an activity. In the context of this standard, indicators can be used to quantify and evaluate environmental performance, or in other words, 'what gets measured, gets managed' [16].

Overall, we can distinguish two types of resource sustainability indicators: footprint indicators and efficiency indicators. The last years, footprint indicators have emerged as a popular mode to report environmental performance. This expansion has led to different, often inconsistent interpretations of the term 'footprint'. Ridoutt et al. [17] and Fang [18] defined several criteria available in the literature to define footprint indicators. For this thesis, we consider 'the footprint family' described by Galli et al. [19], which has attracted considerable interest in the scientific community and in policy making. They define a footprint as 'an indicator to track human pressure on the planet', based on a life cycle perspective and measured in absolute values.

Efficiency indicators on the other hand represent a ratio of 'benefits' over 'costs', e.g. the energy efficiency of a process. There is often a link between efficiency and footprint indicators, when the so-called 'cost' in efficiency indicators is represented by a footprint indicator. For example, a possible efficiency indicator is the ratio of the Gross Domestic Product (benefit) over the material footprint (cost) [20].

1.2 Resource footprint indicators

Galli et al. [19] describe the 'Footprint Family' as consisting of the carbon footprint, the ecological footprint and the water footprint. The carbon footprint is a measure of total greenhouse gas (GHG) emissions, expressed in tons of CO_2-equivalents. As this footprint is focused on emissions instead of natural resources, it will further not be considered as an indicator for resource sustainability. The water footprint, as mentioned earlier, measures the direct and indirect freshwater requirements in m^3, with a distinction between green water (rainwater), blue water (ground and surface water) and gray water (water requirements to dilute emissions). The ecological footprint is a measure of the biologically productive land area, expressed in global hectares (gha). Wiedmann et al. [20] added a fourth indicator to the Footprint Family: the material footprint, which is a measure of the amount of extracted raw materials in kg or ton, including fossil fuels, biomass, minerals and metal ores.

These footprint indicators are calculated by integrating inventory methodologies, summing up the resources consumed by a system, with resource accounting methodologies, providing results in single units. Two major inventory methodologies exist. The first one is Life Cycle Inventory Analysis (LCI), quantifying the amount of natural resources consumed directly and indirectly by processes or companies (microscale). LCI is part of the well-known Life Cycle Assessment (LCA) technique. The second step in LCA is life cycle impact assessment (LCIA), in which the inventoried resource and emissions are translated into environmental impacts (e.g. global warming). In the LCA community, these impact results are often also called 'indicators' [21]. The second methodology is environmentally extended input-output analysis (EEIOA), quantifying the amount of natural resources consumed directly and indirectly by industrial sectors, regions or countries (macroscale) [22]. A more detailed explanation is provided in chapter 3.

The water footprint and ecological footprint have already been applied in many case studies at microscale, e.g. the ecological footprint of particleboard production in Spain [23], the water footprint of potato production in Argentina [24]; and at macroscale, e.g. the ecological footprint of Morocco [25], the water footprint of China [26]. The material footprint on the other hand is only applied at macroscale, e.g. for economically important nations in the work of Wiedmann et al. [20] and Tukker et al. [27]. An example from Tukker et al. [27] is given in Figure 3, showing the water, land and material footprint of large economic regions in the year 2007. The Asia Pacific region including China plays a dominant role, as it is responsible for 54% of the global water footprint, 33% of the global land footprint and 46% of the global material footprint. However, it is important to consider also the share of these regions in the world's population, as illustrated in the figure.

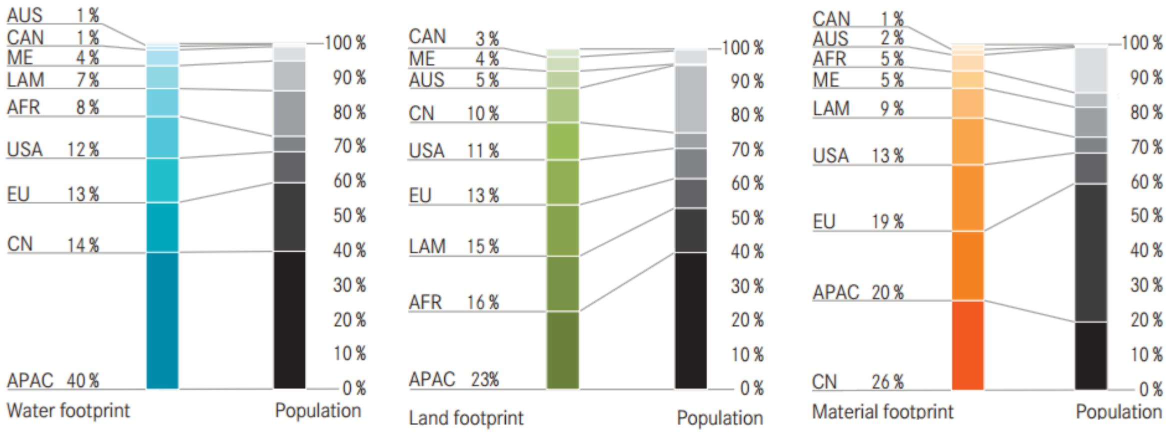

Figure 3: Water, Land and Material Footprint of large economic regions with regard to the global footprint in 2007. AUS = Australia, CAN = Canada, ME = Middle East, LAM = Latin-America, AFR = Africa, USA = the United States of America, EU = Europe, CN = China, APAC = Asia-Pacific. Extracted from Tukker et al. [27]

Nonetheless, to evaluate the overall resource sustainability, each of these three footprints has to be calculated individually. Above that, the material footprint does not account for resources in an adequate way because it is based on equal weighting, e.g. 1 kg sand equals 1 kg copper. Further, there are some issues concerning land resources, as these resources can be accounted in two ways: by the content of the biomass harvested, or by the land occupation needed to produce the biomass [28]. Because the material footprint accounts for biomass, and the ecological footprint accounts for land occupation, this would result in a double counting of land resources.

Hence, an overall resource footprint indicator, which aggregates the different resource types in a consistent and adequate way onto one single scale, is not yet included in the Footprint Family defined by Galli et al. [19] and Wiedmann et al. [20].

First steps in the direction towards an overall resource footprint, capable of integrating multiple resource types onto one single scale, have already been taken by advanced resource accounting methodologies like the cumulative energy consumption and the cumulative exergy consumption. The cumulative energy approach aggregates four different resource types into one indicator, based on their energy content: fossil fuels, nuclear energy, biomass and abiotic renewable resources (solar energy, wind energy, hydropower, geothermal energy). The cumulative exergy approach is based on the exergy concept. Exergy is the maximum useable energy that can be obtained from a resource with respect to a predefined reference environment. For example, not all of the energy in a heat flow can be used to make electricity. The same concept can be applied to materials. Their composition and concentration with respect to a reference environment have a thermodynamic minimum of useful energy [29]. Exergy thus has the major advantage that it enables us to bring mass and energy onto one single scale. This way, a much wider range of resource types can be taken into account, which is a unique feature in resource accounting: fossil fuels, metal ores, minerals, nuclear energy, water resources, biomass, land use and abiotic renewable resources [30]. Therefore, cumulative exergy use methods are considered very suitable for the construction of overall resource footprint indicators. The currently available methods are described in chapter 2. Some of them have already been coupled with LCI-databases [3, 31], resulting in resource footprints at microscale, while others have already been coupled with IO-databases, resulting in resource footprints at macroscale [32].

Of all these exergy-based methodologies, Liao et al. [33] recommend the CEENE (Cumulative Exergy Extraction from the Natural Environment) as the most appropriate one, since it covers the largest number of natural resources: fossil fuels, nuclear resources, metal ores, minerals, water resources, land resources, abiotic renewable resources and atmospheric resources [3]. This methodology has already been coupled with an LCI-databases (Ecoinvent), providing an overall resource footprint for systems at microscale [3, 28]. However, CEENE has not yet been coupled with an IO-database, which would result in an overall resource footprint for systems at macroscale. Such an indicator could be very useful for policy makers, as their decision making is mostly situated at the level of countries and regions.

1.3 Resource efficiency indicators

The issue with resource efficiency indicators is that they are not univocally defined: they are used in different contexts, which generates confusion about the real meaning of resource efficiency. Some studies 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 [11], see Figure 4, while others refer to environmental impacts, e.g. the GDP over the Environmentally Weighted Material Consumption as established by Van der Voet et al. [34].

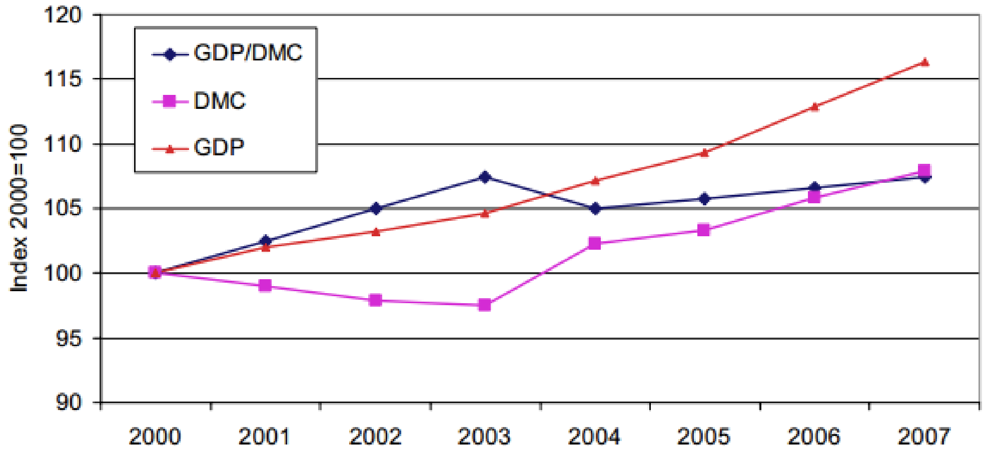

Figure 4: Lead indicator of the European Commission, defined as the Gross Domestic Product (GDP) over the Domestic Material Consumption (DMC). Extracted from [11]

Some studies refer to resources extracted from nature, e.g. the inland water consumption [16] while in others waste is also considered as a resource, e.g. the resources obtained from recycling waste of electric and electronics equipment [35]. Further, different levels of economic activity are considered: from the microscale of specific processes and products, e.g. the energy efficiency of an ethanol-producing system [36], to the meso- and macroscale of sectors and countries, e.g. the energy efficiency of the Norwegian society [37]. At microscale, 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 macroscale: 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 [16]. There is thus an urgent need for clarification.

1.4 Objectives and structure of the PhD

Summarized, the two main objectives of the thesis are the following: (1) developing an overall resource footprint indicator at macroscale, based on the CEENE methodology, and (2) developing a systematized framework in which resource efficiency indicators can be classified and evaluated.

Both developments are illustrated with a case study. First, we will focus on a study of the European Commission's Joint Research Centre (JRC), in which they try to reflect the environmental impacts associated with the consumption of an average citizen of the European Union, based on LCA (microscale) [38]. In this dissertation, we performed a similar study with EEIOA (macroscale). Next to the classical environmental impacts that mainly focus on emissions, we calculated the overall resource footprint associated with the consumption per capita in the European Union, both at macroscale and microscale.

Second, we zoom in on a specific efficiency indicator developed by JRC [39]: the recyclability benefit rate (RBR). This indicator is defined as the ratio of the potential environmental savings related to the recycling of a product over the environmental burdens related to virgin production followed by disposal. The environmental savings and burdens are expressed in terms of environmental impacts. These impacts are quantified with the CEENE-methodology, which has already been operationalized to the Ecoinvent database, as explained earlier. To assess the usefulness of the RBR indicator, it was applied on two cases of plastic waste treatment in Flanders: closed-loop recycling and open-loop recycling.

An overview of the outline of the dissertation is given in Figure 5. Chapter 1 gives a general introduction, while chapter 2 explains the exergy concept, as exergy is a common theme through all the chapters. Chapter 3 addresses the first objective, which is the development of an overall resource footprint at macroscale. Chapter 4 addresses the second objective, which is the development of a systematized framework for resource efficiency indicators. Both chapters are illustrated with a case study in chapters 5 and 6. Chapter 7 describes the conclusions and future perspectives.

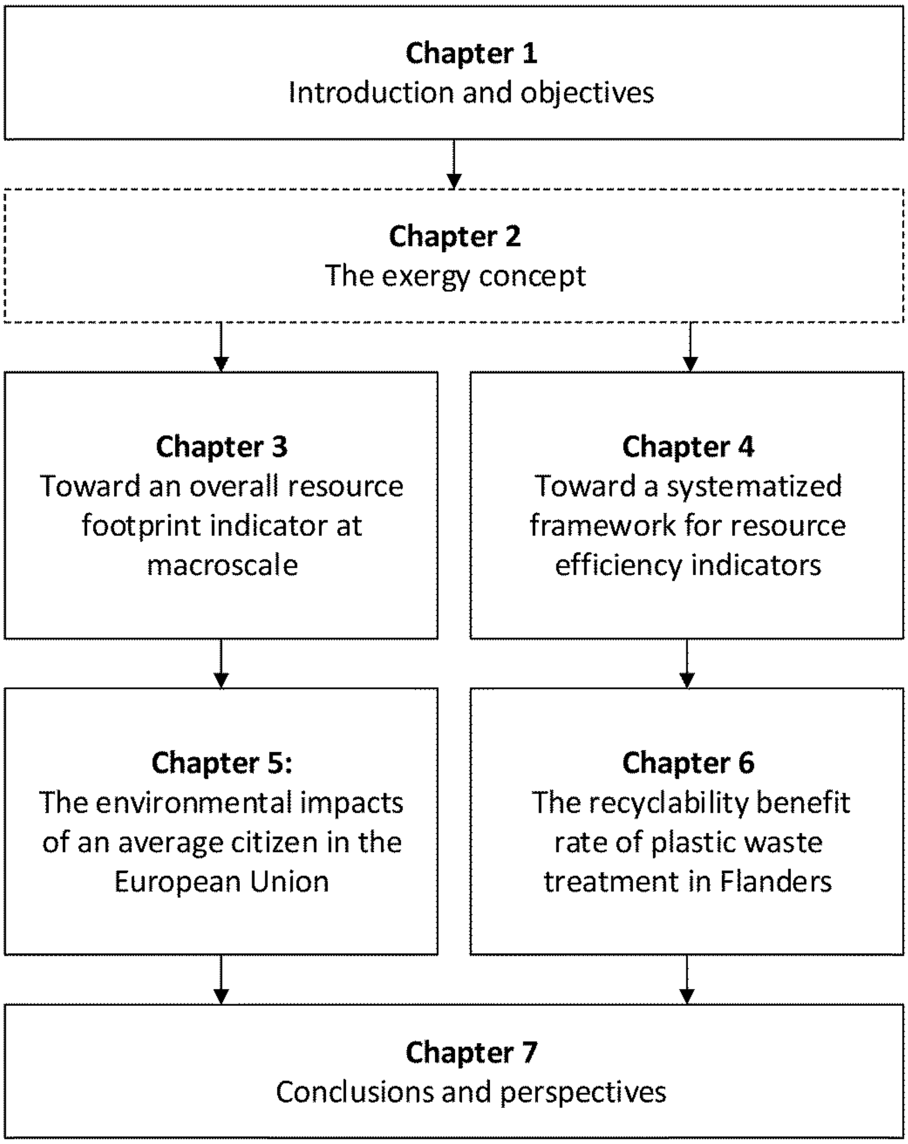

Figure 5: Outline of the dissertation

Chapter 2
The exergy concept

Redrafted from

Huysman, S.; Schaubroeck, T.; Dewulf, J. Exergy and cumulative exergy use analysis. In: Dewulf, J.; Alvarenga, R.A.F., De Meester, S. (Eds) Sustainability Assessment of Renewables-Based Products. John Wiley & Sons, Chichester, 2016.

2.1 What is exergy

To be able to define and evaluate sustainability goals, there is a need for sustainability metrics. These metrics are traditionally called indicators, with exergy being one of them. Exergy relates to the second law of thermodynamics. While the first law of thermodynamics states that mass and energy cannot be created or disappear, the second law states that all spontaneous processes create entropy. Entropy is commonly understood as a measure of disorder, indicating a quality loss of the input energy. Due to entropy generation, the energy that can be made available from the outputs is less than the energy that can be made available from the inputs, although the total energy of the outputs equals the total energy of the inputs. This quality degradation is quantifiable by the loss of exergy, as illustrated in Figure 6 [30, 40].

As a counterpart to entropy, the concept of exergy was introduced by Gibbs in 1873: the case of available energy. Several years later, in 1953, the Slovenian Zoran Rant suggested the term "exergy" to indicate this available energy. The Greek prefix 'ex' refers to external work, while the prefix 'en' in energy refers to internal work.

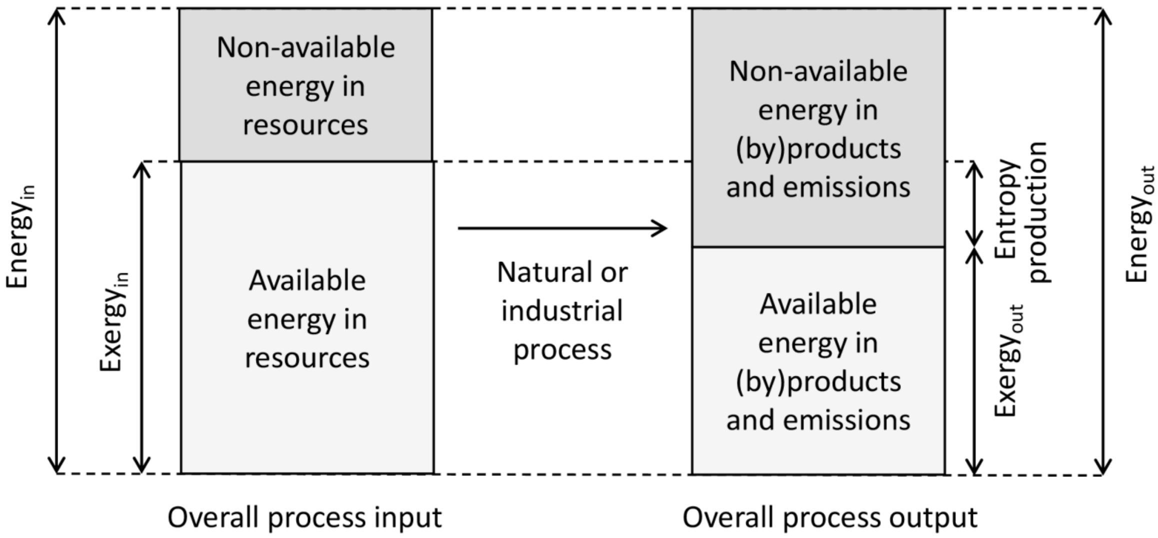

Figure 6: Analysis of a process based on the two laws of thermodynamics. The first law states that all energy going into the process is equal to the energy leaving the process. The second law states that the available energy or exergy embodied in products, by-products and emissions is lower than the exergy entering the system, because of exergy loss, i.e. entropy production. Extracted from Dewulf et al. [40]

In 1988, Szargut introduced a modern definition of exergy, which is still applicable today: "Exergy is the amount of work obtainable when a system is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the above mentioned components of nature" [41, 42]. An important aspect stated in previous definition is that exergy is a metric dependent on the reference environment, i.e. the natural surroundings. When the system and the surroundings reach equilibrium, zero exergy is obtained. The link with entropy is the following: the absolute value of exergy loss due to irreversible processes is equal to the entropy production multiplied with the temperature of the surroundings [30].

2.2 Calculation of exergy

The exergy of a system can be split up into different aspects, the most important ones being: the potential exergy due to its position in a given body force field, the kinetic exergy related to its velocity with respect to a fixed reference frame, the physical exergy specified by its pressure and temperature being different from the surroundings, and the chemical exergy linked with its composition being different from the surroundings. Other possible forms of exergy are electric exergy, nuclear exergy and radiation exergy. Prior to calculation of exergy, the natural surrounding needs to be defined by its characteristics and composition, as done by Szargut [30, 42].

Physical exergy can be calculated from the specific physical enthalpy h and the specific physical entropy of the systems, at the initial state temperature T_i and pressure P_i and at reference state temperature T_0 and pressure P_0 of the environment respectively, see equation 1.

$$Ex_{ph} = (h_i - h_0) - T_0(s_i - s_0) \quad (1)$$

Kinetic exergy, potential exergy, electrical exergy and nuclear exergy have the same value as the corresponding energy terms. For radiation exergy, the exergy-to-energy ratio β is given in equation 2, with T the actual temperature and T_0 the environmental temperature. In case of solar irradiation, the actual temperature T is the temperature of the sun, resulting in an exergy-to-energy ratio of 0,9327 [30, 43]

$$\beta = 1 + \frac{1}{3}\left(\frac{T_0}{T}\right)^4 - \frac{4}{3}\left(\frac{T_0}{T}\right) \quad (2)$$

The calculation of chemical exergy is more complex. For each chemical element in the resource material, one predefines a reference compound in the natural environment, e.g. SiO_2 for Si and O_2 for O. These reference compounds are the most probable products of the interaction of the elements with other common compounds in the natural environment and show typically high chemical stability. The exergy value of the reference compounds is governed by geochemical data: its relative occurrence in the natural environment; this exergy value is the available energy which can be obtained when bringing the reference compound to its reference concentration. Exergy values for reference compounds at standard conditions, e.g. 1 mol per litre for aqueous compounds or 1 atmosphere for gases, are tabulated in the work of Szargut. The exergy of non-reference substances can be calculated as the sum of the standard Gibbs free energy ΔG_r^0 of the reaction needed to convert this substance to reference compounds at standard conditions, and the chemical exergy of these reference compounds (Ex_{ch}^0). This is shown in equation 3, with v_k the number of moles of the kth reference compound. Suffix 0 denotes that the reference system is assumed to be at standard environmental temperature T_0 (usually 298.15K) and pressure (usually 1 atmosphere) [44].

$$Ex_{ch} = \Delta G_r^0 + \sum_k v_k Ex_{ch,k}^0 \quad (3)$$

For the chemical exergy of a system, which is a collection of compounds, the mixing exergy needs to be added. This mixing exergy term is shown in equation 4, with R the universal gas constant, x_i the mole fraction of species in the mixture, T_0 the standard environmental temperature and γ_i the activity coefficient. Values for activity coefficients can be found in literature. They may be greater or smaller than unity for real solutions, and are unity for ideal solutions [43].

$$Ex_{mix} = RT_0 ln(\gamma_i x_i) \quad (4)$$

Additionally for organic compounds, the chemical exergy can be calculated through different techniques: the group contribution method, the exergy-to-energy ratio (β) method and the macronutrient method. In the first method, the molecular structure is subdivided in several functional groups (e.g. -COOH, -CH2-,...) for which exergy values are predefined, all contributing to the total exergy. This method can be used when chemical compounds have been specified and their relative percentages are available. In the second method, β-values are used to link energy streams with their exergy content, mostly used for solid or liquid organic fuels, e.g. wood. The β-value is obtained out of the elementary contents of carbon, oxygen, hydrogen and nitrogen. The lower heating value is used as an energy value. This method can only be used if these data are available. If the necessary data for both methods is available, De Vries [45] says it is preferable to consider the more accurate group contribution method over the β-method. In the macronutrient method, the composition in terms of carbohydrates, proteins, lipids, ash and water is identified [46]. For each of these macronutrients an exergy value is calculated, e.g. for proteins based on their respective average amino acid composition, and then based on the shares of macronutrient fractions, a total exergy value is calculated. This method is evidently only applied for biomass streams.

2.3 Exergy in industrial system analysis

As mentioned in the introduction, the exergy concept found its origin in thermodynamic engineering. Therefore, *industrial systems analysis* has probably been the most common application of exergy. In technical literature, exergy analysis has been extensively used to characterize the thermodynamic efficiency of industrial processes [41]. Exergetic efficiency is here defined as the ratio between the output and input flows, both quantified in exergy, see equation 5. A distinction can be made between the simple efficiency and rational efficiency. Simple efficiency is the ratio of all the outputs (products, heat, waste and exergy loss) over the exergy of the needed inputs, while rational efficiency is the exergy of the desired outputs (products) over the exergy of the needed inputs [43]. The rational efficiency of a process makes it possible to indicate how efficient the inputs are transformed towards products, and not towards waste and lost work.

$$\eta = \frac{\sum Ex_{outputs}}{\sum Ex_{inputs}} \quad (5)$$

In literature, exergy analysis has been applied in many case studies, typically situated at process level: e.g. analysis of biomass gasification [47], solar energy technologies [48], coal-based thermal power plants [49], desalination processes [50], combined heat and power plants [51], etc. Exergy analysis allows one to find the particular hotspots in exergy use or loss of the studied process or system. With this knowledge, the system can be improved through better usage of exergy and thus less entropy production.

Extensions of exergy analysis exist in which the complete supply chain of the considered process is taken into account. These extensions are called 'cumulative exergy consumption (CExC) methods'. CExC is defined as the sum of the exergy contained in all natural resources entering the supply chain of the selected process [42]. This approach is closely related to cumulative energy consumption analysis. However, unlike energy, exergy is a non-conserved property, making it possible to evaluate both the quantity and the quality of resources. Efficiency can here be expressed as the ratio of the exergy contained in the final product to the CExC, see equation 6.

$$\eta = \frac{\sum Ex_{outputs}}{CExC} \quad (6)$$

2.4 Exergy in sustainability analysis

The concept of CExC has evolved from pure technical analysis to sustainability assessment by using the CExC methods as a proxy for the environmental impact related to resource use. One could address this environmental impact at different steps of the impact pathway. At step 1, the natural resources as such are accounted for, and at further steps, the impact of resource depletion is quantified. Methods at step 1 are also called resource accounting methods (RAM). The philosophy behind the RAM methods is that “the less resources consumed, the better, for the same functional unit”.

The CExC methods are RAM methods, situated at the first step in the impact pathway [52]. Being based on exergy, they make it possible to account for both the quality and quantity of extracted resources. Indeed, the two aspects underlying all consumptive processes are both quantified: the first aspect simply defines the resource quantity, while the second aspect defines the extent to which resource extraction removes resource quality [53].

In the work of Swart et al. [52], the existing cumulative exergy methods are summarized: the Cumulative Exergy Demand (CExD) [31], the Cumulative Exergy Extraction from the Natural Environment (CEENE) [3], the Industrial Cumulative Exergy Consumption (ICEC) and the Ecological Cumulative Exergy Consumption (ECEC) [54]. These methods have been used in several case studies, e.g. in resource use analysis of bioethanol production [36], production of transportation fuels [55] and production of pharmaceutical ingredients [56]. The main difference between the first 3 methods (CExD, CEENE, ICEC) and the last method (ECEC) is their system boundary. This is schematically presented in Figure 7.

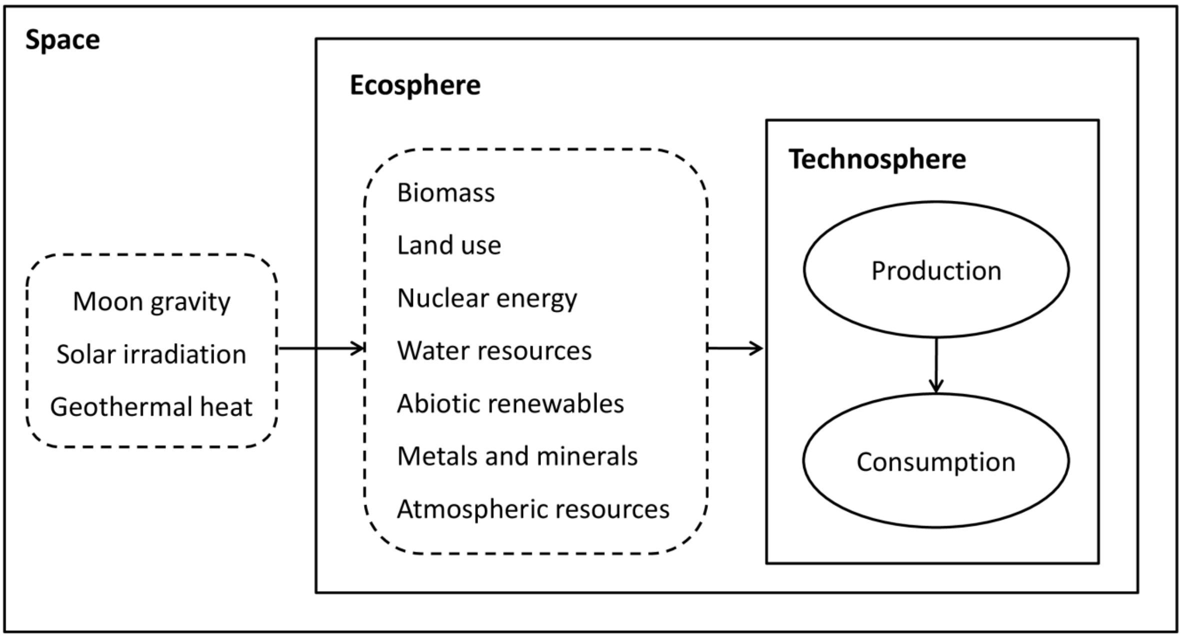

Figure 7: Different system boundaries. Direct inputs of solar irradiation, geothermal heat and moon gravity (tidal energy) occur also in the technosphere and are considered part of the group 'abiotic renewables'. Adapted from Liao et al. [33]

The ECEC method considers its boundary at the planetary ecosystem which supports life in general, called the ecosphere, containing the atmosphere, biosphere, hydrosphere and lithosphere [57]. The main exergy source supporting the ecosphere is solar radiation, together with geothermal heat and tidal energy from moon gravity. The technosphere (also called antroposphere) is the part of the ecosphere that is modified by man for use in human activities. The supply chain of inputs is a subsystem of the technosphere, converting natural resources from the ecosphere into products that are used to deliver services. The system boundary of CExD, ICEC and CEENE is equal to that of the technosphere, i.e. these methods assess the amount of natural resources in exergy withdrawn by the technosphere from the ecosphere. ECEC goes one step further by accounting also for the processes occurring in the ecosphere to produce goods and services [33]. This system boundary is similar to the emergy concept [58], as will be explained further on.

We will priory discuss the methods that have the technosphere as system boundary (CExD, ICEC and CEENE). First, it is important to have a clear definition of what natural resources are. Udo de haes et al. [1] define them as "objects of nature which are extracted by man from nature and taken as useful input to man-controlled processes, mostly economic processes". Natural resources can be split into different categories.

Here, we will refer to the categorization of Dewulf et al. [2]: fossil fuels, minerals, metals, nuclear energy, water resources, land resources, abiotic renewable energy (i.e. wind, hydropower, tidal, wave and geothermal energy) and atmospheric resources. Regarding land resources, there are two ways to account for them: (1) by the amount and type of the biomass harvested; and (2) by the area and time needed to produce the biomass (land occupation). To avoid double counting, one way of accounting has to be chosen [28].

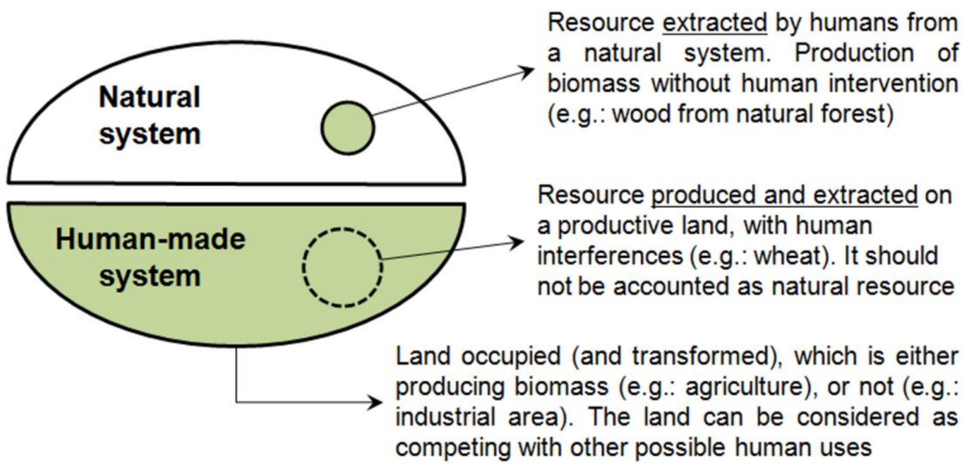

Figure 8: Schematic representation of land resources from two different systems. Extracted from Alvarenga et al. [28]

In both CExD and ICEC, land resources are accounted for by the exergy content of the harvested biomass. In the first version of CEENE (CEENE v.2007) on the other hand, land resources are accounted for by their land occupation. To do so, the solar irradiation available for photosynthesis was used as a proxy [3]. Furthermore, inflow of solar exergy and exergy of harvested biomass products as such are not accounted for in the CEENE method, since they are included in the land occupation, this to avoid double counting.

The CEENE method was further improved concerning land resources by Alvarenga et al. [28]. In this second version of CEENE (CEENE v.2013), a distinction was made between land resources from natural systems and from human-made systems, see Figure 8. A system can be considered natural if its biomass production is maintained with no or negligible human intervention, e.g. primary forest. From these natural systems, extracted biomass resources are accounted for by their exergy content. In human-made systems, land area has been transformed from natural to human-made environment, e.g. forest plantations. Here, the biomass yield is not extracted from nature, since it is produced within the human-made system. What is actually deprived from nature is the land area. Therefore, the land area occupation needed for biotic resource production is accounted for in human-made system.

To do so, the natural potential net primary production (NPP) was used as a proxy, which is the amount of NPP a land area would produce if it was not occupied by humans. Since the natural potential NPP is a result of local natural conditions such as solar exergy, soil quality, temperature, rainfall etc., it is a better proxy than the solar exergy of CEENE v.2007. Site-specific characterization factors were obtained making spatially-differentiated impact assessment of land occupation possible [28].

The main difference between CExD and ICEC are the databases to which they have been operationalized. Inventory databases can be based on different inventory models: LCI-models or input-output (IO)-models, see chapter 3 for more details. The CExD method is operationalized to the LCI-based Ecoinvent database [31], as well as the CEENE method [3, 28]. The ICEC method on the other hand is operationalized to the IO-based United States 1997 database, as well as the ECEC method [32].

The ECEC method has the ecosphere as system boundary. As mentioned earlier, this method is closely related to the emergy concept, in which a certain amount of solar energy is attributed to geothermal heat and tidal waves in order to be able to count in terms of solar energy [58]. The emergy of a product is the available solar energy (i.e. solar exergy) used for its creation [59]. However, the emergy methodology also covers additional methodological assets which have led to a lot of criticism [41]. In the ECEC method, Hau and Bakshi [54] try to account for the exergy that was needed to produce natural resources by natural systems (i.e. embodied exergy) by assigning them emergy values from literature. Although some of the controversial aspects of emergy are avoided in the ECEC method, its use to assess the impact of natural resource consumption is sometimes questioned [1, 52].

2.5 Conclusions

This chapter describes the use of exergy in industrial engineering, where it is used to characterize the efficiency of processes, and in sustainability analysis, where it is used to quantify the environmental impact of resource intake. The latter is done using CExC methods. These methods sum up all the exergy contained in the natural resources required along the life cycle of a system. CExD, CEENE and ICEC account for the resources extracted by the technosphere from the natural environment, while ECEC considers the efforts spent by the ecosphere, including the natural environment, in generating resources.

Liao et al. [33] concluded in their work that the added value of resource impact assessment with thermodynamics-based methods lies in the completeness of the resource scope and scientific robustness and validity. On the other hand, they have lower environmental relevance in terms of resource depletion. Of all the exergy-based methods, CEENE is recommended as the most appropriate method for natural resource accounting, as it considers the largest number of resource groups (fossil fuels, nuclear resources, metal ores, minerals, water resources, land resources, abiotic renewable resources and atmospheric resources), but also a mere utilitarian perspective: CEENE considers the contribution of resources to the technosphere, while ECEC considers the efforts spent by the ecosphere in generating resources, leading to considerably different results.

Chapter 3
Toward an overall resource footprint indicator at macroscale

Redrafted from

Huysman, S.; Schaubroeck, T.; Dewulf, J., Quantification of Spatially Differentiated Resource Footprints for Products and Services through a Macro-Economic and Thermodynamic Approach. Environ Sci Technol 2014, 48, (16), 9709-9716.

3.1 Introduction

As described in chapter 1, resource footprint indicators are calculated by integrating inventory methodologies, summing up the resources consumed by a system, with resource accounting methodologies (RAM), providing results in single units.

Focusing on inventory methodologies, different ones exist for systems at different economic levels: from the macroscale of nations and their industrial activities, to the microscale of processes and their product outputs [60]. To calculate the inventory of systems at microscale, Life Cycle Inventory Analysis (LCI) is used, here shortly called an LCI-model. This model is used in LCA [61]. To calculate the inventory of systems at meso- and macroscale, environmentally extended input-output analysis (EEIOA) is regularly used, here shortly called an IO-model. Originally worked out by Leontief in

1936 [62], input-output analysis was designed to provide a complete picture of the monetary interrelations between industrial sectors in an economy. To combine the strengths of both models, they can be linked in a hybrid form [22]. A thorough explanation of these models is addressed in section 3.2.

These inventory methodologies are then combined with RAM to form footprint indicators, e.g. the earlier mentioned footprint family (ecological, material and water footprint). Nonetheless, there are still some drawbacks related to this footprint family, as explained in chapter 1: to evaluate the overall resource sustainability, each of these three footprints has to be calculated individually. Besides, there is the issue of equal weighting in the material footprint (e.g. 1 kg sand equals 1 kg copper) and double counting of land resources: the material footprint accounts for biomass, while the ecological footprint accounts for land use.

An overall resource footprint indicator, aggregating different natural resources in a consistent way onto one single scale, is currently missing in the footprint family defined by Galli et al. [19] A possible solution is the use of advanced resource accounting methodologies based on exergy, see chapter 1. Exergy can bring mass and energy onto one single scale, making it possible to cover a wide resource range. Because the exergy concept is based on the laws of thermodynamics, it also provides a proper scientific validity [33].

Four exergy accounting methodologies have already been combined with a LCI-model, delivering resource footprint indicators at microscale (see chapter 2): CExD, ICEC, CEENE and ECEC [52]. However, exergy-based resource footprint indicators at macroscale are not yet as mature. Only ICEC and ECEC have been combined with an IO-model. This was done by Ukidwe and Bakshi [32], using the 1997 input-output model of the United States (US). This IO-model is a national model: only resources extracted within the boundaries of the nation are considered. For nations like the US with a large range of natural resources, national IO models can give good estimations. However, when considering more import-dependent nations, it would be better to use world IO-models, covering the whole world. These world IO-models provide a more complete life cycle perspective than national IO-models, since they also consider natural resources embodied in imported and exported products [63].

Another issue is that only ICEC and ECEC have been applied. ECEC is a rather controversial method, because it has the ecosphere as system boundary [54], and ecosystem services appear not to be a resource according to the definition from Udo de Haes [1]. Further, ICEC and ECEC use a different approach regarding land resources compared to CEENE [3]. The latter is recommended by Liao et al. [33] as the most appropriate exergy accounting methodology, covering the largest number of resource types (see Materials and Methods).

The objective of this chapter is the development of an overall resource footprint indicator at macroscale, based on an IO-model. In practice, this is done by combining (1) a world input-output model instead of a national input-output model with (2) the more recent CEENE method. On top of that, (3) the indicator will allow the implementation of several country-specific characterization factors for land use, and partially for metals and minerals. (4) To exemplify the new indicator we applied it in a case study.

The resulting resource footprint indicator will further be referred to as IO-CEENE, to establish the difference with the already existing resource footprint indicator based on a LCI-model, further referred to as LCI-CEENE [3]. By using a world IO-model, IO-CEENE can establish geospatial differentiated resource footprints. Although resource consumption is a global problem, such a geospatial perspective is definitely relevant, as resources are embedded in internationally traded products, and countries are dependent on resources from other countries. It provides an advantage that cannot be obtained with LCI-CEENE today.

3.2 Materials and methods

The two key building blocks for the development of IO-CEENE are a suitable world IO-model (inventory methodology) and the CEENE methodology (RAM). To form a resource footprint indicator, they had to be combined by (1) selecting resource flows from the world IO-model and (2) determining exergy values for each flow. How this was done in practice is explained in the Result & Discussion section. A schematic overview is given in Figure 9.

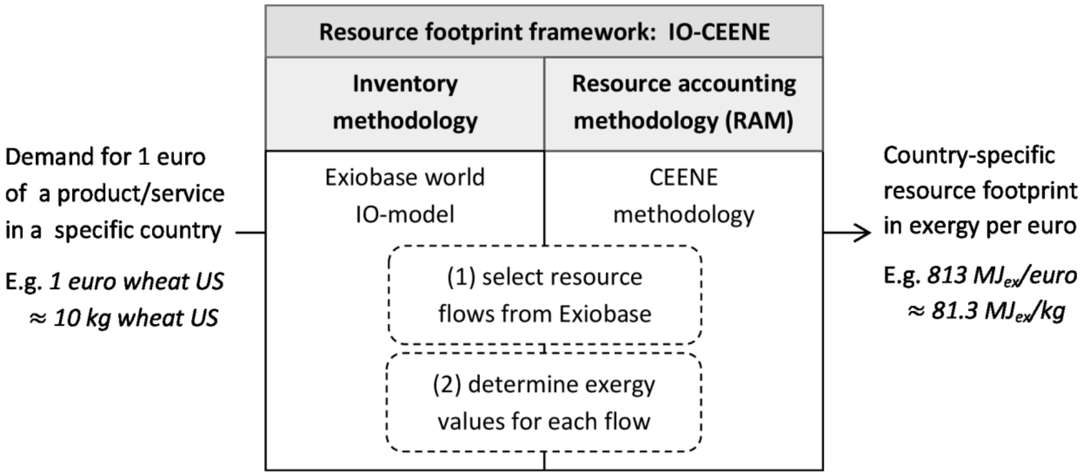

Figure 9: Overview of the IO-CEENE resource footprint indicator.

3.2.1 A world IO-model as inventory methodology

To provide a better understanding of IO-models, their mathematical structure is here shortly described. IO-models are based on the same type of linear inverse model as LCI-models (appendix A.1.1), see equation 7 [64].

$$B.\ A^{-1}.f = g \qquad (7)$$

Matrix B describes the environmental flows transferred between the natural environment and the human/industrial system, matrix A represents the flows within this system and vector f represents the output demanded from this system. The environmental flows can be natural resources extracted by the system and/or emissions emitted by the system. In this study, only resources will be considered.

The IO-model is here described with the often used monetary units. Matrix A can be written as $I - Z$, with I the identity matrix and Z the direct requirements matrix or IO-table. For the construction of IO-tables, two methods of handling multi-output processes (allocation) are possible: the industry-technology assumption, equivalent to partitioning in LCA, and the product-technology assumption, equivalent to system expansion in LCA [65]. Both methods can be used to construct an IO-table in an industry-by-industry form (IxI) or a product-by-product form (PxP). In an IxI form, each row and column represents an industry sector: each element z_{ij} represents the purchases from sector i required per (monetary) unit output of sector j. In a PxP form, each row and column represents an industry output, i.e. a product group or service. A more detailed description is given in the work of Rueda-Cantuche and ten Raa [66]. In this study, we used the PxP form, which is more in accordance with the LCA-approach, because the focus is on products instead of industry sectors [67].

Vector f is the final demand vector, of which each non-zero element f_i represents the final demand in monetary units for a sectoral output. Knowing f, the total sectoral output x required to supply this demand can be calculated by solving equation $x = (I - Z)^{-1} f$. Finally, inventory vector g can be calculated by multiplying x with environmental matrix B, in which each element b_{ij} represents the amount of resources i, mostly expressed in physical units, per (monetary) unit output of sector j.

To obtain a global perspective, a suitable world IO-model had to be selected. Therefore, we consulted the review of Wiedmann et al. [63] in which all existing world input-output databases are summarized: Eora, GTAP 8 (Global Analysis Trade Project), WIOD (World Input-Output Database) and Exiobase. The natural resources in input-output databases are typically subdivided into 4 groups: energy use, land use, water use and material use (the latter including fossil fuels, metal ores, minerals and biomass). However, GTAP 8 does not contain water resources, and both GTAP and Eora are missing material resources. Consequently, WIOD and Exiobase seem to be the most suitable databases for the IO-CEENE. Further on, the industrial sectors are much more disaggregated in Exiobase compared to WIOD, providing more detailed information. For this reason, Exiobase [68, 69], was chosen to serve as world IO-model.

