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**CHARACTERISATION MODELS TO QUANTIFY
THE RESOURCE DEPLETION IMPACT:
THE CASE STUDY OF NON- HAZARDOUS CDW**

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ABBREVIATIONS

AADP	Anthropogenic Stock Extended Abiotic Depletion Potential
ADP	Abiotic Depletion Potential
AoP	Area of Protections
CDW	Construction and Demolition Waste
CED	Cumulative Energy Demand
CEENE	Cumulative Exergy Extraction from Natural Environment
CExD	Cumulative Exergy Demand
CF	Characterization Factor
EDIP	Environmental Design of Industrial Products
EF	Environmental Footprint
EU	European Union
EWC	European Waste Code
ILCD	International Reference Life Cycle Data System
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
RAM	Resource Accounting Method
RA	Recycled Aggregates
RMC	Raw Material Consumption
SED	Solar Energy Demand
UNEP	United Nations Environment Program

Abstract

Construction and demolition waste (CDW) are one of most plentiful waste streams generated in European Union (EU). Most CDW includes mineral inert waste which is used and reused as a secondary material in construction industry after proper treatment. Moreover, this mineral natural resource is replaced with secondary material completely or partially regarding to regulations. The aim of this study is to evaluate the impact of resource depletion associated with the non-hazardous CDW management by applying different life cycle impact assessment (LCIA) models. The life cycle assessment (LCA) of the CDW management system is implemented in Lombardy region (Italy) and it was described by Borghi et al., 2018. The research of Borghi et al., 2018 is taken as a case study. Different LCIA models, related to the impact category of resource depletion, are indicated by impact pathways, indicators, characterization factors (CF), calculation ways and CF units. All models were applied to evaluate three different scenarios: current, best-case and landfill scenarios. Analysis of different scenarios are carried out by means of SimaPro. In the part of results, critical and highly effective minerals for each scenario are also expressed with numerical data. Therefore, this thesis can be considered as a first step to identify proper models regarding to management of CDW for impact category of resource depletion.

Sommario

I rifiuti da costruzione e demolizione (CDW) sono uno dei flussi di rifiuti più abbondanti generati nell'Unione Europea (UE). Inoltre, la maggior parte dei CDW comprende rifiuti inerti minerali che possono essere utilizzati e riutilizzati come materiali secondari nel settore dell'edilizia dopo un adeguato trattamento. Inoltre, questi materiali secondari sono in totale o parziale sostituzione delle risorse minerali naturali a seconda della norme di settore. L'obiettivo di questo studio è valutare l'impatto dell'esaurimento delle risorse associato alla gestione dei rifiuti da costruzione e demolizione (CDW) non pericolosi applicando diversi modelli di valutazione dell'impatto del ciclo di vita (LCIA). La valutazione del ciclo di vita (LCA) del sistema di gestione dei CDW implementato nella regione Lombardia (Italia) e descritta da Borghi et al., 2018 è stata presa come un caso di studio. A tal fine, sono stati analizzati diversi modelli di caratterizzazione correlati alla categoria di impatto dell'esaurimento delle risorse, con i loro percorsi di impatto, indicatori, fattori di caratterizzazione (CF), vie di calcolo e unità di misura dei CF. Tutti i modelli sono stati applicati per valutare 3 diversi scenari: gestione attuale, scenario best-case, scenario tutto in discarica. L'analisi viene effettuata mediante il software SimaPro. Nella parte conclusiva, i minerali critici e i minerali altamente efficaci per ogni scenario sono espressi con i dati. Pertanto, questa tesi può essere considerata come un primo passo per identificare i modelli più corretti per valutare l'impatto esaurimento delle risorse della gestione dei CDW

1. Introduction

Nowadays construction and demolition waste (CDW) is one of the heaviest and most massive waste streams generated in the world. The Waste Framework Directive (2008/98/EC) allows Member States to use non-hazardous CDW by 2020 to achieve at least 70% (by weight) of reuse, recycling and other materials recovery, including backfilling. The management of CDW is an increasingly important issue in Europe and the national context due to possibility of transforming raw materials.

As known that natural resources are fundamental for our society, economy and environment. However, due to the demographic population growth and unsustainable managing of natural resources, the depletion of abiotic and biotic resources is foregone conclusion.

Life cycle thinking and life cycle assessment (LCA) are proper ways to decrease depletion of natural resources. Resource depletion, as an impact category, has economic and geopolitical aspect, besides impacts on the environment and human health.

Numbers of methodology and indicators for resource depletion have been developed in many years. Each of methodology and indicators analyzed natural resources from a different perspective such as consumption related geological/natural reserve, economic availability of resources.

1.1. The Goal of the Study

The present research aims to evaluate the resource depletion impact associated with the non-hazardous Construction and demolition waste (CDW) management by applying the different Life Cycle Impact Assessment (LCIA) models. The LCA of the CDW management system implemented in the Lombardy region (Italy) and described by Borghi et al., 2018 was taken as a case study.

The final goal is the identification of differences between characterization models and understand which characterization model is proper for current system assessment.

The study is focus on impact characterization models and characterization factors (CFs) for resource depletion.

1.2. LCA Structure and Framework

LCA is a methodology to assess the impacts on the environment and on human health connected with the complete life cycle (production, use, end-of-life) of products, processes and activities. It allows creation to model the entire system from which products are derived or in which processes and activities operate.

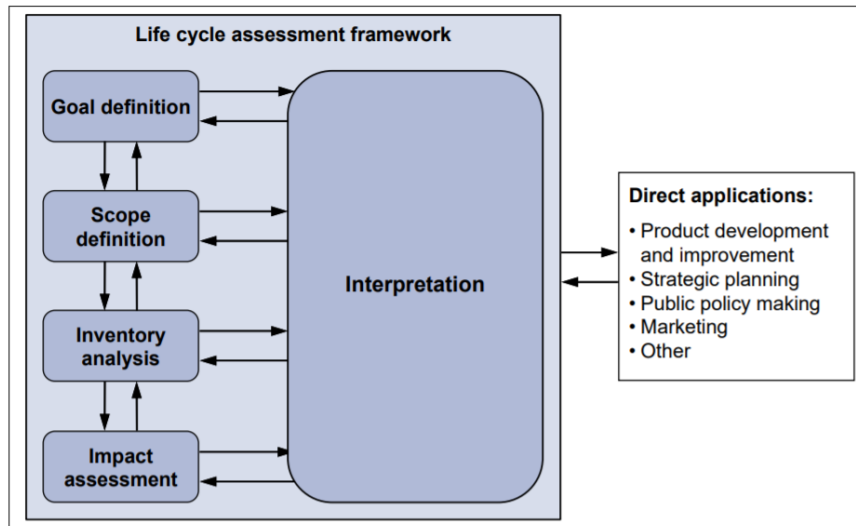


Figure 1: Framework for life cycle assessment (from ISO 14040:2006; modified)

The structure of LCA proposed by ISO 14040 norm consists of four phases as shown as **Figure 1** as follows:

1. Goal and Scope phase contains definition and description of the product, process, or activity, establishing the context in which the assessment is to be made.
2. Inventory analysis phase contains identification and quantification of input and output data regarding to the system being studied. These input/output can be energy, water, and material usage and environmental releases.
3. Impact assessment phase aims to assessing the magnitude and significance of possible environmental impacts for a product system through the life cycle of the product which is identified in the previous steps.
4. Interpretation phase is the final phase of the LCA procedure, in which the results of an LCA are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

Life cycle impact assessment (LCIA) is used in LCA to arrange a link between inventory of elementary flows for the system of the product or process and its potential environmental impacts.