The Exiobase database [69] has the year 2000 as base year and contains two types of IO-models: an industry-by-industry (ixi) form and a product-by-product (pxp) form. For this study, the pxp form was chosen because it is more in accordance with the LCA methodology as it quantifies the impact of product life cycles [65]. Exiobase covers 43 countries (with a total GDP of 2.9E+13 US$), and 1 rest of world region combining the remaining 173 countries (with a total GDP of only 3.0E+12 US$) [68, 70], see appendix A.1.2 for more details. Each country has 129 sectoral products. Consequently, the IO-table Z has a dimension of 5676 x 5676. All implicit prices in this IO-model are basic prices (price minus taxes plus subsidies) [71]. The economic products per country considered are the ones available on the market of that country. Hence, this also includes imported products, produced elsewhere, and not only the ones produced in the specific country. Further, Exiobase contains several natural resource flows, of which a set was selected for the construction of matrix B according to the CEENE method.

3.2.2 CEENE as resource accounting methodology

CEENE v.2013 was chosen as resource accounting methodology. As described in chapter 2, the CEENE method covers eight categories of natural resources: fossil fuels, nuclear resources, metal ores, minerals, water resources, land resources, abiotic renewable resources and atmospheric resources. CEENE distinguishes itself from ICEC through a different quantification of land resources. In ICEC, they are accounted for by the exergy content of the biomass harvested, while CEENE v.2013, land resources from natural systems are accounted for by the exergy content of the extracted biomass, while land resources from human-made systems are accounted for by their land occupation, using the deprived potential natural net primary production (NPP) as a proxy [28].

Furthermore, the exergy content of solar energy and rainwater is set zero in CEENE, given that they are both implied within land occupation. Also atmospheric resources do not feature exergy, being reference species in a reference state [31].

As mentioned in the introduction, a resource footprint indicator combining a LCI-model and the CEENE as exergy accounting methodology is already existing, here called LCI-CEENE. It has been applied in several LCA-studies [56, 57, 72]. For the construction of IO-CEENE, the same approach as used for the development of LCI-CEENE was applied. In this particular LCI-CEENE, inventory calculation is based on the Ecoinvent database. First, 184 elementary resource flows were selected to construct matrix B. Next, the composition of these flows was used to establish characterization factors, the so-called X-factors.

An X-factor is defined as the exergy extracted from the environment (in megajoules of exergy, MJ_{ex}) per unit of this flow (e.g. Nm^3 of natural gas). A distinction can be made between generic and country-specific X-factors. Generic X-factors are similar for each country, while country-specific X-factors may be used when the exergy of a resource depends on its geographical location. After all, the extent of the environmental impact may depend on the location where it occurs [28, 73]. In CEENE v.2007, all X-factors are generic. In CEENE v.2013, also country-specific land use X-factors for 163 countries are available. These country-specific X-factors are highly variable, for example 49.2 MJ_{ex}/m^2.year in Indonesia and 19.5 MJ_{ex}/m^2.year in Norway. Several of these LCI-based X-factors could also be used for IO-CEENE.

Together, the X-factors form a characterisation vector q, in which each element q_i represents the X-factor X_i of elementary flow i. Hence, the CEENE of a product can be calculated by multiplying inventory vector g with q. This is the summation over all the elementary flows of the products of the X-factor X_i and amount g_i of the i^{th} flow, see equation 8.

$$CEENE = q.g = \sum_{i=1}^{184} (X_i . g_i) \qquad (8)$$

In the Results & Discussion section, it is explained how IO-CEENE was developed by integrating the Exiobase IO-model with the CEENE methodology.

3.3 Results and discussion

3.3.1 The new IO-CEENE indicator

The elementary resource flows in Exiobase can be classified into 4 categories: energy use, land use, water use and material extraction. A full description can be found in the technical report of Exiobase [74]. A short summary of the data sources can be found in appendix A.1.3. Figure 10 shows the Exiobase categories and their subcategories of elementary flows, together with the corresponding CEENE categories. All elementary flows with a corresponding CEENE-category are included in matrix B. The unused material extraction flows, part of the Exiobase material extraction category, were not included, because they did not enter the human/industrial system, e.g. overburden from mining. Some resource flows in Exiobase are present in two different categories for the convenience of application, e.g. fossil fuels are available as ‘material extraction’ and as ‘energy use’. From the perspective of the CEENE methodology, accounting for both would result in double counting. In this section is described (1) how flows were selected for the construction of matrix B to avoid double counting and (2) how exergy characterisation factors, called X-factors, were determined for each flow.

3.3.2 Selection of elementary flows for matrix B

To avoid double counting, the elementary flows ‘fossil energy’, ‘nuclear energy’ and ‘energy from biomass’ were excluded from matrix B. These flows are already accounted for in the (used) material extraction subcategories fossil fuels, biomass and (nuclear) metal ores respectively. Furthermore, the elementary flows solar energy and green water (rainwater) were also excluded from matrix B, since they are both implied within land occupation.

As mentioned in Materials and Methods, land resources should be accounted in one of the two ways: by the biomass harvested if originating from the natural system or by the land use/occupation needed for their production if originating from human-made systems. In Exiobase, there are three types of land use flows (arable land, pastures and forest area) and four types of biomass flows (crops, grass, wood and aquatic animals). This data was originally retrieved from the Faostat database, in which no distinction was made between extraction from natural (extensive) systems or human-made (intensive) systems [75]. In case of arable land producing crops, it can be assumed that cultivation is intensive. Therefore, the arable land flows (land use) were included in the B-matrix, while the crop flows (biomass) were excluded to avoid double counting.

For forest area producing wood, making a distinction between extensive and intensive cultivation was not possible. Besides, Exiobase considers both productive and non-productive forest area due to lack of more detailed data. Since only productive forests should be accounted for according to the CEENE methodology, this would result in large overestimations. Therefore, the wood flows (biomass) were included in matrix B, while forest area (land use) was not.

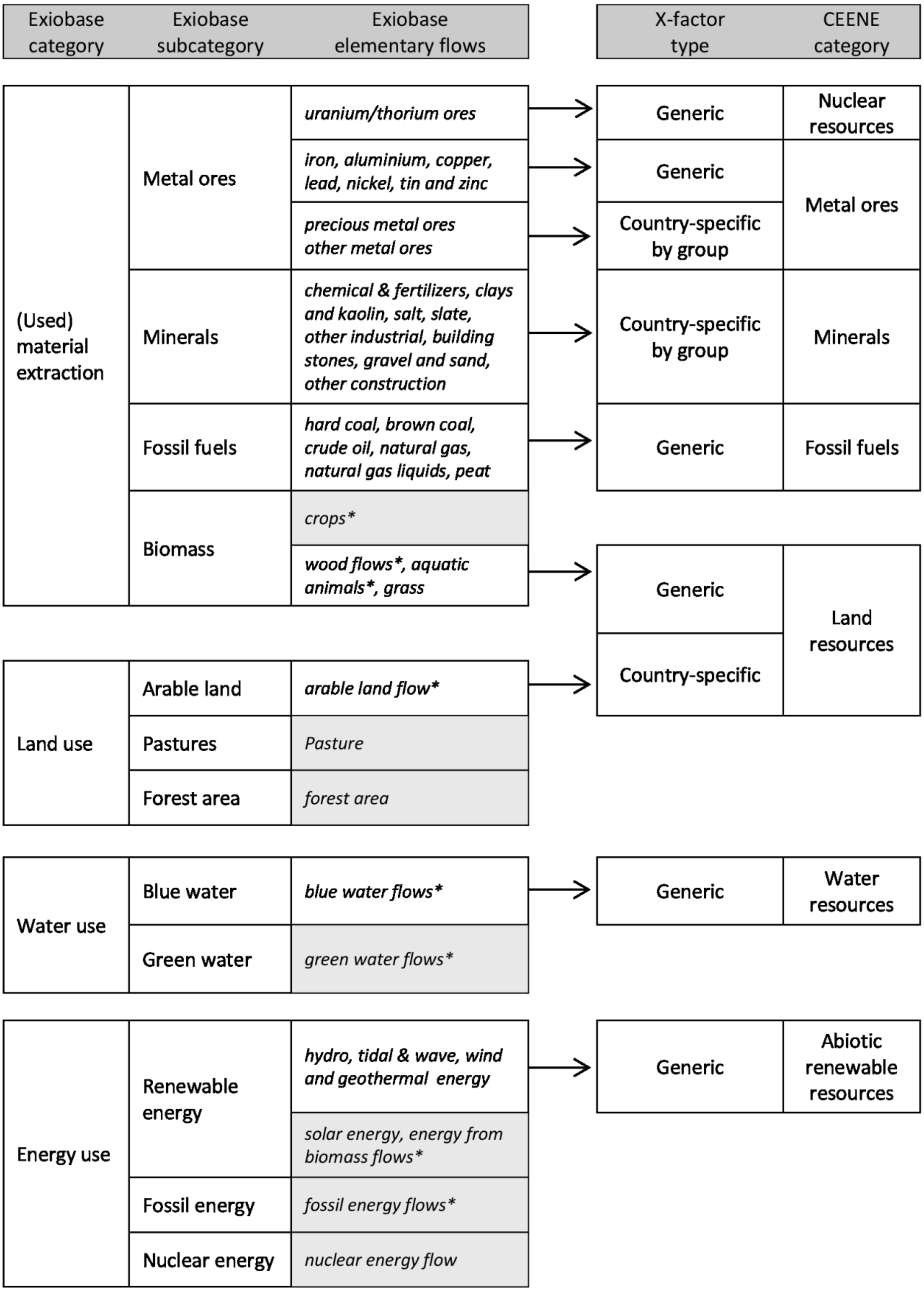

Figure 10: Coupling of elementary resource flow categories between Exiobase and CEENE. Flows marked with an * are shown in aggregated form to provide a good oversight, e.g. 'wood flows*' represents the flows 'wood-timber' and 'wood-other'. The grey coloured blocks are the flows that were excluded from the B-matrix due to double counting. The other blocks have a corresponding CEENE category and contain the flows that will be included in the B-matrix.

Also for pastures, no distinction was possible between extensive and intensive cultivation. Here, the choice was made to include the grass flow (biomass) in matrix B and exclude pastures (land use) to avoid double counting. For aquatic animals, only the amount of biomass is considered in Exiobase, given that no land use data for aquaculture were available. Consequently, only these flows could be taken into account, for both extensive and intensive cultivation. These are important assumptions which might be improved in the future when more detailed IO-databases become available.

In total, 82 elementary flows were selected and classified into CEENE-categories. These flows were used to construct the environmental matrix B. Normally, this would result in a 82 by 5676 matrix. However, to be able to trace back the country of origin of each resource in inventory matrix g, a geospatial B-matrix was constructed by considering each resource to be specific for the country from which it is extracted. This results in a 3608 (82x44) by 5676 matrix, making it later easily possible to see which countries contribute to the total CEENE.

3.3.3 Determination of characterization factors

After constructing matrix B, exergy characterization factors or X-factors were determined for each elementary flow in this matrix. In some cases, X-factors from LCI-CEENE, here referred to as LCI-based X-factors, could also be used in IO-CEENE, here referred to as IO-based X-factors. In this section, a short summary of the determination of X-factors for each CEENE-category will be given. More detailed information can be found in the appendix A.1.4.

In the category land resources, the country-specific X-factors from Alvarenga et al. [28], corresponding with the 43 Exiobase-countries, were used for the arable land flows. For the region Rest of the World (ROW), a weighted, via land area, average was calculated based on the remaining 120 countries. Further, this category also includes biomass flows (wood, grass, wood and aquatic animals). For wood and grass, adaptations were made to the LCI-based X-factors from Alvarenga et al. [28] by expressing them per kg of wet matter instead of per kg of dry matter. For aquatic animals, a new X-factor was determined based on the most captured fish species. For the categories water resources and abiotic renewable resources, the generic LCI-based X-factors were used.

The category metal ores consists of 10 elementary flows, expressed in kg gross ore. The gross ore is the metal-containing material obtained after extraction. Beneficiation concentrates this gross ore to concentrates, and metallurgical processes convert these concentrates into pure metal [3]. The LCI-based X-factors could not be used directly, since they are expressed in exergy per kg metal content. First, they had to be converted into exergy per kg gross ore using general conversion factors from Eurostat [76] and Valero [77]. After conversion, these LCI-based X-factors could be used for every elementary flow, except for the flows 'precious metal ores' and 'other metal ores', because these are aggregates. Therefore, the original disaggregated data was requested from the SERI (Sustainable Europe Research Institute) database [78]. Also for the category minerals, consisting of 9 elementary flows, too aggregated for using LCI-based X-factors, the original disaggregated data had to be requested from SERI [78].

Now, each elementary flow i for country k is subdivided in n_k subflows, each contributing a certain amount $M_{j,k}$ (in kg) to the total flow. To each subflow j, an X-factor was attributed, which is either an existing LCI-based X-factor, an exergy value from De Meester et al. [44] or a newly calculated X-factor. Knowing X_j and conversion factor F_j in case of metal ores, the IO-based X-factor $\hat{X}_{i,k}$ for aggregated flow i in country k (in MJ_{ex}/kg gross ore or MJ_{ex}/kg mineral) could be calculated, see equation 9.

$$\hat{X}_{i,k} = \frac{\sum_{j=1}^{n_k} X_j \,.\, M_{j,k} \,.\, F_j}{\sum_{i=1}^{n_k} M_{j,k}} \qquad (9)$$

Although the X-factors X_j of the subflows are generic, the X-factors $\hat{X}_{i,k}$ of the total flows are country-specific, because the share of subflows is different for each country. To differentiate with the X-factors of the arable land flows, which are country-specific because their exergy content varies geographically, these X-factors are labelled 'country-specific by group'.

The category fossil fuels consists of 6 elementary flows. For the first 4 flows, the LCI-based X-factors could be used, which are based on the lower (LHV) or higher heating values (HHV) of fossil fuels. However, the elementary flows 'natural gas (NG)' and 'natural gas liquids (NGL)' represent the market production (in kg) as defined in the International Energy Agency (IEA) statistics [79]. According to the CEENE methodology, the amount of crude natural gas has to be taken into account, instead of the market production. First, the flows NG and NGL had to be converted into megajoules (MJ) of energy, using MJ HHV/kg conversion factors. Then, they were summed up based on the first law of thermodynamics to estimate the amount of crude natural gas. Finally, this sum was multiplied with a calculated X-factor for crude natural gas (in MJ_{ex}/MJ HHV) to deliver the total exergy amount of crude natural gas extracted.

Together, these X-factors form a characterisation vector q. Further, having matrix B and Z, it is possible to calculate the inventory vector g for 129 different products or services consumed in 44 different countries. Hence, country-specific IO-CEENE results can be obtained for each sectoral product or service by multiplying q with g. The IO-CEENE outcome can be presented through a resource-contribution profile or a country-contribution profile. The resource-contribution presentation shows which resources contribute to the total footprint, while the country-contribution presentation shows which countries contribute to the total footprint. In the next section, the use of IO-CEENE will be illustrated by an example.

3.3.4 Example of the use of IO-CEENE

An environmental sustainability study of aquaculture in Southeast Asia will be used as an example [72]. Aquaculture is seen by many as the best solution for the problem of overfishing, although the question arises if this is truly more environmentally sustainable. The largest resource contribution comes from the production of feed pellets. One of the most important ingredients of these pellets is wheat, imported from Australia (40%), Romania (30%) and Ukraine (30%). Originally, this wheat input was modelled with LCI-CEENE, using an Ecoinvent flow valid for Germany (DE) ‘wheat grains conventional, Saxony-Anhalt, at farm’. However, as mentioned earlier, the geographical location can have a large influence on the resulting impact (CEENE), especially for land resources. Also the upstream supply chain varies from country to country and can influence the final result. To take this into account, IO-CEENE was applied, and the wheat input was modelled by the Exiobase flows ‘wheat, Australia’ (40%) and ‘wheat, Romania’ (60%). Ukraine is not available the Exiobase, but its share (30%) was modelled according to Romanian production, as being its neighbouring country with similar production yields [75] and GDP (order of 3E+10 US$) [70].

To illustrate the influence of the geographical location, the IO-CEENE results of Australia (AU) and Romania (RO) are compared with the IO-CEENE result of Germany (DE), as shown in Figure 11. All results are expressed in in megajoules of exergy (MJ_{ex}) per kg wheat and presented in a country-distribution profile. The main resource contribution is evidently due to extraction of land resources. The IO-CEENE results were originally expressed in exergy per euro wheat and had to be converted into exergy per kilogram, using the producer prices of the year 2000 from the Faostat database [75]. It can be noticed that AU and RO have a much higher footprint than DE. This can be explained by the more intensive agriculture of DE, resulting in higher yields, see Faostat [75]. An additional reason is the arable land use data in Exiobase. This data is based on the reported area used for agriculture. However, the actual area harvested will be smaller than the reported area, as not 100% of the sown area yield return. By using these country-specific footprints for RO and AU, a more accurate result is obtained for the environmental sustainability analysis: the CEENE of the used wheat increases from 1.9E+04 MJ_{ex} to 6.4E+04 MJ_{ex} per ton fish.

In this case study, the key factor to lower the CEENE and thus become more resource efficient is reducing the land use in the feed supply chain. The IO-CEENE results show that the country of import can play an important role in lowering the CEENE.

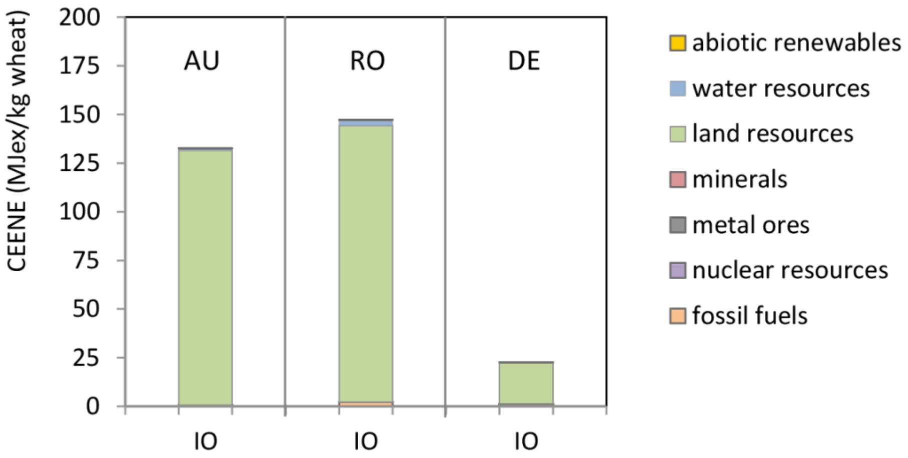

Figure 11: Resource-contribution profiles of IO (input-output) CEENE (Cumulative Exergy Extraction from the Natural Environment) results of 1 kg wheat consumption in Australia (AU), Romania (RO) and Germany (DE).

The different locations of production do not have only consequences for the CEENE of the raw materials like wheat themselves, but they do affect the full supply chain, including the logistics. Indeed, different origin means different transport commodities. Transport by truck in Romania will be used as an example to illustrate the country-contribution profile of IO-CEENE. This transport is mainly determined by diesel consumption, and the resource footprint of diesel consumption is geographically differentiated. If wheat would be imported from another country, for example from the United States (US) or India (IN), the corresponding diesel consumption for transport would also be situated in these countries.

The IO-CEENE country-contribution profiles per litre diesel consumed in RO, the US and IN are shown in Figure 12. The results were originally expressed in exergy (MJ_{ex}) per euro diesel and had to be converted into exergy per litre using the retail prices excl. taxes for diesel in the year 2000 [80]. When consuming diesel in RO, fossil fuels are mostly extracted from Russia (44%) and Europe (47%), more specifically from RO itself. Indeed, Romania is the largest oil producer in Central and Eastern Europe. It has proved reserves are 100 million tons of oil. According to the data provided by the National Agency for Mineral Resources, Romania is deemed to have another 23 years of domestic oil production [81]. The US depends also largely on its own fossil fuels (45%) and partially on its neighbouring countries Canada (6%) and Mexico (7%). Also IN mostly consumes its own fossil fuels (55%). Although resource consumption is a global problem, a country-contribution profile tells us more about local socio-economic consequences. It gives a measure of the resource dependency on other countries for the provisioning of certain goods. In this case study, changing the import country has also consequences for other countries in the world.

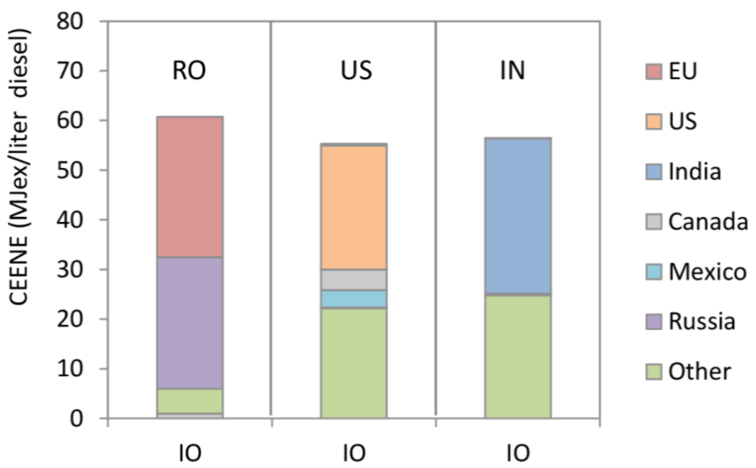

Figure 12: Country-contribution profiles of IO (input-output) CEENE (Cumulative Exergy Extraction from the Natural Environment) results of 1 litre diesel consumption in Romania (RO), the United States of America (US) and India (IN).

3.3.5 Discussion

In this chapter, an overall resource footprint indicator at macroscale (IO-CEENE) was developed by integrating an inventory methodology (IO-model) with an exergy-based resource accounting methodology (CEENE). This indicator considers several new aspects compared to the indicator of Ukidwe and Bakshi [32] by using (1) a world IO-model instead of a national IO-model, providing a more global perspective; (2) the CEENE methodology instead of the ICEC/ECEC methodology, providing a more complete resource range; (3) country-specific X-factors for land use, and partially for metals and minerals. IO-CEENE is also an addition to the earlier developed LCI-CEENE framework: while LCI-CEENE is used to investigate systems at microscale, IO-CEENE makes it possible to easily investigate systems at meso- and macroscale. A detailed analysis of the strengths and limitations of IO-CEENE is given in appendix A.1.6.

The case study illustrates that the main strength of IO-CEENE is its ability to provide country-specific results for 43 countries and a representation of a market mix of a product in a certain country, including the imported share. This geospatial perspective was obtained by using a world IO-model. Further, the implementation of country-specific X-factors allows a better characterization of the extent of the environmental impact. Other strengths of IO-CEENE compared to LCI-CEENE are the more complete upstream system boundary and the possibility to perform calculations very fast.

Nevertheless, the use of an IO-model also involves several weaknesses. First, Exiobase only has 2000 as base year. They are currently working on an update with 2007 as base year. Also, the Exiobase model is based on monetary IO-tables, providing IO-CEENE results expressed in exergy per euro. To make comparisons based on physical units or to perform hybrid studies, the results first have to be converted using basic prices [71]. Yet these prices, often varying from country to country, are not always easy to find. Next to that, an economic model implies that allocation occurs via economic values, which is less recommended than allocation on physical basis [61]. This is because compared to physical metrics like mass and volume, prices are not as stable and vary with market conditions and fluctuations [82].

Physical IO-models would solve these problems, but such models covering the world economy are not available yet, thus this is a next important research step. Another point of discussion is uncertainty analysis. This would be an interesting added value, however uncertainty data is not provided in the Exiobase database so far. Also in other world IO-databases, uncertainty data is either not provided or still in its early stages, mainly due to lack of data and lack of computational power [83].

Because IO-CEENE is based on a IO-model, the data also is aggregated, making it less specific. LCI-CEENE on the other hand is normally based on very detailed process information, providing more specific results. The high aggregation in IO-models is also present in the elementary resource flows, making it rather difficult to apply RAM like CEENE, which are usually originating from LCI-models. In contrast, it is much easier to apply emission-related impact methods, as the elementary emission flows in most IO-models are better adjusted to these methods. It would be interesting for the further development of resource footprint indicators that the elementary resource flows in IO-databases become also more adjusted, through less aggregation, for RAM and other resource-related impact methodologies like resource depletion.

In general, further research is needed for a better integration of RAM, which are often already combined with LCI-models, with IO-models, in order to obtain a better coupling between the microscale and meso-/macroscale.

Chapter 4
Toward a systematized framework for resource efficiency indicators

Redrafted from

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4.1 Establishing a systematized framework

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. As mentioned in chapter 1, this awareness has led to a diversity of resource efficiency indicators, which are not univocally defined. Therefore, the objective of this chapter is to propose a systematized framework in which these 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 policies and (3) to pave the way for further development of indicators in the scientific community. 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"[84]. To be able to establish a systematized framework for resource efficiency indicators, several terms and concepts need to be clarified.

4.1.1 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 [85]. It is defined as the ratio between the useful outputs (or benefits) and the inventoried flows (equation 10).

$$efficiency\ at\ level\ 1 = \frac{benefits}{inventoried\ flows} \quad (10)$$

Efficiency at level 2 is derived from the original eco-efficiency concept [85]. In the first definition by Schaltegger and Sturm [86], eco-efficiency is defined as the ratio between the intended effects (or benefits) and environmental impacts, assessed through specific impact assessment models (equation 11):

$$efficiency\ at\ level\ 2 = \frac{benefits}{environmental\ impacts} \quad (11)$$

4.1.2 Defining benefits, flows and impacts

The inventoried flows can be natural resources, industrial resources, waste-as-resources or emissions. These flows are schematically presented in Figure 13. A definition for natural resources was given in chapter 1 ("objects of nature which are extracted by man from nature and taken as useful input to man-controlled processes, mostly economic processes"[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, ...), 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.

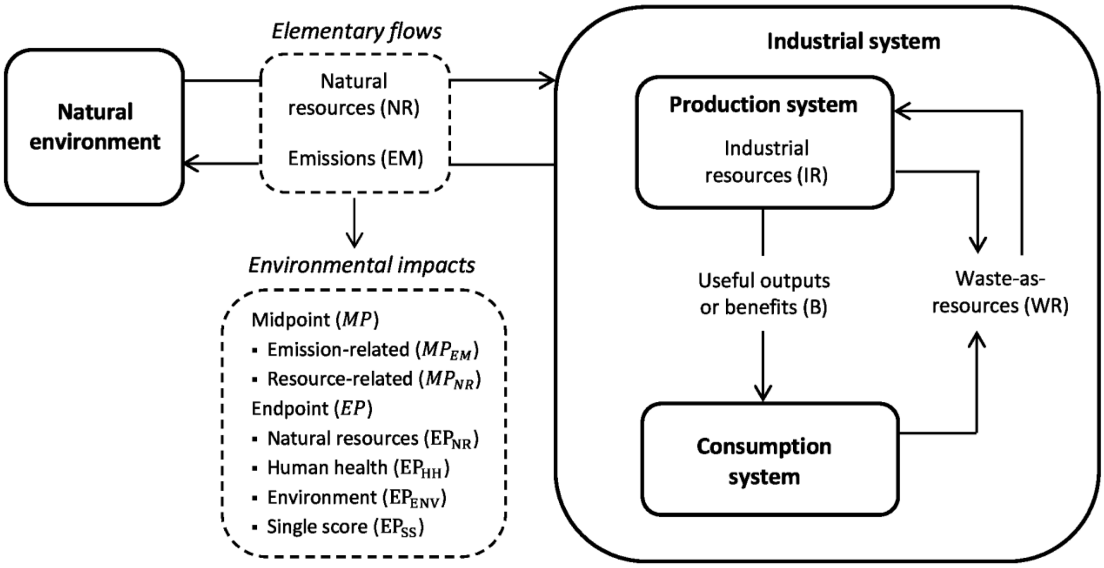

Figure 13: Flows and impacts related to resource use. NR= Natural resources, IR= industrial resources, WR= waste-as-resources, B= useful outputs or benefits, MP= midpoint impact level, MP_{EM}= emission-related midpoint impacts, MP_{NR}= resource-related midpoint impacts, EP= endpoint impact level, EP_{HH}= 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

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.

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

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

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. 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) [61]. To evaluate the environmental impact of these flows, characterization factors can be applied to convert the flows to common units and aggregate them within environmental impact categories [61]. The characterization factor expresses how much the flow contributes to the selected impact level used for reporting and interpretation. This is either midpoint (MP) or endpoint (EP) level [87].

At midpoint level, the characterization factor typically relates to a reference flow, e.g. 'kg CO2- equivalents' per kg elementary flow in case of climate change. A subdivision can be made into impact categories with the focus on emissions (MP_{EM}), e.g. climate change [88], and on natural resources (MP_{NR}), e.g. abiotic resource depletion [89, 90].

The endpoint level covers all relevant damage to the broader areas of protection: human health (EP_{HH}), natural environment (EP_{ENV}) and natural resources (EP_{NR}). The impact categories from the midpoint level are aggregated into these three areas of protection. At single score endpoint impact level (EP_{SS}), all areas of protection are covered by one single indicator [91]. Environmental impacts are quantified by characterization factors, e.g. the abiotic depletion potential is expressed in kg antimony equivalent per year for minerals mining to express their contribution to depletion.

4.1.3 Systematized framework

The proposed systematized framework for resource efficiency indicators is presented in Figure 14, including some general examples to illustrate each family of indicators.

		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 impact on resource depletion*	*benefits over impact on climate changes*	*benefits over single score impact*
	Life cycle Perspective	*benefits over (kg) resources in life cycle*	*benefits over (kg) emissions in life cycle*	*benefits over impact on resource depletion in life cycle*	*benefits over impact on climate change 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 impact on resource depletion*	*GDP over domestic impact on climate change*	*GDP over domestic single score impact*
	Global Perspective	*GDP over (kg) global extracted resources*	*GDP over (kg) global emissions*	*GDP over global impact on resource depletion*	*GDP over global impact on climate change*	*GDP over global single score impact*

Figure 14: Systematized framework with some general examples. GDP= Gross Domestic Product, 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 grey 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. Impact on resource depletion [89], climate change [88].

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, resources have been inventoried in terms of mass consumed in a specific process (gate-to-gate perspective) and subsequently in a supply chain (life cycle perspective) [92-94]. 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) [95]. 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 and, more recently, to impact indicators attributing different impacts to each resource [96, 97].

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) 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. At level 1, there are two possibilities: (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 (eco-efficiency), there are three possibilities: (1) when the environmental impact in the denominator is derived from resource flows, the resulting efficiency is called 'resource efficiency at impact level' (RE-IMP); (2) when the environmental 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 environmental 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 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). The efficiencies that are solely based on associated emissions (EM-FL, EM-IMP), although used by some authors in a resource efficiency context in the most broad sense of the term, 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.

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 versus 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, etc. This field relies on biological, chemical, physical sciences and engineering to solve environmental problems like resource efficiency.

4.2 Illustrating the use of the framework

4.2.1 Structuring indicators for natural/industrial resources

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 2.

Table 2: Typical indicators for natural/industrial resources. 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; FL= flow; IMP= impact; G-to-G= gate-to-gate perspective.

Indicator	Application	Level	Perspective	Example
Process efficiency	Env. Sc. & Eng.	FL (1)	G-to-G	[36]
MIPS	Env. Sc. & Eng.	FL (1)	Life Cycle	[98]
CUMDP	Env. Sc. & Eng.	IMP (2)	Life Cycle	[55]
Eco-efficiencies	Env. Sc. & Eng.	IMP (2)	Life Cycle	[99]
GDP/national accounts	Env. Policy	FL (1)	Domestic	[11]
GDP/global accounts	Env. Policy	FL (1)	Global	[16]
GDP/EMC	Env. Policy	IMP (2)	Domestic	[34]
GDP/overall impact	Env. Policy	IMP (2)	Global	[100]

4.2.1.1 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 [36, 101]. These indicators trace back to the origin of the efficiency concept, which is based on the laws of thermodynamics [85].

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 'exergy', as explained in chapter 2 [30]. Hence, efficiency is defined as the ratio between output and input flows, both quantified by either their mass, energy or exergy content [43]. 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 Intensity Per Service Unit [102]. 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 [98, 103].

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 [55, 104]. 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 [42]. As described in chapter 2, cumulative consumption methods are situated at the first step in the impact pathway related to resource use, in the sense that they go beyond the classic resource inventory (in kg, m^3, ...), providing results in single units (energy or exergy). This first step gives answers to questions of environmental sustainability by consistently accounting for resource use, while the second and third step evaluate the resource scarcity at midpoint and endpoint level [52].

Six operationalized cumulative consumption methods exist: 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) [52]. 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. [1], 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. [99]. 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 equation 11 by the inventoried resource flows, e.g. in Van Caneghem et al. [105]: the denominator represents the water use of a steel company. Similar examples are mentioned in Shonnard et al. [106] and Gomez-Limona et al. [107], all basically using an efficiency ratio conceived as in equation 10. Although all authors refer them to as eco-efficiency (level 2), these indicators should be classified at level 1.

4.2.1.2 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, 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 [11, 16].

Material accounts are derived from economy-wide material flow analysis, 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 [108]. As a national account, the Domestic Material Consumption (DMC) is usually applied, e.g. in [109]. 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 [110]. 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.

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. [34]. 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 [100]. 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).

4.2.2 Structuring indicators for waste-as-resources

Several examples of waste-as-resource indicators have been structured within the framework, see Table 3. 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. [111], are situated entirely in the field of environmental science and engineering, as already described for natural/industrial resources.

Table 3: Typical indicators for waste-as-resources. CumDP = Cumulative Degree of Perfection; RRR=Reuse, Recycling, Recovery, RRR*=Reusability, Recyclability, Recoverability. Env. Sc & Eng.= Environmental Science and Engineering; Env. Policy= Environmental Policy; FL= flow; IMP= impact; G-to-G= gate-to-gate perspective.

Indicator	Application	Level	Perspective	Example
Process efficiency	Env. Sc. & Eng.	FL (1)	G-to-G	[111]
CUMDP	Env. Sc. & Eng	IMP (2)	Life Cycle	[112, 113]
Recycled content	Env. Sc. & Eng Env. Policy	FL (1)	G-to-G	[114, 115]
RRR rates	Env. Sc. & Eng Env. Policy	FL (1)	G-to-G	[116, 117]
RRR* rates	Env. Sc. & Eng Env. Policy	FL (1)	G-to-G	[118, 119]
Recycled content benefit	Env. Sc. & Eng Env. Policy	IMP (2)	Life Cycle	[39]
Environ. weighted RRR*	Env. Sc. & Eng Env. Policy	IMP (2)	Life Cycle	[39, 120]
Product Env. Footprint	Env. Sc. & Eng Env. Policy	IMP (2)	Life Cycle	[121]

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 [116, 117], 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 [119, 122]. These RRR* rates are generally used for ecodesign purpose [118], but there are examples of applications in wider context, as for example in product policies [35]. 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 [114, 115].

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 et al. [112] and Amini et al. [113]. 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 [39, 120] and the recycled content benefit [39], 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 [118]. 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 [121, 123].

4.2.3 Analysis of indicators for natural/industrial resources

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 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 [124], 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, 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 [34] and the GDP over the overall environmental impact [100]. 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 [125].

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 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 [126]. 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.

4.2.4 Analysis of indicators for waste-as-resources

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. Therefore, some authors propose the implementation of quality factors. Such factors can refer to the loss of value in economic terms of recycled materials compare to primary ones [127], or the loss of quality in physical terms e.g. due to tramp elements [121]. This quality aspect is further discussed in chapter 7.

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 proposed framework can be useful to theorize new potential indicators for resource efficiency.

4.3 Conclusion

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 developing proper indicators for the quantitative assessment of resource efficiency and eco-efficiency. The proposed framework can be also used to theorize and define new indicators.

A potential application of the framework was illustrated in section 4.2. 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 [128]. Concerning life cycle impact assessment, the ILCD handbook provides recommendations on which impact categories to consider for the comprehensive assessment of environmental impact [2]. So far, resource-related environmental impact methods are not yet as mature as emission-related impacts methods [129]. Ideally, level 2 indicators should reflect the wider spectrum of potential impacts in a consistent, transparent and reproducible way, which remains a challenge [130].

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 [28, 57]. 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.

Chapter 5
The environmental impacts of an average citizen in the European Union

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5.1 Introduction

Today, sustainable development is one of the main challenges in many governmental policies, especially in that of the European Union (EU) [131]. To guide and monitor the transition towards a more sustainable society in terms of environmental performance, proper indicators are needed. The environmental impacts of an economic society are ultimately driven by consumption, either directly, as impact of the use phase of consumer products, or indirectly, as impact of the production and end-of-life phase of these products [132]. Hence, the indicators should provide a clear view on the links between final consumption and environmental impacts [100].

In 2006, the European Commission's Joint Research Centre (JRC) published a report on the environmental impacts related to the final consumption in the EU25 [133]. This report, together with the corresponding article of Tukker and Jansen [132], includes a review of the 11 most relevant studies about consumption in the EU over the last 5 years, identifying two different approaches: bottom-up and top-down.

The bottom-up approach is based on traditional Life Cycle Assessment (LCA), which involves detailed data collection on production processes to quantify the environmental impacts of a product system, e.g. in [72, 134, 135]. The alternative for the LCA-approach is the top-down approach, referring to environmentally extended input-output analysis (EEIOA), e.g. in [20, 134, 136-138]. EEIOA links IO-tables, describing the transactions between industry sectors in an economy, with environmental extensions, describing the pollutants emitted and resources extracted by industry sectors per (monetary) unit output [22].

The top-down approach will further be called 'IO-approach', and the bottom-up approach will further be called 'LCA-approach'. They are described more detailed in Materials and Methods section. Both approaches have their strengths and limitations. They complement each other: the strengths of the one are the limitations of the other, and vice versa.

The main strength of the LCA-approach is its high level of detail: it is possible to evaluate the contribution of specific products as such. Furthermore, the elementary flows (i.e. emissions and natural resources) in Life Cycle Inventory (LCI) databases are often very detailed, making it possible to calculate environmental impacts in an accurate way. However, the main advantage of the LCA-approach, i.e. its high level of detail, goes hand in hand with some limitations. The first limitation is the truncation or cut-off problem [67]: as the product system under study represents only a part of the materials-product chain, a system boundary has to be drawn. However, because there is no information available on the flows outside this boundary, it cannot be ensured that these neglected flows are indeed negligible. Another limitation is that representative products have to be selected when the LCA-approach is used for analyzing the final consumption, because it is not possible to include all the products due to the lack of readily available datasets. Furthermore, LCI datasets are often a mix of linked processes from different years and countries. This could have an influence on the impact results, since the upstream supply chain of a product may differ from country to country. These problems could improve when more complete LCI databases would become available in the future. Nevertheless, performing an LCA for new product systems remains a time-consuming task.

An IO-approach can overcome some of these limitations. First, there is no cut-off problem, since IO-databases cover entire material-product chains in an economy. For the same reason, it is no longer necessary to select representative products, when one wants to assess the impact of product groups, as all the products are already present as aggregated product groups in the IO-database. Another strength is that IO-databases are more consistent than LCA-databases: all datasets have the same reference year. A third strength is the availability of interregional data when multi-regional/world IO-databases are used, with a subdivision into various countries. These global databases enable the calculation of all indirect resource and emission flows embodied in imports and exports [63]. This is relevant for countries depending largely on import or export, as is the case for most member states of the EU. Of course, an IO-approach also has its limitations. The main limitation is the high level of aggregation: the product as such is not visible, and because many elementary flows are aggregated, some impact categories (e.g. ecotoxicity) cannot be calculated accurately. Another important limitation is the publication time of IO-databases. Often, there are several years between the publication of an IO-database and its base year [67]. Nonetheless, once the database is established, calculations can be performed very quickly and easily.

These limitations of the IO-approach are counterparts of the strengths of the LCA-approach, as described above. It is also possible to combine the strengths of both approaches through a hybrid analysis, as has been done in several studies [139-141].

The insights gained in the review [132, 133] paved the way for further research, aiming to calculate the environmental impacts of an average EU citizen with one of these two approaches. In theory, both approaches would lead to the same result - given that IO-tables of very high level of disaggregation and LCA data for a vast number of processes - geographically and temporally explicit - are available.

In 2012, JRC published a new study in which they used the LCA-approach to calculate the environmental impacts per capita in the EU27 for the year 2006 [38]. By the EU27, we understand its 27 member states since 2007. It must be mentioned that this study of JRC was a pilot project, and not intended to be directly used for policy support.

During the same period, a new IO-database was being developed in the Sixth and Seventh Framework Program of the European Commission on compiling and refining environmental and economic accounts [69, 142]. This new database, Exiobase, addresses the issues mentioned in the review of 2006 [132]. The main asset is that Exiobase is a multi-regional database, interlinking 43 countries with the rest of the world. This means all EU27 countries are included, and that flows embodied in imports can be taken into account. This global database is very suitable for the IO-approach.

Hence, the objective of this chapter is to assess the annual environmental impact of the consumption of an average EU27 citizen through an IO-approach, using Exiobase v.2. This database has 2007 as reference year, which is close to the reference year 2006 of the LCA-study performed by JRC [38]. The focus will not be on a one-on-one comparison between the LCA-results and the IO-results, but on a comparison between both approaches for this particular study. This way, policy makers can see both approaches applied in practice.

5.2 Materials and methods

5.2.1 Mathematical structure

EEIOA and LCA are based on the same mathematical structure, see equation 12. This structure was described in chapter 3 and is here shortly repeated.

$$g = B.A^{-1}.f \qquad (12)$$

Matrix B is the environmental matrix, describing the amounts of natural resources extracted or emissions released by the industrial system. Matrix A is the technology matrix, describing the transfer of flows within the industrial system. In EEIOA, matrix A is written as $I - Z$, with I the identity matrix and Z the IO-table. Vector f is the final demand vector, representing the output demanded from the industrial system. Finally, the inventory vector g of all direct and indirect resources extracted or emissions released for a certain final demand f can be obtained [22].

Having obtained the inventory g, it is possible to calculate the corresponding environmental impacts. To calculate impact h_i for impact category i, inventory g has to be multiplied with characterization vector q_i, see equation 13.

This vector consists of characterisation factors, corresponding with the chosen impact characterisation method.

$$h_i = q_i . g = \sum_{k=1}^{n} q_{i_k} . g_i \qquad (13)$$

5.2.2 The LCA-approach

In the study of JRC, five household activities were defined: food, consumer goods, mobility, shelter and services [38, 100]. For each activity, a selection of key product groups was made, and for each product group, representative products were selected from the GaBi database [21, 143], see Table 4.

Table 4: Composition of the basket-of-products in the LCA-approach

Household activity	Product groups	Representative products
Food	Meat and seafood	Beef, pork, poultry
	Dairy products and eggs	Milk, butter, cheese
	Crop based products	Sugar, oils and fats
	Vegetables	Potatoes
	Fruits including tomatoes	Apples, oranges
	(non)alcoholic beverages	Coffee, beer
Consumer goods	Clothing	Shoes, cotton shirt
	White goods	(dish)washer, refrigerator
	Electronics	Laptop
Mobility	Private transport	Mid-class car
	Public transport	Train, bus, plane
Shelter	Single/two-family house	Single house
	Multi-family houses	Multi-family house
	High-rise buildings	High-rise building
Services	Bars and restaurants	(omitted from study)
	Leisure, tourism	(omitted from study)
	Education, health	(omitted from study)

Subsequently, the environmental impacts of these representative products were calculated based on equation 13. More details are given in section 5.2.4. Next, the impact of each representative product was multiplied with the consumption of an average EU citizen in the year 2006, e.g. (impact per cotton shirt) x (number of cotton shirts consumed per capita). If consumption data of different reference years was used, it would also be possible to see changes in consumption patterns over time. Theoretically, this result could be scaled up to account for the entire product group or activity. However, the methodological choice was made not to apply scaling in order to arrive at the index rather than the coverage of the total impact [38]. This means that the impacts reflect only the representative products in the basket.

5.2.3 The IO-approach

We used the Exiobase database to perform the IO-approach. Whilst writing this chapter, two versions of Exiobase had become available: version 1 (v.1) with reference year 2000 [69], as used in chapter 3, and version 2 (v.2) with reference year 2007 [142], as used in this chapter. While version 1 interlinks 43 countries with one rest of the world (RoW) region, version 2 interlinks 43 countries with 5 RoW regions: Asia and the Pacific, America, Europe, Africa and the Middle East. Further on, version 1 considers 129 product groups per country in its PxP form, while version 2 considers 200 product groups per country in its PxP form. This increase in detail is situated in the waste treatment sectors. Exiobase version 3 (v.3) is currently under development and will cover a time period of 19 years, from 1995 till 2014 [142].

The first step was the calculation of inventory g, corresponding with the final household demand vector f, using equation 12. However, before this could be done, the IO-table needed to be altered. In Exiobase v.2, capital investments are not part of the IO-table, but of the final demand, and hence the contribution of capital goods would not be included in the impact results. Since this would lead to serious underestimations, capital investments had to be integrated in the IO-table. The calculations were based on the FORWAST report [144] and can be found in appendix A.2.1.

The second step was the calculation of the environmental impacts, using equation 13. In this step, inventory g was multiplied with a characterisation vector q, associated with a certain impact category. Finally, impact vector h was obtained, consisting of 9600 (200 x 48) rows which represent the product groups and services in each country.

These product groups had to be classified into the five household activities defined by JRC [38]: food, consumer goods, shelter, mobility, services. To do so, we used the FORWAST report [145]. This report classifies the product groups in Exiobase into ten activities instead of five: clothing, communication, education, health care, housing, hygiene, leisure, meals, security and social care. For example, the product group ‘dairy products’ is classified into the activity ‘meals’. These ten activities were distributed over the five main household activities as described in Table 5 and appendix A.2.2.

Table 5: Distribution of activities over the five household activities

main activities	Distribution of activities in FORWAST report
Food	▪ food from activity meals
Consumer Goods	▪ activity leisure ▪ goods from activity meals (e.g. tableware) ▪ energy and water use from activity meals ▪ goods from activity hygiene (e.g. soap)
Mobility	▪ activity communication, except for ‘radio, television and communication equipment’
Shelter	▪ activity housing ▪ energy and water from activity hygiene (e.g. showering)
Services	▪ activities education, security, health care and social care ▪ services from other activities, except for public transport

5.2.4 Impact assessment

In the LCA-approach of JRC, the impact assessment follows the recommendations of the ILCD handbook [21, 143], covering the impact categories Global Warming, Particulate Matter, Photochemical Ozone Formation, Acidification, Eutrophication Terrestrial, Eutrophication Freshwater, Eutrophication Marine, Human Toxicity cancer, Human Toxicity non-cancer, Ecotoxicity, Ozone Depletion, Ionizing Radiation, Water Depletion, Land Use and Resource Depletion.

The goal was to cover the same impact categories in the IO-approach. However, this was not possible for each impact category. The impact category Ionizing Radiation could not be included because none of the required elementary flows are covered in Exiobase. For the impact categories Human Toxicity and Ecotoxicity, elementary flows are insufficiently available to make, in our opinion, an adequate assessment of the impact category. The elementary flows in Exiobase represent only 0.2-0.4% of the total list of elementary flows in the toxicity impact methods. But also in the LCA-approach, a remark was made concerning the toxicity impacts: their precision is relatively low compared to other impact methods.

For the impact category Abiotic Resource Depletion, the most dominant elementary flows are aggregated in one group, making a comprehensive impact assessment impossible. These are the flows for metals with a high depletion risk, which have high characterization factors compared to more common metals, minerals and fossil fuels. Germanium for example has a characterization factor of 19500 kg Sb eq./kg, which is very high compared to the characterization factor of iron (1.66E-06 kg Sb eq./kg) or natural gas (3.73E-07 kg Sb eq./kg). However, in Exiobase, these dominant metal flows (40 in total) are aggregated in only one group ('other metals'). Hence, the impact of Abiotic Resource Depletion cannot be assessed properly in Exiobase.

In summary, the ILCD impact categories included in the IO-approach are: Global Warming, Particulate Matter, Photochemical Ozone Formation, Acidification, Eutrophication Terrestrial, Eutrophication Freshwater, Eutrophication Marine, Ozone Depletion, Water Depletion and Land Use. The most widely known impact category in this list is of course Global Warming, characterizing the effect of emitted greenhouse gases. Therefore, the results of Global Warming are discussed thoroughly in section 5.3.1. This impact in terms of Global Warming is also called the carbon footprint. Or in other words: the carbon footprint is a (life cycle) impact assessment limited to emissions that have an effect on climate change [146]. The results of the other impact categories are included in appendix A.2.4 and discussed shortly in section 5.3.2.

From a historical perspective, most of these ILCD impact categories are focussed on impacts related to emissions. Only Land Use, Water Depletion and Abiotic Resource Depletion are considered regarding natural resource consumption. But due to the reasons mentioned above, Abiotic Resource Depletion could not be properly assessed in the IO-approach. This means our impact assessment would lack a good analysis of natural resource consumption. Therefore, we selected an additional, more comprehensive, characterisation method to assess the impact of natural resource use: CEENE, see chapter 2 [3, 52]. This method is recommended by Liao et al. [33] since it covers all resource types. In chapter 3, CEENE v.2013 was coupled with the Exiobase v.1 database, resulting in an overall resource footprint indicator at macroscale. During the writing of this chapter, the more recent Exiobase v.2 database had become available. Hence, CEENE v.2013 was coupled with Exiobase v.2 in a similar way. This coupling is described in appendix A.2.3. The CEENE results are discussed in section 5.3.1. These results are usually expressed in megajoules of exergy (MJ_{ex}). To make the results easier to interpret, they can be converted into exergy-based tons of oil-equivalent. In analogy to energy based tons of oil-equivalent, 1 exergy-based ton of oil-equivalents is defined as the amount of exergy contained in one ton of crude oil: 45.7 MJ_{ex}.

5.3 Results and Discussion

5.3.1 Global Warming and Resource Consumption

The impact results of the IO-approach and the LCA-approach are presented in Figure 15. Figure 15a shows the results for the impact in terms of Global Warming (carbon footprint), while Figure 15b shows the results for the impact in terms of Resource Consumption (resource footprint). Figure 15c presents again the results for Resource Consumption, but this time in a resource-contribution profile, illustrating how much each natural resource type contributes to the total impact. However, in the LCA-approach, land resources are not included due to lack of characterisation factors in the ILCD methods [38]. To allow a better comparison between the IO-results and LCA-results, the IO-results are presented twice: once including land resources and once excluding land resources. From Figure 15c, it can be noticed that land resources are only highly significant (75%) for the activity food, in which they are needed for agriculture and livestock. There is also a small contribution of land resources to the activity consumer goods. This is mainly due to extracted wood, e.g. for the production of paper and wooden furniture.

These figures illustrate that the IO-results are higher than the LCA-results, for both Global Warming and Resource Consumption. The main reason for this difference in results is of course the difference in methodology: EEIOA versus LCA. As mentioned in the introduction, EEIOA does not have to deal with the mentioned cut-off problem. Suh [67] describes this problem as follows: ‘In LCA, the system under study represents only a part of the whole materials-product chain. One needs to draw a system boundary, assuming that the effects by the flows outside the boundary to the final result are negligible. EEIOA on the other hand provides a complete picture of the materials-product chain, and all the industrial sectors are interlinked.' Therefore, IO-results are generally higher than LCA-results.

The second reason is the basket-of-products selection for each activity. The IO-approach gives higher impact results, because it considers a much broader product range for each activity than the LCA-approach. This is mainly because no upscaling was applied in the LCA-study [38], meaning that the impacts reflect the representative products only.

For the activity food, the IO-results are presented more detailed in Figures 16a and 16b. When considering for example Global Warming, the largest impact contribution comes from the group 'other products' (39%, a.o. rice, cereals, bread, pasta, preserved food), followed by meat (24%), vegetables and fruits (12%), dairy products (11%), fish products (6%), beverages (6%) and sugar, fats, vegetable oils (2%).

These results can be compared with those presented by Schmidt and Merciai [147], who calculated the impact on Global Warming of the world food consumption in 2007. To do so, they used a hybrid version of Exiobase v.2, integrating the economic IO-model with mass flows analysis . In their results, the largest impact contribution comes from meat (40%), followed by dairy products (19%), other products (17%), vegetables and fruits (10%), beverages (7%), fish products (5%) and sugar, fat and vegetable oils (2%). The main reason for this shift in contribution is that diets from all over the world are included, instead of only from the EU27. Furthermore, Schmidt and Merciai [147] includes the contribution from indirect land use changes, and also, their work is based on a hybrid form of Exiobase v.2, while our results are calculated with the economic model.

For the activity consumer goods, the IO-results are presented more detailed in Figures 16c and 16d. For both Global Warming and Resource Consumption, the largest impact contribution comes from wearing apparel (e.g. clothing, shoes), followed by furniture and other manufactured goods (e.g. toys, sport goods).

Furthermore, for the activity mobility, the IO-approach considers a broader range of private and public transport modes. For example, public transport includes not only trains, buses and planes (see Table 4), but also sea transportation, inland water transportation and other land transportation services, e.g. taxis.

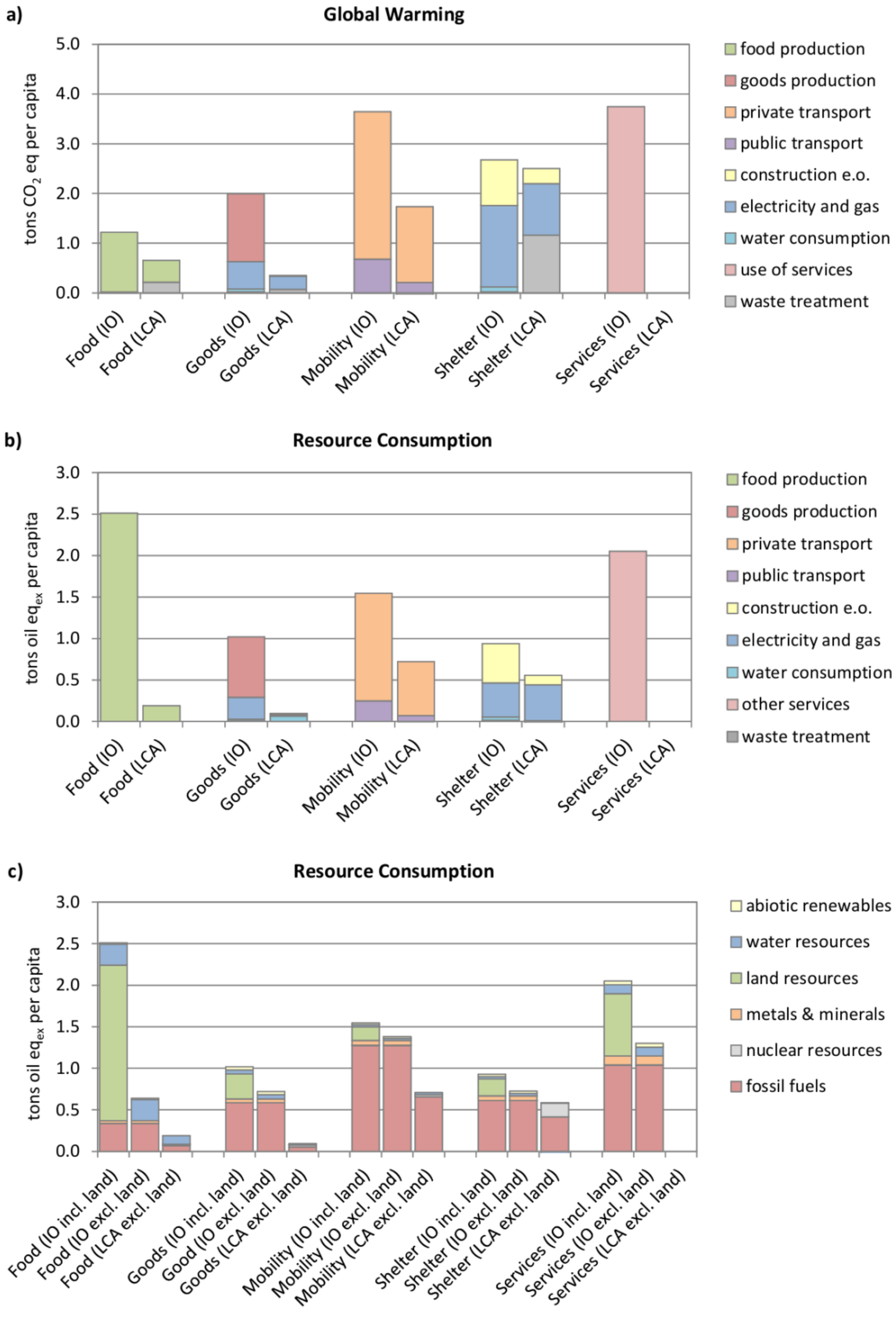

Figure 15: IO-results and LCA-results of the consumption of an EU citizen in the year 2007. Impacts are expressed in terms of (a) Global Warming, in tons of CO2 equivalents per capita (tons CO2 eq) and (b,c) Resource Consumption, in exergy-based tons of oil-equivalents per capita (tons oil eq_{ex},). In (b) and (c), the IO-results are presented inclusive and exclusive land resources. Goods = Consumer Goods. To be in accordance with the study of JRC, the activity services includes all services except public transportation, which is part of the activity mobility.

Regarding the activity shelter, a remark needs to be made concerning the Global Warming impact. For 'construction' (which also includes refurbishment and maintenance of the house), and 'electricity and gas', the IO-results are higher than the LCA-results, which can be explained by two reasons mentioned above. However, for 'waste treatment' (e.g. water from flushing the toilet, cleaning), the LCA-result is higher than the IO-result. Hence, the impact of wastewater treatment may be underestimated in the IO-approach or overestimated in the LCA-approach. When making a comparison with other studies [133, 148], it seems that an overestimation in the LCA-results is more likely.

For the activity services, no LCA-results were available in the study of JRC due to lack of data [38]. Hence, a comparison with the IO-results is not possible. These IO-results are presented more detailed in Figures 16e and 16f. Figure 16e shows that the largest contribution to Global Warming comes from wholesale and retail trade services (28%), followed by real estate services (25%) and hotel and restaurant services (16%).

Figure 16f illustrates that the largest contribution to Resource Consumption comes from hotel and restaurant services (29%), followed by wholesale and retail trade (26%) and real estate services (20%). Both wholesale/retail trade services and real estate services involve a lot of transport, which results in a high consumption of fossil fuels (more than 50%) and thus a high Global Warming impact. For Resource Consumption, hotel and restaurant services have an even higher impact contribution due to their high consumption of land resources needed for food production. If the alternative approach would be used (see section 5.2.3), these high-impact services would be distributed over the other household activities. For example, real estate services would be assigned to the activity shelter, while hotel and restaurant services would be assigned to the activity food. As a consequence, the global warming impact would increase for the activities food (+43%) and shelter (+35%), while it would decrease for the activity services (-40%). Similar, the resource consumption impact would increase for the activities food (+21%) and shelter (+42%) and decrease for the activity services (-47%).

The impact contributions of the IO-results are also presented by their geographical location in Figures 16g and 16h. This way of presenting is unique for our IO-approach, since it is based on a world input-output database. Figure 16g indicates that the largest impact contribution to Global Warming is situated in Europe (54%), since the services are also consumed in the EU. However, Figure 16h shows that the impact contribution to

Resource Consumption is more globally spread: 34% of resources is extracted in Europe, 11% in America, 21% in Asia-Pacific, 11% in Russia, 16% in Africa and the 7% in the Middle-East. This is intuitively logical, since extraction of natural resources like metals, minerals and fossil fuels, is mostly situated outside of Europe.

As mentioned in the beginning of the paragraph, the main reason for the difference between the IO-results and LCA-results is the higher completeness of the IO-approach. Moreover, there is an additional reason for the difference between both results: the reference year and country of origin of the datasets. In the IO-approach, data is available for 48 different countries, all having 2007 as reference year. To calculate the impact of a European citizen, we used the data of the EU27 countries. In the LCA-approach, LCI-data are multiplied with macro-economic consumption data of the EU27. These macro-economic consumption data have 2006 as reference year, but the LCI-data are based on different years and different countries of origin.

For example, the dataset for potatoes is associated with production in Germany in 2010, while the dataset for apples is associated with production in China in 2009. However, we expect the influence of this additional reason to be much lower.

Of course, the IO-results also have their limitations: they are determined by the way product groups are selected and classified into five household activities. In the classification chosen for this study, all the services are assigned to the activity services (except for public transportation), to allow a good comparison with the LCA-approach of JRC. Alternatively, it would also be possible to apply the classification of the FORWAST report [145]. For example, they assign 'real estate services' to housing (shelter), and 'hotel and restaurant services' to meals (food). Using this alternative approach, the final result will be somewhat different.

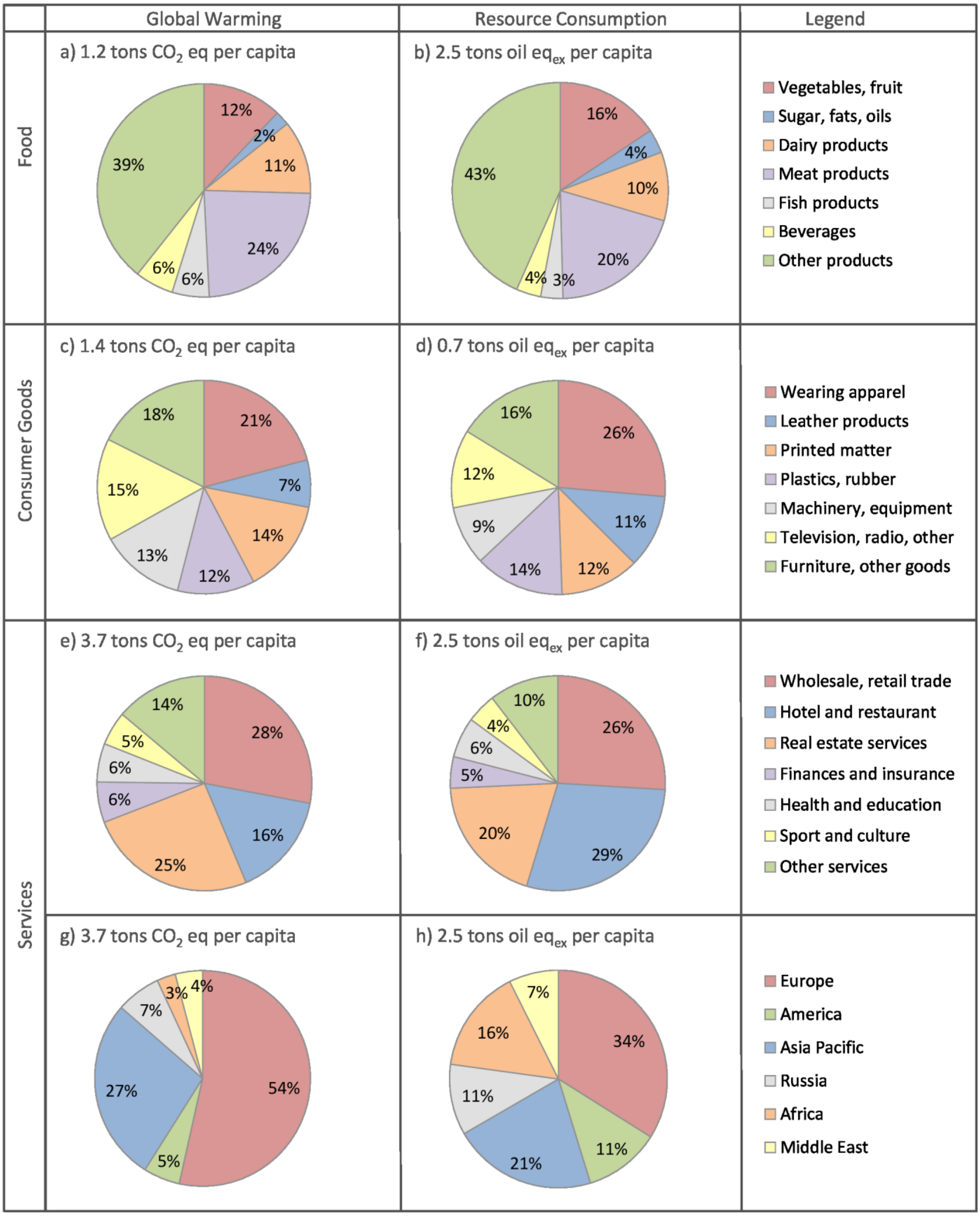

Figure 16: IO-results of the consumption of an EU citizen in the year 2007. Contribution to total impact in terms of Global Warming, in tons of CO2 equivalents per capita (tons CO2 eq), or Resource Consumption, in exergy-based tons of oil-equivalents per capita (tons oil eq_{ex}), is presented per product group (a, b, c, d, e, f) and per geographical location (g,h).

5.3.2 Other impact categories

As mentioned earlier the results for the ILCD impact categories Particulate Matter, Photochemical Ozone Formation, Freshwater Eutrophication, Marine Eutrophication, Ozone Depletion, Water Depletion and Land Use are given in appendix A.2.4.

When comparing the IO-results to the LCA-results, an overall observation is the notable shift in the ranking of activities. Consider for example Particulate Matter. In the LCA-results, the hotspot activity is shelter, followed by food, mobility and consumer goods. In the IO-results on the other hand, the hotspot activity is mobility, followed by services, consumer goods, shelter and food. The main reason is again the higher completeness of the IO-results (no cut-offs, broader range of products, services are included). This means that the influence of using a different approach should not be underestimated.

Specific for Acidification and Terrestrial Eutrophication, some remarks need to be made. In the LCA-results, the hotspot activity is food, followed by shelter, mobility and goods. The large impact of food is mainly caused by ammonia emissions from meat and dairy production. The impacts of shelter and mobility are caused by NO_x and SO_x emissions from cars and energy use. In the IO-results, the hotspot activities are mobility and services, followed by shelter, consumer goods and food. The low impact of food appears to be caused by a underestimation of ammonia emissions from meat and dairy products in Exiobase. Meat and dairy products contribute only 0.3% (Acidification) and 0.6% (Terrestrial Eutrophication) to the total impact of the activity food, compared to 83% and 86% in the LCA-results. A comparison with the study of Weidema et al. [149], which reports that meat and dairy products contribute 25% (Acidification) and 30% (Terrestrial Eutrophication) to the total impact of EU27 consumption in the year 2000, indicates that ammonia emissions are indeed underestimated in the Exiobase database.

5.4 Conclusions

In this article, we calculated the environmental impacts of the consumption of an average EU citizen through a top-down IO-approach. The results were compared with an earlier study of JRC, in which a bottom-up LCA-approach was used. Yet, as mentioned in the introduction, the study of JRC was a pilot project, meaning that revision and improvement is ongoing. This must be taken into account when interpreting the results.

The goal was to obtain IO-results for all the ILCD recommended impact categories, as done in the LCA-approach. However, it was not possible to make an adequate, comprehensive impact assessment regarding (1) Ionizing Radiation, because none of the required elementary flows are present in Exiobase; (2) toxicity impacts, as the elementary flows in Exiobase represent less than 0.5% of required flows; and (3) Abiotic Resource Depletion, since the most dominant elementary flows are aggregated in one group. However, since Abiotic Resource Depletion could not be included, the study would lack a good assessment of natural resource extraction. Therefore, the CEENE method was used, which accounts for a wide range of natural resources. This way, the overall resource footprint indicator developed in chapter 3 could be calculated.

Summarized, the focus in the article is on the impact in terms of Global Warming (carbon footprint) and in terms of Resource Consumption (resource footprint). The results of other impact categories are provided in the appendix.

The main difference between our study and other studies that apply the IO-approach, is the impact assessment. For example, the similar studies mentioned in the introduction do not perform an impact assessment based on ILCD handbook. Mostly, they stay at inventory level by calculating the material footprint (in kg metals, minerals, fossil fuels and biomass), the water footprint (in m^3 blue water) or the ecological footprint (in global hectares). Moreover, our study is the first to apply the CEENE method in an IO-approach, making it possible to calculate an overall resource footprint. Further, our paper includes renewing figures on the geographical distribution of impacts, illustrating from which countries resources are extracted, or in which countries pollutants are emitted. Such figures provide more information about socio-economic consequences, as the burden of EU consumption is often shifted to other countries.

When comparing the IO-results with the LCA-results, one of the main observations is that there are large shifts in the ranking of the consumption activities, caused by the higher completeness of the IO-approach (no cut-offs, inclusion of a broader range of products, inclusion of services). Consider for example Global Warming: in the LCA-results, the hotspot activity is shelter, followed by mobility, food and goods. In the IO-results, the hotspot activities are mobility and services, followed by shelter, goods and food. This means that the influence of using a different approach on the final results is large and should not be underestimated, which may be relevant input to policy support. They use the results to monitor the environmental impacts associated with the consumption behaviour of EU citizens, but also to develop policies that will reduce this environmental impact.

Overall, we can conclude that the IO-approach (based on Exiobase) is very suitable for this type of studies. The main limitation is that not every ILCD impact category can be calculated. However, there are also precision issues with toxicity impacts in the LCA-approach, and the CEENE method can be used as a substitute for Abiotic Resource Depletion. Nonetheless, the CEENE method cannot assess the actual depletion of metals. To be able to calculate the impact of metal depletion with IO-databases, the elementary metal flows and associated mining sectors need to be disaggregated, which is a difficult issue that will probably not be solved in the near future.

A possible preliminary solution to include the impact of metal depletion is a hybrid analysis. In a hybrid analysis, the IO-based inventory and the LCA-based inventory are linked to combine the strengths of both approaches. In this particular case, a tiered hybrid analysis would be the most suitable. This type of hybrid analysis can be performed by simply adding up LCA-results and IO-results, e.g. to fill up data gaps [22].

Chapter 6
The recyclability benefit rate of plastic waste treatment in Flanders

Redrafted from

Huysman, S.; Debaveye, S.; Schaubroeck, T.; De Meester, S.; Ardente, F.; Mathieux, F.; Dewulf, J., The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders. Resour Conserv Recy 2015, 101, 53-60

6.1 Introduction

As mentioned in chapter 1, our society has to utilize resources more efficiently, or in other words, drastically increase its resource efficiency, to balance economic growth and natural resource consumption [16]. Apart from finding more efficient processes, a better management of waste represents the most apparent potential to increase resource efficiency [16]. This management can be achieved by preventing waste or by reusing, recovering energy from or recycling the waste [150]. Instead of focusing on waste disposal, waste materials can be considered as potential new resources, so-called 'waste-as-resources'. This change in mindset from waste disposal to waste-as-resources is becoming increasingly implemented in the waste management strategies of governmental policies. One of the leading governmental organizations in the field of developing 'waste-as-resources' efficiency indicators is the European Union.

Various waste-as-resources indicators have been developed by the European Commission's Joint Research Centre (JRC) [35, 39, 151]. One of these indicators is the Recyclability Benefit Rate (RBR), expressing the potential environmental savings related to the recycling of a product over the environmental burdens of virgin production followed by disposal. This indicator is generally calculated using environmental impact values obtained through Life Cycle Assessment (LCA) [61]. The intended application of this indicator is to support the European Commission with the integration of measures aiming at improving resource efficiency in European product policies [39].

The first objective of this chapter is to explore the applicability of the recyclability benefit rate indicator concept in two cases of plastic waste treatment in Flanders: closed-loop recycling (case A) and open-loop recycling (case B). In closed-loop recycling, the inherent properties of the recycled material are not considerably different from those of the virgin material. The recycled material can thus substitute the virgin material and be used in the identical type of products as before. In open-loop recycling, the inherent properties of the recycled material differ from those of the virgin material in a way that it is only usable for other product applications, mostly substituting other materials [152-154]. Based on these two cases, the indicator is further developed for open-loop recycling and cascaded use.

The considered plastic waste originates from small domestic appliances (e.g., radios, vacuum cleaners) and household plastics other than plastic bottles (e.g., foils, bags). Given the indispensable role of plastics in our modern society, these products provide a relevant case study. In 2012, the global production of plastics was 288 million tons [155]. The development of synthetic polymers used to make these plastics consumes almost 8% of the global crude oil production [156]. However, after use, plastics become a major waste management challenge. Because the degradation of plastics in the environment takes a considerable amount of time, plastics impose risks to human health and the natural environment [156].

These environmental concerns, combined with the impending supply risk of crude oil, are important incentives to stimulate the recovery of plastics. To compare different plastic waste treatments, several LCA studies have been performed in the literature. Comprehensive reviews can be found in the work of Lazarevic et al. [157] and Laurent et al. [158]. In all of these studies, the environmental impact assessment is largely focused on the emissions and to a lesser extent on resources, the latter by using the abiotic depletion potential as an indicator. However, a good analysis focusing on the full asset of natural resources [52] in combination with resource efficiency indicators is still missing. Therefore, the second objective of this chapter is to perform such an analysis using an impact methodology which accounts for resource use: the Cumulative Exergy Extraction from the Natural Environment or CEENE [3].

6.2 Materials and methods

6.2.1 Scope definition

The scope of this chapter is to evaluate the resource efficiency in two cases of plastic waste treatment in Flanders (see Figure 17):

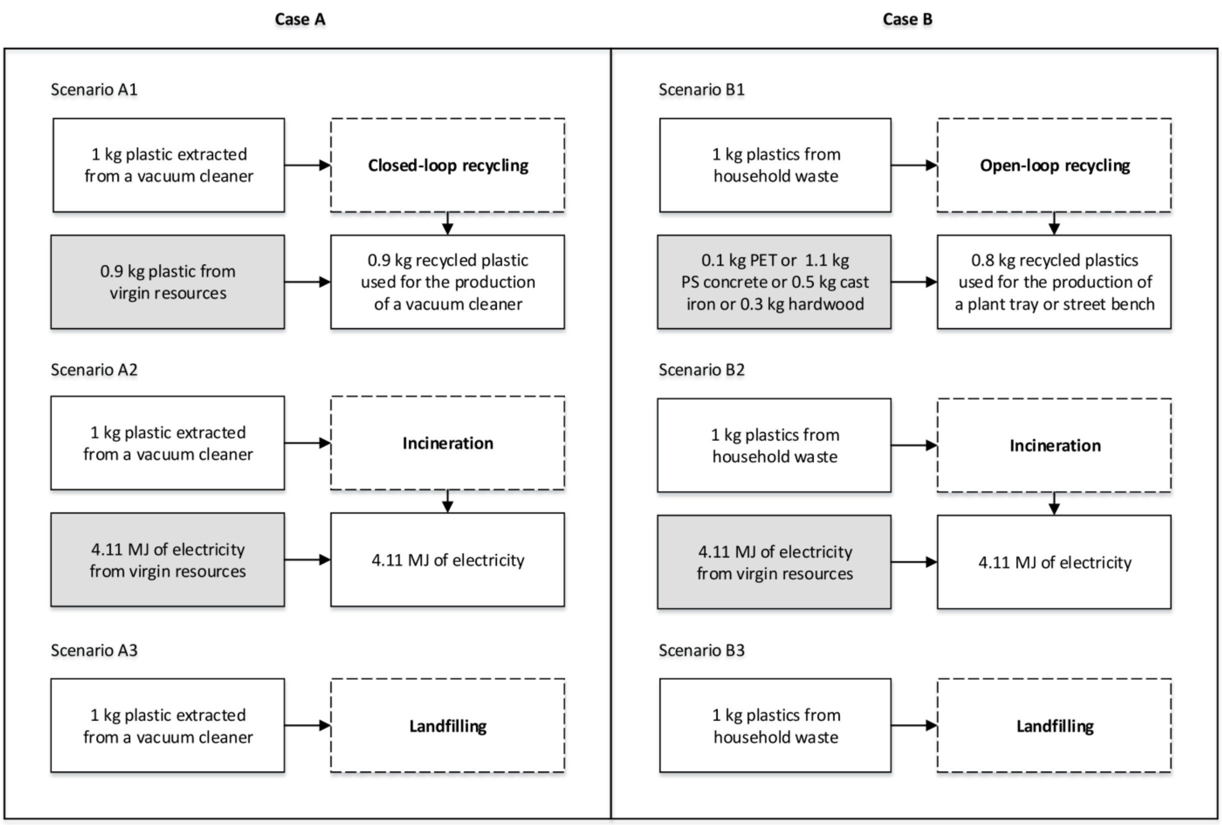

Figure 17: Presentation of case A and case B. For each case, three possible scenarios are available: closed-loop/open-loop recycling, incineration for electricity recovery and landfilling. The grey colored blocks are the products for which the production from virgin resources ('virgin production') can be avoided.

Closed-loop recycling of plastics extracted from electronic waste (case A) and open-loop recycling of plastics from household waste (case B). For each case, there are three possible scenarios: (1) material recovery by closed-loop or open-loop recycling, (2) incineration for electricity recovery and (3) landfilling. The calculations are based on LCA practices performed according to the ISO 14040/14044 guidelines [61].Foreground data were collected in close collaboration with the companies. To model the background system and assess the environmental impacts, we used the Ecoinvent v2.2 database [159] and OpenLCA software [160].

6.2.2 Description of case A

The functional unit of case A is the waste treatment of 1 kg of plastics extracted from small domestic appliances, e.g., a vacuum cleaner. Possible waste treatment scenarios are closed-loop recycling (A1), incineration for electricity recovery (A2) and landfilling (A3).

The closed-loop recycling scenario (A1) is performed by the company Galloo. This company recycles plastics extracted from electronic waste. The recycling process consists of four main steps: shredding, separation of metal and plastics, further separation of plastics and extrusion of plastics into pellets. The subdivision of the recycled plastic pellets is in general 50% polystyrene (PS), 20% acrylonitrile butadiene styrene (ABS), 15% polyethylene (PE) and 15% polypropylene (PP). The recycling rate of Galloo is 90%, indicating that 0.9 kg of recycled plastic is produced per kg waste input. The recycled plastics can be used in the identical product as before, i.e., a vacuum cleaner. This implies that the production of 0.9 kg plastics from virgin resources can be avoided. Data for the foreground system was gathered on-site. These data includes the detailed mass balance, electricity use, additives and on-site transport. Transport of waste from the waste-producing activity to the company and collection of waste are not included because of the unavailability of data. Data for the background system was retrieved from the Ecoinvent v2.2 database. Additional detailed information can be found in appendix A.3.2.

In the incineration scenario (A2), the plastic waste is incinerated for electricity recovery. The incineration was modeled by the Ecoinvent process 'Disposal, plastics, mixture, 15.3% water, to municipal incineration'. This process does not include waste collection and transport [161]. Per kg incinerated plastics, 4.11 MJ of electricity is delivered [159]. Considering the Belgian electricity mix, this result implies that the production of the identical amount of electricity from virgin resources, mainly fossil fuels and nuclear ores, can be avoided. The avoided virgin electricity production was modeled by the processes 'Electricity, medium voltage, production BE, at grid' [162].

The landfilling scenario (A3) was modeled by the Ecoinvent process 'disposal, plastics, mixture, 15.3% water, to sanitary landfill'. This process does not include waste collection and transport [161]. Further, the vacuum cleaner itself is modeled as a 'Commercial Canister' type [163]. This type of vacuum cleaner has a plastic fraction consisting of 1.96 kg PS, 1.96 kg PP and 1.96 kg acrylonitrile butadiene styrene (ABS), and a metal fraction consisting of 1.45 kg ferrous and 2.25 kg non-ferrous materials. Data for the production phase of these materials was retrieved from the Ecoinvent v2.2 database, see appendix A.3.4. The assembling phase was assumed to be negligible [164]. During the use phase, the vacuum cleaner consumes 1650 kWh electricity over its lifetime [165], which was modeled by the Ecoinvent process 'Electricity, low voltage, at grid BE'. We assumed that all of the plastics in the vacuum cleaner are recycled by Galloo. Next, the recycled plastics are used for the production of a new vacuum cleaner. For this study, it was assumed that the entire plastic fraction in this new vacuum cleaner is comprised from recycled material. In practice, the maximum fraction of recycled plastic in vacuum cleaners currently on the Belgian market is 70% [166]. Recycling of the metal fraction was not considered in this study because the focus is on plastic waste treatment.

6.2.3 Description of case B

The functional unit of case B is the waste treatment of 1 kg of household plastics (e.g., bags, foils, toys) other than plastic bottles. Possible waste treatment scenarios are open-loop recycling (B1), incineration for electricity recovery (B2) and landfilling (B3).

The open-loop recycling scenario (B1) is performed by the company Ekol. This company recycles plastic waste from households excluding plastic bottles; plastic bottles are collected separately. The main steps in the recycling process are the following: depollution, shredding, separation, drying, wind sifting and extrusion into pellets. Two types of polymer composites are produced at Ekol: one consists of 80% polyethylene (PE) and 20% polypropylene (PP), and the other consists of 20% polyvinylchloride (PVC), 40% polystyrene (PS) and 40% polyethylene terephthalate (PET). In this study, the focus will be on the PE-PP polymer. The recycling rate of Ekol is 80%, indicating that 0.8 kg PE-PP pellets are produced per kg waste input. The PE-PP pellets are used to produce new products, i.e., plant trays and street benches. The production of one plant tray requires 140 kg PE-PP pellets, whereas the production of one street bench requires 95.5 kg PE-PP pellets.

With 0.8 kg PE-PP pellets obtained per kg waste input, either 1/175th (=0.8/140) of a plant tray or 1/119th (=0.8/95.5) of a street bench can be produced. However, the 'virgin alternatives' of the plant tray and the street bench are produced from other materials. A 'virgin' plant tray is often produced from polyethylene terephthalate (PET) (19 kg) or PS concrete (195 kg) [167]. The latter is a type of concrete that utilizes polymers to substitute cement [168]. A 'virgin' street bench is mostly comprised of cast iron (63 kg) or tropical hardwood (32.5 kg) with a cast iron pedestal (26 kg) [169]. This composition indicates that 0.8 kg recycled PE-PP can substitute the virgin production of 0.1 kg PET (=1/175*19 kg), 1.1 kg PS concrete (=1/175*195 kg), 0.5 kg cast iron (=1/119*63 kg) or 0.3 kg hardwood + 0.2 kg cast iron (= 1/119*32.5 kg + 1/119*26 kg). The products produced by Ekol are heavier than their virgin alternatives because of the quality loss in the recycled material: additional mass is required to fulfill the identical requirements.

Data for the foreground system was gathered on-site. These data includes the detailed mass balance, electricity use, natural gas, water and additives. Data for the transport of waste from the waste-producing activity to the company and collection of waste was not included because of the unavailability of data. Data for the background system and the substituted materials was retrieved from the Ecoinvent v2.2 database. Additional detailed information can be found in appendices A.3.3 and A.3.5. A remark must be made concerning the substituted material cast iron. In Ecoinvent, cast iron consists of 65% pig iron and 35% scrap. The substituted cast iron is thus produced from both virgin resources and recycled material. The incineration scenario (B2) and the landfilling scenario (B3) are modeled by the identical Ecoinvent processes as used in case A.

6.2.4 Life cycle impact assessment

In this study, the focus lies on the environmental impact savings related to changes in resource consumption. Therefore, the Cumulative Exergy Extraction from the Natural Environment (CEENE) v.2013 was applied as impact assessment method [3, 28], see chapter 2. As already mentioned in the previous chapters, this method has been operationalized to the Ecoinvent database, resulting in a resource footprint indicator at microscale. CEENE was selected over other exergy-based impact methods because it offers the most comprehensive coverage of natural resources [33, 52]: fossil energy, nuclear energy, metal ores, minerals, water resources, land use, abiotic renewable resources and atmospheric resources.

6.2.5 Resource efficiency indicator

The impact assessment results will be used in the recyclability benefit rate (RBR) indicator concept [39]. This indicator is defined as the ratio of the potential environmental savings that can be achieved from recycling the product over the environmental burdens of virgin production followed by disposal:

$$RBR_n = \frac{\sum_{j=1}^{P} \sum_{i=1}^{N} m_{recyc,i,j}\ RCR_{i,j}\ \left(V_{n,i,j} + D_{n,i,j} - R_{n,i,j}\right)}{\left(\sum_{j=1}^{P} \sum_{i=1}^{N} m_{i,j}\, V_{n,i,j} + M_n + U_n + \sum_{j=1}^{P} \sum_{i=1}^{N} m_{i,j}\, D_{n,i,j}\right)} \quad (14)$$

In equation 14, RBR_n is the recyclability benefit rate for the n^{th} impact category, m_{ij} is the mass of the i^{th} material of the j^{th} part of the product [kg], $D_{n,i,j}$ is the impact of disposing 1 kg of the i^{th} material of the j^{th} part [unit/kg], $V_{n,i,j}$ is the impact of producing 1 kg of the i^{th} virgin material of the j^{th} part [unit/kg], $R_{n,i,j}$ is the impact of producing 1 kg of the i^{th} recycled material of the j^{th} part [unit/kg], M_n is the impact of manufacturing the product [unit], U_n is the impact of the use phase of the product [unit], N is the number of materials in the j^{th} part of the product, P is the number of parts of the product and $RCR_{i,j}$ is the recycling rate of the i^{th} material of the j^{th} part. The recycling rate is defined as the amount of recycled material produced per kg waste input when considering that part of the materials are lost during recycling.

6.3 Results and discussion

6.3.1 Impact results of case A

Figure 18 shows the environmental burdens and savings in terms of resource consumption (CEENE) related to the treatment of 1 kg of plastic waste extracted from a vacuum cleaner. The results are presented in a resource-contribution profile, showing how much each natural resource category contributes to the total environmental impact. The positive part of the y-axis shows the environmental burdens of each scenario. The recycling scenario (A1) has an impact of 11.39 MJ_{ex} per kg waste, the incineration scenario (A2) has an impact of 1.06 MJ_{ex} per kg waste and the landfilling scenario (A3) has an impact of 0.54 MJ_{ex} per kg waste. In all of these scenarios, the main resource contribution comes from fossil fuels and nuclear energy, which mainly results from electricity consumption.

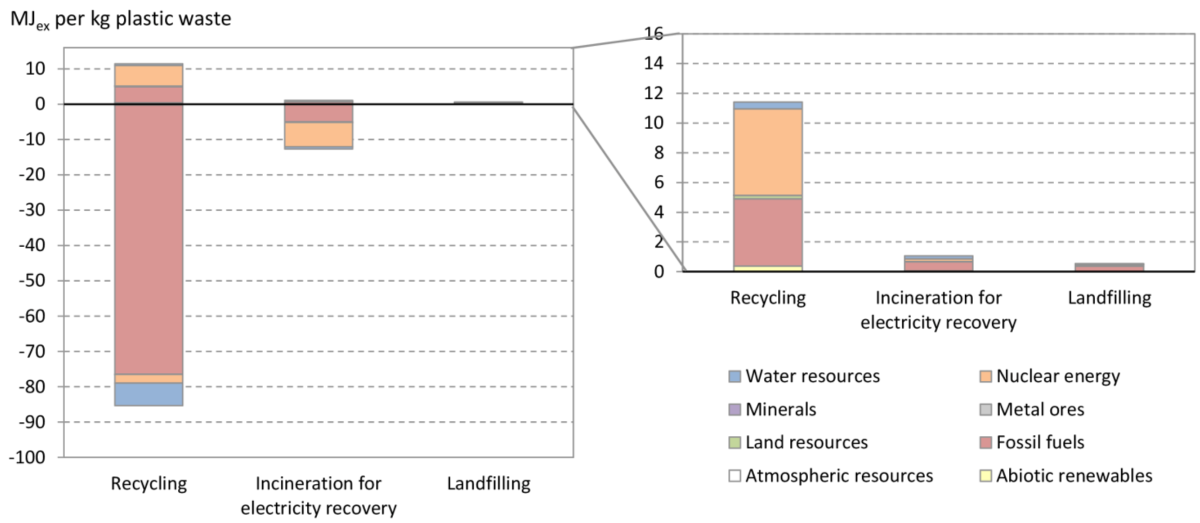

Figure 18: Environmental burdens and savings related to the treatment of 1 kg of plastic waste. The different treatment scenarios are recycling (A1), incineration (A2) and landfilling (A3). The positive y-axis shows the environmental burdens and the negative y-axis shows the environmental savings for each treatment scenario.

The negative part of the y-axis shows the environmental savings, which are the impacts that can be avoided by each treatment scenario. In the recycling scenario, the impact of producing 0.9 kg plastics from virgin resources can be avoided when taking the recycling rate into account. As an example, we consider the virgin production of 0.9 kg PS. This avoided impact has a value of 85.32 MJ_{ex}. The main resource contribution originates from fossil fuels because virgin PS is synthetized from crude oil. In the incineration scenario, the impact of producing 4.11 MJ of electricity from virgin resources can be avoided. This avoided impact has a value of 12.70 MJ_{ex}. In the landfilling scenario, no impact savings are noted in terms of resource consumption.