In an LCA, the emissions and resources expended linked to a specific product are compiled and documented in a Life Cycle Inventory (LCI). An impact assessment is carried out, generally considering three areas of protection: human health, natural environment, and issues related to natural resource use. Impact categories considered in the so-called LCIA include;

- Climate change
- Ozone depletion
- Eutrophication
- Acidification
- Human toxicity (cancer and non-cancer related)

- Respiratory inorganics
- Ionizing radiation
- Ecotoxicity
- Photochemical ozone formation
- Land use
- Resource depletion.

The LCIA phase consists of mandatory steps, which lead to LCIA results in the considered impact categories, and optional steps that can be used to further aggregate them as shown below **Figure 2**. The first three steps are the mandatory steps in conducting an LCIA according to ISO 14040 standard.

The LCIA phase consists of key steps:

1. Selection and Definition of Impact Categories
2. Classification (which involves assigning the elementary flows to the one or more relevant categories of impact)
3. Characterization (which involves a multiplication of the individual substances with the characterization factors from the applied LCIA method)
4. Normalization (optional)
5. Grouping (optional)
6. Weighting (optional)
7. Evaluation and report of LCIA results in order to gain a better understanding of the reliability of the LCIA results

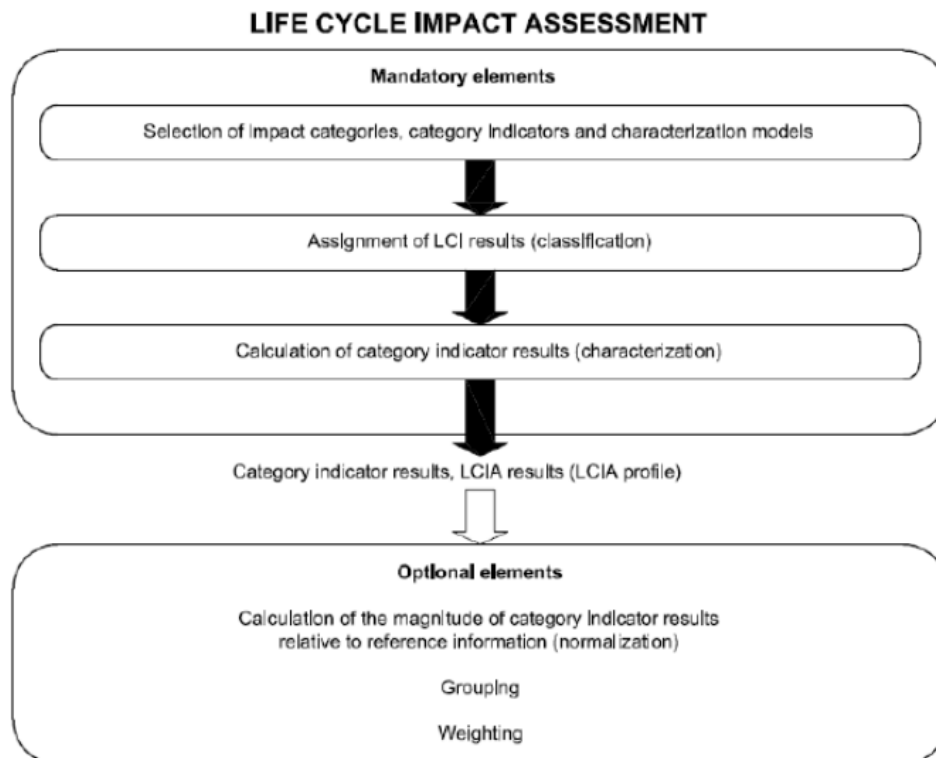


Figure 2: Mandatory and optional elements of LCIA (ISO 14040)

1.3. The Structure of the Study

In chapter 2, LCA methodology is presented, with references to its application for the calculation of the resource depletion impact. The software SimaPro is also briefly described. Chapter 3 deals with the construction and demolition waste: initially a bibliographic review gives an overview of the existing options for the recycling of CDW and of the related issues; then importance of natural resources is explained by giving data about sustainability of natural aggregates. Chapter 4 explains the case study which is implemented already by Borghi et al., 2018. Chapter 5 reports the results of the impact assessment of the LCA: the different methods are applied. Chapter 6 is conclusion part.