The net balance of environmental burdens versus savings is -73.93 MJ_{ex} (=11.39 - 85.32 MJ_{ex}) for the recycling scenario, -11.64 MJ_{ex} (=1.06 - 12.70 MJ_{ex}) for the incineration scenario and 0.54 MJ_{ex} (=0.54 - 0 MJ_{ex}) for the landfilling scenario. These net balances indicate that in this case study, recycling is the most resource efficient scenario.

6.3.2 Impact results of case B

Figure 19 shows the environmental burdens and savings in terms of resource consumption (CEENE) related to the treatment of 1 kg of waste from household plastics.

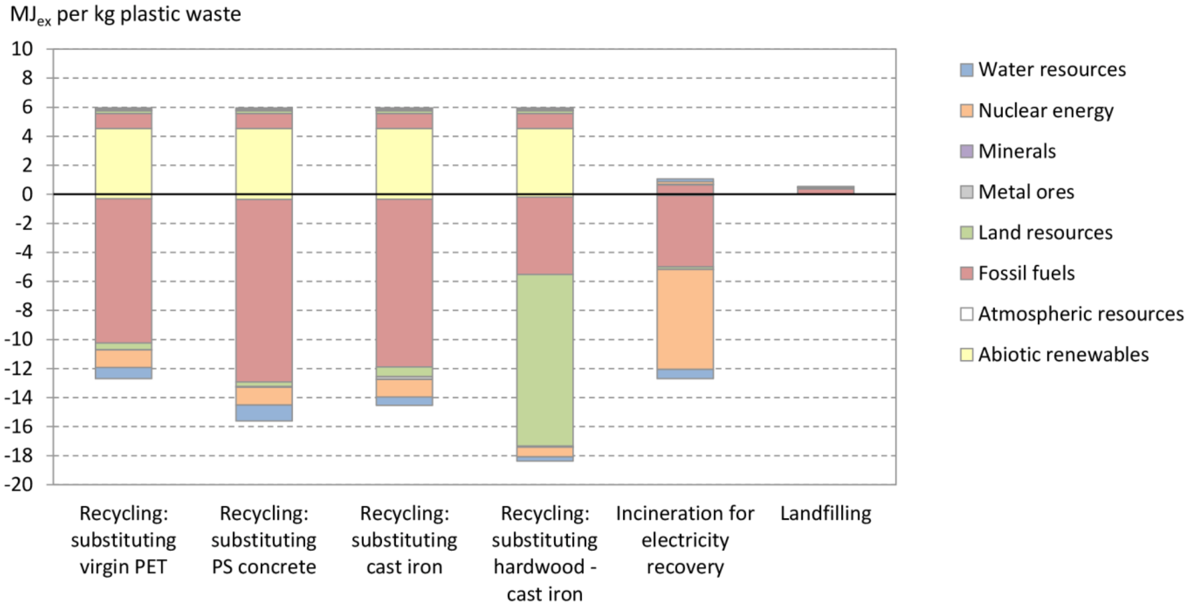

Figure 19: Environmental burdens and savings related to the treatment of 1 kg of plastic waste. The different treatment scenarios are open-loop recycling (B1), incineration (B2) and landfilling (B3). The positive y-axis shows the environmental burdens and the negative y-axis shows the environmental savings for each treatment scenario.

The results are again presented in a resource-contribution profile. The positive part of the y-axis shows the environmental burdens of each scenario. The environmental impact of the recycling scenario (B1) is 5.96 MJ_{ex} per kg waste. Because Ekol uses a green electricity mix based on a European Guarantee of Origin for electricity from renewable resources [170], the main resource contribution comes from wind energy and hydropower. The environmental impacts of the incineration scenario (B2) and the landfilling scenario (B3) are identical to case A: 1.06 MJ_{ex} per kg waste and 0.54 MJ_{ex} per kg waste, respectively.

The negative part of the y-axis shows the environmental savings. These are the environmental impacts avoided by each treatment scenario. In the recycling scenario, different avoided impacts are possible. As mentioned earlier, 1 kg of waste delivers 0.8 kg of pellets. We will focus on the PE-PP pellets. If these pellets are used to produce a plant tray, then the substituted material is either 0.1 kg virgin PET or 1.1 kg virgin PS concrete. In the first case, the avoided impact is 12.69 MJ_{ex}, and in the second case, the avoided impact is 15.61 MJ_{ex}. The main resource contribution comes from fossil fuels, which are required to produce plastics from virgin resources. If the pellets are used to produce a street bench, the substituted material is either 0.5 kg cast iron or 0.3 kg hardwood (with a 0.2 kg cast iron pedestal). In the first case, the avoided impact is 14.54 MJ_{ex}. The main resource contribution comes from fossil fuels because of energy consumption. In the second case, the avoided impact is 18.38 MJ_{ex}. The main resource contribution comes from land resources, specifically wood extracted from nature.

In the incineration scenario, the avoided impact is the production of 4.11 MJ of electricity from virgin resources, which has a value of 12.60 MJ_{ex}. In the landfilling scenario, no avoided impacts are noted in terms of resource consumption.

The net balance of environmental burdens versus savings is -6.73 MJ_{ex} (=5.96 - 12.69 MJ_{ex}) for recycling with the substitution of PET, -9.66 MJ_{ex} (=5.96 - 15.61 MJ_{ex}) for recycling with the substitution of PS concrete, -8.59 MJ_{ex} (=5.96 - 14.54 MJ_{ex}) for recycling with the substitution of cast iron, -12.42 MJ_{ex} (=5.96 - 18.38 MJ_{ex}) for recycling with the substitution of the combination hardwood-cast iron, -11.64 MJ_{ex} for incineration and 0.54 MJ_{ex} for landfilling. These net balances show that in this case study, recycling with the substitution of hardwood-cast iron is the most resource efficient scenario. Additionally, incineration appears to be more resource efficient than the other recycling scenarios. However, Ekol uses a green electricity mix [170], consuming mainly abiotic renewable resources (i.e., wind energy and hydropower). If these renewable resources are considered as freely available and thus not as an environmental impact, the open-loop recycling scenarios have the highest resource efficiency: -11.26 MJ_{ex} for the substitution of PET, -14.19 MJ_{ex} for the substitution of PS concrete, -13.12 MJ_{ex} for the substitution of cast iron and -16.96 MJ_{ex} for the substitution of hardwood.

Incineration and landfilling are finite scenarios, whereas open-loop recycling is not necessarily finite. Recycling delivers new products, which might in turn be recycled, incinerated or landfilled at the end of their life. This concept is called cascaded use, i.e., the use of the identical material for multiple successive applications [171].

Consequently, additional avoided impacts may occur for each recycling scenario, resulting in higher resource efficiencies, see section 6.3.4.

6.3.3 Indicator results of case A

The impact assessment results are then used to calculate and evaluate the recyclability benefit rate indicator. Originally, the impact of disposal D in equation 14 refers to landfilling. However, incineration is also a possible disposal scenario. To provide a distinction, subscripts will be used: L refers to landfilling and I refers to incineration. Consequently, D_L is the impact of landfilling, whereas D_I is the impact of incineration minus the avoided impact of virgin electricity production (when applicable). The recyclable product is the vacuum cleaner, as described in the Materials & Methods. The required inputs for the calculation of the RBR indicator are summarized in Table 6.

Table 6: Input for the calculation of the recyclability benefit rate of the vacuum cleaner. PS = polystyrene, ABS = acrylonitrile butadiene styrene, PP = polypropylene, m = mass (kg), V = impact of virgin production (MJ_{ex}/kg), D_L = impact of landfilling (MJ_{ex}/kg), D_I = impact of incineration minus the avoided impact of virgin electricity production (MJ_{ex}/kg). R = impact of recycling (MJ_{ex}/kg), RCR = recycling rate. (The impact of the recycling scenario was 11.39 MJ_{ex} per kg plastic waste. For the indicator, we need the impact R for producing 1 kg of recycled plastics, which is calculated as 11.39 MJ_{ex} divided by the recycling rate).

Material	m	V	D_L	D_I	R	RCR
PS	1.96	94.80	0.54	-11.64	12.67	0.9
ABS	1.96	107.2	0.54	-11.64	12.67	0.9
PP	1.96	76.93	0.54	-11.64	12.67	0.9
Ferro	1.45	27.56	0.25	0.44	/	/
Non-ferro	2.25	55.52	0.25	0.78	/	/

Because the focus of this study is on plastic waste, we did not consider recycling the metal fraction. When the impact of the use phase of the vacuum cleaner is included (i.e., 19793 MJ_{ex} per vacuum cleaner), the resulting RBR is only 1.8% (in case D_I) or 2.1% (in case D_L). Because the impact of the use phase of an electronic device such as a vacuum cleaner is high resulting from electricity consumption, this results in a low RBR indicator. However, such a result can be misleading when compared to the products in case B (i.e., a plant tray and a street bench), for which the impact of the use phase is negligible. This result could give the impression that the recycling scenario in case B is much better than in case A, which is not necessarily correct. In our study, we excluded the impact of the use phase because the focus is on plastic waste treatment, in which the production and end-of-life are key. When the impact of the use phase U of the vacuum cleaner is excluded, the resulting RBR is 56% (in case D_I) or 60% (in case D_L). This result indicates that in terms of resource consumption, the environmental benefit of recycling all of the plastics in the vacuum cleaner is 60% relative to the virgin production followed by landfilling, and 56% relative to virgin production followed by incineration with electricity recovery.

6.3.4 Indicator results of case B

The recyclability benefit rate in equation 14 is based on the assumption that the recycled material will be used to replace the identical material as in the original product. Therefore, this indicator cannot be used for open-loop recycling involving different materials and products, as in case B. Additionally, the indicator is not suitable for cascaded use (as introduced in section 6.3.2.). To overcome these issues, we further developed the indicator to be more comprehensive and suitable for open-loop recycling and cascaded use involving different materials and products. To draw a clear distinction, the new indicator is named 'the open-loop recyclability benefit rate' (RBR_{OL}). A simplified version of the current indicator is given in equation 15. The denominator describes the environmental burdens of the product that is going to be recycled, further called product α_0, and the numerator describes the environmental savings obtained from the recycling of product α_0. The impacts of manufacturing and use were left out because they were assumed to be negligible for the basic products (plant tray and street bench) in case B.

$$RBR = \frac{RCR\left(V_{\alpha_0} + D_{\alpha_0} - R_{\alpha_0}\right)}{V_{\alpha_0} + D_{\alpha_0}} \qquad (15)$$

We further developed equation 15 to include open-loop recycling. This RBR_{OL} indicator is presented in equation 16 for a one-step cascaded use, indicating that product α_0 is recycled into product α_1. Equation 17 provides a general expression for n-step cascaded use, indicating that product α_0 is recycled n times until product α_n is obtained.

$$RBR_{OL,1} = \frac{RCR\left(\frac{m_{v,\alpha_1}}{m_{r,\alpha_1}}\ V_{\alpha_1} - R_{\alpha_0 \to \alpha_1} + D_{\alpha_0}\right)}{V_{\alpha_0} + D_{\alpha_0}} \quad (16)$$

$$RBR_{OL,n} = \frac{\sum_{i=1}^{n}\left(RCR^{i}\ \left(\frac{m_{v,\alpha_i}}{m_{r,\alpha_i}}\ \ V_{\alpha_i} - R_{\alpha_i \to \alpha_{i+1}}\right)\right) + RCR^{n}(\ D_{\alpha_0})}{V_{\alpha_0} + D_{\alpha_0}} \quad (17)$$

Equations 16 and 17 will be explained using Figure 20 as an example. Here, product α_0 is 1 kg of household plastics. The denominator describes the environmental burdens of product α_0, which are the impact of virgin production, V_{α_0}, and the impact of disposal, D_{α_0}. At the end of its life, product α_0 is recycled by Ekol with a recycling rate, RCR, of 80%, delivering 0.8 kg of PE-PP pellets. These PE-PP pellets are used for product α_1, which is a plant tray. To produce one plant tray, 140 kg of recycled PE-PP is required (m_{r,α_1}). However, the 'virgin alternative' of this plant tray would be produced from 19 kg of PET (m_{v,α_1}). Therefore, 1 kg of recycled PE-PP can substitute for 0.14 kg (= 19/140 = $m_{v,\alpha_1}/m_{r,\alpha_1}$) virgin PET, or 0.8 kg of recycled PE-PP can substitute for 0.11 kg (= 0.8 * 19/140 = $RCR * m_{v,\alpha_1}/m_{r,\alpha_1}$) virgin PET. This value is multiplied with the avoided impact V_{α_1} related to the virgin production of 1 kg PET.At the end of its life, product α_1 can also be recycled by Ekol.

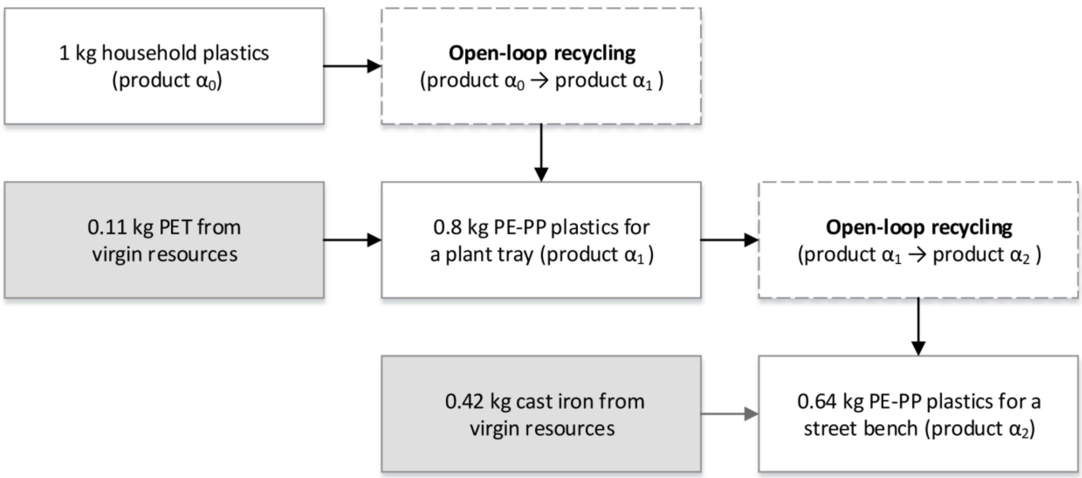

Figure 20: Example of two-step cascaded use in case B. PE= polyethylene, PP = polypropylene, PET = polyethylene terephthalate. The grey colored blocks are the materials for which the virgin production can be avoided.

A recycling rate of 80% results in 0.64 kg of PE-PP pellets. The pellets are used to make product α_2, which is a street bench. To produce one street bench, 95.5 kg of recycled PE-

PP is required (m_{r,α_2}). However, the 'virgin alternative' of this street bench would be produced from 63 kg cast iron (m_{v,α_2}). Therefore, 1 kg of recycled PE-PP can substitute for 0.66 kg (= 63/95.5 = $m_{v,\alpha_2}/m_{r,\alpha_2}$) virgin cast iron, or 0.64 kg of recycled PE-PP can substitute for 0.42 kg (= 0.64 * 63/95.5 = $RCR^2 * m_{v,\alpha_2}/m_{r,\alpha_2}$) virgin cast iron. This value is multiplied with the avoided impact V_{α_2} related to the virgin production of 1 kg of cast iron. Further, the impact of the recycling process, which is identical for both steps, is now counted twice because both products α_0 ($R_{\alpha_0 \to \alpha_1}$) and α_1 ($R_{\alpha_1 \to \alpha_2}$) are recycled.

Table 7 presents several open-loop recyclability benefit rates for one- and two-step cascaded use in case B. A complete list with all possible scenarios for two-step cascaded use can be found in appendix A.3.6.

Table 7: Open-loop recyclability benefit rates for one- and two-step cascaded uses in case B. PS = polystyrene, PET = polyethylene terephthalate. L = disposal is the impact of landfilling, I = disposal is the impact of incineration minus the avoided impact of virgin electricity production. L^* = identical to L, but the abiotic renewable resources are considered freely available, I^* = identical to I, but the abiotic renewable resources are considered freely available

Open-loop recycling: one-step cascade				
Possible scenarios for avoided product α_1	L	I	L*	I*
plant tray (PET)	10%	-2%	15%	3%
plant tray (PS concrete)	14%	2%	18%	8%
street bench (cast iron)	13%	1%	17%	6%
street bench (hardwood)	17%	6%	22%	12%
Open-loop recycling: two-step cascade				
Possible scenarios for avoided products α_1 and α_2	L	I	L*	I*
plant tray (PET) - plant tray (PET)	18%	10%	26%	19%
plant tray (PS concrete) - street bench (cast iron)	24%	16%	32%	26%
street bench (cast iron) - plant tray (PS concrete)	23%	16%	31%	26%
street bench (hardwood) - street bench (hardwood)	31%	25%	39%	34%

These benefit rates represent the ratio of the environmental savings over the environmental burdens for virgin production followed by disposal, which can be either landfilling (L) or incineration with electricity recovery (I). The benefits increase when abiotic renewables resources, coming from the green electricity mix of Ekol, are considered as freely available and thus not as an environmental impact (L^*, I^*).For the one-step cascaded use, the open-loop recyclability benefit rate varies between 15 and 22% (L^*) and between 3 and 12% (I^*). The benefit of recycling is higher relative to landfilling (L^*) than incineration (I^*). For the two-step cascaded use, the open-loop recyclability benefit rate varies between 26 and 39% (L^*) and between 19 and 34% (I^*). This result shows that cascaded use increases the recyclability benefit rate.

6.4 Conclusion

In this chapter, we studied the applicability of the recyclability benefit rate indicator concept in two plastic waste treatment cases: closed-loop recycling (case A) and open-loop recycling (case B). Both cases were compared with an incineration scenario and a landfilling scenario. As an environmental impact assessment method, the CEENE methodology (Cumulative Exergy Extraction from the Natural Environment) was used. The impact assessment results present the environmental burdens and savings per kg plastic waste in terms of resource consumption for each scenario. In case A, the net balance of environmental burdens versus savings showed that closed-loop recycling is more resource efficient than incineration and landfilling. Additionally, in case B, the net balances showed that when the abiotic renewable resources used for the green electricity mix are considered as freely available, the open-loop recycling scenarios are also the most resource efficient.

These impact assessment results were used to calculate the recyclability benefit rate indicator, which is based on LCA practices. The RBR is defined as the ratio of the environmental savings that can be achieved from recycling over the environmental burdens of virgin production followed by disposal (landfill or incineration).

However, the current indicator is only applicable when the recycled materials are used to replace the identical materials as in the original product. Consequently, this indicator could be calculated for case A but not for case B. To overcome this issue, we further developed the indicator for open-loop recycling and cascaded use among different materials and products. To develop a distinction, the new indicator was named the ‘open-loop recyclability benefit rate’ (RBR_{OL}). The RBR of case A varies between 56- 60%, whereas the RBR_{OL} of case B varies between 3-22% for one-step cascaded use and 19-39% for two-step cascaded use when the abiotic renewable resources are considered as freely available.

A drawback of the RBR indicator is that the results of two cases can only be compared with each other if they treat the same waste stream, or in other words, if they have the same denominator. In this chapter, the two companies treat a different waste stream: case A considers plastics extracted from small domestic appliances, while case B considers plastics extracted from household waste. Therefore, the RBR results can only be evaluated as such, and not in comparison with each other.

These quantitative results might be useful for policy makers. First, the results show that the recycling of these two plastic waste flows in Flanders is more resource efficient than incineration or landfilling. Second, the results show that cascaded use can increase the benefit rate of open-loop recycling. Policy makers could for example implement these indicator results in the legislation on subsidies and taxes for plastic waste management. Specifically for case B, policy makers could encourage administrative divisions such as municipalities to purchase products (e.g., street furniture) comprised of recycled plastics produced by local recyclers by introducing specific criteria in Green Public Procurement schemes. This is relevant not only from an environmental perspective but also from a social perspective: several studies have already highlighted that recycling provides more jobs than landfilling and incineration [172].

The RBR indicator can still be improved. For example, the final step in cascaded use, i.e., incineration or landfilling, is not yet included in the indicator. Further, the lifetime was not considered, i.e., how long the recycled plastics last when compared to their virgin alternatives. An economic analysis, e.g., a cost-benefit analysis, could complement our environmental analysis for policy making.

Chapter 7
Conclusions and perspectives

7.1 General conclusions

The transition toward a more sustainable society in terms of natural resource consumption is currently one of the main challenges in governmental policies. This transition has led to a proliferation of meanings related to resource sustainability, resulting in a wide variety of indicators. We made a distinction between two types of resource-based indicators: footprint and efficiency indicators.

As explained in chapter 1, the family of footprint indicators is missing an overall resource footprint, which accounts for all natural resource types in an adequate, comprehensive way. The water footprint is a measure for the freshwater requirements (in m^3), the ecological footprint is a measure for the productive land area (in global hectares), and the material footprint is a measure for the extracted raw materials (in kg), which includes metals, minerals, fossil fuels and biomass. To be able to evaluate the sustainability of natural resource use, each of these indicators has to be calculated individually. Another disadvantage is that several resources are equally weighted (e.g. 1 kg sand versus 1 kg copper) or double counted (e.g. land resources in the material footprint and the ecological footprint).

Therefore, we developed an overall resource footprint indicator at macroscale in chapter 3, capable of aggregating the different resource types in a consistent way onto one single scale. This was done by coupling the CEENE method with the Exiobase database. The resulting indicator is called IO-CEENE. This resource footprint covers a wide range of natural resources: fossil fuels, metals, minerals, nuclear resources, water resources, land resources and abiotic renewable resources. Further, the indicator is based on the Exiobase world IO-database, covering 43 countries and a rest of the world region. This means that natural resources embodied in imported and exported goods are included. Consequently, it is also possible to present the results of IO-CEENE in a geospatially differentiated profile, showing from which countries and regions the natural resources are extracted. This global perspective is one of the most important assets of IO-CEENE, compared to the exergy-based resource footprint indicator developed by Ukidwe and Bakshi [32], which is based on the national IO-database of the United States.

Resource footprint indicators are often linked with resource efficiency indicators. As explained in chapter 1, efficiency indicators are defined as the ratio of 'benefits' over environmental 'costs', and these costs can be represented by a footprint indicator. However, a diversity of resource efficiency indicators is currently available, generating confusion about their actual meaning.

To overcome this issue, we developed a systematized framework for the classification of resource efficiency indicators in chapter 4. This framework was subdivided in two levels. At level 1, the 'cost' in the denominator contains inventoried flows. At level 2, the 'cost' contains environmental impacts. This cost can be based on resource flows only (*resource efficiency in sensu stricto*), or a combination of resource and emission flows in case of single score impacts (*resource efficiency in sensu lato*). Further, the systematized framework includes the provenience of resources (natural or waste resources), the considered perspective (gate-to-gate or life cycle, national or global), the economic scale (micro or macro), and the field of study (environmental policy or environmental science and engineering).

The framework can for example be used to evaluate the policy indicators in the resource efficiency scoreboard [173], covering as many as possible of the themes and subthemes identified in the Roadmap to a resource efficient Europe [11]. The lead indicator is the resource productivity or GDP over DMC. The Roadmap states that "Because this provisional lead indicator only gives a partial picture, it should be complemented by a dashboard of indicators on materials, land water and carbon". The dashboard indicators are subdivided in those with a territory perspective (i.e. domestic perspective), and those with a global supply chain perspective (i.e. global perspective).

For the domestic perspective, the Roadmap considers the DMC per capita (tons) for materials, artificial or built-up area (km^2) for land, the water exploitation index (%) for water and GHG emissions per capita (tons) for carbon. Built-up areas cover roofed constructions for permanent purposes which can be entered by people. Non built-up areas are characterized by an artificial cover of hard artificial materials, concrete, or gravel, for example transport infrastructure. Total artificial land is composed of both built-up areas and artificial non built-up areas. The water exploitation index is calculated as total fresh water abstraction (m^3) divided by the long term average available water (m^3), separated into groundwater and surface water.

Table 8: Resource efficiency indicators in the Roadmap and the Scoreboard

		Domestic	Global
Lead	Materials	Resource productivity: GDP/DMC	n.a.
Dashboard	Materials	DMC (per capita)	n.a.
	Land	Artificial or built-up area Productivity of artificial land	Indirect land use
	Water	Water exploitation index Water productivity	Water footprint
	Carbon	GHG emissions (per capita) Energy productivity Energy dependence Share of renewable energy	Carbon footprint

The resource efficiency scoreboard also includes the productivity of artificial land (million PPS per km^2), the water productivity (EUR per m^3), energy productivity (EUR per kg), energy dependence (%) and share of renewable energy in gross final energy consumption (%). A PPS is the purchasing power standard. Theoretically, one PPS can buy the same amount of goods and services in each country. The energy dependence is calculated as total imports minus total exports divided by the sum of the gross inland energy consumption and maritime bunkers. For the global perspective, the Roadmap consider the indirect land use (km^2), the water footprint (m^3) and the carbon footprint (tons).

Only the productivities can be considered as actual resource efficiency indicators, representing a ratio of 'benefits' over 'costs'. They can be classified at level 1 in the framework, and consider a domestic perspective. This corresponds with 'GDP over national accounts' in Table 2. The problem with these national accounts is that natural resources embodied in internationally traded products are not accounted for. However, with the growing awareness for environmental burden shifting due to international trade, policy makers should choose global accounts over national accounts.

The indicators with the global perspective (indirect land use, water footprint, carbon footprint) correspond with the global accounts. However, they are not expressed as an efficiency indicator, but as a footprint indicator. They could be used to represent the 'cost' in the denominator of efficiency indicator. In that case, it is possible to classify them at level 2 in the framework. Another remark can be made concerning the carbon footprint. This is focused on emissions, while resource efficiency indicators (in sensu stricto) should be focused on resources.

Further, the DMC, artificial or built-up area and GHG emissions are simply inventoried flows. They do not represent an actual efficiency. The same is valid for the water exploitation index, energy dependence and share of renewable energy. Although they are expressed as a percentage, they do not actually represent a benefit over a cost, and cannot be classified within the resource efficiency framework. The roadmap and the scoreboard also consider some thematic indicators to show progress in key areas, e.g. biodiversity, which are out of the scope of this thesis.

The scoreboard and the roadmap clearly illustrate that policy makers use a diversity of resource-related indicators, without making a clear distinction between resource efficiency and footprint indicators, although they consider them all as resource efficiency indicators. Further, emissions are still part of the scoreboard and the roadmap, while the objective of these initiatives is to focus on natural resource use. And although burden shifting due to international trade is an widely acknowledged problem in literature, and limiting environmental monitoring to a national level would provide misleading information, the indicators in the scoreboard and the roadmap are mainly focused on a domestic perspective. Even the lead indicator considers only a national level. These conclusions lead to several perspectives, which are included in section 7.2.

Summarized, chapters 3 and 4 provide methodological 'tools' to assist policy makers in the implementation and further development of indicators for a sustainable resource use. The use of these tools is illustrated with two case studies in chapters 5 and 6. The first case study is focused on natural resources, while the second is focused in waste-as-resources. This is presented schematically in Figure 21.

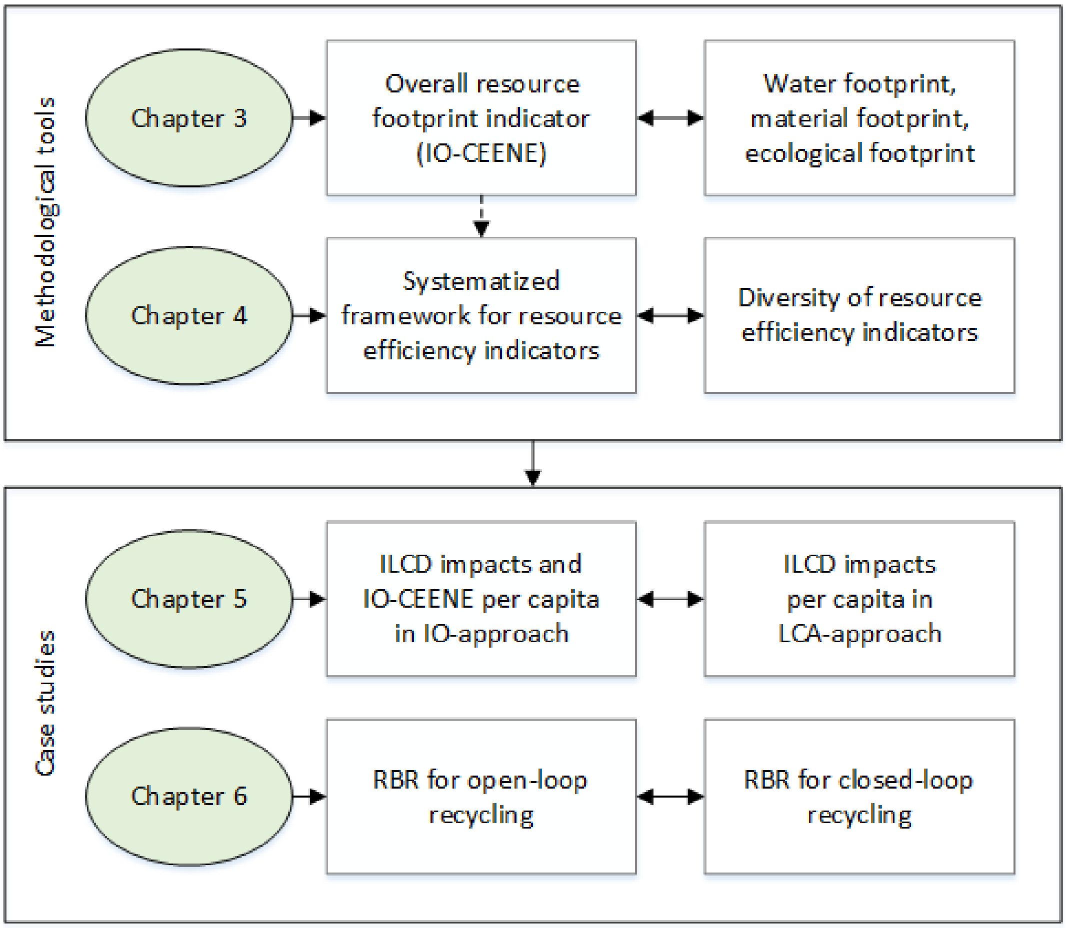

Figure 21: Schematic representation of the new developments in each chapter, compared to the current practices. IO = Input-Output, LCA= Life Cycle Assessment, CEENE = Cumulative Exergy Extraction from the Natural Environment, ILCD = International reference Life Cycle Data system, RBR = Recyclability Benefit Rate.

7.1.1 Focus on natural resources

The first case study (chapter 5) was based on the work of the European Commission's Joint Research Centre (JRC), in which they attempted to calculate the environmental impacts of an average EU citizen through a bottom-up LCA-approach, for all the impact categories recommended by the ILCD handbook [2]. In this thesis, the environmental impacts were calculated through a top-down IO-approach, using the Exiobase database.

However, it was not possible to make an adequate impact assessment for each ILCD recommended impact category. For Ionizing Radiation, Human Toxicity and Ecotoxicity, insufficient elementary flows are present in Exiobase (less than 0.5% of the required elementary flows). Nonetheless, there are also precision issues with the toxicity impact categories in the LCA-approach.

For Abiotic Resource Depletion, the most dominant elementary flows are aggregated in one group. These are metals and mineral flows with a high risk for depletion, for example Germanium. To avoid that our top-down study would lack a profound analysis of natural resource consumption, we also calculated the new overall resource footprint indicator, IO-CEENE.

When comparing the top-down approach with the bottom-up approach, we noticed a considerable shift in the results. This is mainly because of the higher completeness of the IO-approach (broader product range, services are included). The overall conclusion is that an IO-approach based on Exiobase is recommended for this type of studies. Above that, the IO-CEENE indicator is a valuable addition to the environmental impact results, which would otherwise only be focused on emissions.

7.1.2 Focus on waste-as-resources

The second case study (chapter 6) is based on the recyclability benefit rate (RBR) of JRC, developed for policy purposes. This indicator expresses the potential environmental savings that can be achieved from recycling the product over the environmental burdens of virgin production followed by disposal. We quantified these savings and burdens by using an exergy-based approach, more specifically the CEENE method.

The indicator was applied to two cases of plastic waste recycling in Flanders: closed-loop recycling (case A, company Galloo) and open-loop recycling (case B, company Ekol). Case A considers plastics extracted from electronic waste (e.g. a vacuum cleaner). The recycled plastic is of good quality and can be used in similar products as before. Case B considers plastics from household waste (e.g. plastic bags). The recycled plastic is of lower quality, making it only useable for other products, e.g. street benches, in which it substitutes other materials, e.g. wood. Hence, the indicator had to be adapted for open-loop recycling.

Overall, the results show that recycling of these two waste flows is more resource efficient than landfilling or incineration: the average RBR of case A (closed-loop recycling) is 58%. This means that there is an environmental saving of 58% in terms of resource consumption relative to virgin production followed by disposal. The average RBR of case BA (open-loop recycling) is 13%, when abiotic renewable resources are considered as freely available. This means that there is an environmental saving of 13% in terms of resource consumption relative to virgin production followed by disposal. Cascaded use of the product (i.e. the product is recycled again at the end of its life) can increase the recyclability benefit rate of case B up to 28%.

These quantitative results can give useful information to policy makers. However, it was also mentioned in chapter 6 that a disadvantage of the RBR indicator is that two cases can only be compared with each other if they treat the same waste stream, or in other words, if they have the same denominator. But the companies in chapter 6 treat a different waste stream. Therefore, the RBR results of the cases cannot be compared with each other. They can only be evaluated as such (i.e. relative to disposal).

This led to the conclusion that additional indicators are needed, that can be compared with each other although the treated waste stream is different. These indicators should start from quality of the waste stream, which determines the most suitable waste treatment and thus the maximal obtainable environmental savings. Such indicators would provide a different view on the classical waste management hierarchy, in which recycling is on top, followed by incineration for energy recovery and landfill [174]. This idea is further elaborated in the perspectives, section 7.2.2.

It must be remarked that whilst writing chapter 6, data on the collection phase was unavailable. Therefore, the environmental burden related to collection was not included in the R-value of the indicator. However, in a later study on metal recycling at Galloo by Van Eygen et al. [175], the collection phase was taken into account. They concluded that "the end-processing step has by far the biggest CEENE impact, compared to the impact of the collection and primary treatment steps". Based on these results, we can conclude that omitting the collection phase was an acceptable assumption.

7.2 Perspectives

The results from this dissertation leave some challenges for further research. These challenges are presented schematically in Figure 22. Also here, a distinction is made between natural resources and waste-as-resources.

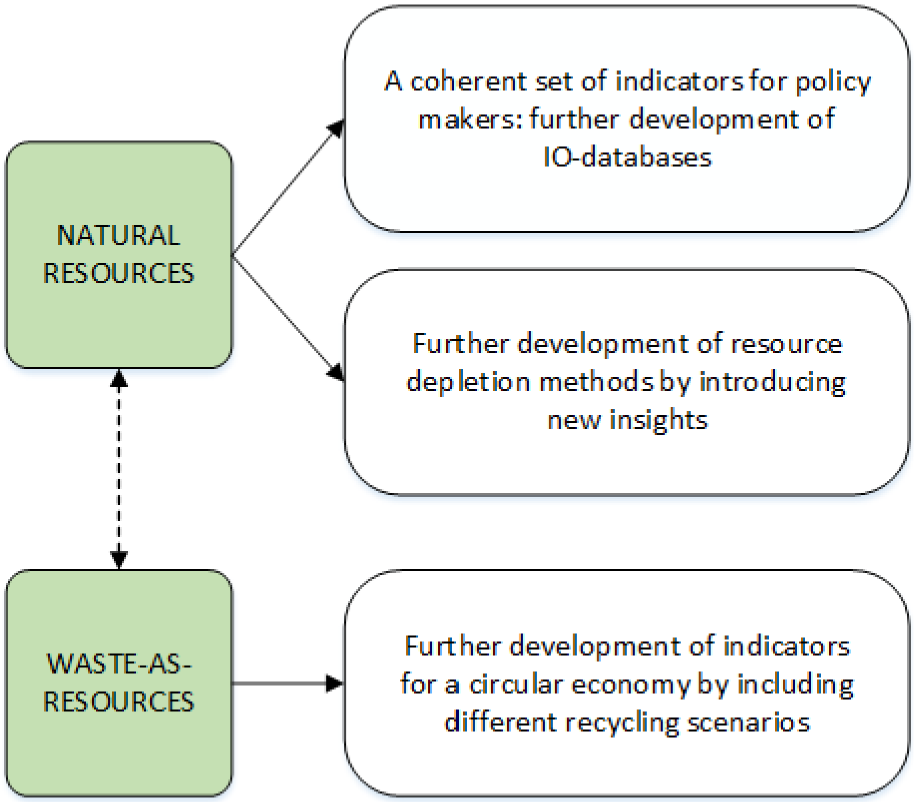

Figure 22: Schematic representation of the research challenges

7.2.1 Focus on natural resources

Perspective 1: a coherent set of indicators for policy makers

Analysis of the resource efficiency indicators in the roadmap and the scoreboard of the European Commission (section 7.1) led to the conclusion that policy makers now use an incoherent set of indicators.

Based on this thesis, I would recommend policy makers to use one common methodology to calculate a coherent set of resource-related indicators at macroscale: environmentally extended IO-analysis. Therefore, policy makers should stimulate (and invest in) the further development of world IO-database like Exiobase, This way, it is possible to calculate a set of footprint indicators with a global perspective: (1) the classical footprint family, providing a first estimate of resource consumption, and (2) the overall IO-CEENE footprint, aggregating all resource types in a consistent way.

Next, resource efficiency indicators can be calculated by using the obtained footprints to represent the 'cost' in the denominator. The 'benefit' in the numerator can be represented by the GDP, or even better, by a metric from the 'beyond GDP' report [125]. The GDP simply assumes that every monetary transaction adds to social well-being by definition. In this way, expenditures triggered for example by crime, accidents or corporate fraud count the same as socially productive investments in housing, education and healthcare. To address these deficiencies, measures like the Genuine Progress Indicator (GPI) are available. Once the database is available, calculating this set of indicators is relatively easy. The difficulty lies in the development of the database, e.g. time-series and detailed data on resources.

Perspective 2: further development of resource depletion methods

Chapters 3, 4 and 5 led to a common challenge for future research: resource-based impact methods are still in their infancy compared to emission-based impact methods, and they require further development.

This issue is also addressed in the work of Dewulf et al. [176], which is focused on the area of protection (AoP) natural resources. The AoP's are that part of the environment we are concerned about protecting when using impact assessment methods [177]. The three AoP's in LCA are ecosystem health, human health and natural resources. To allow a better elaboration of the AoP natural resources, Dewulf et al. [176] provided a framework in which impact methods with respect to this AoP can be classified into five different perspectives. The first perspective considers the asset of natural resources. These are resource accounting methodologies, e.g. CEENE. The second perspective considers the provisioning capacity of resources. These are resource depletion methods, e.g. the abiotic depletion method of CML [89, 178]. The last three perspectives consider a more multidisciplinary approach by including effects on ecosystem services (e.g. water purification) and socio-economic consequences (e.g. child labor).

The focus in this dissertation was mainly on the first and second perspective, which are typically used in LCA. The second perspective, depletion of a resource, means that its amount on earth is being reduced. It refers to the geological stocks [7]. A selection of commonly applied resource depletion methods is given in Table 9 [179]. However, the extent to which these resource depletion methods can give answer to questions of environmental sustainability is widely debated [129]. This is especially the case for minerals and metals, as discussed by Drielsma et al. [177]: *'Despite 20 years of research, there remains no robust, globally agreed upon method - or even problem statement - for assessing mineral resource inputs in LCA*'. There are several reasons for this, summarized by Van Oers and Guinée [180]: 1) it is a problem crossing the economy-environment system boundary, since reserves of resources depend on future technologies for extracting them; 2) there are different ways to define this problem, which can all be justified from different perspectives; 3) there are different ways to quantify this problem, and none of them can be empirically verified.

Table 9: A selection of commonly applied resource depletion methods.

Method name	Applied concept
CML method [89]	use to availability ratios of resources in the earth
Ecoindicator 99 [181]	Surplus energy that will be required in the future to produce a metal from lower ore grades
Recipe [182]	additional monetary costs associated with mining for the extraction of 1 kg metal
EPS2000 [183, 184]	cost associated with substituting the extraction process by a hypothetical sustainable process

To provide a better understanding on the advantages and the disadvantages of the methods in Table 9, they are shortly described.

The first method was used in chapter 5. This method is based on the use to availability ratios of resources. The characterization factor, called the Abiotic Depletion Potential (ADP) [90, 185], is calculated by dividing the annual extraction rate by the square of the natural reserves, relative to the depletion of the element antimony as a reference. The characterization factors are based on the ultimate reserves, calculated from the concentration of elements in the Earth's crust. These ultimate reserve data were considered to be the best proxy for the 'ultimately extractable reserves' (i.e. reserves that can ultimately be technically extracted), because data on the latter are unavailable. Nonetheless, the ILCD handbook and the Product Environmental Footprint (PEF) of the

European Commission recommend the use of 'reserve base' data, instead of ultimate reserves. These are resources that meet specified minimum physical and chemical criteria relating to current mining practice. They have reasonable potential for becoming economically available within planning horizons. However, Van Oers and Guinée [180] and Drielsma et al. [177] disagree with the use of reserve base data, because estimates of economic reserves are far less stable due to technological changes and economic developments, and estimates of reserve bases are no longer reported by the US Geological Survey due to data constraints.

The Ecoindicator method uses a different approach: it quantifies the extra energy that will be required in the future to produce a metal from lower ore grades. The method is based on historical data on the cumulative amount of mined metals in function of the ore grade. A lognormal distribution gives linearized trends for some important metals [186]. This leads to the following equation (with Q the cumulative amount, g the ore grade and m the slope of the curve):

$$\log(Q) = c - m.\log(g) \qquad (18)$$

If the current ore grade g_1 is known, ore grade g_2 can be calculated at a time when the cumulative amount is five times the current cumulative amount Q. The choice to consider $5Q$, and not another $N.Q$, was arbitrary. If $\log(Q)$ is subtracted from $\log(5Q)$, the equation becomes $\log(g_2) = \log(g_1) - 0.6989/m$. Chapman [186] determined the slope m for 10 metals. These values were updated by De Vries in 1988 [187]. He also calculated the *m*-value for two additional metals. The current ore grades g_1 are based on the year 1980 [186]. The surplus energy (in MJ per ton metal) can now be calculated with equation 19:

$$E = A.(1/g_2 - 1/g_1) \qquad (19)$$

A is defined as 'the direct use of fuels in the production process, and also the fuel used to produce materials and machines used in the process'. Based on technologies of the years 1970-1980, this was 400 MJ per ton for open-pit mining, and 1000 MJ per ton for underground mining. Although the idea of estimating a surplus energy is interesting, the Ecoindicator method has many flaws. First of all, the data is very outdated. Even the 'current' ore grades date back to 1980. Second, there is an issue with '*five times the current cumulative amount*'. If metals are not extracted at the same rate, this point is reached at different times in the future. Third, only 12 metals are included in the method, because the historical data was limited to these metals. Further, using the decrease in ore grades over short periods of time (e.g. 20 years) as a parameter for resource depletion, is heavily debated. A shift to lower grades ores over time can for example also be caused by a movement to high volume and lower cost extraction technologies, characterized by lower ore selectivity in the mining process [188].

The method of EPS 2000 is based on the willigness to pay (WTP) for the - preferably sustainable - production of metal ores from the earth's crust, which are otherwise obtained through natural processes [183, 184]. Consider for example sulphide ores, from which copper can be obtained. The natural processes creating these reserves are weathering, leaching by rain and precipitation. The alternative production by humans is assumed to be similar to the natural processes. Weathering can be exchanged by mining, crushing and grinding. Leaching by rain can be exchanged by leaching with something more active, for example hydrofluoric acid. The metal in the leachate is than precipitated by using a sulphide containing solution. For a more sustainable process, hydrofluoric acid might be substituted by micro-organisms.

Next, a life cycle inventory is made of all the resources and emissions related to this process. Each resource or emission flow corresponds with an environmental load unit (ELU), i.e. an environment damage cost of one euro per unit. The total cost of this process is used as a rough estimate of the willigness of future generations to pay. This method was critised by Müller-Wenk [189] because the point when metals would be extracted from average rocks lies far in the future, which questions the relevance of the hypothetical scenarios. Also Klinglmair et al. [129] state the assumptions and long timeframe in determining willingness to pay result in high uncertainty.

Finally, the method of Recipe quantifies the extra monetary costs (in $) associated with mining for the extraction of 1 kg metal [91]. One of the most important data sources is the US Geological Survey, which contains historical data from over 3000 mines on 50 deposits [190]. A deposit is what is extracted from the mine, and most deposits contain several mineral ores. Mining results in deposit with lower ore grades, and thus a lower value ($), because they contains less valuable metal. For each decrease in the value ($) of the ore grade, there is an extra mining cost ($). This cost is based on two internet sources: CostMine, with data of an open-pit mine in western USA, and InfoMine, with data about the open-pit Grasberg copper-gold mine in Indonesia. Both sources estimate an average mining cost 0.004$ per kg ore for mining, and 0.013$ per kg ore for milling.

The method assumes that this cost is valid for all deposits, without making a distinction between open-pit mining and underground mining. Concerning data on minerals deposits, the Recipe method uses a renown data source, the US Geological Survey. However, for mining cost, the data is very limited, as it is based on only two sources, without a distinction between open-pit and underground mining. Further, the used metal market prices are not averaged over longer time periods [179].

As existing and future resource constraints are of great relevance for policy makers [177], there is an urgent need for a better elaboration of resource depletion methods. This can be done by introducing new insights from other research. As an example, we will discuss the work of Valero et al. [191, 192], in which the surplus energy concept (Ecoindicator99), the production of metal ores from the earth's crust (Recipe) and the exergy approach are combined. They calculate the 'replacement cost' as a measure for resource depletion. This replacement cost is the energy that would be required to recover a mineral from the Earth's crust instead of the mine, with the currently available technology [191]. The approach of Valero et al. is presented in Figure 23.

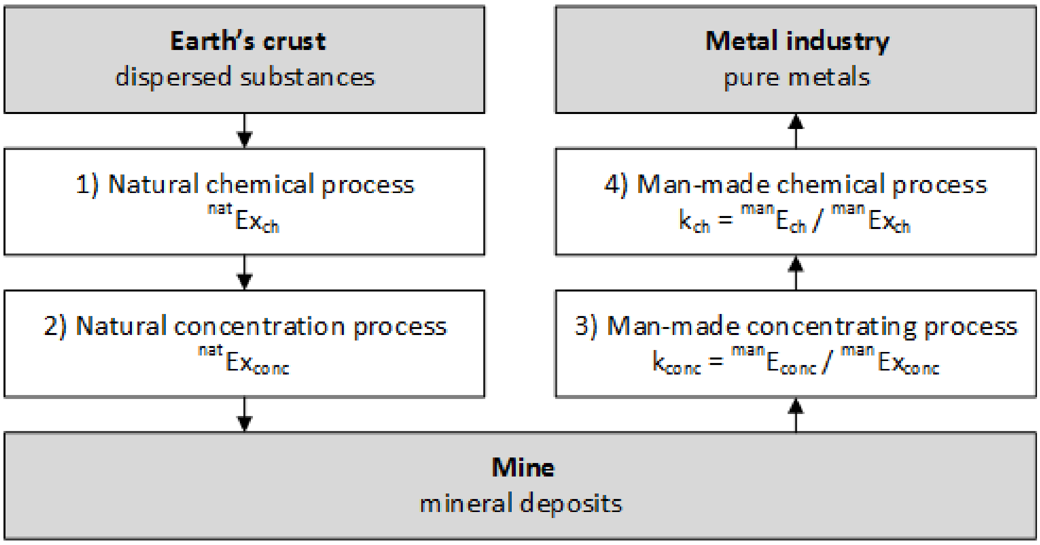

Figure 23: Representation of the approach by Valero et al. [191]

They start at the Earth's crust, for which a reference environment is defined. This is a hypothetical thermodynamic state, in which all chemical elements are dispersed. For each element, the most common and stable compound in the Earth's crust is selected as reference substance [191]. Through naturally occurring chemical processes, these substances are transformed into minerals. For example: the copper mineral chalcopyrite $CuFeS_2$ is formed from the substances Cu^{2+}, Fe_2O_3 and SO_4^{2-} [193]. Through naturally occurring concentration processes, these minerals are aggregated into mineral rocks or deposits. Mines are infrequent aggregates of such deposits. When extracting deposits from a mine, the minerals are separated from the rocks through man-made concentration processes, like grinding, crushing, etc. After that, the mineral is refined to the final product, for example pure copper, through man-made chemical (metallurgical) processes.

It is possible to calculate the exergy value of the natural chemical process (${}^{nat}Ex_{ch}$) and the natural concentration process (${}^{nat}Ex_{conc}$) with the formulas of Szargut [194]. The total exergy required to bring the mineral from the Earth's crust to the mine is the sum of the chemical exergy ${}^{nat}Ex_{ch}$ and concentration exergy ${}^{nat}Ex_{conc}$. But exergy represents only the minimal energy required to produce resources from the reference environment. If the minerals had to be created from the Earth's crust with the currently available technology, the energy requirements would have been much higher [195].

Therefore, 'unit costs' factors are calculated, based on the man-made processes. For these processes, both the minimum energy requirements (exergy) and the actual energy requirements are known. Factor k_{ch} is the ratio of the energy invested in the man-made chemical process (${}^{man}E_{ch}$) over the exergy required if this process was reversible (${}^{man}Ex_{ch}$) and factor k_{conc} is the ratio of the energy invested in the man-made concentration process (${}^{man}E_{conc}$) over the exergy required if this process was reversible (${}^{man}Ex_{conc}$). Finally, the replacement cost can be calculated by equation 20 [196]. This replacement cost is the bonus that nature gives us for free by providing minerals concentrated in mines, and not only dispersed in the Earth's crust.

$$E^* = k_{ch}\left({}^{nat}Ex_{ch}\right) + k_{conc}\left({}^{nat}Ex_{conc}\right) \qquad (20)$$

The replacement cost is thus also an estimate of the surplus energy, as in the method of Ecoindicator 99 [181]. However, Valero et al. look at this concept from a different angle.

The replacement cost avoids the '*five times 1980 level*' problem from the Ecoindicator method, as it is not based on cumulative extraction data. Instead, it is based on the concentration of minerals in the Earth's crust and in the mines. This availability of resources in the Earth's crust is also used in the method of CML [180]. Further, the replacement costs makes it possible to consider a much wider range of metals than the Ecoindicator method. In conclusion, the insights that can be gained from the work of

Valero et al. could be useful in the further development of resource depletion methods for metals and minerals.

7.2.2 Focus on waste-as-resources

Another challenge is the further development of recycling indicators for a circular economy [197]. The Ellen McArthur Foundation defines circular economy as follows: "*a circular economy is one that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles*" [198]. Experience in LCA however has shown that in order to promote a circular economy, trade-offs between environmental burdens and benefits related to recycling should also be taken into account [199]. As the recyclability benefit rate considers both the environmental burdens and benefits, this indicator is very useful for decision-making in the context of a circular economy.

However, as mentioned in section 7.1.2, additional indicators are needed, that consider all the different waste treatment options. The ISO 14044 [61] standard makes a distinction between two types of recycling: closed-loop recycling occurs when 'a material from a product is recycled in the same product system', open-loop recycling occurs when 'a material from one product system is recycled in a different product system'. However, in this classification, the link with the material quality is missing. In fact, it is the 'quality' of the (plastic) waste which determines which waste treatment option is the most preferable in terms of resource savings [127].

Therefore, the following classification for the possible waste treatment options is proposed: if the plastic is of high quality, it can substitute the virgin original material in a 1:1 ratio (closed-loop recycling). If the quality is lower, there are two possibilities: (1) the recycled material can still substitute the original virgin material, but not in a 1:1 ratio, as additional virgin material has to be added to meet the same quality requirements (semi closed-loop recycling); (2) the recycled plastic can only be used in lower-grade applications, in which it substitutes different types of materials (open-loop recycling). In the worst case scenario, if the quality is extremely low, the waste can be incinerated for energy recovery (incineration).

These insights should lead to improved indicators, capable of taking the quality aspect and maximal environmental benefit of each waste treatment scenario into account.

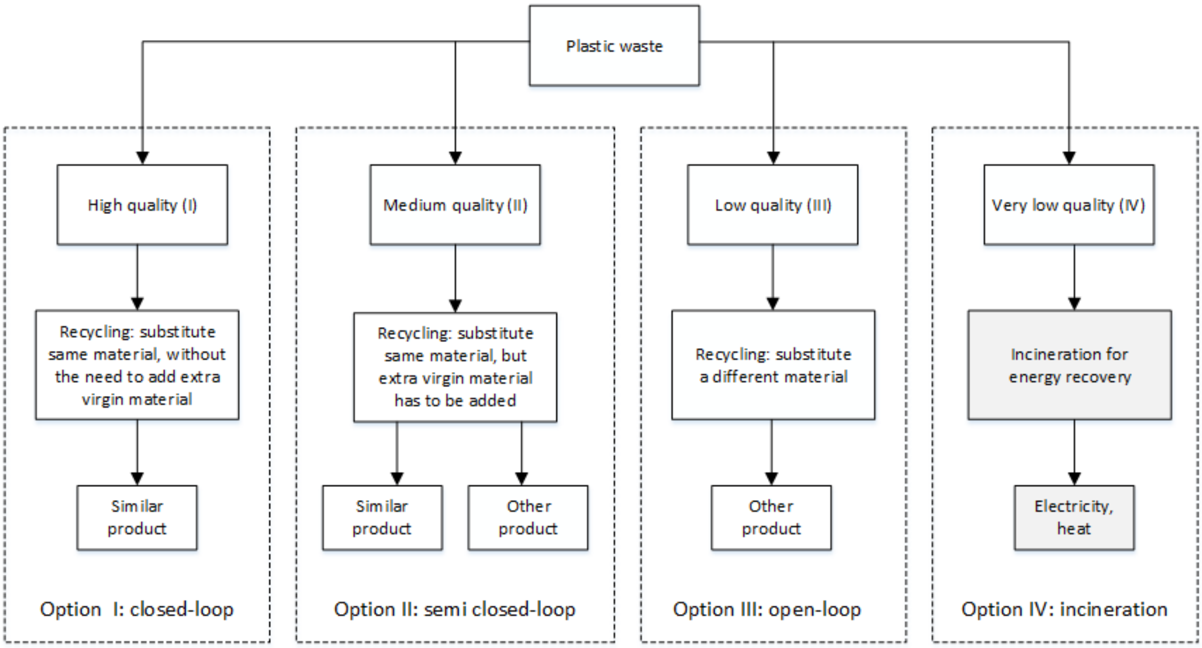

Figure 24: Different waste treatment options

Figure 24 will be explained by means of existing examples. The first waste treatment option, closed-loop recycling, corresponds with the recycling of plastics extracted from domestic appliances by the company Galloo. This plastic waste is of high quality, as 1 kg recycled plastic can substitute 1 kg of the original virgin plastic: no extra virgin material has to be added to fulfill to product requirements. This interpretation of 'closed-loop' stands alone from the recycling rate (a percentage of the materials is still lost during the recycling process) and the addition of chemicals (e.g. stabilizers) during the recycling process.

The second option, semi closed-loop recycling, corresponds with a case study from the master thesis of Jonas De Schaepmeester [200]. In this case study, industrial plastic waste is recycled by the company Powerpack into garbage bags. The produced garbage bags are composed of 80% recycled material and 20% virgin material, to fulfill certain requirements that are regulated at the federal level: drop impact resistance and resistance to leakage. This means that 1 kg recycled material cannot substitute 1 kg virgin material: extra virgin material has to be added to fulfill the product requirement.

The third waste treatment option, open-loop recycling, corresponds with the recycling of household plastics by the company Ekol. The plastic waste is of low quality, and can only be used for low-grade applications, in which it substitutes another type of virgin, e.g. wood or cast iron in case of a street bench.

A preliminary estimate to estimate the quality of plastic waste has been introduced in the master thesis of Jonas de Schaepmeester [200]. This indicator is based on the compatibility of the different polymers in the blend [201]. To predict the compatibility of the waste stream, the interfacial tension between the polymers was calculated. The ability to calculate quality factors in advance makes it possible to 'design for recycling'. This means that the plastic waste stream can be assigned to its most suitable application. As this master thesis was a preliminary study, several assumptions were made: the waste consists of only two polymers, no compatibilizers were added and no chain degradation occurs. Future research could focus on the further development of such a quality parameter.

Furthermore, other material types could be investigated as well. It would be useful to develop material-specific indicators, as different materials require different recycling processes, in particular metal recycling. Generally, metals are highly amenable to recycling [202]. However, these recycling processes can be energy-intensive and are often based on complex technologies. The latter is especially the case for critical metals, e.g. cobalt recycling from rechargeable batteries [203]. In terms of resource depletion, the environmental benefit from recycling critical metals can be much larger than the environmental burden of the recycling process. Trade-offs need to be made between impacts on resource depletion and impacts on global warming. Hence, the recyclability benefit rate indicator could be further elaborated for metal recycling. Hereby, it is useful to make a distinction between bulk metals (e.g. steel) and critical metals [204]. Also the selection of the impact methodology is very important. The latter can be combined with the research challenge from the previous section (i.e. the improvement of resource depletion methods), to elaborate well-defined indicators for metal recycling.

Appendices

A.1. Appendix of chapter 3

A.1.1. Mathematical structure of LCI-models

The linear inverse model of a LCI-model has the following matrix structure (equation 21) [64].

$$B.\ A^{-1}.f = g \qquad (21)$$

Matrix A is called the technology matrix. Each column of A represents a process, and each element a_{ij} represents the input or output products i from process j, expressed in any unit per flow, mostly physical ones. Inputs are noted by positive values, outputs by negative values. The technology matrix can only be inverted if it is a square matrix. If A is not square, it should be made square by using either partitioning (allocation) or system expansion [65]. Vector f is called the final demand vector. The non-zero elements f_i correspond with the demanded output, expressed in physical units. To achieve this final demand f, the technology matrix has to be scaled with a scaling vector x. This scaling vector can consequently be calculated by solving the equation: $x = A^{-1} f$. The last step in life cycle inventory analysis is the multiplication of vector x with environmental matrix B. Each element b_{ij} of matrix B represents consumed resources or emitted pollutants i by process j, also expressed in any units possible, often physical. The resulting vector is the inventory g of environmental flows associated with a final demand f.

A.1.2. Countries in Exiobase

The 43 countries and 1 rest of the world region used in the Exiobase database are listed in Table 10 [74].

Table 10: countries in the Exiobase database

AT	Austria	RO	Romania
BE	Belgium	SE	Sweden
BG	Bulgaria	SI	Slovenia
CY	Cyprus	SK	Slovak Republic
CZ	Czech Republic	GB	United Kingdom
DE	Germany	US	United States
DK	Denmark	JP	Japan
EE	Estonia	CN	China
ES	Spain	CA	Canada
FI	Finland	KR	South Korea
FR	France	BR	Brazil
GR	Greece	IN	India
HU	Hungary	MX	Mexico
IE	Ireland	RU	Russia
IT	Italy	AU	Australia
LT	Lithuania	CH	Switzerland
LU	Luxembourg	TR	Turkey
LV	Latvia	TW	Taiwan
MT	Malta	NO	Norway
NL	Netherlands	ID	Indonesia
PL	Poland	ZA	South Africa
PT	Portugal	WW	Rest of World

A.1.3. Elementary flows in Exiobase

In the Exiobase database, elementary flows are called 'environmental extensions'. They are derived from different data sources, which are shortly summarized in Table 11.

Table 11: data sources of the environmental extensions

Metals and minerals
British Geological Survey [205]. Additional sources are US Geological Survey [190], World Mining Database of the Austrian Ministry for Economy and Labour (WMD) and UNSTATS data [206].
Fossil fuels
IEA energy statistics [207]. IEA reports all of these categories in primary units of 1000 tons. Only the values of natural gas had to be converted from TJ into 1000 tons, using a conversion factor provided by IEA itself.
Biomass
FAO database [75]. For crops, all data is reported in fresh weight (80% water content) and had to be transformed into hay weight (15 % water content). For wood, the data is reported in cubic metres and had to be transformed into tons by using density coefficients. For grass, the data had to be derived from the pasture area (≈ yield * pasture area). For aquatic animals, some of the data is not reported in tonnes but in numbers of catched animals (e.g. seals), these values were transformed into tons using average weight factors.
Land use
FAO database [75]. For arable land, the category 'arable and permanent crops' was used. In regular cases the actual area harvested will be smaller than the reported area used for agriculture, as not 100% of the sown area yield return. For pastures, the category 'permanent meadows and pastures' was used. For forest area, the category 'forest and woodland' was used. However, this forest data makes no differentiation between used and non-used forests.
Water use
For agricultural water use and consumption, data was modelled with the LPJmL model [15]. For industrial water use and consumption, data was modelled with the WaterGAP2 model [29].
Energy use
IEA extended energy balances [208, 209]. In the IEA statistics, calorific values are used to transform fuels from mass and volume to energy units. Renewable energy

inputs are expressed in megajoules of electricity and not in terms of primary energy.
Emissions to air
The air emissions have been calculated using the methods provided by the IPCC Guidelines and the EMEP/EEA Guidebook. The main sources for activity rates are the IEA Energy Statistics [207], the FAO statistics [75], the US Geological Survey Minerals Yearbook [190] and the UNSTAT data [206] .
Emissions to soil
For the calculation of the data on N and P emissions to soil the following data source was used: FAO database [75] livestock units.

A.1.4. Characterisation factors

A.1.4.1. Metal ores

The category metal ores includes 9 elementary flows: iron ores, aluminium ores, copper ores, lead ores, nickel ores, tin ores, zinc ores, precious metal ores and other metal ores. All these flows in Exiobase are expressed in kg gross ore, which is common for data originating from economy-wide material flow analysis. The gross ore is the metal-containing material obtained after extraction. Beneficiation concentrates this gross ore to concentrates/minerals, and metallurgical processes convert these minerals into pure metal (Figure 25) [3].

In LCI-CEENE, almost all elementary flow are expressed in kg pure metal, whereby the corresponding LCI-based X-factors have been calculated per kg metal content (based on the Ecoinvent database). For example, even though aluminium is extracted in the form of the mineral bauxite, it is the weight of the aluminum metal that is calculated by Ecoinvent. The corresponding LCI-based X-factor of this aluminium flow was calculated based on the exergy value of the representative minerals, the share of these minerals in the metal supply and the mole fraction of the minerals mined to obtain one mole of metal.

To apply the LCI-based X-factors also in IO-CEENE, they have to be converted from exergy per kg metal content to exergy per kg gross ore, using appropriate conversion factors. For this study, the general conversion factors from the Eurostat manual were used [76]. The estimation of those factors is predominantly based on information from annual business reports for about 160 metal mines. It was possible to apply these conversion factors on the LCI-based X-factors corresponding with the first eight elementary flows. The two other elementary flows 'precious metal ores' and 'other metals ores' are too aggregated to apply the LCI-based X-factors. Therefore, the original disaggregated data was requested from the SERI (Sustainable Europe Research Institute) database [78].

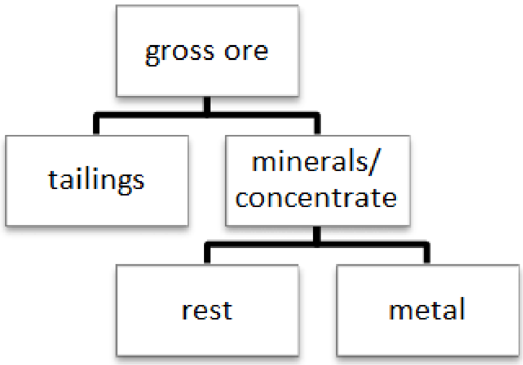

Figure 25: From gross ore to metal content

The elementary flow 'precious metal ores' consists of three subflows (silver, gold and platinum group metals), while the elementary flow 'other metal ores' consists of 21 subflows (antimony, arsenic, beryllium, bismuth, cadmium, chromium, cobalt, germanium, lithium, magnesium, manganese, mercury, molybdenum, niobium and tantalum, rare earths, selenium, tellurium, titanium, tungsten, vanadium, zirconium and hafnium). The share of these subflows (in kg gross ore) to the total elementary flow is known for each country.

Knowing the exergy value of each subflow and the amount of subflow extracted by each country, it is possible to calculate IO-based X-factors for the two elementary flows 'precious metal ores' and 'other metal ores' (see Table 12). The calculation method is show in equation 22, with X_j the exergy value of subflow j (in MJ_{ex}/kg metal content), F_j the conversion factor of subflow j (in kg metal content per kg gross ore), $M_{j,k}$ the amount of subflow j to the total elementary flow i in country k (in kg gross ore), n the number of subflows contributing to elementary flow i for country k and $\hat{X}_{i,k}$ the Exiobase X-factor for elementary flow i (in MJ_{ex}/kg gross ore) in country k. These X-factors are labelled 'country-specific by group', because the share of subflows is different for each country.

$$\hat{X}_{i,k} = \frac{\sum_{j=1}^{n_k} X_j \,.\, F_j \,.\, M_{j,k}}{\sum_{i=1}^{n_k} M_{j,k}} \qquad (22)$$

For certain metals (i.e. titanium, antimony, mercury, tungsten, beryllium and vanadium), the factor X_j (MJ_{ex}/kg metal content) had to be calculated first (see Table 13). The calculation method is based on the supporting information from Dewulf et al. [3] (see equation 23), with MW_j the molar weight of the element j, v_i the mole fraction of the nth mineral that will be mined for 1 mole of the element, $e_{ch,n}$ the chemical exergy of the nth mineral. v_n is calculated by dividing the estimated share of the respective minerals by the number of element atoms in its formula.

$$X_j = \frac{\sum_n (v_n \, e_{ch,n})}{MW_j} \qquad (23)$$

Table 12: X-factors for the category metal ores. When no gross ore/metal content conversion factors from Eurostat were available, factors from Valero [77] were used (underlined). ‘USGS’ = United States Geological Survey [190]; ‘BGS’ = British Geological Survey [205]; ‘LCI-based X-factor’ = exergy value of the pure metal is the same as the X-factor from LCI-CEENE; ‘Refinery byproduct’ = low quantities, exergy value is assumed zero; ‘Assumed from brines’ = according to the BGS, the main magnesium sources are brines, dolomite and magnesite. Since dolomite and magnesite are already covered in the category (non-metallic) minerals, magnesium was here assumed to be coming mainly from brines. In the CEENE methodology, resources in brines are considered as resources in seawater, and because seawater is a reference species according to Szargut, resources in brine have an exergy content equal to zero [31, 210].

Elementary flow	MJ_{ex}/kg pure metal	Type/Explanation	Conversion factor	MJ_{ex}/kg gross ore
Iron	3.62E-01	LCI-based X-factor	4.33E+01	1.57E-01
Aluminium	4.75E-01	LCI-based X-factor	1.90E+01	9.01E-02
Copper	1.58E+01	LCI-based X-factor	1.04E+00	1.64E-01
Lead	3.58E+00	LCI-based X-factor	1.19E+01	4.25E-01
Nickel	2.51E+01	LCI-based X-factor	1.83E+00	4.59E-01
Tin	3.63E-01	LCI-based X-factor	2.40E-01	8.71E-04
Zinc	1.14E+01	LCI-based X-factor	8.34E+00	9.54E-01
Uranium	4.69E+05	LCI-based X-factor	2.00E-01	9.39E+02
precious metals				
Gold	7.82E-02	LCI-based X-factor	2.10E-04	1.64E-07
Platinum group	5.29E+00	LCI-based X-factor	5.00E-05	2.64E-06
Silver	3.28E+00	LCI-based X-factor	3.40E-02	1.11E-03
other metals				
Chromium	1.02E+01	LCI-based X-factor	3.78E+00	3.87E-01
Cobalt	0.00E+00	LCI-based X-factor	1.00E+00	0.00E+00

Lithium	2.10E+00	LCI-based X-factor	1.00E+00	2.10E-02
Manganese	0.00E+00	LCI-based X-factor	5.00E-01	0.00E+00
Molybdenum*	0.00E+00	LCI-based X-factor	1.00E-02	0.00E+00
Niobium,tantalum	1.60E+00	LCI-based X-factor	2.57E+01	4.11E-01
Zirconium,hafnium	1.18E+00	LCI-based X-factor	7.70E-01	9.12E-03
Arsenic	0.00E+00	Refinery byproduct (USGS)	5.00E-03	0.00E+00
Bismuth	0.00E+00	Refinery byproduct (USGS)	4.00E-02	0.00E+00
Cadmium	0.00E+00	Refinery byproduct (USGS)		0.00E+00
Germanium	1.01E+00	Refinery byproduct (USGS)	3.59E+01	3.62E-01
Selenium	3.34E+00	Refinery byproduct (USGS)	3.80E-01	1.27E-02
Tellurium	1.75E+01	Refinery byproduct (USGS)	1.30E-01	2.27E-02
rare earths	0.00E+00	Too small amounts: zero	6.40E-01	0.00E+00
Magnesium	0.00E+00	Assumed from brines (BGS)	1.00E-01	0.00E+00
Antimony	0.00E+00	See Table 13	2.50E+00	0.00E+00
Mercury	0.00E+00	See Table 13		0.00E+00
Titanium	2.38E+00	See Table 13	Mix	3.79E-01
Tungsten	7.07E-01	See Table 13	3.90E-01	2.76E-03
Beryllium	7.78E+00	See Table 13	2.00E+00	1.56E-01
Vanadium	0.00E+00	See Table 13	2.70E-01	0.00E+00

Table 13: X-factors for specific metals. MW = molecular weight. For titanium, antimony and mercury, data for the main minerals and their exergy value was taken from the Supporting Information of De Meester et al. [44] The shares of ilmenite and rutile were estimated based on values from the United States Geological Survey (91 % ilmenite and 9% rutile) [190]. For tungsten, beryllium and vanadium, data for the main minerals and their exergy value was taken from Valero [77].

Element	MW element (g/mol)	Main Minerals	Exergy mineral (kJ_{ex}/mol)	Share	metal atoms	mole fraction	Exergy metal (MJ_{ex}/kg)
Titanium	4.79E+01	Ilmenite	1.35E+02	0.84	1	0.84	
		Rutile	2.64E-01	0.16	1	0.16	2.38E+00
Antimony	1.22E+02	Stibnite	2.49E+03	1	2	0.5	1.02E+01
Mercury	2.01E+02	Cinnabar	6.71E+02	1	1	1	3.34E+00
Tungsten	1.84E+02	Scheelite	1.40E+02	0.5	1	0.5	7.07E-01
		Wolframite	1.20E+02	0.5	1	0.5	
Beryllium	9.01E+00	Beryl	5.69E+01	1	3	0.33	2.10E+00
Vanadium	5.09E+01	Carnotite	7.92E+02	1	2	0.5	7.78E+00

A.1.4.2. Nuclear resources

The CEENE category nuclear resources consists of the elementary flow 'uranium and thorium ores', which was originally classified in the Exiobase (sub)category 'metal ores'. This elementary flow is thus also expressed in kg gross ore instead of kg metal content. Consequently, the LCI-based X-factor (469259.56 MJ_{ex}/kg uranium) had to be converted from exergy per kg metal content to exergy per kg gross ore, using the conversion factor from Eurostat [76].

A.1.4.3. Minerals (non-metallic)

The category minerals consists of nine elementary flows: 'Chemical and fertilizer minerals', 'Clays and kaolin', 'Limestone, gypsum, chalk, dolomite', 'Salt', 'Slate', 'Other industrial minerals', 'Building stones', 'Gravel and sand' and 'Other construction minerals'. All these flows are too aggregated for using the existing LCI-based X-factors. Again, the original disaggregated data was requested from the SERI database for each country. To each of these subflows, an exergy value was assigned.

Knowing the exergy value of each subflow and the amount of subflow extracted by each country, it is possible to calculate IO-based X-factors for each elementary flow (see Table 14). These X-factors are thus also country-specific by group. The calculation method is shown in equation 24.

$$\hat{X}_{i,k} = \frac{\sum_{j=1}^{n_k} X_j \, . M_{j,k}}{\sum_{i=1}^{n_k} M_{j,k}} \qquad (24)$$

with X_j the exergy value of subflow j (in MJ_{ex}/kg mineral), $M_{j,k}$ the amount of subflow j to the total elementary flow i in country k (in kg mineral), n_k the number of subflows contributing to elementary flow i for country k and $\hat{X}_{i,k}$ the IO-based X-factor for elementary flow i (in MJ_{ex}/kg mineral) in country k.

Table 14: X-factors for the category minerals (in MJ_{ex}/kg). 'old'= exergy value is the same as the X-factor from LCI-CEENE; 'new' = newly calculated X-factor.

Elementary flows and subflows	X-factor	Origin (old, new) and explanation
Chemicals and fertilizers		
Barite	1.28E-01	Old (Barite)
Borate minerals	2.43E-01	Old, average X-factors borax, colemanite, ulexite [44]

Fluorspar	4.40E-01	Old (Fluorspar)
Phosphate rock	2.60E-02	Old (Apatite)
Sulphur (also by-product)	1.89E+01	Old (Sulfur) Includes recovered sulfur [3]
Sulphur from pyrites	2.23E+01	New, see Table 15
Clays and kaolin		
Ball clay	5.70E-02	Old (Kaolinite), see table 51.02 in [211]
Bentonite, sepiolite, ...	1.09E-01	Old (Bentonite): represented by montmorillonite [3]
Fire clay, flint, kyanite, ...	5.70E-02	Old (Kaolinite), see table 51.02 in [211]
Fuller's earth	1.09E-01	Old (Bentonite), see table 51.02 in [211]
Kaolin	5.70E-02	Old (Kaolinite),
Potter clay	5.70E-02	Old (Kaolinite), see section 51.5 in [211]
Special clay	1.06E-01	Old (unspecified clay): represented by illite [3]
Limestone, gypsum, dolomite		
Dolomite	1.26E-01	Old (Dolomite)
Gypsum and anhydrite	1.55E-01	Old, average anhydrite (0,16 MJ/kg) & gypsum (0,15 MJ/kg)
Salt		
Rock salt	2.48E-01	Old (Sodium chloride)
Salt from brine	0.00E+00	New: exergy from brines is zero [31]
Solar salt	0.00E+00	New: also from seawater or brines [212], exergy is zero [31]
Slate		
Slate including fill	8.23E-02	Old (Shale): shale turns into a slate [211]
Other industrial minerals		
Industrial sand	3.10E-02	Old (Sand): Industrial sand, often called silica sand or quartz sand, is sand with high silicon dioxide content [190]
Sillica sand (quartzsand)	3.10E-02	
Calcite	1.84E-01	Old (Calcite)
Chalk	1.84E-01	Old (Calcite): chalk is composed of calcite [44]
Peat for agricultural use	1.02E+01	Old (Peat)
Abrasives natural (pumice)	7.29E-02	Old (Pumice)
Diamonds, gems or industrial	3.86E+01	New: group contribution method $C(sp^3)$
Diatomite	3.86E+01	Old (Diatomite)
Feldspar	4.05E+00	Old (Feldspar)
Graphite, natural	1.03E-01	Old (Graphite)
Iron ore for pigments	3.42E+01	New: see Table 15
Magnesite	1.57E-01	Old (Magnesite)
Mica	1.15E-01	New: mineral of micas is muscovite [44]
Potash	3.08E-02	Old (Sylvite) mineral name of potash is sylvite [44]
Qartz and quartzite	2.68E-01	New: exergy value of quartz [44]
Strontium minerals	2.30E-02	New: see Table 15
Talc (steatite, etc)	1.76E-01	Old (Talc)
Asbestos	5.65E-02	Old (Chrysotile) [44]
Perlite	1.06E-01	Old (Perlite)
Building stones		
Marble, travertines etc.	1.84E-01	Old (Calcite), see table 02.01 in [211]
Gravel and sand		
Sand and gravel	6.00E-02	Old: average between X-factors sand and gravel

Other construction minerals		
Igneous rock (basalt,…)	2.00E-01	Old: average between X-factors basalt and granite
Sandstone	2.30E-02	New: see 'Qartz' in table 02.01 in [211]
Crushed stone	1.38E-01	New: average between X-factors of chalk, dolomite, sandstone, quartz, gypsum, granite, basalt [76]
Asphalt	1.86E+01	New: specific exergy of asphaltite [213]
Common clay, etc.	1.06E-01	Old (Clay unspecified): assumed to be mainly illite [44]
Construction Minerals nec	9.88E-02	New: average of sand & gravel and crushed stone

Table 15: X-factors for specific minerals. MW = molecular weight. For sulfur from pyrites, data for the main minerals and their exergy value was taken from the supporting information of Dewulf et al. [3] For strontium, data for the main minerals and their exergy value was taken from Valero [77].

Element	Main minerals	Exergy mineral (kJex/mol)	MW mineral (g/mol)	Share	metal atoms	mole fraction	Exergy metal (MJ/kg)	Exergy concen. (MJ/kg)
Sulfur from pyrites	pyrite	1.43E+03	1.20E+02	1	2	0.5	2.23E+01	1.19E+01
Strontium	celestine	3.24E+01	1.84E+02	1	1	1	3.70E-01	1.76E-01

A.1.4.4. Fossil fuels

The category fossil fuels consists of six elementary flows: hard coal, brown coal, crude oil, peat, natural gas, natural gas liquids. For first 4 elementary flows, the generic LCI-based X-factors were used. The calculation of these X-factors is based on the average higher heating values (HHV) and lower heating values (LHV) of hard coal, brown coal and peat and crude oil. Afterwards, these HHV (or LHV) were multiplied with exergy/MJ HVV (or LHV) ratio's from Szargut [194]. More details can be found in Dewulf et al. [3]. However, the LCI-based X-factors could not be used for the elementary flows natural gas and natural gas liquids, because these flows don't correspond with the Ecoinvent flows. In Ecoinvent, the elementary flow natural gas represents crude natural gas as it is extracted from the environment. In Exiobase on the other hand, the elementary flows 'natural gas' and 'natural gas liquids' represent both the market production as defined by the IEA (International Energy Agency).

In the IEA statistics manual [79], two types of crude natural gas (CNG) are distinguished: crude natural gas produced in association with crude oil extraction (associated crude natural gas, ACNG) and crude natural gas extracted from a gas reservoir (non-associated crude natural gas, NCNG). First, impurities and sulphur can be removed from the NCNG. Next, natural gas liquids are separated from both the ACNG and the NCNG. Natural gas liquids are heavier hydrocarbons such as ethane, propane, butane, pentane and C5+. Consequently, the remaining gas is almost purely methane. This remaining gas and the separated natural gas liquids form the market production. They are further called market natural gas (MNG) and market natural gas liquids (MNGL), see Figure 26.

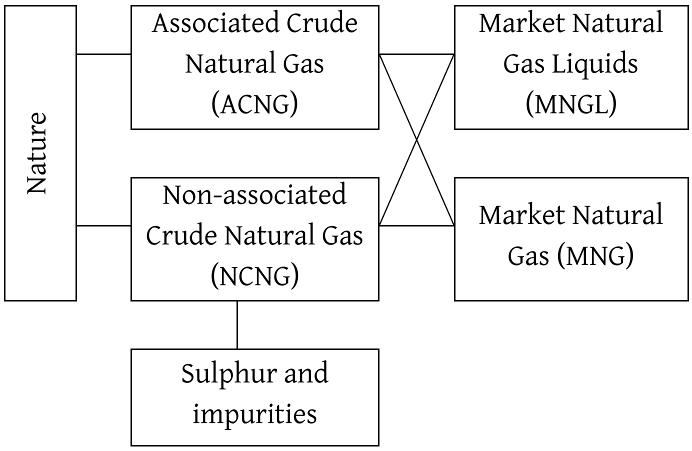

Figure 26: Natural gas in the International Energy Agency (IEA) statistics

In Exiobase, MNG and MNGL are represented by the elementary flows ‘natural gas’ and ‘natural gas liquids’, both expressed in terms of mass (kg).

To use the same approach as in LCI-CEENE, the amount of crude natural gas had to be calculated. Considering the production of MNG and MNGL as one process (crude natural gas → market natural gas + natural gas liquids), the first law of thermodynamics (conservation of energy) could be applied. The influence of sulphur and impurity removal was assumed to be negligible. The sum of MNG and MNGL, both expressed in terms of energy (MJ HVV), gives the amount of crude natural gas (in MJ HHV) extracted from the environment. Therefore, conversion factors had to be determined to convert the MNG and MNGL flows from mass (kg) to energy (MJ HHV).

For MNG, the HHV of methane (55.52 MJ/kg) was used as conversion factor. To calculate a conversion factor for the MNGL flow, the average composition of MNGL supply in the US was used (Table 16) [214]. This supply includes MNGL originating from both associated and non-associated gas. Imported MNGL were not taken into account. Knowing the densities and HHV’s of ethane, propane, butane and condensate from Table A3.8 in the IEA statistics manual [79], an average MJ HHV/kg conversion factor (50.03 MJ/kg) for the total MNGL flow was calculated. Due to lack of more international data, this conversion factor was assumed to be similar for each country.

Table 16: Market natural gas liquid supply in the United States. NGL = natural gas liquids; HHV = higher heating value (MJ/kg)

year 2011	vol%	m^3/year	density (kg/m^3)	kg/year
NGL from gas processing		3.5E+05		
Ethane	42%	1.47E+05	3.66E+02	5.38E+07
Propane	29%	1.00E+05	5.08E+02	5.10E+07
Butane	17%	5.85E+04	5.73E+02	3.35E+07
condensate (C5+)	13%	4.65E+04	5.73E+02	2.66E+07
NGL from refineries		9.8E+04		
Ethane	3%	3.15E+03	3.66E+02	1.15E+06
Propane	89%	8.77E+04	5.08E+02	4.45E+07
Butane	8%	7.58E+03	5.73E+02	4.34E+06

	kg/year	m%	kg/kg NGL	HHV (MJ/kg)
NGL total				5.03E+01
Ethane	5.50E+07	25.6%	0.26	5.19E+01
Propane	9.55E+07	44.4%	0.44	5.03E+01
Butane	3.78E+07	17.6%	0.18	4.95E+01
Condensate	2.66E+07	12.4%	0.12	4.59E+01

The total amount of crude natural gas (CNG, in MJ HHV) can be estimated by multiplying the MNG and MNGL flows with these conversion factors, further called (α) and (β), and adding them up. Next, an average exergy/HHV ratio (0.93 MJ_{ex}/ MJ HHV) for crude natural gas was calculated based on Ecoinvent report 6-V (Table 17) [215].

Table 17: Calculation of an average X-factor for natural gas. HHV = higher heating value

	Exergy ($kJex/m^3$) (Table 3.2)	HHV (kJ/m^3) (Table 3.2)	exergy content/HHV (MJ_{ex}/MJ)
Netherlands	3.01E+01	3.23E+04	9.30E-01
Norway	3.64E+01	3.88E+04	9.38E-01
Russia	3.37E+01	3.61E+04	9.34E-01
Germany	3.07E+01	3.24E+04	9.46E-01
weighted average			9.34E-01

Multiplying the total amount of crude natural gas with this generic X-factor gives the amount of exergy extracted from the environment (equation 25).

$$(a\ kg\ MNG\ .\ \alpha + b\ kg\ MNGL\ .\ \beta)\ .\ X \qquad (25)$$

Equation 25 can be rewritten as (equation 26):

$$a\ kg\ MNG\ .(\alpha\ .\ X) + \ \ b\ kg\ MNGL\ .(\beta\ .X) \qquad (26)$$

In practice, the approach of equation 26 was applied, as the original matrix is then less altered this way. Each elementary flow is here multiplied with its HHV/kg conversion factor, respectively (α) and (β), and the X-factor. These outcomes should then be summed up to deliver the total exergy amount of crude natural gas extracted.

A.1.4.5. Land resources

The biomass elementary flows can be subdivided into three types: grass, wood and aquatic animals. In Exiobase, these flows are expressed per mass (kg) of wet matter.

For wood and grass, a new exergy factor was calculated based on section S2 in the supporting information from Alvarenga et al. [28]. In this supporting information, exergy values (in MJ_{ex}) per kg of dry matter were calculated for roots, leaves, grass, herbaceous plants and wood. This was done using two methods: the contribution method and the β-LHV (lower heating value) method [210]. For both of them, data was collected from the Phyllis database [216]. For this thesis, we recalculated the results for grass and wood to obtain the exergy per kg of wet matter. This was done through the β-LHV method, using equations 27 and 28. The values to be put in equation 28 are the atomic ratios of the corresponding elements. e_{ch} is the chemical exergy and LHV is the lower heating value.

$$e_{ch} = \ \beta\ .\ LHV \qquad (27)$$

$$\beta = \frac{1.044 + 0.016\ \cdot {}^{H}/_{C} - 0.3493 \cdot {}^{O}/_{C}\ .(1 + 0.053 \cdot {}^{H}/_{C}) + 0.0493\ \cdot {}^{N}/_{C}}{1 - 0.4124 \cdot {}^{O}/_{C}} \qquad (28)$$

Instead of implementing the LHV_{dry} (LHV per mass of dry matter) in equation 27, LHV_{wet} (LHV per mass of wet matter) was used. This value can be calculated with equation 29, with MC the moisture content.

$$LHV_{wet} = LHV_{dry}\ .(1 - MC) - 2.442\ .MC \qquad (29)$$

Both LHV_{dry} and MC data was collected from the Phyllis database. Because there wasn't a MC value available for each type of wood and grass, the MC of 'grass from nature reserve' was used for each grass type, and the MC of 'wood, oak' was used for each wood type. An average exergy value per kg of wet matter was obtained for grass (16.6 MJ_{ex}/kg) and wood (18.6 MJ_{ex}/kg). Further, an exergy value per kg of wet matter is needed for the aquatic animals flows. This was done by taking the most captured fish species as a reference: Peruvian Anchovy [217]. To calculate the exergy content, the generic macro-nutrient method was used [210]. This method is based on the composition of the biomass, and the molecules (carbohydrates, proteins, lipids, ash and water) are accounted separately and multiplied with their chemical exergy value, see Table 18.

Table 18: Exergy value for aquatic animals

Composition	%	MJ_{ex}/kg
Protein	20.0%	2.46E+01
Lipid	5.0%	4.06E+01
Ash	1.4%	2.11E+00
Moisture	73.0%	5.00E-02
Exergy (MJ_{ex}/kg wet matter)		7.02E+00

The selected land use elementary flows all refer to arable land use. For these flows, the country-specific land use X-factors from Alvarenga et al. [28] corresponding with the 43 Exiobase-countries were used. For the region Rest of the World (ROW), a weighted average value was calculated based on the remaining 120 countries, using the arable land area (in hectares) per country from the Faostat database [75] as shown in Table 19.

Table 19: Weighted X-factor for land use in the Rest of the World (ROW).