2. Methodology

The methodology for supporting the interpretation of the results has been focus on the impact category of resource depletion.

2.1. The Use of Resource Depletion as Impact Category

Natural resources are generally categorized in the context of LCA and beyond as

- Renewable and non-renewable
- Biotic and abiotic
- Funds, flows and stocks resources (Swart, Alvarenga, & Dewulf, 2015)

Renewable resources are natural resources that can be regenerated at about the same level as used (e.g. solar energy). On the other site, non-renewable resources cannot be presented at the same rate at which they are consumed (e.g., coal and natural gas).

Abiotic resources are inorganic or non-living materials at the moment of extraction (e.g. water, metals, also dead organic matter such as peat and coal) (Klinglmair, Sala, & Brandão, 2014). Biotic resources are materials derived from that are currently living organisms (e.g. wood, livestock, fish).

Classification of stocks extraction necessarily is leading to the depletion of the resource, i.e. reduction of the available amounts in nature, whereas funds may be depleted but also have a renewal rate which is high enough to allow the resource to recover. Usually biotic resources are classified as funds, but also groundwater can be seen a fund resource. Flow resources however cannot be depleted. Its availability per unit time however is limited, and hence their extraction is characterized by competition (e.g. wind energy) (Swart et al., 2015).

Abiotic resource use in LCA discusses environmental concerns by use of resources such as metals, minerals, fossil energy, nuclear energy, atmospheric resources, and flow energy resources (e.g. wind energy) (Swart et al., 2015).

2.2. Characterization Methods and Models for the Impact Category of Resource Depletion

The availability of variety methods allows the LCIA to be performed in many ways. Understanding the differences in assessment methods principles used to derive from resource depletion indicators and the effects on the impact assessment results is critical for indicator selection and interpretation of the results.

The aim of study is to provide an evaluation and interpretation of existing assessment methods to enable an informed selection of resource depletion indicators within LCA.

As shown in the **Figure 3** “LCIA methodology refers to a collection of individual characterization “methods”, which together address the different impact categories, which are covered by the methodology. A characterization method usually includes more than one characterization model. The characterization factor is “the factor derived from a characterization model which is applied to convert an assigned life cycle inventory result to the common unit of the category indicator” (European Commission Joint Research Center, 2012).

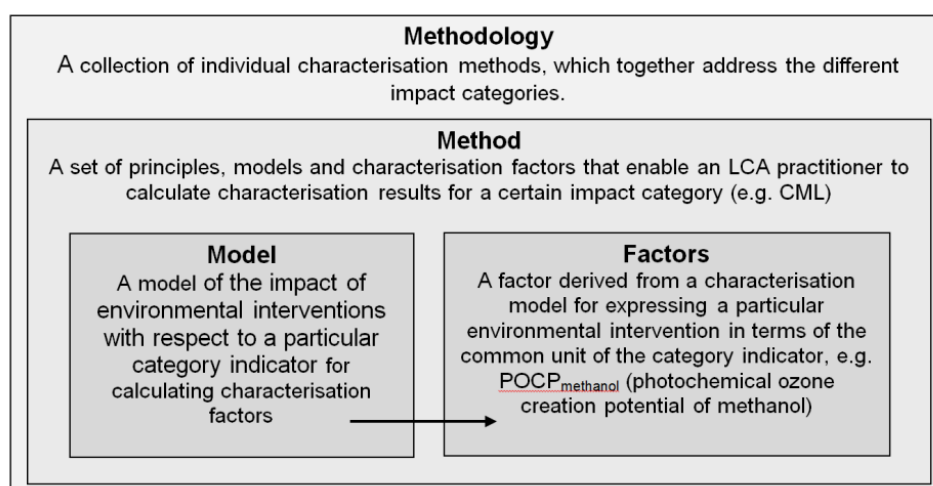


Figure 3: Methodology explanations (European Commission Joint Research Center, 2012)

There are two different methods of classification for abiotic resource use methods. One of them is ILCD classification, the other definition is taken from Swart et al., 2015.

The ILCD Handbook (European Commission Joint Research Center, 2011) classified the methods for abiotic resource use in four categories:

- (1) Category 1 includes methods that use an inherent property of the material as basis for the characterization
- (2) Category 2 includes methods that address the scarcity of resource
- (3) Category 3 includes methods focused on water depletion
- (4) Category 4 includes methods that evaluate the depletion of resources at an endpoint level.

According to Swart et al., 2015, LCIA methods for ‘abiotic resource use’ can be classified in four categories, considering some common characteristics:

- (1) Approaches based on energy or mass
- (2) Approaches based on ratio of use to deposits
- (3) Approaches based on future consequences of current resource extractions
- (4) Approaches based on exergy consumption or entropy production.

According to Alvarenga, Lins, & Neto, 2016, as shown in **Figure 4**, there are three impact pathways that can be evaluated by abiotic resource use. The first one is resource accounting method (RAM), the second is a group of approaches that evaluate the scarcity of resources at a midpoint level, finally the third one is a group of approaches that evaluate the scarcity of resources at endpoint level.

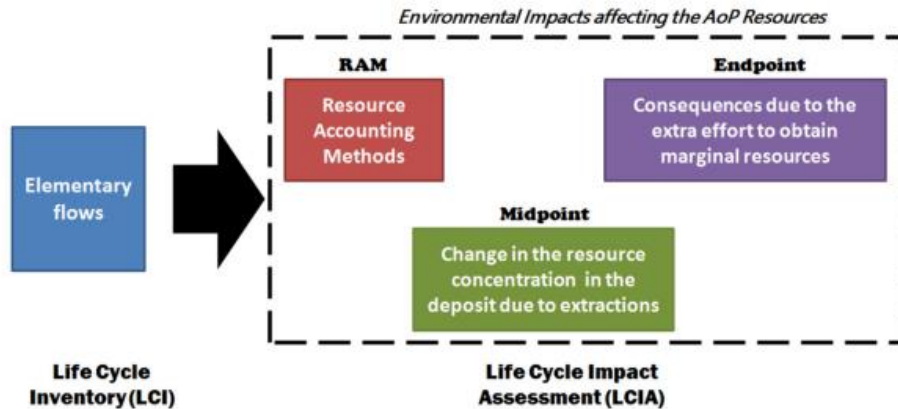


Figure 4: Simplified representation of cause-effect on area of protections (AoP) Resources, based on traditional LCIA groupings proposed by Alvarenga et al., 2016

Resource accounting methods (RAM) in general summarize all the resources consumed/used in the life cycle of a product in terms of mass, energy, exergy, energy, ecological footprint and ecological scarcity (Swart, Alvarenga, & Dewulf, 2015).

In the following subsections, we evaluate different LCIA models which are related to the impact category of resource depletion, indicating the impact pathways, indicators, characterization factors, calculation ways and CF units. A summary of the models is shown in **Table 6** after describing each of them.

2.2.1. Cumulative Energy Demand (CED)

The Cumulative Energy Demand (CED) is “one example of an operational LCIA method for quantifying the cumulative energy use, which was introduced in the 1970s by Boustead and Hancock and Pimentel et al., and standardized by VDI (the Association of German Engineers). It is a RAM (resource accounting method) that uses the heating value of materials as an aggregation unit” (Alvarenga et al., 2016).

Impact category indicator of CED implements the ‘energy harvested’ concept on all energy resources, i.e. renewable, fossil and nuclear (Frischknecht, Wyss, Büsser Knöpfel, Lützkendorf, & Balouktsi, 2015).

Energy based RAMs account for the energy extracted from the natural environment to support the technosphere system. They account not only for energy flow but also for material flows, by calculating their energy content (Swart et al., 2015). Instead, generally, CED accounts exclusively for resources with a specific energy or heating value (such as high or low heating values), which may be seen as a constraint of the approach because it becomes limited to energetic resources (fossil, nuclear, solar, geothermal, wind, and hydropower) and biomass (Alvarenga et al., 2016).