ROW countries	X-factor (MJ_{ex}/m^2.year)	1000 ha arable land
Afghanistan	8.40E+00	7.68E+03
Albania	2.47E+01	5.78E+02
Algeria	1.80E+00	7.66E+03
Angola	3.31E+01	3.00E+03
Argentina	2.40E+01	2.76E+04
Armenia	1.60E+01	4.50E+02
Azerbaijan	1.58E+01	1.83E+03
Bangladesh	3.67E+01	8.35E+03
Belarus	2.62E+01	6.13E+03
Belize	4.98E+01	6.40E+01
Benin	2.78E+01	2.38E+03
Bhutan	2.74E+01	1.06E+02

Bolivia	3.46E+01	3.00E+03
Bosnia and Herzegovina	2.97E+01	1.00E+03
Botswana	1.48E+01	3.50E+02
Brunei Darussalam	4.80E+01	2.00E+00
Burkina Faso	2.45E+01	3.70E+03
Burundi	4.39E+01	9.60E+02
Cambodia	4.04E+01	3.70E+03
Cameroon	3.93E+01	5.96E+03
Central African Rep.	3.90E+01	1.93E+03
Chad	1.05E+01	3.60E+03
Chile	1.47E+01	1.75E+03
Colombia	4.56E+01	2.82E+03
Congo	4.53E+01	4.90E+02
Costa Rica	5.17E+01	2.10E+02
Côte d'Ivoire	3.57E+01	2.80E+03
Croatia	2.87E+01	8.42E+02
Cuba	3.97E+01	3.50E+03
Dem. Rep. of Congo	4.26E+01	6.70E+03
Djibouti	1.15E+01	1.00E+00
Dominican Republic	5.13E+01	8.68E+02
Ecuador	3.92E+01	1.62E+03
Egypt	2.00E-01	2.80E+03
El Salvador	4.09E+01	6.50E+02
Equatorial Guinea	4.25E+01	1.30E+02
Eritrea	8.40E+00	5.60E+02
Ethiopia	2.57E+01	1.00E+04
French Guiana	4.92E+01	1.20E+01
Gabon	3.98E+01	3.25E+02
Gambia	2.47E+01	2.80E+02
Georgia	2.59E+01	7.93E+02
Ghana	3.05E+01	3.95E+03
Guatemala	4.82E+01	1.40E+03
Guinea	3.23E+01	2.15E+03
Guinea-Bissau	2.61E+01	3.00E+02
Guyana	4.91E+01	4.50E+02
Haiti	4.52E+01	9.00E+02
Honduras	5.09E+01	1.07E+03
Iceland	1.42E+01	1.29E+02
Iran (Islamic Rep. of)	7.80E+00	1.49E+04
Iraq	6.70E+00	4.10E+03
Island of Man	2.47E+01	1.81E+01
Israel	7.50E+00	3.38E+02
Jamaica	4.48E+01	1.40E+02
Jordan	2.00E+00	1.90E+02
Kazakhstan	1.30E+01	2.15E+04
Kenya	2.79E+01	4.89E+03
Korea (Dem. Ppl's. Rep. of)	2.60E+01	2.30E+03
Kuwait	2.20E+00	1.00E+01
Kyrgyzstan	1.62E+01	1.36E+03
Lao People's Dem. Rep.	4.20E+01	8.77E+02
Lebanon	1.83E+01	1.29E+02
Lesotho	3.47E+01	3.30E+02

Liberia	4.15E+01	3.80E+02
Libyan Arab Jamah.	7.00E-01	1.82E+03
Macedonia (T.F. Yug. Rep.)	2.29E+01	5.55E+02
Madagascar	4.21E+01	2.90E+03
Malawi	3.18E+01	2.75E+03
Malaysia	4.83E+01	1.82E+03
Mali	1.10E+01	4.59E+03
Mauritania	2.80E+00	4.88E+02
Moldova (Republic of)	2.24E+01	1.83E+03
Monaco	2.67E+01	0.00E+00
Montenegro	2.86E+01	0.00E+00
Morocco	1.08E+01	8.77E+03
Mozambique	3.16E+01	3.90E+03
Myanmar	3.40E+01	9.91E+03
Namibia	8.60E+00	8.16E+02
Nepal	2.30E+01	2.35E+03
New Zeland	3.07E+01	1.50E+03
Nicaragua	4.93E+01	1.92E+03
Niger	6.20E+00	1.40E+04
Nigeria	2.83E+01	3.00E+04
Oman	6.00E-01	3.10E+01
Pakistan	5.50E+00	2.13E+04
Panama	5.21E+01	5.48E+02
Papua New Guinea	4.85E+01	2.05E+02
Paraguay	3.68E+01	3.02E+03
Peru	3.37E+01	3.70E+03
Philippines	4.51E+01	5.03E+03
Puerto Rico	5.38E+01	5.97E+01
Qatar	1.00E+00	1.30E+01
Republic of Mongolia	8.20E+00	1.17E+03
Rwanda	4.63E+01	9.00E+02
Saudi Arabia	4.00E-01	3.59E+03
Senegal	2.26E+01	3.05E+03
Serbia	2.65E+01	0.00E+00
Sierra Leone	3.25E+01	4.90E+02
Somalia	5.40E+00	1.04E+03
Sri Lanka	4.01E+01	9.15E+02
Sudan	1.49E+01	1.62E+04
Suriname	4.80E+01	5.70E+01
Swaziland	2.70E+01	1.78E+02
Syrian Arab Republic	9.70E+00	4.54E+03
Tajikistan	1.20E+01	7.84E+02
Thailand	3.63E+01	1.57E+04
Togo	2.95E+01	2.50E+03
Trinidad and Tobago	4.49E+01	3.50E+01
Tunisia	6.30E+00	2.86E+03
Turkmenistan	5.70E+00	1.62E+03
Uganda	4.96E+01	5.30E+03
Ukraine	2.45E+01	3.26E+04
United Arab Emirates	9.00E-01	6.00E+01
United Rep. Tanzania	3.55E+01	8.60E+03
Uruguay	3.17E+01	1.37E+03

Uzbekistan	6.80E+00	4.48E+03
Venezuela	4.25E+01	2.60E+03
Viet Nam	4.12E+01	6.20E+03
Western Sahara	4.00E-01	5.00E+00
Yemen	9.00E-01	1.55E+03
Zambia	3.12E+01	2.82E+03
Zimbabwe	2.70E+01	3.58E+03
	weighted average	2.36E+01

A.1.4.6. Water resources

All elementary flows in this category, both blue water consumption and total water consumption, are freshwater flows. Assuming the geospatial variation in the exergy content of freshwater to be negligible, the generic LCI-based X-factor could also be used as IO-based X-factor. This X-factor is the chemical exergy value for water (50 MJ_{ex}/m^3) from Szargut [31].

A.1.4.7. Abiotic renewable resources

In Exiobase, these elementary flows are expressed in megajoules of electricity, since they enter the human system through electricity producing sectors. However, in the CEENE methodology, the resource extracted from the natural environment has to be accounted for, which is the primary energy form instead of the converted energy form (i.e. electricity).

Also in the Ecoinvent database, on which the LCI-CEENE is based, the elementary flows for abiotic renewable resources are expressed in terms of electricity. Here, X-factors have been calculated in two steps. First, exergy values were determined for the primary energy forms, which are the kinetic energy in wind and the potential energy in barrage water, and second, these exergy values were divided by electricity conversion efficiencies [218, 219].

For the first step, according to Szargut [194], kinetic energy is equal to kinetic exergy, as the energy can ideally be converted to work entirely. The exergy value of kinetic wind energy therefore equals 1 (megajoule exergy per megajoule primary energy). For potential energy one can imagine an ideal process to completely convert it to work as well. The exergy value of potential energy in water thus also equals 1. In the second step, these exergy values were divided by the electricity conversion efficiencies, which are 25% for wind energy and 80% for hydro-energy respectively. The resulting LCI-based

X-factors are 4 MJ_{ex}/MJ for converted wind energy, and 1.253 MJ_{ex}/MJ for converted hydropower. These LCI-based X-factors were also used as IO-based X-factors for IO-CEENE.

A.1.5. List of X-factors

Nuclear resources (generic)		unit	MJ_{ex}/unit
Domestic Extraction Used - Metal Ores - uranium and thorium ores		kg	9.39E+02
Metal ores (generic)			
Domestic Extraction Used - Metal Ores - iron ores		kg	1.57E-01
Domestic Extraction Used - Metal Ores - aluminium ores		kg	9.01E-02
Domestic Extraction Used - Metal Ores - copper ores		kg	1.64E-01
Domestic Extraction Used - Metal Ores - lead ores		kg	4.25E-01
Domestic Extraction Used - Metal Ores - nickel ores		kg	4.59E-01
Domestic Extraction Used - Metal Ores - tin ores		kg	8.71E-04
Domestic Extraction Used - Metal Ores - zinc ores		kg	9.54E-01
Metal ores (country-specific by group)			
AT	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
AT	Domestic Extraction Used - Metal Ores - other metal ores	kg	2.92E-03
BE	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
BE	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
BG	Domestic Extraction Used - Metal Ores - precious metal ores	kg	1.04E-03
BG	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
CY	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
CY	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
CZ	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
CZ	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
DE	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
DE	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
DK	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
DK	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
EE	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
EE	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
ES	Domestic Extraction Used - Metal Ores - precious metal ores	kg	4.11E-04
ES	Domestic Extraction Used - Metal Ores - other metal ores	kg	1.27E-02
FI	Domestic Extraction Used - Metal Ores - precious metal ores	kg	1.84E-07
FI	Domestic Extraction Used - Metal Ores - other metal ores	kg	4.11E-01
FR	Domestic Extraction Used - Metal Ores - precious metal ores	kg	6.83E-06
FR	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
GR	Domestic Extraction Used - Metal Ores - precious metal ores	kg	1.11E-03
GR	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.62E-01
HU	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
HU	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.62E-01
IE	Domestic Extraction Used - Metal Ores - precious metal ores	kg	1.11E-03

IE	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
IT	Domestic Extraction Used - Metal Ores - precious metal ores	kg	2.46E-07
IT	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.16E-01
LT	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
LT	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
LU	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
LU	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
LV	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
LV	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
MT	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
MT	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
NL	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
NL	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
PL	Domestic Extraction Used - Metal Ores - precious metal ores	kg	4.53E-05
PL	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
PT	Domestic Extraction Used - Metal Ores - precious metal ores	kg	1.11E-03
PT	Domestic Extraction Used - Metal Ores - other metal ores	kg	2.74E-03
RO	Domestic Extraction Used - Metal Ores - precious metal ores	kg	3.71E-04
RO	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.62E-01
SE	Domestic Extraction Used - Metal Ores - precious metal ores	kg	4.72E-07
SE	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
SI	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
SI	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
SK	Domestic Extraction Used - Metal Ores - precious metal ores	kg	1.64E-07
SK	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
GB	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
GB	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
US	Domestic Extraction Used - Metal Ores - precious metal ores	kg	1.75E-07
US	Domestic Extraction Used - Metal Ores - other metal ores	kg	1.65E-01
JP	Domestic Extraction Used - Metal Ores - precious metal ores	kg	3.23E-04
JP	Domestic Extraction Used - Metal Ores - other metal ores	kg	1.45E-01
CN	Domestic Extraction Used - Metal Ores - precious metal ores	kg	2.43E-07
CN	Domestic Extraction Used - Metal Ores - other metal ores	kg	1.48E-01
CA	Domestic Extraction Used - Metal Ores - precious metal ores	kg	4.73E-05
CA	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.61E-01
KR	Domestic Extraction Used - Metal Ores - precious metal ores	kg	1.03E-03
KR	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.75E-01
BR	Domestic Extraction Used - Metal Ores - precious metal ores	kg	2.85E-06
BR	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.60E-01
IN	Domestic Extraction Used - Metal Ores - precious metal ores	kg	4.13E-04
IN	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.80E-01
MX	Domestic Extraction Used - Metal Ores - precious metal ores	kg	1.33E-05
MX	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.85E-02
RU	Domestic Extraction Used - Metal Ores - precious metal ores	kg	2.43E-05
RU	Domestic Extraction Used - Metal Ores - other metal ores	kg	2.14E-02
AU	Domestic Extraction Used - Metal Ores - precious metal ores	kg	1.79E-07

AU	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.44E-01
CH	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
CH	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
TR	Domestic Extraction Used - Metal Ores - precious metal ores	kg	1.03E-03
TR	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.96E-01
TW	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
TW	Domestic Extraction Used - Metal Ores - other metal ores	kg	0.00E+00
NO	Domestic Extraction Used - Metal Ores - precious metal ores	kg	0.00E+00
NO	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.58E-01
ID	Domestic Extraction Used - Metal Ores - precious metal ores	kg	4.42E-05
ID	Domestic Extraction Used - Metal Ores - other metal ores	kg	6.58E-03
ZA	Domestic Extraction Used - Metal Ores - precious metal ores	kg	5.20E-06
ZA	Domestic Extraction Used - Metal Ores - other metal ores	kg	3.76E-01
WW	Domestic Extraction Used - Metal Ores - precious metal ores	kg	5.43E-04
WW	Domestic Extraction Used - Metal Ores - other metal ores	kg	2.36E-01
Non-metallic minerals (country-specific by group)			
AT	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
AT	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	5.70E-02
AT	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
AT	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	4.95E-04
AT	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
AT	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.32E-01
AT	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
AT	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
AT	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.17E-01
BE	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.77E+01
BE	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	5.70E-02
BE	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	0.00E+00
BE	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
BE	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
BE	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	0.00E+00
BE	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
BE	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
BE	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.22E-01
BG	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.54E+01
BG	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	8.49E-02
BG	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
BG	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
BG	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
BG	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	8.50E-02
BG	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
BG	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
BG	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.38E-01
CY	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	0.00E+00
CY	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	1.09E-01
CY	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01

CY	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
CY	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
CY	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	0.00E+00
CY	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
CY	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
CY	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	9.88E-02
CZ	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
CZ	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	8.75E-02
CZ	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.31E-01
CZ	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
CZ	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
CZ	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	4.15E-01
CZ	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
CZ	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
CZ	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.32E-01
DE	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.80E+01
DE	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	6.29E-02
DE	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
DE	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	1.06E-01
DE	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
DE	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	7.31E+00
DE	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
DE	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
DE	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.01E-01
DK	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.99E+01
DK	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	1.09E-01
DK	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	0.00E+00
DK	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
DK	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
DK	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	3.67E+00
DK	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
DK	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
DK	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.05E-01
EE	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	0.00E+00
EE	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
EE	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	0.00E+00
EE	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
EE	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
EE	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	3.10E-02
EE	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
EE	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
EE	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.28E-01
ES	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.46E+01
ES	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	9.18E-02
ES	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.41E-01
ES	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	1.56E-01

ES	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	8.23E-02
ES	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.13E-01
ES	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
ES	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
ES	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.29E-01
FI	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.20E+01
FI	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
FI	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	0.00E+00
FI	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
FI	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
FI	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	6.69E+00
FI	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
FI	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
FI	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	9.88E-02
FR	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.67E+01
FR	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	5.70E-02
FR	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
FR	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.01E-02
FR	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	8.23E-02
FR	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.21E+00
FR	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
FR	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
FR	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.37E-01
GR	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
GR	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	1.07E-01
GR	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
GR	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
GR	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
GR	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	7.69E-02
GR	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
GR	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
GR	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	2.75E-01
HU	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
HU	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	9.15E-02
HU	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
HU	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
HU	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
HU	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.10E-01
HU	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
HU	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
HU	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.38E-01
IE	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	0.00E+00
IE	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
IE	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
IE	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
IE	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00

IE	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.02E+01
IE	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
IE	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
IE	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.38E-01
IT	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.70E+01
IT	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	7.79E-02
IT	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.46E-01
IT	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
IT	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	8.23E-02
IT	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	5.53E-02
IT	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
IT	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
IT	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.43E-01
LT	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
LT	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
LT	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	0.00E+00
LT	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
LT	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
LT	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.02E+01
LT	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
LT	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
LT	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.38E-01
LU	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	0.00E+00
LU	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
LU	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	0.00E+00
LU	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
LU	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
LU	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	0.00E+00
LU	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
LU	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	0.00E+00
LU	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	0.00E+00
LV	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	0.00E+00
LV	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
LV	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
LV	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
LV	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
LV	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.02E+01
LV	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
LV	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
LV	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.02E-01
MT	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	0.00E+00
MT	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
MT	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	0.00E+00
MT	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
MT	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
MT	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	0.00E+00

MT	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
MT	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	0.00E+00
MT	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.38E-01
NL	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
NL	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
NL	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
NL	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
NL	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
NL	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.15E-01
NL	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
NL	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
NL	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	9.88E-02
PL	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
PL	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	5.70E-02
PL	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.26E-01
PL	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	5.97E-02
PL	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
PL	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.74E+00
PL	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
PL	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
PL	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.16E-01
PT	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
PT	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	5.70E-02
PT	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
PT	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.20E-01
PT	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	8.23E-02
PT	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	9.91E-02
PT	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
PT	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
PT	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.52E-01
RO	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.23E+01
RO	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	9.16E-02
RO	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
RO	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
RO	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
RO	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.55E+00
RO	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
RO	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
RO	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	9.88E-02
SE	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
SE	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
SE	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	0.00E+00
SE	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
SE	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	8.23E-02
SE	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	6.72E+00
SE	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00

SE	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
SE	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.26E-01
SI	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	0.00E+00
SI	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
SI	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	0.00E+00
SI	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
SI	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
SI	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	3.79E-02
SI	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
SI	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
SI	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.38E-01
SK	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.52E+01
SK	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	9.79E-02
SK	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.28E-01
SK	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
SK	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
SK	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.14E-01
SK	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
SK	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
SK	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.13E-01
GB	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.30E+01
GB	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	5.92E-02
GB	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.29E-01
GB	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	7.27E-02
GB	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	8.23E-02
GB	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.89E-01
GB	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
GB	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
GB	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.45E-01
US	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	3.96E+00
US	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	8.11E-02
US	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
US	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	7.80E-02
US	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	8.23E-02
US	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	3.60E-01
US	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	1.84E-01
US	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
US	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.48E-01
JP	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
JP	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	1.07E-01
JP	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.44E-01
JP	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
JP	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
JP	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.33E-01
JP	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
JP	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	0.00E+00

JP	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.09E-01
CN	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	3.83E+00
CN	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	7.90E-02
CN	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
CN	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
CN	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
CN	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	3.41E+00
CN	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
CN	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	0.00E+00
CN	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	9.88E-02
CA	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.80E+01
CA	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
CA	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
CA	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
CA	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
CA	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.30E+00
CA	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
CA	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
CA	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	0.00E+00
KR	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
KR	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	6.32E-02
KR	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	0.00E+00
KR	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
KR	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
KR	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	7.72E-02
KR	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
KR	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
KR	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.06E-01
BR	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	2.77E+00
BR	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	6.54E-02
BR	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
BR	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	5.91E-02
BR	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
BR	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	6.11E-01
BR	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
BR	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	0.00E+00
BR	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.47E-01
IN	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	4.93E+00
IN	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	7.67E-02
IN	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
IN	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	7.02E-02
IN	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	8.23E-02
IN	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.35E+00
IN	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
IN	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
IN	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.04E-01

MX	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.04E+01
MX	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	7.66E-02
MX	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
MX	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
MX	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
MX	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	6.18E-01
MX	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
MX	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
MX	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.20E-01
RU	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	6.35E+00
RU	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	1.05E-01
RU	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
RU	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
RU	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
RU	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	2.54E+00
RU	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
RU	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	0.00E+00
RU	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	9.88E-02
AU	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	7.75E+00
AU	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	7.43E-02
AU	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
AU	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
AU	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
AU	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	6.25E-02
AU	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
AU	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
AU	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.20E-01
CH	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	0.00E+00
CH	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
CH	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
CH	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
CH	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
CH	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	0.00E+00
CH	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
CH	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
CH	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.04E-01
TR	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	7.70E-01
TR	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	1.04E-01
TR	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.33E-01
TR	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	1.79E-01
TR	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
TR	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	7.75E-02
TR	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
TR	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	0.00E+00
TR	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.03E-01
TW	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01

TW	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	5.70E-02
TW	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
TW	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
TW	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
TW	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	6.29E-02
TW	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
TW	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	0.00E+00
TW	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	9.88E-02
NO	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
NO	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	0.00E+00
NO	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	0.00E+00
NO	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	0.00E+00
NO	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
NO	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	4.47E-01
NO	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
NO	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	0.00E+00
NO	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.28E-01
ID	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	1.89E+01
ID	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	5.71E-02
ID	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.43E-01
ID	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
ID	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	0.00E+00
ID	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	3.97E-02
ID	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
ID	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	0.00E+00
ID	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.03E-01
ZA	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	2.65E+00
ZA	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	7.10E-02
ZA	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.55E-01
ZA	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.48E-01
ZA	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	8.23E-02
ZA	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	3.57E-02
ZA	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
ZA	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	0.00E+00
ZA	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.08E-01
WW	Domestic Extraction Used - Non-Metallic Minerals - chemical and fertilizer	kg	3.23E+00
WW	Domestic Extraction Used - Non-Metallic Minerals - clays and kaolin	kg	6.74E-02
WW	Domestic Extraction Used - Non-Metallic Minerals - limestone, gypsum, etc.	kg	1.46E-01
WW	Domestic Extraction Used - Non-Metallic Minerals - salt	kg	2.42E-01
WW	Domestic Extraction Used - Non-Metallic Minerals - slate	kg	8.23E-02
WW	Domestic Extraction Used - Non-Metallic Minerals - other industrial minerals	kg	1.33E-01
WW	Domestic Extraction Used - Non-Metallic Minerals - building stones	kg	0.00E+00
WW	Domestic Extraction Used - Non-Metallic Minerals - gravel and sand	kg	6.00E-02
WW	Domestic Extraction Used - Non-Metallic Minerals - other construction	kg	1.10E-01
Fossil fuels: generic			
Domestic Extraction Used - Fossil Energy Carriers - hard coal		kg	1.97E+01

Domestic Extraction Used - Fossil Energy Carriers - lignite/brown coal	kg	1.03E+01
Domestic Extraction Used - Fossil Energy Carriers - crude oil	kg	4.62E+01
Domestic Extraction Used - Fossil Energy Carriers - peat for energy use	kg	5.19E+01
Domestic Extraction Used - Fossil Energy Carriers - natural gas	kg	4.67E+01
Domestic Extraction Used - Fossil Energy Carriers - natural gas liquids	kg	1.02E+01
Land resources – biomass (generic)		
Domestic Extraction Used - Biomass - Grazed Biomass - grazing	kg	1.66E+01
Domestic Extraction Used - Biomass - Wood - timber	kg	1.86E+01
Domestic Extraction Used - Biomass - Wood - other extractions	kg	1.86E+01
Domestic Extraction Used - Biomass - Animals - marine fish	kg	7.02E+00
Domestic Extraction Used - Biomass - Animals - inland water fish	kg	7.02E+00
Domestic Extraction Used - Biomass - Animals - other aquatic animals	kg	7.02E+00
Land resources – land occupation (country-specific)		
AT Land Use - Arable Land – rice	m^2	2.72E+01
AT Land Use - Arable Land – wheat	m^2	2.72E+01
AT Land Use - Arable Land - other cereals	m^2	2.72E+01
AT Land Use - Arable Land - roots and tubers	m^2	2.72E+01
AT Land Use - Arable Land - sugar crops	m^2	2.72E+01
AT Land Use - Arable Land – pulses	m^2	2.72E+01
AT Land Use - Arable Land – nuts	m^2	2.72E+01
AT Land Use - Arable Land - oil crops	m^2	2.72E+01
AT Land Use - Arable Land – vegetables	m^2	2.72E+01
AT Land Use - Arable Land – fruits	m^2	2.72E+01
AT Land Use - Arable Land – fibres	m^2	2.72E+01
AT Land Use - Arable Land - other crops	m^2	2.72E+01
AT Land Use - Arable Land - fodder crops	m^2	2.72E+01
BE Land Use - Arable Land – rice	m^2	2.69E+01
BE Land Use - Arable Land – wheat	m^2	2.69E+01
BE Land Use - Arable Land - other cereals	m^2	2.69E+01
BE Land Use - Arable Land - roots and tubers	m^2	2.69E+01
BE Land Use - Arable Land - sugar crops	m^2	2.69E+01
BE Land Use - Arable Land – pulses	m^2	2.69E+01
BE Land Use - Arable Land – nuts	m^2	2.69E+01
BE Land Use - Arable Land - oil crops	m^2	2.69E+01
BE Land Use - Arable Land - vegetables	m^2	2.69E+01
BE Land Use - Arable Land – fruits	m^2	2.69E+01
BE Land Use - Arable Land – fibres	m^2	2.69E+01
BE Land Use - Arable Land - other crops	m^2	2.69E+01
BE Land Use - Arable Land - fodder crops	m^2	2.69E+01
BG Land Use - Arable Land – rice	m^2	2.35E+01
BG Land Use - Arable Land – wheat	m^2	2.35E+01
BG Land Use - Arable Land - other cereals	m^2	2.35E+01
BG Land Use - Arable Land - roots and tubers	m^2	2.35E+01
BG Land Use - Arable Land - sugar crops	m^2	2.35E+01
BG Land Use - Arable Land – pulses	m^2	2.35E+01

BG	Land Use - Arable Land – nuts	m²	2.35E+01
BG	Land Use - Arable Land - oil crops	m²	2.35E+01
BG	Land Use - Arable Land - vegetables	m²	2.35E+01
BG	Land Use - Arable Land – fruits	m²	2.35E+01
BG	Land Use - Arable Land – fibres	m²	2.35E+01
BG	Land Use - Arable Land - other crops	m²	2.35E+01
BG	Land Use - Arable Land - fodder crops	m²	2.35E+01
CYP	Land Use - Arable Land – rice	m²	1.79E+01
CYP	Land Use - Arable Land – wheat	m²	1.79E+01
CYP	Land Use - Arable Land - other cereals	m²	1.79E+01
CYP	Land Use - Arable Land - roots and tubers	m²	1.79E+01
CYP	Land Use - Arable Land - sugar crops	m²	1.79E+01
CYP	Land Use - Arable Land – pulses	m²	1.79E+01
CYP	Land Use - Arable Land – nuts	m²	1.79E+01
CYP	Land Use - Arable Land - oil crops	m²	1.79E+01
CYP	Land Use - Arable Land - vegetables	m²	1.79E+01
CYP	Land Use - Arable Land – fruits	m²	1.79E+01
CYP	Land Use - Arable Land – fibres	m²	1.79E+01
CYP	Land Use - Arable Land - other crops	m²	1.79E+01
CYP	Land Use - Arable Land - fodder crops	m²	1.79E+01
CZ	Land Use - Arable Land – rice	m²	2.71E+01
CZ	Land Use - Arable Land – wheat	m²	2.71E+01
CZ	Land Use - Arable Land - other cereals	m²	2.71E+01
CZ	Land Use - Arable Land - roots and tubers	m²	2.71E+01
CZ	Land Use - Arable Land - sugar crops	m²	2.71E+01
CZ	Land Use - Arable Land – pulses	m²	2.71E+01
CZ	Land Use - Arable Land – nuts	m²	2.71E+01
CZ	Land Use - Arable Land - oil crops	m²	2.71E+01
CZ	Land Use - Arable Land – vegetables	m²	2.71E+01
CZ	Land Use - Arable Land – fruits	m²	2.71E+01
CZ	Land Use - Arable Land – fibres	m²	2.71E+01
CZ	Land Use - Arable Land - other crops	m²	2.71E+01
CZ	Land Use - Arable Land - fodder crops	m²	2.71E+01
DE	Land Use - Arable Land – rice	m²	2.65E+01
DE	Land Use - Arable Land – wheat	m²	2.65E+01
DE	Land Use - Arable Land - other cereals	m²	2.65E+01
DE	Land Use - Arable Land - roots and tubers	m²	2.65E+01
DE	Land Use - Arable Land - sugar crops	m²	2.65E+01
DE	Land Use - Arable Land – pulses	m²	2.65E+01
DE	Land Use - Arable Land – nuts	m²	2.65E+01
DE	Land Use - Arable Land - oil crops	m²	2.65E+01
DE	Land Use - Arable Land – vegetables	m²	2.65E+01
DE	Land Use - Arable Land – fruits	m²	2.65E+01
DE	Land Use - Arable Land – fibres	m²	2.65E+01
DE	Land Use - Arable Land - other crops	m²	2.65E+01
DE	Land Use - Arable Land - fodder crops	m²	2.65E+01

DK	Land Use - Arable Land – rice	m²	2.64E+01
DK	Land Use - Arable Land – wheat	m²	2.64E+01
DK	Land Use - Arable Land - other cereals	m²	2.64E+01
DK	Land Use - Arable Land - roots and tubers	m²	2.64E+01
DK	Land Use - Arable Land - sugar crops	m²	2.64E+01
DK	Land Use - Arable Land – pulses	m²	2.64E+01
DK	Land Use - Arable Land – nuts	m²	2.64E+01
DK	Land Use - Arable Land - oil crops	m²	2.64E+01
DK	Land Use - Arable Land – vegetables	m²	2.64E+01
DK	Land Use - Arable Land – fruits	m²	2.64E+01
DK	Land Use - Arable Land – fibres	m²	2.64E+01
DK	Land Use - Arable Land - other crops	m²	2.64E+01
DK	Land Use - Arable Land - fodder crops	m²	2.64E+01
EE	Land Use - Arable Land – rice	m²	2.46E+01
EE	Land Use - Arable Land – wheat	m²	2.46E+01
EE	Land Use - Arable Land - other cereals	m²	2.46E+01
EE	Land Use - Arable Land - roots and tubers	m²	2.46E+01
EE	Land Use - Arable Land - sugar crops	m²	2.46E+01
EE	Land Use - Arable Land – pulses	m²	2.46E+01
EE	Land Use - Arable Land – nuts	m²	2.46E+01
EE	Land Use - Arable Land - oil crops	m²	2.46E+01
EE	Land Use - Arable Land – vegetables	m²	2.46E+01
EE	Land Use - Arable Land – fruits	m²	2.46E+01
EE	Land Use - Arable Land – fibres	m²	2.46E+01
EE	Land Use - Arable Land - other crops	m²	2.46E+01
EE	Land Use - Arable Land - fodder crops	m²	2.46E+01
ES	Land Use - Arable Land – rice	m²	2.30E+01
ES	Land Use - Arable Land – wheat	m²	2.30E+01
ES	Land Use - Arable Land - other cereals	m²	2.30E+01
ES	Land Use - Arable Land - roots and tubers	m²	2.30E+01
ES	Land Use - Arable Land - sugar crops	m²	2.30E+01
ES	Land Use - Arable Land – pulses	m²	2.30E+01
ES	Land Use - Arable Land – nuts	m²	2.30E+01
ES	Land Use - Arable Land - oil crops	m²	2.30E+01
ES	Land Use - Arable Land - vegetables	m²	2.30E+01
ES	Land Use - Arable Land – fruits	m²	2.30E+01
ES	Land Use - Arable Land – fibres	m²	2.30E+01
ES	Land Use - Arable Land - other crops	m²	2.30E+01
ES	Land Use - Arable Land - fodder crops	m²	2.30E+01
FI	Land Use - Arable Land – rice	m²	2.20E+01
FI	Land Use - Arable Land – wheat	m²	2.20E+01
FI	Land Use - Arable Land - other cereals	m²	2.20E+01
FI	Land Use - Arable Land - roots and tubers	m²	2.20E+01
FI	Land Use - Arable Land - sugar crops	m²	2.20E+01
FI	Land Use - Arable Land – pulses	m²	2.20E+01
FI	Land Use - Arable Land – nuts	m²	2.20E+01

FI	Land Use - Arable Land - oil crops	m²	2.20E+01
FI	Land Use - Arable Land - vegetables	m²	2.20E+01
FI	Land Use - Arable Land – fruits	m²	2.20E+01
FI	Land Use - Arable Land – fibres	m²	2.20E+01
FI	Land Use - Arable Land - other crops	m²	2.20E+01
FI	Land Use - Arable Land - fodder crops	m²	2.20E+01
FR	Land Use - Arable Land – rice	m²	2.80E+01
FR	Land Use - Arable Land – wheat	m²	2.80E+01
FR	Land Use - Arable Land - other cereals	m²	2.80E+01
FR	Land Use - Arable Land - roots and tubers	m²	2.80E+01
FR	Land Use - Arable Land - sugar crops	m²	2.80E+01
FR	Land Use - Arable Land – pulses	m²	2.80E+01
FR	Land Use - Arable Land – nuts	m²	2.80E+01
FR	Land Use - Arable Land - oil crops	m²	2.80E+01
FR	Land Use - Arable Land - vegetables	m²	2.80E+01
FR	Land Use - Arable Land – fruits	m²	2.80E+01
FR	Land Use - Arable Land – fibres	m²	2.80E+01
FR	Land Use - Arable Land - other crops	m²	2.80E+01
FR	Land Use - Arable Land - fodder crops	m²	2.80E+01
GR	Land Use - Arable Land – rice	m²	1.92E+01
GR	Land Use - Arable Land – wheat	m²	1.92E+01
GR	Land Use - Arable Land - other cereals	m²	1.92E+01
GR	Land Use - Arable Land - roots and tubers	m²	1.92E+01
GR	Land Use - Arable Land - sugar crops	m²	1.92E+01
GR	Land Use - Arable Land – pulses	m²	1.92E+01
GR	Land Use - Arable Land – nuts	m²	1.92E+01
GR	Land Use - Arable Land - oil crops	m²	1.92E+01
GR	Land Use - Arable Land – vegetables	m²	1.92E+01
GR	Land Use - Arable Land – fruits	m²	1.92E+01
GR	Land Use - Arable Land – fibres	m²	1.92E+01
GR	Land Use - Arable Land - other crops	m²	1.92E+01
GR	Land Use - Arable Land - fodder crops	m²	1.92E+01
HU	Land Use - Arable Land – rice	m²	2.62E+01
HU	Land Use - Arable Land – wheat	m²	2.62E+01
HU	Land Use - Arable Land - other cereals	m²	2.62E+01
HU	Land Use - Arable Land - roots and tubers	m²	2.62E+01
HU	Land Use - Arable Land - sugar crops	m²	2.62E+01
HU	Land Use - Arable Land – pulses	m²	2.62E+01
HU	Land Use - Arable Land – nuts	m²	2.62E+01
HU	Land Use - Arable Land - oil crops	m²	2.62E+01
HU	Land Use - Arable Land – vegetables	m²	2.62E+01
HU	Land Use - Arable Land – fruits	m²	2.62E+01
HU	Land Use - Arable Land – fibres	m²	2.62E+01
HU	Land Use - Arable Land - other crops	m²	2.62E+01
HU	Land Use - Arable Land - fodder crops	m²	2.62E+01
IE	Land Use - Arable Land – rice	m²	2.57E+01

IE	Land Use - Arable Land – wheat	m^2	2.57E+01
IE	Land Use - Arable Land - other cereals	m^2	2.57E+01
IE	Land Use - Arable Land - roots and tubers	m^2	2.57E+01
IE	Land Use - Arable Land - sugar crops	m^2	2.57E+01
IE	Land Use - Arable Land – pulses	m^2	2.57E+01
IE	Land Use - Arable Land – nuts	m^2	2.57E+01
IE	Land Use - Arable Land - oil crops	m^2	2.57E+01
IE	Land Use - Arable Land – vegetables	m^2	2.57E+01
IE	Land Use - Arable Land – fruits	m^2	2.57E+01
IE	Land Use - Arable Land – fibres	m^2	2.57E+01
IE	Land Use - Arable Land - other crops	m^2	2.57E+01
IE	Land Use - Arable Land - fodder crops	m^2	2.57E+01
IT	Land Use - Arable Land – rice	m^2	2.38E+01
IT	Land Use - Arable Land – wheat	m^2	2.38E+01
IT	Land Use - Arable Land - other cereals	m^2	2.38E+01
IT	Land Use - Arable Land - roots and tubers	m^2	2.38E+01
IT	Land Use - Arable Land - sugar crops	m^2	2.38E+01
IT	Land Use - Arable Land – pulses	m^2	2.38E+01
IT	Land Use - Arable Land – nuts	m^2	2.38E+01
IT	Land Use - Arable Land - oil crops	m^2	2.38E+01
IT	Land Use - Arable Land – vegetables	m^2	2.38E+01
IT	Land Use - Arable Land – fruits	m^2	2.38E+01
IT	Land Use - Arable Land – fibres	m^2	2.38E+01
IT	Land Use - Arable Land - other crops	m^2	2.38E+01
IT	Land Use - Arable Land - fodder crops	m^2	2.38E+01
LT	Land Use - Arable Land – rice	m^2	2.63E+01
LT	Land Use - Arable Land – wheat	m^2	2.63E+01
LT	Land Use - Arable Land - other cereals	m^2	2.63E+01
LT	Land Use - Arable Land - roots and tubers	m^2	2.63E+01
LT	Land Use - Arable Land - sugar crops	m^2	2.63E+01
LT	Land Use - Arable Land – pulses	m^2	2.63E+01
LT	Land Use - Arable Land – nuts	m^2	2.63E+01
LT	Land Use - Arable Land - oil crops	m^2	2.63E+01
LT	Land Use - Arable Land - vegetables	m^2	2.63E+01
LT	Land Use - Arable Land – fruits	m^2	2.63E+01
LT	Land Use - Arable Land – fibres	m^2	2.63E+01
LT	Land Use - Arable Land - other crops	m^2	2.63E+01
LT	Land Use - Arable Land - fodder crops	m^2	2.63E+01
LU	Land Use - Arable Land – rice	m^2	2.72E+01
LU	Land Use - Arable Land – wheat	m^2	2.72E+01
LU	Land Use - Arable Land - other cereals	m^2	2.72E+01
LU	Land Use - Arable Land - roots and tubers	m^2	2.72E+01
LU	Land Use - Arable Land - sugar crops	m^2	2.72E+01
LU	Land Use - Arable Land – pulses	m^2	2.72E+01
LU	Land Use - Arable Land – nuts	m^2	2.72E+01
LU	Land Use - Arable Land - oil crops	m^2	2.72E+01

LU	Land Use - Arable Land – vegetables	m²	2.72E+01
LU	Land Use - Arable Land – fruits	m²	2.72E+01
LU	Land Use - Arable Land – fibres	m²	2.72E+01
LU	Land Use - Arable Land - other crops	m²	2.72E+01
LU	Land Use - Arable Land - fodder crops	m²	2.72E+01
LV	Land Use - Arable Land – rice	m²	2.57E+01
LV	Land Use - Arable Land – wheat	m²	2.57E+01
LV	Land Use - Arable Land - other cereals	m²	2.57E+01
LV	Land Use - Arable Land - roots and tubers	m²	2.57E+01
LV	Land Use - Arable Land - sugar crops	m²	2.57E+01
LV	Land Use - Arable Land – pulses	m²	2.57E+01
LV	Land Use - Arable Land – nuts	m²	2.57E+01
LV	Land Use - Arable Land - oil crops	m²	2.57E+01
LV	Land Use - Arable Land – vegetables	m²	2.57E+01
LV	Land Use - Arable Land – fruits	m²	2.57E+01
LV	Land Use - Arable Land – fibres	m²	2.57E+01
LV	Land Use - Arable Land - other crops	m²	2.57E+01
LV	Land Use - Arable Land - fodder crops	m²	2.57E+01
MT	Land Use - Arable Land – rice	m²	2.38E+01
MT	Land Use - Arable Land – wheat	m²	2.38E+01
MT	Land Use - Arable Land - other cereals	m²	2.38E+01
MT	Land Use - Arable Land - roots and tubers	m²	2.38E+01
MT	Land Use - Arable Land - sugar crops	m²	2.38E+01
MT	Land Use - Arable Land – pulses	m²	2.38E+01
MT	Land Use - Arable Land – nuts	m²	2.38E+01
MT	Land Use - Arable Land - oil crops	m²	2.38E+01
MT	Land Use - Arable Land – vegetables	m²	2.38E+01
MT	Land Use - Arable Land – fruits	m²	2.38E+01
MT	Land Use - Arable Land – fibres	m²	2.38E+01
MT	Land Use - Arable Land - other crops	m²	2.38E+01
MT	Land Use - Arable Land - fodder crops	m²	2.38E+01
NL	Land Use - Arable Land – rice	m²	2.53E+01
NL	Land Use - Arable Land – wheat	m²	2.53E+01
NL	Land Use - Arable Land - other cereals	m²	2.53E+01
NL	Land Use - Arable Land - roots and tubers	m²	2.53E+01
NL	Land Use - Arable Land - sugar crops	m²	2.53E+01
NL	Land Use - Arable Land – pulses	m²	2.53E+01
NL	Land Use - Arable Land – nuts	m²	2.53E+01
NL	Land Use - Arable Land - oil crops	m²	2.53E+01
NL	Land Use - Arable Land – vegetables	m²	2.53E+01
NL	Land Use - Arable Land – fruits	m²	2.53E+01
NL	Land Use - Arable Land – fibres	m²	2.53E+01
NL	Land Use - Arable Land - other crops	m²	2.53E+01
NL	Land Use - Arable Land - fodder crops	m²	2.53E+01
PL	Land Use - Arable Land – rice	m²	2.74E+01
PL	Land Use - Arable Land – wheat	m²	2.74E+01

PL	Land Use - Arable Land - other cereals	m^2	2.74E+01
PL	Land Use - Arable Land - roots and tubers	m^2	2.74E+01
PL	Land Use - Arable Land - sugar crops	m^2	2.74E+01
PL	Land Use - Arable Land – pulses	m^2	2.74E+01
PL	Land Use - Arable Land – nuts	m^2	2.74E+01
PL	Land Use - Arable Land - oil crops	m^2	2.74E+01
PL	Land Use - Arable Land – vegetables	m^2	2.74E+01
PL	Land Use - Arable Land – fruits	m^2	2.74E+01
PL	Land Use - Arable Land – fibres	m^2	2.74E+01
PL	Land Use - Arable Land - other crops	m^2	2.74E+01
PL	Land Use - Arable Land - fodder crops	m^2	2.74E+01
PT	Land Use - Arable Land – rice	m^2	2.47E+01
PT	Land Use - Arable Land – wheat	m^2	2.47E+01
PT	Land Use - Arable Land - other cereals	m^2	2.47E+01
PT	Land Use - Arable Land - roots and tubers	m^2	2.47E+01
PT	Land Use - Arable Land - sugar crops	m^2	2.47E+01
PT	Land Use - Arable Land – pulses	m^2	2.47E+01
PT	Land Use - Arable Land – nuts	m^2	2.47E+01
PT	Land Use - Arable Land - oil crops	m^2	2.47E+01
PT	Land Use - Arable Land – vegetables	m^2	2.47E+01
PT	Land Use - Arable Land – fruits	m^2	2.47E+01
PT	Land Use - Arable Land – fibres	m^2	2.47E+01
PT	Land Use - Arable Land - other crops	m^2	2.47E+01
PT	Land Use - Arable Land - fodder crops	m^2	2.47E+01
RO	Land Use - Arable Land – rice	m^2	2.32E+01
RO	Land Use - Arable Land – wheat	m^2	2.32E+01
RO	Land Use - Arable Land - other cereals	m^2	2.32E+01
RO	Land Use - Arable Land - roots and tubers	m^2	2.32E+01
RO	Land Use - Arable Land - sugar crops	m^2	2.32E+01
RO	Land Use - Arable Land – pulses	m^2	2.32E+01
RO	Land Use - Arable Land – nuts	m^2	2.32E+01
RO	Land Use - Arable Land - oil crops	m^2	2.32E+01
RO	Land Use - Arable Land – vegetables	m^2	2.32E+01
RO	Land Use - Arable Land – fruits	m^2	2.32E+01
RO	Land Use - Arable Land – fibres	m^2	2.32E+01
RO	Land Use - Arable Land - other crops	m^2	2.32E+01
RO	Land Use - Arable Land - fodder crops	m^2	2.32E+01
SE	Land Use - Arable Land – rice	m^2	2.20E+01
SE	Land Use - Arable Land – wheat	m^2	2.20E+01
SE	Land Use - Arable Land - other cereals	m^2	2.20E+01
SE	Land Use - Arable Land - roots and tubers	m^2	2.20E+01
SE	Land Use - Arable Land - sugar crops	m^2	2.20E+01
SE	Land Use - Arable Land – pulses	m^2	2.20E+01
SE	Land Use - Arable Land – nuts	m^2	2.20E+01
SE	Land Use - Arable Land - oil crops	m^2	2.20E+01
SE	Land Use - Arable Land – vegetables	m^2	2.20E+01

SE	Land Use - Arable Land – fruits	m²	2.20E+01
SE	Land Use - Arable Land – fibres	m²	2.20E+01
SE	Land Use - Arable Land - other crops	m²	2.20E+01
SE	Land Use - Arable Land - fodder crops	m²	2.20E+01
SI	Land Use - Arable Land – rice	m²	2.98E+01
SI	Land Use - Arable Land – wheat	m²	2.98E+01
SI	Land Use - Arable Land - other cereals	m²	2.98E+01
SI	Land Use - Arable Land - roots and tubers	m²	2.98E+01
SI	Land Use - Arable Land - sugar crops	m²	2.98E+01
SI	Land Use - Arable Land – pulses	m²	2.98E+01
SI	Land Use - Arable Land – nuts	m²	2.98E+01
SI	Land Use - Arable Land - oil crops	m²	2.98E+01
SI	Land Use - Arable Land – vegetables	m²	2.98E+01
SI	Land Use - Arable Land – fruits	m²	2.98E+01
SI	Land Use - Arable Land – fibres	m²	2.98E+01
SI	Land Use - Arable Land - other crops	m²	2.98E+01
SI	Land Use - Arable Land - fodder crops	m²	2.98E+01
SK	Land Use - Arable Land – rice	m²	2.82E+01
SK	Land Use - Arable Land – wheat	m²	2.82E+01
SK	Land Use - Arable Land - other cereals	m²	2.82E+01
SK	Land Use - Arable Land - roots and tubers	m²	2.82E+01
SK	Land Use - Arable Land - sugar crops	m²	2.82E+01
SK	Land Use - Arable Land – pulses	m²	2.82E+01
SK	Land Use - Arable Land – nuts	m²	2.82E+01
SK	Land Use - Arable Land - oil crops	m²	2.82E+01
SK	Land Use - Arable Land – vegetables	m²	2.82E+01
SK	Land Use - Arable Land – fruits	m²	2.82E+01
SK	Land Use - Arable Land – fibres	m²	2.82E+01
SK	Land Use - Arable Land - other crops	m²	2.82E+01
SK	Land Use - Arable Land - fodder crops	m²	2.82E+01
GB	Land Use - Arable Land – rice	m²	2.32E+01
GB	Land Use - Arable Land – wheat	m²	2.32E+01
GB	Land Use - Arable Land - other cereals	m²	2.32E+01
GB	Land Use - Arable Land - roots and tubers	m²	2.32E+01
GB	Land Use - Arable Land - sugar crops	m²	2.32E+01
GB	Land Use - Arable Land – pulses	m²	2.32E+01
GB	Land Use - Arable Land – nuts	m²	2.32E+01
GB	Land Use - Arable Land - oil crops	m²	2.32E+01
GB	Land Use - Arable Land – vegetables	m²	2.32E+01
GB	Land Use - Arable Land – fruits	m²	2.32E+01
GB	Land Use - Arable Land – fibres	m²	2.32E+01
GB	Land Use - Arable Land - other crops	m²	2.32E+01
GB	Land Use - Arable Land - fodder crops	m²	2.32E+01
US	Land Use - Arable Land – rice	m²	1.98E+01
US	Land Use - Arable Land – wheat	m²	1.98E+01
US	Land Use - Arable Land - other cereals	m²	1.98E+01

US	Land Use - Arable Land - roots and tubers	m^2	1.98E+01
US	Land Use - Arable Land - sugar crops	m^2	1.98E+01
US	Land Use - Arable Land – pulses	m^2	1.98E+01
US	Land Use - Arable Land – nuts	m^2	1.98E+01
US	Land Use - Arable Land - oil crops	m^2	1.98E+01
US	Land Use - Arable Land – vegetables	m^2	1.98E+01
US	Land Use - Arable Land – fruits	m^2	1.98E+01
US	Land Use - Arable Land – fibres	m^2	1.98E+01
US	Land Use - Arable Land - other crops	m^2	1.98E+01
US	Land Use - Arable Land - fodder crops	m^2	1.98E+01
JP	Land Use - Arable Land – rice	m^2	2.57E+01
JP	Land Use - Arable Land – wheat	m^2	2.57E+01
JP	Land Use - Arable Land - other cereals	m^2	2.57E+01
JP	Land Use - Arable Land - roots and tubers	m^2	2.57E+01
JP	Land Use - Arable Land - sugar crops	m^2	2.57E+01
JP	Land Use - Arable Land – pulses	m^2	2.57E+01
JP	Land Use - Arable Land – nuts	m^2	2.57E+01
JP	Land Use - Arable Land - oil crops	m^2	2.57E+01
JP	Land Use - Arable Land – vegetables	m^2	2.57E+01
JP	Land Use - Arable Land – fruits	m^2	2.57E+01
JP	Land Use - Arable Land – fibres	m^2	2.57E+01
JP	Land Use - Arable Land - other crops	m^2	2.57E+01
JP	Land Use - Arable Land - fodder crops	m^2	2.57E+01
CN	Land Use - Arable Land – rice	m^2	1.60E+01
CN	Land Use - Arable Land – wheat	m^2	1.60E+01
CN	Land Use - Arable Land - other cereals	m^2	1.60E+01
CN	Land Use - Arable Land - roots and tubers	m^2	1.60E+01
CN	Land Use - Arable Land - sugar crops	m^2	1.60E+01
CN	Land Use - Arable Land – pulses	m^2	1.60E+01
CN	Land Use - Arable Land – nuts	m^2	1.60E+01
CN	Land Use - Arable Land - oil crops	m^2	1.60E+01
CN	Land Use - Arable Land – vegetables	m^2	1.60E+01
CN	Land Use - Arable Land – fruits	m^2	1.60E+01
CN	Land Use - Arable Land – fibres	m^2	1.60E+01
CN	Land Use - Arable Land - other crops	m^2	1.60E+01
CN	Land Use - Arable Land - fodder crops	m^2	1.60E+01
CA	Land Use - Arable Land – rice	m^2	1.73E+01
CA	Land Use - Arable Land – wheat	m^2	1.73E+01
CA	Land Use - Arable Land - other cereals	m^2	1.73E+01
CA	Land Use - Arable Land - roots and tubers	m^2	1.73E+01
CA	Land Use - Arable Land - sugar crops	m^2	1.73E+01
CA	Land Use - Arable Land – pulses	m^2	1.73E+01
CA	Land Use - Arable Land – nuts	m^2	1.73E+01
CA	Land Use - Arable Land - oil crops	m^2	1.73E+01
CA	Land Use - Arable Land – vegetables	m^2	1.73E+01
CA	Land Use - Arable Land – fruits	m^2	1.73E+01

CA	Land Use - Arable Land – fibres	m²	1.73E+01
CA	Land Use - Arable Land - other crops	m²	1.73E+01
CA	Land Use - Arable Land - fodder crops	m²	1.73E+01
KR	Land Use - Arable Land – rice	m²	2.72E+01
KR	Land Use - Arable Land – wheat	m²	2.72E+01
KR	Land Use - Arable Land - other cereals	m²	2.72E+01
KR	Land Use - Arable Land - roots and tubers	m²	2.72E+01
KR	Land Use - Arable Land - sugar crops	m²	2.72E+01
KR	Land Use - Arable Land – pulses	m²	2.72E+01
KR	Land Use - Arable Land – nuts	m²	2.72E+01
KR	Land Use - Arable Land - oil crops	m²	2.72E+01
KR	Land Use - Arable Land – vegetables	m²	2.72E+01
KR	Land Use - Arable Land – fruits	m²	2.72E+01
KR	Land Use - Arable Land – fibres	m²	2.72E+01
KR	Land Use - Arable Land - other crops	m²	2.72E+01
KR	Land Use - Arable Land - fodder crops	m²	2.72E+01
BR	Land Use - Arable Land – rice	m²	3.88E+01
BR	Land Use - Arable Land – wheat	m²	3.88E+01
BR	Land Use - Arable Land - other cereals	m²	3.88E+01
BR	Land Use - Arable Land - roots and tubers	m²	3.88E+01
BR	Land Use - Arable Land - sugar crops	m²	3.88E+01
BR	Land Use - Arable Land – pulses	m²	3.88E+01
BR	Land Use - Arable Land – nuts	m²	3.88E+01
BR	Land Use - Arable Land - oil crops	m²	3.88E+01
BR	Land Use - Arable Land – vegetables	m²	3.88E+01
BR	Land Use - Arable Land – fruits	m²	3.88E+01
BR	Land Use - Arable Land – fibres	m²	3.88E+01
BR	Land Use - Arable Land - other crops	m²	3.88E+01
BR	Land Use - Arable Land - fodder crops	m²	3.88E+01
IN	Land Use - Arable Land – rice	m²	2.35E+01
IN	Land Use - Arable Land – wheat	m²	2.35E+01
IN	Land Use - Arable Land - other cereals	m²	2.35E+01
IN	Land Use - Arable Land - roots and tubers	m²	2.35E+01
IN	Land Use - Arable Land - sugar crops	m²	2.35E+01
IN	Land Use - Arable Land – pulses	m²	2.35E+01
IN	Land Use - Arable Land – nuts	m²	2.35E+01
IN	Land Use - Arable Land - oil crops	m²	2.35E+01
IN	Land Use - Arable Land – vegetables	m²	2.35E+01
IN	Land Use - Arable Land – fruits	m²	2.35E+01
IN	Land Use - Arable Land – fibres	m²	2.35E+01
IN	Land Use - Arable Land - other crops	m²	2.35E+01
IN	Land Use - Arable Land - fodder crops	m²	2.35E+01
MX	Land Use - Arable Land – rice	m²	2.18E+01
MX	Land Use - Arable Land – wheat	m²	2.18E+01
MX	Land Use - Arable Land - other cereals	m²	2.18E+01
MX	Land Use - Arable Land - roots and tubers	m²	2.18E+01

MX	Land Use - Arable Land - sugar crops	m²	2.18E+01
MX	Land Use - Arable Land – pulses	m²	2.18E+01
MX	Land Use - Arable Land – nuts	m²	2.18E+01
MX	Land Use - Arable Land - oil crops	m²	2.18E+01
MX	Land Use - Arable Land – vegetables	m²	2.18E+01
MX	Land Use - Arable Land – fruits	m²	2.18E+01
MX	Land Use - Arable Land – fibres	m²	2.18E+01
MX	Land Use - Arable Land - other crops	m²	2.18E+01
MX	Land Use - Arable Land - fodder crops	m²	2.18E+01
RU	Land Use - Arable Land – rice	m²	1.87E+01
RU	Land Use - Arable Land – wheat	m²	1.87E+01
RU	Land Use - Arable Land - other cereals	m²	1.87E+01
RU	Land Use - Arable Land - roots and tubers	m²	1.87E+01
RU	Land Use - Arable Land - sugar crops	m²	1.87E+01
RU	Land Use - Arable Land – pulses	m²	1.87E+01
RU	Land Use - Arable Land – nuts	m²	1.87E+01
RU	Land Use - Arable Land - oil crops	m²	1.87E+01
RU	Land Use - Arable Land – vegetables	m²	1.87E+01
RU	Land Use - Arable Land – fruits	m²	1.87E+01
RU	Land Use - Arable Land – fibres	m²	1.87E+01
RU	Land Use - Arable Land - other crops	m²	1.87E+01
RU	Land Use - Arable Land - fodder crops	m²	1.87E+01
AU	Land Use - Arable Land – rice	m²	1.73E+01
AU	Land Use - Arable Land – wheat	m²	1.73E+01
AU	Land Use - Arable Land - other cereals	m²	1.73E+01
AU	Land Use - Arable Land - roots and tubers	m²	1.73E+01
AU	Land Use - Arable Land - sugar crops	m²	1.73E+01
AU	Land Use - Arable Land – pulses	m²	1.73E+01
AU	Land Use - Arable Land – nuts	m²	1.73E+01
AU	Land Use - Arable Land - oil crops	m²	1.73E+01
AU	Land Use - Arable Land – vegetables	m²	1.73E+01
AU	Land Use - Arable Land – fruits	m²	1.73E+01
AU	Land Use - Arable Land – fibres	m²	1.73E+01
AU	Land Use - Arable Land - other crops	m²	1.73E+01
AU	Land Use - Arable Land - fodder crops	m²	1.73E+01
CH	Land Use - Arable Land – rice	m²	2.44E+01
CH	Land Use - Arable Land – wheat	m²	2.44E+01
CH	Land Use - Arable Land - other cereals	m²	2.44E+01
CH	Land Use - Arable Land - roots and tubers	m²	2.44E+01
CH	Land Use - Arable Land - sugar crops	m²	2.44E+01
CH	Land Use - Arable Land – pulses	m²	2.44E+01
CH	Land Use - Arable Land – nuts	m²	2.44E+01
CH	Land Use - Arable Land - oil crops	m²	2.44E+01
CH	Land Use - Arable Land – vegetables	m²	2.44E+01
CH	Land Use - Arable Land – fruits	m²	2.44E+01
CH	Land Use - Arable Land – fibres	m²	2.44E+01

CH	Land Use - Arable Land - other crops	m^2	2.44E+01
CH	Land Use - Arable Land - fodder crops	m^2	2.44E+01
TR	Land Use - Arable Land – rice	m^2	1.89E+01
TR	Land Use - Arable Land – wheat	m^2	1.89E+01
TR	Land Use - Arable Land - other cereals	m^2	1.89E+01
TR	Land Use - Arable Land - roots and tubers	m^2	1.89E+01
TR	Land Use - Arable Land - sugar crops	m^2	1.89E+01
TR	Land Use - Arable Land – pulses	m^2	1.89E+01
TR	Land Use - Arable Land – nuts	m^2	1.89E+01
TR	Land Use - Arable Land - oil crops	m^2	1.89E+01
TR	Land Use - Arable Land – vegetables	m^2	1.89E+01
TR	Land Use - Arable Land – fruits	m^2	1.89E+01
TR	Land Use - Arable Land – fibres	m^2	1.89E+01
TR	Land Use - Arable Land - other crops	m^2	1.89E+01
TR	Land Use - Arable Land - fodder crops	m^2	1.89E+01
TW	Land Use - Arable Land – rice	m^2	3.37E+01
TW	Land Use - Arable Land – wheat	m^2	3.37E+01
TW	Land Use - Arable Land - other cereals	m^2	3.37E+01
TW	Land Use - Arable Land - roots and tubers	m^2	3.37E+01
TW	Land Use - Arable Land - sugar crops	m^2	3.37E+01
TW	Land Use - Arable Land – pulses	m^2	3.37E+01
TW	Land Use - Arable Land – nuts	m^2	3.37E+01
TW	Land Use - Arable Land - oil crops	m^2	3.37E+01
TW	Land Use - Arable Land – vegetables	m^2	3.37E+01
TW	Land Use - Arable Land – fruits	m^2	3.37E+01
TW	Land Use - Arable Land – fibres	m^2	3.37E+01
TW	Land Use - Arable Land - other crops	m^2	3.37E+01
TW	Land Use - Arable Land - fodder crops	m^2	3.37E+01
NO	Land Use - Arable Land – rice	m^2	1.95E+01
NO	Land Use - Arable Land – wheat	m^2	1.95E+01
NO	Land Use - Arable Land - other cereals	m^2	1.95E+01
NO	Land Use - Arable Land - roots and tubers	m^2	1.95E+01
NO	Land Use - Arable Land - sugar crops	m^2	1.95E+01
NO	Land Use - Arable Land – pulses	m^2	1.95E+01
NO	Land Use - Arable Land – nuts	m^2	1.95E+01
NO	Land Use - Arable Land - oil crops	m^2	1.95E+01
NO	Land Use - Arable Land – vegetables	m^2	1.95E+01
NO	Land Use - Arable Land – fruits	m^2	1.95E+01
NO	Land Use - Arable Land – fibres	m^2	1.95E+01
NO	Land Use - Arable Land - other crops	m^2	1.95E+01
NO	Land Use - Arable Land - fodder crops	m^2	1.95E+01
ID	Land Use - Arable Land – rice	m^2	4.92E+01
ID	Land Use - Arable Land – wheat	m^2	4.92E+01
ID	Land Use - Arable Land - other cereals	m^2	4.92E+01
ID	Land Use - Arable Land - roots and tubers	m^2	4.92E+01
ID	Land Use - Arable Land - sugar crops	m^2	4.92E+01

ID	Land Use - Arable Land – pulses	m²	4.92E+01
ID	Land Use - Arable Land – nuts	m²	4.92E+01
ID	Land Use - Arable Land - oil crops	m²	4.92E+01
ID	Land Use - Arable Land – vegetables	m²	4.92E+01
ID	Land Use - Arable Land – fruits	m²	4.92E+01
ID	Land Use - Arable Land – fibres	m²	4.92E+01
ID	Land Use - Arable Land - other crops	m²	4.92E+01
ID	Land Use - Arable Land - fodder crops	m²	4.92E+01
ZA	Land Use - Arable Land – rice	m²	1.67E+01
ZA	Land Use - Arable Land – wheat	m²	1.67E+01
ZA	Land Use - Arable Land - other cereals	m²	1.67E+01
ZA	Land Use - Arable Land - roots and tubers	m²	1.67E+01
ZA	Land Use - Arable Land - sugar crops	m²	1.67E+01
ZA	Land Use - Arable Land – pulses	m²	1.67E+01
ZA	Land Use - Arable Land – nuts	m²	1.67E+01
ZA	Land Use - Arable Land - oil crops	m²	1.67E+01
ZA	Land Use - Arable Land – vegetables	m²	1.67E+01
ZA	Land Use - Arable Land – fruits	m²	1.67E+01
ZA	Land Use - Arable Land – fibres	m²	1.67E+01
ZA	Land Use - Arable Land - other crops	m²	1.67E+01
ZA	Land Use - Arable Land - fodder crops	m²	1.67E+01
WW	Land Use - Arable Land – rice	m²	1.01E+00
WW	Land Use - Arable Land – wheat	m²	1.01E+00
WW	Land Use - Arable Land - other cereals	m²	1.01E+00
WW	Land Use - Arable Land - roots and tubers	m²	1.01E+00
WW	Land Use - Arable Land - sugar crops	m²	1.01E+00
WW	Land Use - Arable Land – pulses	m²	1.01E+00
WW	Land Use - Arable Land – nuts	m²	1.01E+00
WW	Land Use - Arable Land - oil crops	m²	1.01E+00
WW	Land Use - Arable Land – vegetables	m²	1.01E+00
WW	Land Use - Arable Land – fruits	m²	1.01E+00
WW	Land Use - Arable Land – fibres	m²	1.01E+00
WW	Land Use - Arable Land - other crops	m²	1.01E+00
WW	Land Use - Arable Land - fodder crops	m²	1.01E+00
Water resources (generic)			
Water Consumption Blue - Agriculture – rice		m³	5.00E+01
Water Consumption Blue - Agriculture – wheat		m³	5.00E+01
Water Consumption Blue - Agriculture - other cereals		m³	5.00E+01
Water Consumption Blue - Agriculture - roots and tubers		m³	5.00E+01
Water Consumption Blue - Agriculture - sugar crops		m³	5.00E+01
Water Consumption Blue - Agriculture – pulses		m³	5.00E+01
Water Consumption Blue - Agriculture – nuts		m³	5.00E+01
Water Consumption Blue - Agriculture - oil crops		m³	5.00E+01
Water Consumption Blue - Agriculture – vegetables		m³	5.00E+01
Water Consumption Blue - Agriculture – fruits		m³	5.00E+01
Water Consumption Blue - Agriculture – fibres		m³	5.00E+01

Water Consumption Blue - Agriculture - other crops	m^3	5.00E+01
Water Consumption Blue - Agriculture - fodder crops	m^3	5.00E+01
Water Consumption Total - Livestock - dairy cattle	m^3	5.00E+01
Water Consumption Total - Livestock - nondairy cattle	m^3	5.00E+01
Water Consumption Total - Livestock – pigs	m^3	5.00E+01
Water Consumption Total - Livestock – sheep	m^3	5.00E+01
Water Consumption Total - Livestock – goats	m^3	5.00E+01
Water Consumption Total - Livestock – buffaloes	m^3	5.00E+01
Water Consumption Total - Livestock – camels	m^3	5.00E+01
Water Consumption Total - Livestock – horses	m^3	5.00E+01
Water Consumption Total - Livestock – chicken	m^3	5.00E+01
Water Consumption Total - Livestock – turkeys	m^3	5.00E+01
Water Consumption Total - Livestock – ducks	m^3	5.00E+01
Water Consumption Total - Livestock – geese	m^3	5.00E+01
Water Consumption Total - Manufacturing - food products, beverages and tobacco	m^3	5.00E+01
Water Consumption Total - Manufacturing - textiles and textile products	m^3	5.00E+01
Water Consumption Total - Manufacturing - pulp, paper, publishing and printing	m^3	5.00E+01
Water Consumption Total - Manufacturing - chemicals, man-made fibres	m^3	5.00E+01
Water Consumption Total - Manufacturing - non-metallic, mineral products	m^3	5.00E+01
Water Consumption Total - Manufacturing - basic metals and fabrication of metals	m^3	5.00E+01
Water Consumption Total - Domestic - domestic Water Consumption Total	m^3	5.00E+01
Water Consumption Total - Electricity – tower	m^3	5.00E+01
Water Consumption Total - Electricity - once-through	m^3	5.00E+01
Abiotic renewable resources (generic)		
Gross Energy Use – Wind	MJ	4.00E+00
Gross Energy Use – Hydro	MJ	1.25E+00
Gross Energy Use - Tide, Wave and Ocean	MJ	1.25E+00
Gross Energy Use – Geothermal	MJ	0.00E+00

Table 20: List of X-factors for IO-CEENE

A.1.6. SWOT analysis

Table 21 presents a SWOT (*Strengths-Weaknesses-Opportunities-Threats)* analysis to describe the potential shortcomings and limitations of the new resource footprint framework IO-CEENE.

Table 21: SWOT (*Strengths-Weaknesses-Opportunities-Threats*) analysis of the framework

<table>
<tr><th>Strengths</th><th>Weaknesses</th></tr>
<tr><td>• Geospatial perspective by its country-specific results for 44 countries.
• Use of country-specific characterization factors to better address the extent of the environmental impact
• More complete upstream system boundary
• Calculations are relatively fast
• Having both IO-CEENE (macro/meso-level) and LCI-CEENE (microscale) available it is possible to perform hybrid studies.
• Product data represent an average market mix, while process-level data is often from a selected number of case studies</td><td>• Exiobase has 2000 as base year
• The timescale of the flux data is only at an annual level.
• Exiobase is based on monetary units, so results have to be converted into physical units using basic prices.
• High level of aggregation in IO-databases of natural flows and products.
• Uncertainty data is not provided for the Exiobase database.
• Economic allocation
• The remaining 173 countries are aggregated into one group (‘rest of the world’)</td></tr>
<tr><th>Opportunities</th><th>Threats</th></tr>
<tr><td>• Update of Exiobase for more recent years
• Physical world IO-databases are currently under development, leading to physical allocation. The successor of Exiobase will include such a model
• The country-specific X-factors are weighted averages for the land owned by the country. The framework could be further improved if the exact location where the resource extraction occurs, is considered.</td><td>• Because world IO-databases are based on national IO-statistics, disaggregation of natural flows is not likely to change soon
• Analysis on a process level, using LCI-CEENE, can be more accurate if more precise data(bases) are made available. Latter is though for now a costly and time-consuming undertaking.</td></tr>
</table>

A.2. Appendix of chapter 5

A.2.1. Inclusion of capital investments

The calculations are based on the FORWAST report [144]. First, we need the global total final demand (f_{total}). This global total final demand is the sum of the Gross fixed capital formation ($f_{capital}$), Final consumption expenditure by households, Final consumption expenditure by non-profit organizations serving households, Final consumption expenditure by government, Changes in inventories and Changes in valuables (f_{other}), see equation 30.

$$f_{total} = f_{capital} + f_{other} \qquad (30)$$

Next, scaling factors y_{ij} can be determined using f_{total}, with Z the direct requirements matrix or IO-table and I the identity matrix (equations 31- 33).

$$S = inv(I - Z) * f_{total} \qquad (31)$$

$$X = Z * diagonalmatrix(S) \qquad (32)$$

$$y_{ij} = x_{ij} / \sum_{j=1}^{9600} x_{ij} \qquad (33)$$

After that, the IO-table can be upscaled with the integrated investments:

$$c_{ij} = x_{ij} + y_{ij} * f_{capital_i} \qquad (34)$$

Finally, the upscaled IO-table C has to be transformed into a coefficient matrix by dividing each column element by the corresponding scaling factor:

$$z_{ij} = c_{ij} / s_j \qquad (35)$$

A.2.2. Selection of the basket-of-products

Table 22 shows the distribution of the 200 Exiobase product groups and services into the five demand categories (Food, Consumer Goods, Mobility, Shelter, Services). This distribution is based on the FORWAST report [145].

Table 22: Distribution of the Exiobase product groups and services

Products and services	Food	Goods	Mobility	Shelter	Services
Paddy rice	100%	0%	0%	0%	0%
Wheat	100%	0%	0%	0%	0%
Cereal grains nec	100%	0%	0%	0%	0%
Vegetables, fruit, nuts	100%	0%	0%	0%	0%
Oil seeds	100%	0%	0%	0%	0%
Sugar cane, sugar beet	100%	0%	0%	0%	0%
Plant-based fibers	100%	0%	0%	0%	0%
Crops nec	100%	0%	0%	0%	0%
Cattle	100%	0%	0%	0%	0%
Pigs	100%	0%	0%	0%	0%
Poultry	100%	0%	0%	0%	0%
Meat animals nec	100%	0%	0%	0%	0%
Animal products nec	100%	0%	0%	0%	0%
Raw milk	100%	0%	0%	0%	0%
Wool, silk-worm cocoons	0%	0%	0%	0%	0%
Manure (conventional treatment)	0%	0%	0%	0%	0%
Manure (biogas treatment)	0%	0%	0%	0%	0%
Products of forestry, logging and related services	0%	28%	0%	72%	0%
Fish and other fishing products; services incidental of fishing	100%	0%	0%	0%	0%
Anthracite	3%	0%	0%	97%	0%
Coking Coal	3%	0%	0%	97%	0%
Other Bituminous Coal	3%	0%	0%	97%	0%
Sub-Bituminous Coal	3%	0%	0%	97%	0%
Patent Fuel	3%	0%	0%	97%	0%
Lignite/Brown Coal	3%	0%	0%	97%	0%
BKB/Peat Briquettes	3%	0%	0%	97%	0%

Peat	3%	0%	0%	97%	0%
Crude petroleum and services related to crude oil extraction, excluding surveying	3%	0%	0%	97%	0%
Natural gas and services related to natural gas extraction, excluding surveying	3%	0%	0%	97%	0%
Natural Gas Liquids	0%	0%	0%	0%	0%
Other Hydrocarbons	0%	0%	0%	0%	0%
Uranium and thorium ores	0%	0%	0%	0%	0%
Iron ores	0%	0%	0%	100%	0%
Copper ores and concentrates	0%	0%	0%	100%	0%
Nickel ores and concentrates	0%	0%	0%	100%	0%
Aluminium ores and concentrates	0%	0%	0%	100%	0%
Precious metal ores and concentrates	0%	0%	0%	100%	0%
Lead, zinc and tin ores and concentrates	0%	0%	0%	100%	0%
Other non-ferrous metal ores and concentrates	0%	0%	0%	100%	0%
Stone	0%	0%	0%	100%	0%
Sand and clay	0%	0%	0%	100%	0%
Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.	0%	0%	0%	100%	0%
Products of meat cattle	100%	0%	0%	0%	0%
Products of meat pigs	100%	0%	0%	0%	0%
Products of meat poultry	100%	0%	0%	0%	0%
Meat products nec	100%	0%	0%	0%	0%
products of Vegetable oils and fats	100%	0%	0%	0%	0%
Dairy products	100%	0%	0%	0%	0%
Processed rice	100%	0%	0%	0%	0%
Sugar	100%	0%	0%	0%	0%
Food products nec	100%	0%	0%	0%	0%
Beverages	100%	0%	0%	0%	0%

Fish products	100%	0%	0%	0%	0%
Tobacco products	0%	100%	0%	0%	0%
Textiles	0%	0%	0%	100%	0%
Wearing apparel; furs	0%	100%	0%	0%	0%
Leather and leather products	0%	100%	0%	0%	0%
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials	0%	28%	0%	72%	0%
Wood material for treatment, Re-processing of secondary wood material into new wood material	0%	28%	0%	72%	0%
Pulp	0%	100%	0%	0%	0%
Secondary paper for treatment, Re-processing of secondary paper into new pulp	0%	100%	0%	0%	0%
Paper and paper products	0%	78%	0%	22%	0%
Printed matter and recorded media	0%	100%	0%	0%	0%
Coke Oven Coke	0%	0%	0%	0%	0%
Gas Coke	0%	0%	0%	0%	0%
Coal Tar	0%	0%	0%	0%	0%
Motor Gasoline	0%	0%	100%	0%	0%
Aviation Gasoline	0%	0%	100%	0%	0%
Gasoline Type Jet Fuel	0%	0%	100%	0%	0%
Kerosene Type Jet Fuel	0%	0%	100%	0%	0%
Kerosene	0%	0%	100%	0%	0%
Gas/Diesel Oil	0%	0%	100%	0%	0%
Heavy Fuel Oil	0%	0%	100%	0%	0%
Refinery Gas	0%	0%	0%	0%	0%
Liquefied Petroleum Gases (LPG)	0%	0%	100%	0%	0%
Refinery Feedstocks	0%	0%	0%	0%	0%
Ethane	0%	0%	0%	0%	0%
Naphtha	0%	0%	0%	0%	0%

White Spirit & SBP	0%	0%	0%	0%	0%
Lubricants	0%	0%	0%	0%	0%
Bitumen	0%	0%	0%	0%	0%
Paraffin Waxes	0%	0%	0%	0%	0%
Petroleum Coke	0%	0%	0%	0%	0%
Non-specified Petroleum Products	0%	0%	0%	0%	0%
Nuclear fuel	0%	0%	0%	0%	0%
Plastics, basic	0%	0%	0%	100%	0%
Secondary plastic for treatment, Re-processing of secondary plastic into new plastic	0%	0%	0%	100%	0%
N-fertiliser	0%	0%	0%	0%	0%
P- and other fertilizer	0%	0%	0%	0%	0%
Chemicals nec	0%	50%	7%	24%	12%
Charcoal	0%	0%	0%	0%	0%
Additives/Blending Components	0%	0%	0%	0%	0%
Biogasoline	0%	0%	100%	0%	0%
Biodiesels	0%	0%	100%	0%	0%
Other Liquid Biofuels	0%	0%	100%	0%	0%
Rubber and plastic products	0%	21%	12%	67%	0%
Glass and glass products	0%	48%	0%	52%	0%
Secondary glass for treatment, Re-processing of secondary glass into new glass	0%	48%	0%	52%	0%
Ceramic goods	0%	48%	0%	52%	0%
Bricks, tiles and construction products, in baked clay	0%	0%	0%	100%	0%
Cement, lime and plaster	0%	0%	0%	100%	0%
Ash for treatment, Re-processing of ash into clinker	0%	0%	0%	0%	0%
Other non-metallic mineral products	0%	0%	0%	100%	0%
Basic iron and steel and of ferro-alloys and first products thereof	0%	0%	0%	100%	0%
Secondary steel for treatment, Re-processing of secondary steel into	0%	0%	0%	100%	0%

new steel					
Precious metals	0%	0%	0%	100%	0%
Secondary preciuos metals for treatment, Re-processing of secondary preciuos metals into new preciuos metals	0%	0%	0%	100%	0%
Aluminium and aluminium products	0%	0%	0%	100%	0%
Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium	0%	0%	0%	100%	0%
Lead, zinc and tin and products thereof	0%	0%	0%	100%	0%
Secondary lead for treatment, Re-processing of secondary lead into new lead	0%	0%	0%	100%	0%
Copper products	0%	0%	0%	100%	0%
Secondary copper for treatment, Re-processing of secondary copper into new copper	0%	0%	0%	100%	0%
Other non-ferrous metal products	0%	0%	0%	100%	0%
Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	0%	0%	0%	100%	0%
Foundry work services	0%	0%	0%	100%	0%
Fabricated metal products, except machinery and equipment	0%	63%	0%	36%	0%
Machinery and equipment n.e.c.	0%	30%	0%	8%	0%
Office machinery and computers	0%	100%	0%	0%	0%
Electrical machinery and apparatus n.e.c.	0%	0%	4%	91%	0%
Radio, television and communication equipment and apparatus	0%	100%	0%	0%	0%
Medical, precision and optical instruments, watches and clocks	0%	41%	0%	0%	0%
Motor vehicles, trailers and semi-trailers	0%	0%	100%	0%	0%
Other transport equipment	0%	0%	100%	0%	0%
Furniture; other manufactured goods n.e.c.	0%	38%	0%	62%	0%
Secondary raw materials	0%	0%	0%	100%	0%

Bottles for treatment, Recycling of bottles by direct reuse	0%	100%	0%	0%	0%
Electricity by coal	34%	26%	0%	40%	0%
Electricity by gas	34%	26%	0%	40%	0%
Electricity by nuclear	34%	26%	0%	40%	0%
Electricity by hydro	34%	26%	0%	40%	0%
Electricity by wind	34%	26%	0%	40%	0%
Electricity by petroleum and other oil derivatives	34%	26%	0%	40%	0%
Electricity by biomass and waste	34%	26%	0%	40%	0%
Electricity by solar photovoltaic	34%	26%	0%	40%	0%
Electricity by solar thermal	34%	26%	0%	40%	0%
Electricity by tide, wave, ocean	34%	26%	0%	40%	0%
Electricity by Geothermal	34%	26%	0%	40%	0%
Electricity nec	34%	26%	0%	40%	0%
Transmission services of electricity	34%	26%	0%	40%	0%
Distribution and trade services of electricity	34%	26%	0%	40%	0%
Coke oven gas	0%	0%	0%	0%	0%
Blast Furnace Gas	0%	0%	0%	0%	0%
Oxygen Steel Furnace Gas	0%	0%	0%	0%	0%
Gas Works Gas	0%	0%	0%	0%	0%
Biogas	0%	3%	0%	97%	0%
Distribution services of gaseous fuels through mains	0%	3%	0%	97%	0%
Steam and hot water supply services	0%	60%	0%	40%	0%
Collected and purified water, distribution services of water	0%	60%	0%	40%	0%
Construction work	0%	0%	0%	100%	0%
Secondary construction material for treatment, Re-processing of secondary construction material into aggregates	0%	0%	0%	100%	0%
Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts	0%	0%	0%	0%	100%

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Retail trade services of motor fuel	0%	0%	0%	0%	100%
Wholesale trade and commission trade services, except of motor vehicles and motorcycles	0%	0%	0%	0%	100%
Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods	0%	0%	0%	0%	100%
Hotel and restaurant services	0%	0%	0%	0%	100%
Railway transportation services	0%	0%	100%	0%	0%
Other land transportation services	0%	0%	100%	0%	0%
Transportation services via pipelines	0%	0%	100%	0%	0%
Sea and coastal water transportation services	0%	0%	100%	0%	0%
Inland water transportation services	0%	0%	100%	0%	0%
Air transport services	0%	0%	100%	0%	0%
Supporting and auxiliary transport services; travel agency services	0%	0%	0%	0%	100%
Post and telecommunication services	0%	0%	0%	0%	100%
Financial intermediation services, except insurance and pension funding services	0%	0%	0%	0%	100%
Insurance and pension funding services, except compulsory social security services	0%	0%	0%	0%	100%
Services auxiliary to financial intermediation	0%	0%	0%	0%	100%
Real estate services	0%	0%	0%	0%	100%
Renting services of machinery and equipment without operator and of personal and household goods	0%	0%	0%	0%	100%
Computer and related services	0%	0%	0%	0%	100%
Research and development services	0%	0%	0%	0%	100%
Other business services	0%	0%	0%	0%	100%
Public administration and defence services; compulsory social security services	0%	0%	0%	0%	100%
Education services	0%	0%	0%	0%	100%
Health and social work services	0%	0%	0%	0%	100%

Food waste for treatment: incineration	100%	0%	0%	0%	0%
Paper waste for treatment: incineration	0%	94%	0%	6%	0%
Plastic waste for treatment: incineration	0%	1%	4%	94%	0%
Intert/metal waste for treatment: incineration	0%	59%	1%	40%	0%
Textiles waste for treatment: incineration	0%	92%	0%	8%	0%
Wood waste for treatment: incineration	0%	7%	0%	93%	0%
Oil/hazardous waste for treatment: incineration	0%	46%	5%	38%	0%
Food waste for treatment: biogasification and land application	100%	0%	0%	0%	0%
Paper waste for treatment: biogasification and land application	0%	100%	0%	0%	0%
Sewage sludge for treatment: biogasification and land application	100%	0%	0%	0%	0%
Food waste for treatment: composting and land application	100%	0%	0%	0%	0%
Paper and wood waste for treatment: composting and land application	0%	5%	0%	96%	0%
Food waste for treatment: waste water treatment	100%	0%	0%	0%	0%
Other waste for treatment: waste water treatment	0%	0%	0%	100%	0%
Food waste for treatment: landfill	100%	0%	0%	0%	0%
Paper for treatment: landfill	0%	94%	0%	6%	0%
Plastic waste for treatment: landfill	0%	20%	3%	75%	0%
Inert/metal/hazardous waste for treatment: landfill	0%	53%	2%	42%	0%
Textiles waste for treatment: landfill	0%	92%	0%	8%	0%
Wood waste for treatment: landfill	0%	30%	0%	70%	0%
Membership organisation services n.e.c.	0%	0%	0%	0%	100%
Recreational, cultural and sporting services	0%	0%	0%	0%	100%
Other services	0%	0%	0%	0%	100%
Private households with employed persons	0%	0%	0%	0%	0%
Extra-territorial organizations and bodies	0%	0%	0%	0%	0%

A.2.3. The CEENE impact method

To make a clear distinction, the indicator based on Exiobase v.1 will be called IO-CEENE v.1 (see chapter 3), and the indicator based on Exiobase v.2. will be called IO-CEENE v.2. (see chapter 5) Most X-factors in IO-CEENE v.2 are the same as in IO-CEENE v.1. However, the country-specific X-factors are different, since there are five rest of the world (RoW) regions in Exiobase v.2. These are the X-factors corresponding with the elementary flows arable land, metals and minerals.

A.2.3.1. X-factors for arable land

The X-factors for arable land are based on the country-specific exergy values of Alvarenga et al. [28]. For the five RoW regions, a weighted value was calculated based on the countries situated in these regions, using the arable land area per country from the Faostat database [75], see Table 23.

Table 23: Weighted average X-factors for the Rest of the World (RoW) regions. MJ_{ex}/m^3= megajoules of exergy per square metre, ha = hectares of land.

RoW Africa	X-factor (MJ_{ex}/m^2.year)	Arable land (1000 ha)
Algeria	1.8	7662
Angola	33.1	3000
Benin	27.8	2380
Botswana	14.8	350
Burkina Faso	24.5	3700
Burundi	43.9	960
Cameroon	39.3	5960
Central African Rep.	39	1930
Chad	10.5	3600
Congo	45.3	490
Côte d'Ivoire	35.7	2800
Dem. Rep. of Congo	42.6	6700
Djibouti	11.5	1
Equatorial Guinea	42.5	130
Eritrea	8.4	560
Ethiopia	25.7	10000
Gabon	39.8	325
Gambia	24.7	280
Ghana	30.5	3950
Guinea	32.3	2149
Guinea-Bissau	26.1	300
Kenya	27.9	4891
Lesotho	34.7	330

Liberia	41.5	380
Libyan Arab Jamah.	0.7	1815
Madagascar	42.1	2900
Malawi	31.8	2750
Mali	11	4589
Mauritania	2.8	488
Morocco	10.8	8767
Mozambique	31.6	3900
Namibia	8.6	816
Niger	6.2	13980
Nigeria	28.3	30000
Rwanda	46.3	900
Senegal	22.6	3050
Sierra Leone	32.5	490
Somalia	5.4	1043
Sudan	14.9	16233
Swaziland	27	178
Togo	29.5	2500
Tunisia	6.3	2864
Uganda	49.6	5300
United Rep. Tanzania	35.5	8600
Western Sahara	0.4	5
Zambia	31.2	2816
Zimbabwe	27	3580
weighted average	24.21	

RoW America	X-factor (MJ_{ex}/m2.year)	Arable land (1000 ha)
Cuba	39.7	3504
Dominican Republic	51.3	868
Haiti	45.2	900
Jamaica	44.8	140
Puerto Rico	53.8	59.7
Trinidad and Tobago	44.9	35
Belize	49.8	64
Costa Rica	51.7	210
El Salvador	40.9	650
Guatemala	48.2	1395
Honduras	50.9	1068
Nicaragua	49.3	1917
Panama	52.1	548
Argentina	24	27640
Bolivia	34.6	3000
Chile	14.7	1750
Colombia	45.6	2818
Ecuador	39.2	1616
French Guiana	49.2	12
Guyana	49.1	450

Paraguay	36.8	3020
Peru	33.7	3700
Suriname	48	57
Uruguay	31.7	1373
Venezuela	42.5	2595
weighted average	32.34	

RoW Asia-Pacific	X-factor (MJ_{ex}/m2.year)	Arable land (1000 ha)
Afghanistan	8.4	7683
Armenia	16	450
Azerbaijan	15.8	1825.6
Bangladesh	36.7	8350
Bhutan	27.4	106
Brunei Darussalam	48	2
Cambodia	40.4	3700
Georgia	25.9	793
Kazakhstan	13	21535
Korea (Dem. Ppl's. Rep)	26	2300
Kyrgyzstan	16.2	1356
Lao People's Dem. Rep.	42	877
Malaysia	48.3	1820
Myanmar	34	9909
Nepal	23	2354
Pakistan	5.5	21292
Papua New Guinea	48.5	205
Philippines	45.1	5034
Republic of Mongolia	8.2	1174
Sri Lanka	40.1	915
Tajikistan	12	784
Thailand	36.3	15654
Turkmenistan	5.7	1620
Uzbekistan	6.8	4475
Viet Nam	41.2	6200
New Zeland	30.7	1500
weighted average	22.78	

RoW Middle East	X-factor (MJ_{ex}/m2.year)	Arable land (1000 ha)
Egypt	0.2	2801
Iraq	6.7	4100
Israel	7.5	338
Jordan	2	190
Iran (Islamic Rep. of)	7.8	14924
Kuwait	2.2	10
Lebanon	18.3	129

Oman	0.6	31
Qatar	1	13
Saudi Arabia	0.4	3592
Syrian Arab Republic	9.7	4542
United Arab Emirates	0.9	60
Yemen	0.9	1545
weighted average	6.09	

RoW Europe	X-factor (MJ_{ex}/m2.year)	Arable land (1000 ha)
Albania	24.7	578
Belarus	26.2	6133
Bosnia, Herzegovina	29.7	1000
Croatia	28.7	842
Iceland	14.2	129
Island of Man	24.7	18.1
Macedonia	22.9	555
Moldova (Republic of)	22.4	1827
Monaco	26.7	0
Montenegro	28.6	0
Serbia	26.5	0
Ukraine	24.5	32564
weighted average	24.80	

A.2.3.2. X-factors for metals and minerals

The calculation of the X-factors for metals and minerals is the same as in appendix A.1.4. To perform the calculation, disaggregated data of the year 2007 was requested from SERI [220]. The X-factors are presented in Table 24.

Table 24: Country-specific X-factors for the aggregated elementary flows, 'Chemical and fertilizer minerals', 'Clays and kaolin', 'Limestone, gypsum, chalk, dolomite', 'Salt', 'Slate', 'Other industrial minerals', 'Building stones', 'Gravel and sand', 'Other construction minerals', 'Precious metal ores' and 'Other metals ores', all expressed in megajoules of exergy per kg flow (MJ_{ex}/kg).

	Chemical and fertilizer minerals	Clays and kaolin	Limestone, gypsum, dolomite	Salt	Slate	Other industrial minerals	Building stones	Gravel and sand	Other construction minerals	Precious metal ores	Other metal ores
AT	1.9E+01	5.7E-02	1.6E-01	3.9E-04	0.0E+00	1.1E-01	0.0E+00	6.0E-02	1.3E-01	0.0E+00	5.9E-03
BE	1.9E+01	5.7E-02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	6.0E-02	1.5E-01	0.0E+00	0.0E+00

BG	1.7E+01	7.2E-02	1.6E-01	2.5E-01	0.0E+00	4.2E-02	0.0E+00	6.0E-02	1.2E-01	9.5E-04	3.6E-01
CY	0.0E+00	1.1E-01	1.6E-01	0.0E+00	0.0E+00	2.5E-01	0.0E+00	6.0E-02	1.2E-01	0.0E+00	0.0E+00
CZ	1.9E+01	8.7E-02	1.3E-01	0.0E+00	0.0E+00	1.2E-01	0.0E+00	6.0E-02	1.5E-01	0.0E+00	0.0E+00
DE	1.8E+01	6.2E-02	1.6E-01	8.9E-02	0.0E+00	2.4E-01	0.0E+00	6.0E-02	1.5E-01	0.0E+00	0.0E+00
DK	2.1E+01	1.1E-01	0.0E+00	2.5E-01	0.0E+00	1.1E+00	0.0E+00	6.0E-02	1.2E-01	0.0E+00	0.0E+00
EE	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.0E+01	0.0E+00	6.0E-02	1.7E-01	0.0E+00	0.0E+00
ES	1.5E+01	9.1E-02	1.4E-01	1.7E-01	0.0E+00	1.1E-01	0.0E+00	6.0E-02	1.5E-01	0.0E+00	0.0E+00
FI	1.2E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	7.2E+00	0.0E+00	6.0E-02	1.2E-01	2.5E-07	4.1E-01
FR	1.8E+01	5.7E-02	1.6E-01	0.0E+00	8.2E-02	1.5E+00	0.0E+00	6.0E-02	1.7E-01	0.0E+00	0.0E+00
GR	1.9E+01	1.1E-01	1.6E-01	2.5E-01	0.0E+00	7.5E-02	0.0E+00	6.0E-02	0.0E+00	1.1E-03	3.6E-01
HU	1.9E+01	1.1E-01	1.6E-01	0.0E+00	0.0E+00	1.5E-01	0.0E+00	6.0E-02	1.4E-01	0.0E+00	3.6E-01
IE	0.0E+00	0.0E+00	1.6E-01	0.0E+00	0.0E+00	1.0E+01	0.0E+00	6.0E-02	1.6E-01	1.1E-03	0.0E+00
IT	1.9E+01	6.4E-02	1.4E-01	2.5E-01	8.2E-02	5.1E-02	0.0E+00	6.0E-02	2.6E-01	0.0E+00	0.0E+00
LT	1.9E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.0E+01	0.0E+00	6.0E-02	1.5E-01	0.0E+00	0.0E+00
LU	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.2E-01	0.0E+00	0.0E+00
LV	0.0E+00	0.0E+00	1.6E-01	0.0E+00	0.0E+00	2.0E+00	0.0E+00	6.0E-02	1.4E-01	0.0E+00	0.0E+00
MT	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.7E-01	0.0E+00	0.0E+00
NL	1.9E+01	0.0E+00	0.0E+00	2.5E-01	0.0E+00	1.1E-01	0.0E+00	6.0E-02	0.0E+00	0.0E+00	0.0E+00
PL	1.9E+01	5.7E-02	1.4E-01	7.9E-02	0.0E+00	1.9E+00	0.0E+00	6.0E-02	1.4E-01	2.0E-05	0.0E+00
PT	1.9E+01	5.7E-02	1.6E-01	2.2E-01	8.2E-02	8.8E-02	0.0E+00	0.0E+00	1.4E-01	1.1E-03	4.8E-03
RO	1.9E+01	9.3E-02	1.6E-01	2.5E-01	0.0E+00	2.8E-01	0.0E+00	6.0E-02	1.2E-01	6.1E-04	3.6E-01
SE	1.9E+01	0.0E+00	0.0E+00	0.0E+00	8.2E-02	6.6E+00	0.0E+00	6.0E-02	1.6E-01	3.7E-07	0.0E+00
SI	0.0E+00	0.0E+00	0.0E+00	2.5E-01	0.0E+00	3.1E-02	0.0E+00	6.0E-02	1.7E-01	1.1E-03	0.0E+00
SK	1.1E+01	9.7E-02	1.3E-01	2.5E-01	0.0E+00	1.1E-01	0.0E+00	6.0E-02	1.4E-01	1.6E-07	0.0E+00
GB	1.1E+01	5.7E-02	1.3E-01	2.5E-01	8.2E-02	2.2E-01	0.0E+00	6.0E-02	1.6E-01	2.5E-05	9.1E-03
US	4.3E+00	8.3E-02	1.6E-01	9.4E-02	8.2E-02	2.2E+00	1.8E-01	6.0E-02	1.8E-01	1.8E-07	7.4E-02
JP	1.9E+01	1.1E-01	1.4E-01	2.5E-01	0.0E+00	5.6E-02	0.0E+00	0.0E+00	1.3E-01	1.6E-07	3.7E-01
CN	3.8E+00	8.5E-02	1.6E-01	2.5E-01	0.0E+00	2.5E+00	0.0E+00	0.0E+00	1.2E-01	2.5E-07	1.7E-01
CA	1.8E+01	0.0E+00	1.6E-01	2.5E-01	0.0E+00	1.1E+00	0.0E+00	6.0E-02	0.0E+00	4.9E-05	1.2E-01
KR	1.9E+01	6.2E-02	0.0E+00	2.5E-01	0.0E+00	3.8E-02	0.0E+00	6.0E-02	1.3E-01	2.5E-04	1.3E-01
BR	2.5E+00	6.3E-02	1.6E-01	5.8E-02	0.0E+00	6.2E-01	0.0E+00	0.0E+00	1.5E-01	5.2E-06	3.4E-01
IN	7.5E+00	7.8E-02	1.6E-01	7.7E-02	8.2E-02	2.6E-01	0.0E+00	6.0E-02	1.2E-01	5.3E-04	3.7E-01
MX	1.3E+01	7.8E-02	1.6E-01	2.5E-01	0.0E+00	2.3E-01	0.0E+00	6.0E-02	1.3E-01	1.1E-05	3.9E-02
RU	7.4E+00	1.0E-01	1.6E-01	2.5E-01	0.0E+00	1.4E+00	0.0E+00	0.0E+00	1.2E-01	4.9E-05	4.7E-02
AU	5.9E+00	7.6E-02	1.6E-01	2.5E-01	0.0E+00	6.1E-02	0.0E+00	6.0E-02	1.7E-01	1.8E-07	3.0E-01
CH	0.0E+00	0.0E+00	1.6E-01	2.5E-01	0.0E+00	0.0E+00	0.0E+00	6.0E-02	1.7E-01	0.0E+00	0.0E+00
TR	1.4E+00	8.9E-02	1.3E-01	2.0E-01	0.0E+00	1.1E-01	0.0E+00	0.0E+00	1.5E-01	5.7E-04	4.1E-01
TW	1.9E+01	5.7E-02	0.0E+00	2.5E-01	0.0E+00	3.1E-02	0.0E+00	0.0E+00	1.2E-01	1.6E-07	0.0E+00
NO	1.9E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	9.1E-01	0.0E+00	6.0E-02	1.7E-01	0.0E+00	1.3E-01
ID	1.9E+01	5.7E-02	1.4E-01	2.5E-01	0.0E+00	6.1E-02	0.0E+00	0.0E+00	1.2E-01	4.1E-05	5.3E-05
ZA	3.6E+00	7.1E-02	1.6E-01	2.5E-01	8.2E-02	8.6E-02	0.0E+00	0.0E+00	1.3E-01	4.0E-06	3.6E-01
WA	7.7E+00	6.7E-02	1.5E-01	2.5E-01	0.0E+00	3.7E-01	0.0E+00	6.0E-02	1.3E-01	2.7E-04	2.0E-01
WL	1.2E+01	8.0E-02	1.6E-01	2.4E-01	8.2E-02	1.6E-01	0.0E+00	6.0E-02	1.2E-01	7.4E-04	3.2E-01
WE	1.9E+01	8.6E-02	1.6E-01	2.5E-01	0.0E+00	3.4E+00	0.0E+00	6.0E-02	1.2E-01	1.0E-03	3.4E-01
WF	1.7E-01	9.1E-02	1.6E-01	2.3E-01	0.0E+00	3.0E-01	0.0E+00	6.0E-02	1.2E-01	1.6E-05	3.3E-01
WM	6.9E+00	8.0E-02	1.3E-01	2.5E-01	0.0E+00	1.2E-01	0.0E+00	6.0E-02	1.3E-01	2.8E-04	1.5E-01

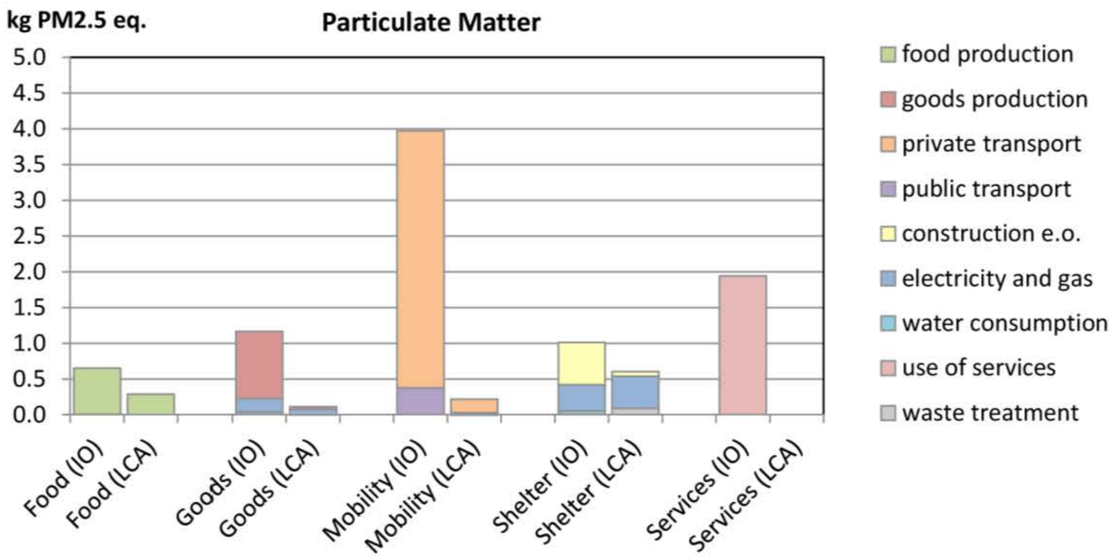
A.2.4. ILCD recommended impact methods

Table 25 summarizes the 16 midpoint impact categories and the corresponding characterization methods recommended by the ILCD handbook [21, 143].

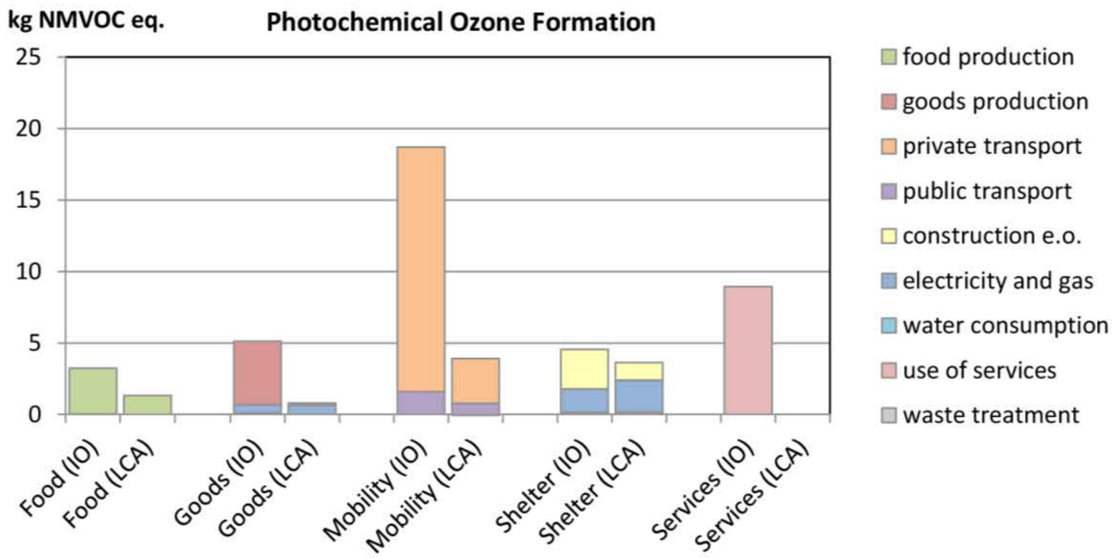
Table 25: Overview of the ILCD impact categories and methods

ILCD impact categories (midpoint)	Characterization method	LCA	IO
Climate Change	IPCC [88]	X	X
Particulate matter	Rabl et al. [221], Greco et al. [222]	X	X
Photochemical ozone formation	Recipe2008, Van Zelm et al. [223]	X	X
Acidification	Seppala et al. [224], Posch et al. [225]	X	X
Eutrophication terrestrial	Seppala et al. [224], Posch et al. [225]	X	X
Eutrophication freshwater	Recipe2008, Struijs et al. [226]	X	X
Eutrophication marine	Recipe2008, Struijs et al. [226]	X	X
Ionizing radiation (human health)	Frishknecht et al. [227]	X	
Ionizing radiation (ecosystems)	Garnier-Laplace et al. [228]	X	
Human toxicity (cancer)	USEtox, Rosenbaum et al. [229]	X	
Human toxicity (non-cancer)	USEtox, Rosenbaum et al. [229]	X	
Ecotoxicity freshwater	USEtox, Rosenbaum et al. [229]	X	
Ozone depletion	WMO [230]	X	X
Land use	Mila I Canals et al. [231]		X
Water depletion	Ecoscarcity, Frishknecht et al. [232]		X
Resource depletion	CML2002, Guinée et al. [178]	X	

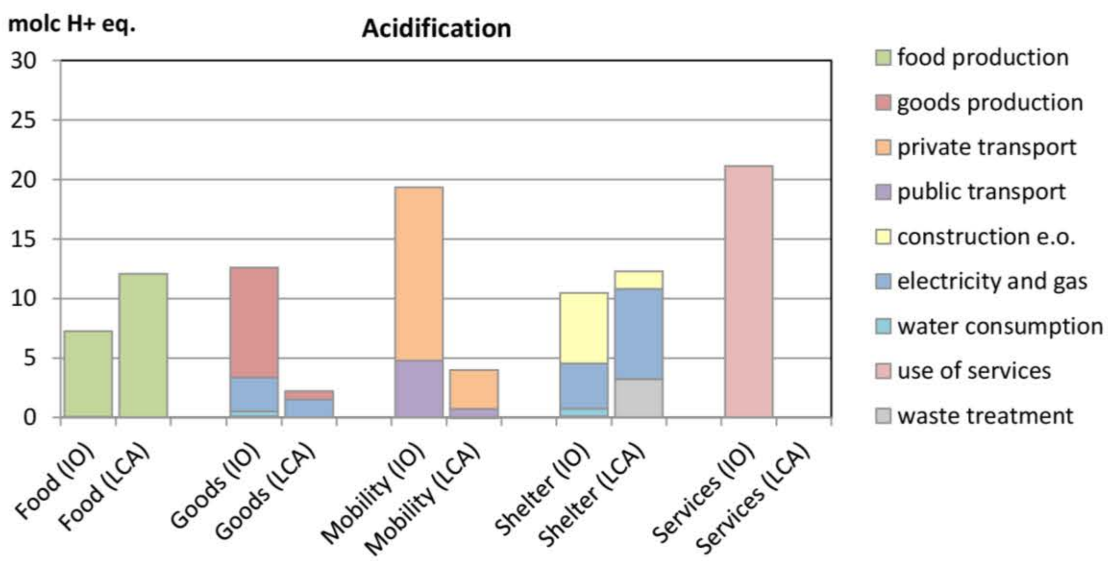
In the LCA-study of JRC, 14 of these impact categories were calculated. They excluded Land Use and Water Depletion because the required data were not covered in the inventory. In our IO-study, we focused on Global Warming. If possible, other ILCD impact categories were also calculated, see Figure 27. The coupling of their characterization factors with Exiobase is given in Table 26. As explained in the article, Ionizing Radiation could not be included because the required elementary flows are not covered in Exiobase. Also for Human Toxicity and Ecotoxicity, insufficient elementary flows are available to make, in our opinion, an adequate assessment of the impact category. For Abiotic Resource Depletion, the most dominant elementary flows are aggregated in one group, making a comprehensive impact assessment impossible. Specific for Acidification and Terrestrial Eutrophication, the IO-results for food are much lower than the LCA-results, because there is an underestimation of ammonia emissions related to meat and dairy in Exiobase.



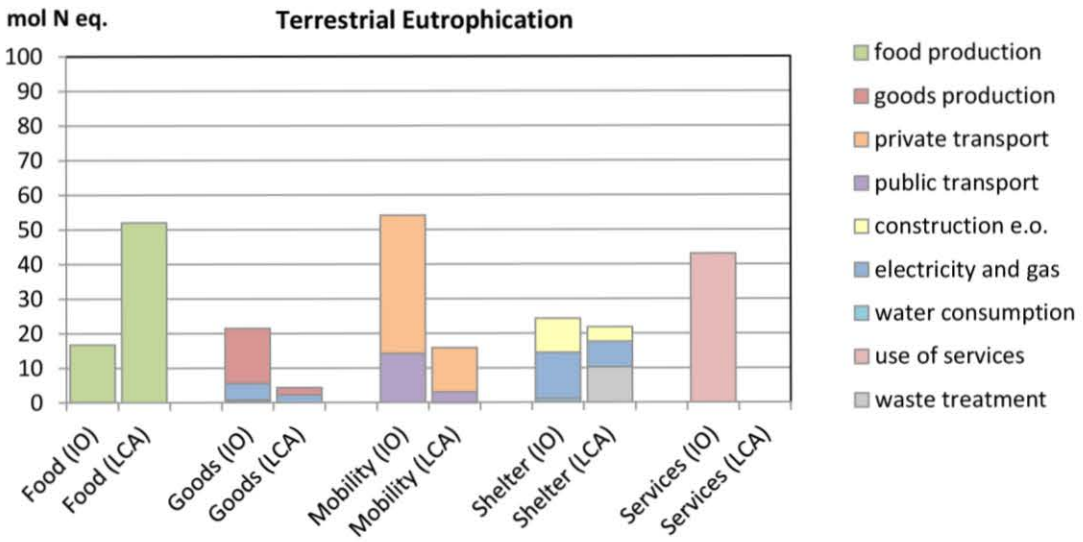
kg PM2.5 eq.
Particulate Matter
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Food (IO)
Food (LCA)
Goods (IO)
Goods (LCA)
Mobility (IO)
Mobility (LCA)
Shelter (IO)
Shelter (LCA)
Services (IO)
Services (LCA)
food production
goods production
private transport
public transport
construction e.o.
electricity and gas
water consumption
use of services
waste treatment

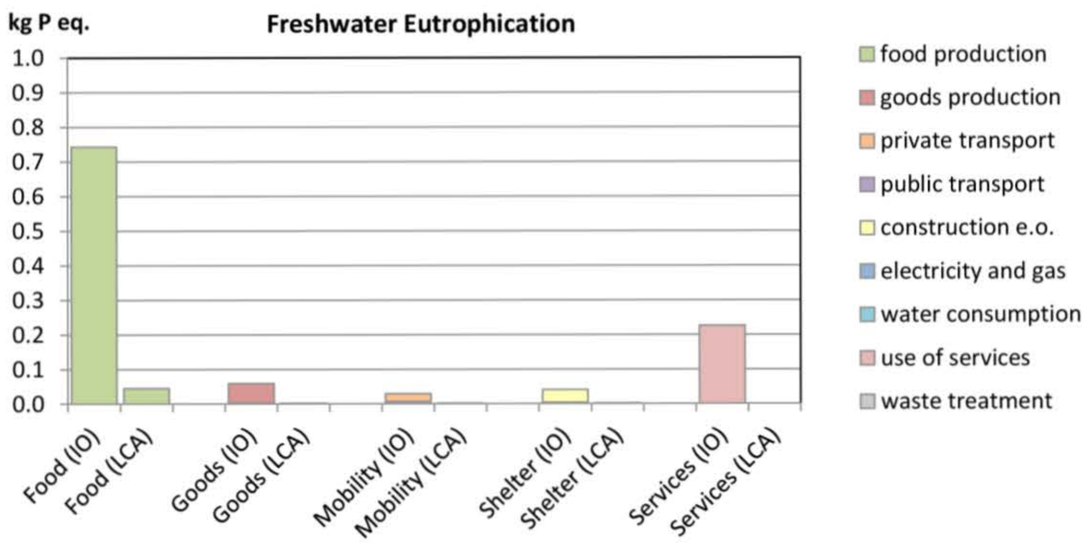


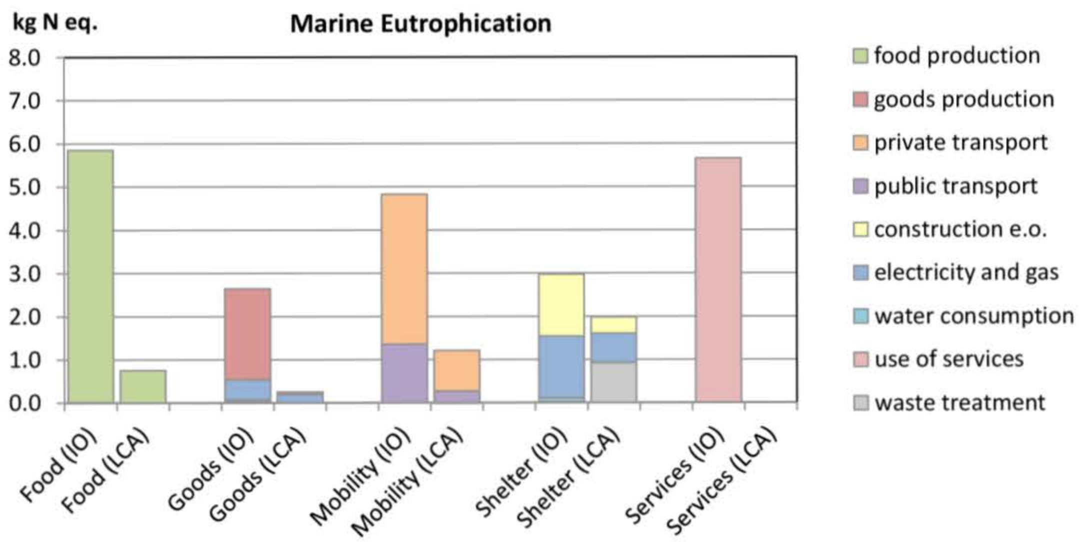
kg NMVOC eq.
Photochemical Ozone Formation
25
20
15
10
5
0
Food (IO)
Food (LCA)
Goods (IO)
Goods (LCA)
Mobility (IO)
Mobility (LCA)
Shelter (IO)
Shelter (LCA)
Services (IO)
Services (LCA)
food production
goods production
private transport
public transport
construction e.o.
electricity and gas
water consumption
use of services
waste treatment



molc H+ eq.
Acidification
30
25
20
15
10
5
0
Food (IO)
Food (LCA)
Goods (IO)
Goods (LCA)
Mobility (IO)
Mobility (LCA)
Shelter (IO)
Shelter (LCA)
Services (IO)
Services (LCA)
food production
goods production
private transport
public transport
construction e.o.
electricity and gas
water consumption
use of services
waste treatment


mol N eq.
Terrestrial Eutrophication
100
90
80
70
60
50
40
30
20
10
0
Food (IO)
Food (LCA)
Goods (IO)
Goods (LCA)
Mobility (IO)
Mobility (LCA)
Shelter (IO)
Shelter (LCA)
Services (IO)
Services (LCA)
food production
goods production
private transport
public transport
construction e.o.
electricity and gas
water consumption
use of services
waste treatment


kg P eq.
Freshwater Eutrophication
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Food (IO)
Food (LCA)
Goods (IO)
Goods (LCA)
Mobility (IO)
Mobility (LCA)
Shelter (IO)
Shelter (LCA)
Services (IO)
Services (LCA)
food production
goods production
private transport
public transport
construction e.o.
electricity and gas
water consumption
use of services
waste treatment


kg N eq.
Marine Eutrophication
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Food (IO)
Food (LCA)
Goods (IO)
Goods (LCA)
Mobility (IO)
Mobility (LCA)
Shelter (IO)
Shelter (LCA)
Services (IO)
Services (LCA)
food production
goods production
private transport
public transport
construction e.o.
electricity and gas
water consumption
use of services
waste treatment

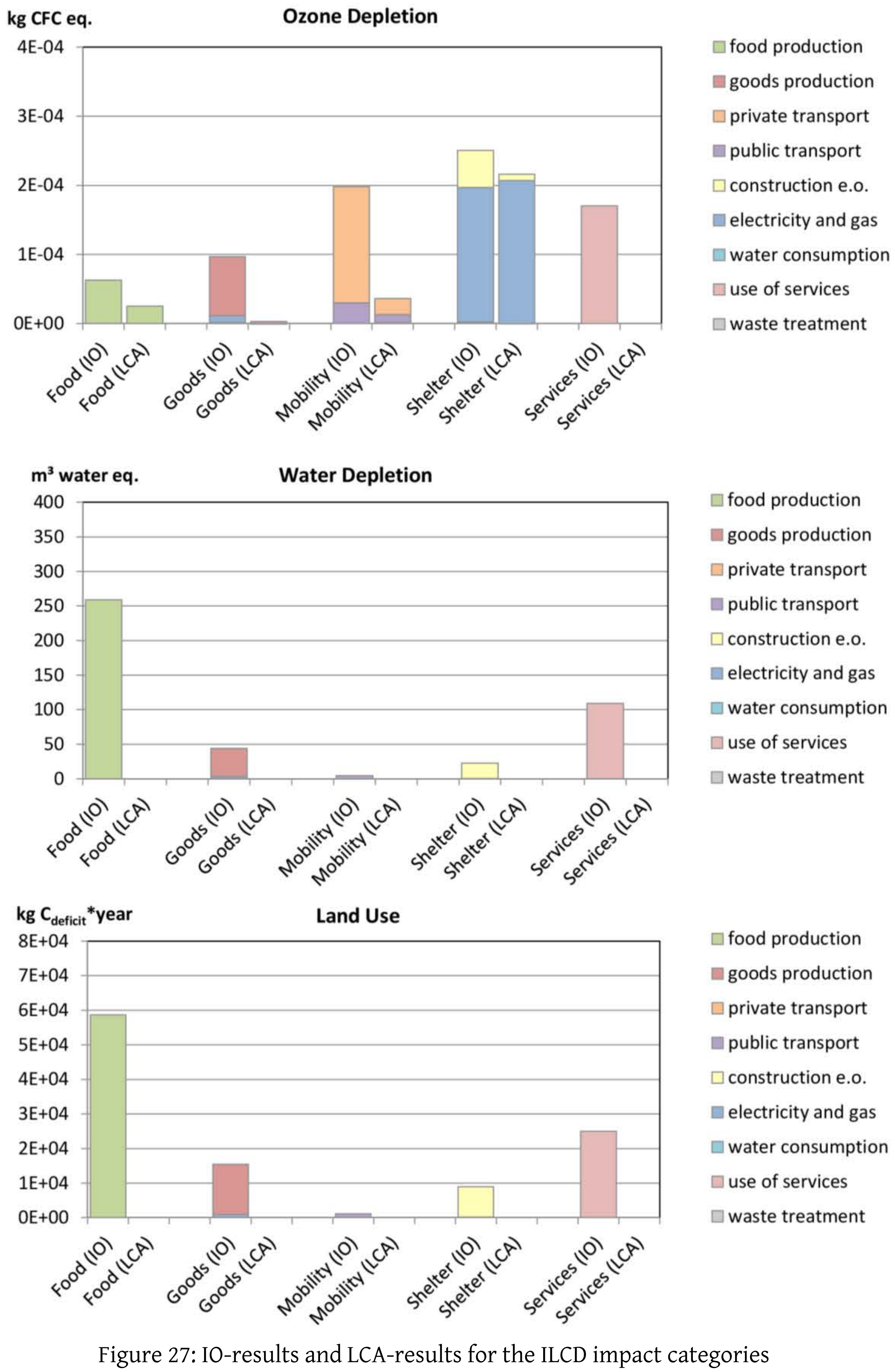


Figure 27: IO-results and LCA-results for the ILCD impact categories

Table 26: Coupling of the ILCD methods with Exiobase elementary flows. Eq = equivalents, PM2.5= particulate matter smaller than 2.5 µm, PM10 = particulate matter smaller than 10 µm, NMVOC = non methane volatile organic compounds, CFC = chlorofluorocarbon-11 or trichlorofluoromethane, P = Phosphorus, N = Nitrogen, Cdeficit = carbon deficit, TSP = Total Suspended Particles.

Global Warming	
Exiobase flows	kg CO2 eq/kg
CO2 - combustion (air)	1
CO2 - non combustion (air)	1
N2O - combustion (air)	298
N2O - non combustion (air)	298
CH4 - combustion (air)	25
CH4 – non combustion (air)	25
SF6 (air)	22800

Particulate matter	
Exiobase elementary flows	kg PM2.5 eq/kg
NH3 - combustion (air)	0.0667
NH3 – non combustion (air)	0.0667
CO – combustion (air)	0.000356
CO – non combustion (air)	0.000356
NOx – combustion (air)	0.00722
NOx – non combustion (air)	0.00722
PM10 – combustion (air)	0.228
PM10 – non combustion (air)	0.228
PM2.5 – combustion (air)	1
PM2.5 – non combustion (air)	1
SOx – combustion (air)	0.0611
SOx – non combustion (air)	0.0611
TSP – combustion (air)	0
TSP – non combustion (air)	0

Photochemical ozone formation	
Exiobase elementary flows	kg NMVOC eq/kg
CH4 – combustion (air)	0.0101
CH4 – non combustion (air)	0.0101
SOx – combustion (air)	0.0811
SOx – non combustion (air)	0.0811
CO – combustion (air)	0.0456
CO – non combustion (air)	0.0456
NMVOC – combustion (air)	1.000
NMVOC – non combustion (air)	1.000

Acidification	
Exiobase elementary flows	mol H+ eq/kg
NH3 - combustion (air)	3.02
NH3 – non combustion (air)	3.02
NOx – combustion (air)	0.74
NOx – non combustion (air)	0.74
SOx – combustion (air)	1.31
SOx – non combustion (air)	1.31

Eutrophication terrestrial	
Exiobase elementary flows	molc N eq/kg
NH3 - combustion (air)	13.5
NH3 – non combustion (air)	13.5
NOx – combustion (air)	4.26
NOx – non combustion (air)	4.26

Eutrophication freshwater	
Exiobase elementary flows	kg P eq/kg
Phosphorus - Agriculture - Paddy rice (water)	1
Phosphorus - Agriculture – Wheat (water)	1
Phosphorus - Agriculture - Other cereals (water)	1
Phosphorus - Agriculture - Roots and tubers (water)	1
Phosphorus - Agriculture – Sugar Crops (water)	1
Phosphorus - Agriculture – Pulses (water)	1
Phosphorus - Agriculture – Nutes (water)	1
Phosphorus - Agriculture - Oil crops (water)	1

Eutrophication marine	
Exiobase elementary flows	kg N eq/kg
NH3 - combustion (air)	0.092
NH3 – non combustion (air)	0.092
NH3 - combustion (water)	0.824
NH3 – non combustion (water)	0.824
NOx – combustion (air)	0.389
NOx – non combustion (air)	0.389
water_Nitrogen - Agriculture - Paddy rice	1
water_Nitrogen - Agriculture – Wheat	1
water_Nitrogen - Agriculture - Other cereals	1
water_Nitrogen - Agriculture - Roots and tubers	1
water_Nitrogen - Agriculture – SugarCrops	1
water_Nitrogen - Agriculture – Pulses	1
water_Nitrogen - Agriculture – Nutes	1
water_Nitrogen - Agriculture - Oil crops	1
water_Nitrogen - Agriculture – Vegetables	1

water_Nitrogen - Agriculture – Fruits	1

Ozone Depletion	
Exiobase elementary flows	kg CFC eq./kg
NMVOC, air	0.000023

Land use	
Exiobase elementary flows	kg $C_{deficit}$*year/m²a
Land use-Arable Land – Rice	9.7
Land use-Arable Land – Wheat	9.7
Land use-Arable Land - Other cereals	9.7
Land use-Arable Land - Roots and tubers	9.7
Land use-Arable Land - Sugar crops	9.7
Land use-Arable Land – Pulses	9.7
Land use-Arable Land – Nuts	9.7
Land use-Arable Land - Oil crops	9.7
Land use-Arable Land – Vegetables	9.7
Land use-Arable Land – Fruits	9.7
Land use-Arable Land – Fibres	9.7
Land use-Arable Land - Other crops	9.7
Land use-Arable Land - Fodder crops	9.7
Land use- Pasture - Permanent pasture	5
Land use-Forest - Wood land	2

Water Depletion	
Exiobase elementary flows	m^3 water / m^3
green water consumption	0.162
blue water consumption in Austria	0.012
blue water consumption in Belgium	2.840
blue water consumption in Bulgaria	4.010
blue water consumption in Cyprus	1.540
blue water consumption in Czech Republic	0.619
blue water consumption in Germany	1.520
blue water consumption in Denmark	0.736
blue water consumption in Estonia	0.037
blue water consumption in Spain	1.660
blue water consumption in Finland	0.008
blue water consumption in France	0.619
blue water consumption in Greece	0.184
blue water consumption in Hungary	0.089
blue water consumption in Ireland	0.008
blue water consumption in Italy	0.870
blue water consumption in Lithuania	0.002

blue water consumption in Luxembourg	2.840
blue water consumption in Latvia	0.001
blue water consumption in Malta	16.200
blue water consumption in Netherlands	0.124
blue water consumption in Poland	1.120
blue water consumption in Portugal	0.435
blue water consumption in Romania	0.201
blue water consumption in Sweden	0.005
blue water consumption in Slovenia	0.000
blue water consumption in Slovak Republic	0.162
blue water consumption in United Kingdom	0.069
blue water consumption in United States	0.401
blue water consumption in Japan	0.686
blue water consumption in China	0.803
blue water consumption in Canada	0.004
blue water consumption in South Korea	0.217
blue water consumption in Brazil	0.001
blue water consumption in India	1.840
blue water consumption in Mexico	0.468
blue water consumption in Russian Federation	0.005
blue water consumption in Australia	0.039
blue water consumption in Switzerland	0.037
blue water consumption in Turkey	0.502
blue water consumption in Taiwan	0.162
blue water consumption in Norway	0.001
blue water consumption in Indonesia	0.014
blue water consumption in South Africa	1.020
blue water consumption in RoW Asia and Pacific	0.162
blue water consumption in RoW America	0.162
blue water consumption in RoW Europe	0.162
blue water consumption in RoW Africa	0.162
blue water consumption in RoW Middle East	0.162

A.3. Appendix of chapter 6

A.3.1. Overview of the data

An overview of the data inventory of both cases is given in Table 27. Possible waste treatment scenarios for case A are closed-loop recycling (A1), incineration for energy recovery (A2) and landfilling (A3). Possible waste treatment scenarios for case B are open-loop recycling (B1), incineration for energy recovery (B2) and landfilling (B3).

Table 27: overview of the data used for case A and case B.

Case A		
Scenario	Description	Data source
Scenario A1	Recycling process End-products	See appendix A.3.2 See appendix A.3.4
Scenario A2	Incineration Energy recovery	Modeled by Ecoinvent process 'Disposal, plastics, mixture, 15.3% water, to municipal incineration' Modeled by Ecoinvent process 'Electricity, medium voltage, production BE, at grid'
Scenario A3	Landfilling	Modeled by the Ecoinvent process 'disposal, plastics, mixture, 15.3% water, to sanitary landfill'.
Case B		
Scenario	Description	Data Source
Scenario B1	Recycling process End-products	See appendix A.3.3 See appendix A.3.5
Scenario B2	Incineration Energy recovery	Modeled by Ecoinvent process 'Disposal, plastics, mixture, 15.3% water, to municipal incineration' Modeled by Ecoinvent process 'Electricity, medium voltage, production BE, at grid'
Scenario B3	Landfilling	Modeled by the Ecoinvent process 'disposal, plastics, mixture, 15.3% water, to sanitary landfill'.

A.3.2. Process description of Galloo

The recycling process at Galloo (case A) is presented in Figure 28. First, the electronic appliances are sorted manually in the depollution step. The next step is the shredder, followed by flotation to separate the plastics from the metals. In the plastic line, the plastics are separated further into different polymer types. After this separation, they are extruded into pellets. The inventory per kg plastic waste is given in Table 28.

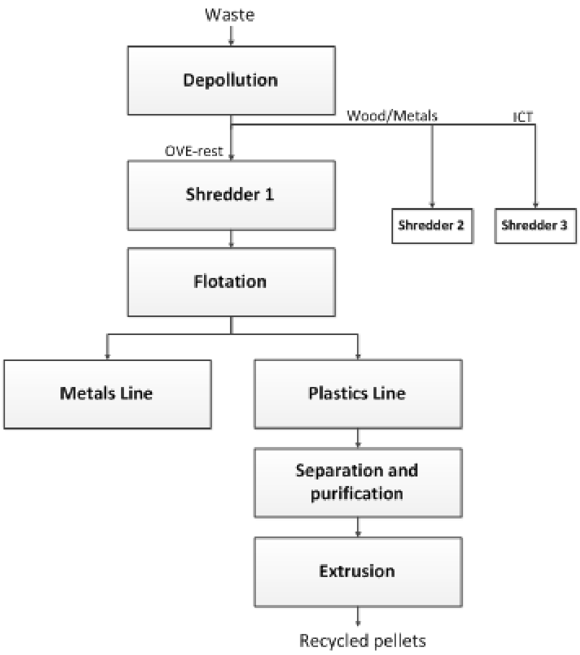


Figure 28: Recycling process at Galloo.

Table 28: Inventory of Galloo per kg plastic waste

Amount	Unit	Ecoinvent process
1,80E-02	kg	carbon black, at plant
1,24E-02	kg	Magnetite, at plant
2,70E-02	kg	chemicals organic, at plant
7,94E-02	kg	limestone, milled, packed, at plant
8,76E-02	kwh	electricity, medium voltage, production BE, at grid
5,65E-01	kwh	electricity, medium voltage, production FR, at grid
2,06E-03	tkm	transport, lorry 3.5-16t, fleet average
6,20E-02	kg	disposal, glass, 0% water, to inert material landfill
3,33E-01	kg	disposal, plastics, mixture, 15.3% water, to sanitary landfill
5,40E-02	kg	disposal, limestone residue, 5% water, to inert material landfill
4,78E-02	kg	disposal, rubber, unspecified, 0% water, to municipal incineration
5,98E-02	kg	disposal, wood untreated, 20% water, to sanitary landfill

A.3.3. Process description of Ekol

The recycling process at Ekol (case B) is presented in Figure 29. The first step is again depollution of the incoming waste. Next, the plastic waste is shredded and separated in water. Afterwards, the plastics are dried and extruded into pellets. The inventory of this process (per kg waste plastics) is given in Table 29.

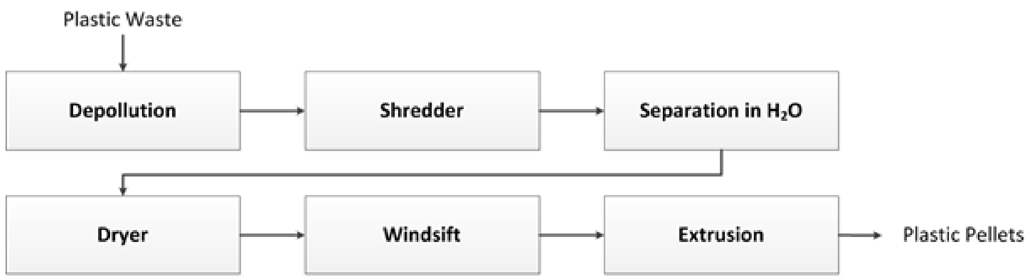


Figure 29: Recycling process at Ekol

Table 29: Inventory of Ekol per kg plastic waste

Amount	Unit	Ecoinvent process
2,7E-04	Ton	tap water, at user
4,8E-02	MJ	diesel, burned in building machine
1,4E-01	Kwh	natural gas, high pressure, at consumer
2,3E-04	kg	chemicals organic, at plant
2,2E-03	kg	iron (III) chloride, 40% in H2O, at plant
3,8E-03	kg	sodium hydroxide, 50% in H2O, production mix, at plant
6,5E-01	kwh	Own process: Luminus Green electricity mix
1,0E-04	m^3	treatment, sewage, unpolluted, to wastewater treatment, class 3
2,9E-02	kg	disposal, glass, 0% water, to municipal incineration
1,4E-01	kg	disposal, plastics, mixture, 15.3% water, to municipal incineration

A.3.4. Modelling of the vacuum cleaner

The considered vacuum cleaner is a 'Commercial Canister' type, which has a plastic fraction consisting of 1.96 kg PS, 1.96 kg PP and 1.96 kg acrylonitrile butadiene styrene (ABS), and a metal fraction consisting of 1.45 kg ferrous and 2.25 kg non-ferrous metals. The production phase and disposal phase of these materials was modeled by processes from the Ecoinvent v2.2 database, see Table 30 and Table 31.

Table 30: Modeling of the production phase of each material in the vacuum cleaner (PS = polystyrene, PP = polypropylene, ABS = Acrylonitrile butadiene styrene)

Material	Mass	Ecoinvent process
PS	1.96	*polystyrene, general purpose, GPPS, at plant*
PP	1.96	*polypropylene, granulate, at plant*
ABS	1.96	*Acrylonitrile-butadiene-styrene copolymer, ABS, at plant*
Ferrous	1.45	*cast iron, at plant*
Non-ferrous	2.25	*copper, at regional storage*

Table 31: Modeling of the disposal phase of each fraction in the vacuum cleaner

Fraction	Disposal	Ecoinvent process
Plastic fraction	Landfilling	disposal, plastics, mixture, 15.3% water, to sanitary landfill
	Incineration	disposal, plastics, mixture, 15.3% water, to municipal incineration
Metal fraction	Landfilling	disposal, steel, 0% water, to inert material landfill
	Incineration	disposal, copper, 0% in water, to municipal incineration disposal, steel, 0% water, to municipal incineration

A.3.5. Modelling of the plant tray and street bench

A plant tray produced from virgin materials is often made from polyethylene terephthalate (PET) (19 kg) or polystyrene concrete (195 kg) (Plantenbak, 2014). A street bench produced from virgin materials is mostly made from cast iron (63 kg) or tropical hardwood (32.5 kg) with a cast iron pedestal (26 kg) (Claerbout, 2014). The production of these materials was modeled by processes from the Ecoinvent v2.2 database, see Table 32.

Table 32: Modeling of a plant tray and street bench made from virgin materials

Product	Material	mass	Ecoinvent process
Plant tray	PET	19	polyethylene terephthalate, granulate, amorphous, at plant and injection moulding
	PS concrete	195	lightweight concrete block, polystyrene, at plant
Street bench	Cast iron	63	cast iron, at plant
	Hardwood with cast iron pedestal	32.5 + 26	hardwood, planed, air/kiln dried, u=10%, at plant cast iron, at plant and "sawn timber

A.3.6. Open-loop recyclability benefit rates

All possible scenarios for one-step and two-step cascaded use recycling in case B are shown in Table 33. The open-loop recyclability benefit rate is calculated for each of these scenario. This benefit rate represents the ratio of the environmental savings over the environmental impacts for virgin production followed by disposal, which can be either landfill (L) or incineration with electricity recovery (I). The abiotic renewables resources coming from the green electricity mix of Ekol can be considered as environmental impact (L, I) or as freely available (L^*, I^*).

Table 33: Open-loop recyclability benefit rates for case B. PS = polystyrene, PET = polyethylene terephthalate. L = disposal is impact for landfill, I = disposal is impact for incineration minus the avoided impact for virgin electricity production. L^*= same as L, but abiotic renewable resources are considered freely available, I^* = same as I, but abiotic renewable resources are considered freely available

Open-loop recycling: one-step cascade				
Possible scenarios for avoided product α_1	L	I	L^*	I^*
Plant tray (PET)	10%	-2%	15%	3%
Plant tray (PS concrete)	14%	2%	18%	8%
Street bench (cast iron)	13%	1%	17%	6%
Street bench (hardwood)	17%	6%	22%	12%
Open-loop recycling: two-step cascade				
Possible scenarios for avoided products α_1 and α_2	L	I	L^*	I^*
Plant tray (PET) - Plant tray (PET)	18%	10%	26%	19%
Plant tray (PET) - Plant tray (PS concrete)	21%	13%	29%	23%
Plant tray (PET) - Street bench (cast iron)	20%	12%	28%	22%
Plant tray (PET) - Street bench (hardwood)	24%	17%	32%	26%
Plant tray (PS concrete) - Plant tray (PET)	22%	14%	30%	24%
Plant tray (PS concrete) - Plant tray (PS concrete)	25%	18%	33%	27%
Plant tray (PS concrete) - Street bench (cast iron)	24%	16%	32%	26%
Plant tray (PS concrete) - Street bench (hardwood)	27%	21%	35%	30%
Street bench (cast iron) - Plant tray (PET)	20%	13%	28%	22%
Street bench (cast iron) - Plant tray (PS concrete)	23%	16%	31%	26%
Street bench (cast iron) - Street bench (cast iron)	22%	15%	30%	24%
Street bench (cast iron) - Street bench (hardwood)	26%	19%	34%	29%
Street bench (cast iron) - Plant tray (PET)	25%	18%	33%	28%
Street bench (cast iron) - Plant tray (PS concrete)	28%	22%	36%	31%
Street bench (cast iron) - Street bench (cast iron)	27%	20%	35%	30%
Street bench (cast iron) - Street bench (hardwood)	31%	25%	39%	34%

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Publications

Peer-reviewed articles (A1)

Huysman, S.; Schaubroeck, T.; Dewulf, J., Quantification of Spatially Differentiated Resource Footprints for Products and Services through a Macro-Economic and Thermodynamic Approach. Environ Sci Technol 2014, 48, (16), 9709-9716. (IF: 5.5)

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Presentations at conferences

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Non-peer reviewed publication

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Teaching and tutoring activities

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