As it uses energy, based on the first law of thermodynamics, the scientific robustness is not so high as there are other LCIA methods (e.g. CExD, CEENE) that use the second law of thermodynamics, which has a higher scientific robustness (Alvarenga, Lins, & Neto, 2016).

However, some substances have lower energy heating value (LHV) (e.g. water, metals and minerals), which are not so effective on energy-based RAMs for abiotic resource use accounting (Swart et al., 2015).

2.2.2. Cumulative Exergy Demand (CExD)

The indicator Cumulative Exergy Demand (CExD) is introduced in order to describe total exergy removal from nature to supply product, summing up the exergy of all resources required. CExD evaluates the quality of energy demand and includes the exergy of energy carriers and also of non-energetic materials (Bösch, Hellweg, Huijbregts, & Frischknecht, 2007).

The CExD is a “RAM that uses the CED as a baseline, but instead of using energy as the indicator, it uses exergy” (Alvarenga et al., 2016). Exergy is the maximum amount of useful work that can be obtained from resource or system. Land resource use is not accounted for in order to avoid double-counting with biomass. Mineral, rocks, and non-metallic ores resources are instead included (Bösch et al., 2007). CExD uses 2nd law of thermodynamics rules when calculate the exergy, that’s why it has a higher scientific robustness than CED and a higher number of CFs.

CExD includes minerals (mineral aggregates) resource as a sub-categorization, whereas minerals are not considered as a sub-categorization in the CED (Bösch et al., 2007).

Calculation formula of the CExD is defined as the sum of exergy (**Equation 1**) of all resources required to provide a process or product (**Equation 2**):

Calculation Formula:

$$\delta Ex = T_0 \sum \Delta S \quad \text{Equation 1: Exergy calculation}$$

Ex = Exergy (MJ)
T₀ = Temperature of the surroundings (K)
S = Entropy (MJ/K)

$$CExD = \sum_i m_i \times Ex_{(ch),i} + \sum_j n_j \times r_{ex-e(k,p,n,r,t),j} \quad \text{Equation 2: CExD calculation}$$

CExD = Cumulative Exergy Demand per Unit of Production (MJ-eq)
m_i = Mass of material resources I (kg)
Ex_{(ch), i} = Exergy per kg of substances I (MJ-eq/kg)
n_j = Amount of energy from energy carrier j (MJ)
r_{ex-e(k,p,n,r,t),j} = Exergy to energy ratio of energy carrier j (MJ-eq/MJ)
ch = Chemical

k = Kinetic
 p = Potential
 n = Nuclear
 r = Radioactive
 t = Thermal exergy

Table 1 provides an overview about CExD factors for minerals and minerals aggregates (Bösch et al., 2007)

Table 1: CExD Factors (Bösch et al., 2007)

Flow	Flow property	Factor	Unit
Anhydrite	Mass	0.06	MJ/kg
Basalt	Mass	0.28	MJ/kg
Calcite	Mass	0.01	MJ/kg
Clay	Mass	0.059	MJ/kg
Gravel	Mass	0.068	MJ/kg
Sand	Mass	0.068	MJ/kg

2.2.3. Cumulative Exergy Extraction from Natural Environment (CEENE)

The method is based on the exergy concept. Consistent exergy data on fossils, nuclear and metal ores, minerals, air, water, land occupation, and renewable energy sources were developed, with well defined system boundaries. Based on these data, “the method quantifies the exergy “taken away” from natural ecosystems and is thus called the cumulative exergy extraction from the natural environment” (CEENE) (Dewulf et al., 2007).

CEENE takes into accounts many elementary flows, with a higher number of CFs than other RAM that use the same exergy approach (e.g., CExD). Additionally, according to Alvarenga et al., 2016, CEENE is seen as an upgraded version of CExD, and by using exergy calculation approach instead of energy, CEENE has a higher scientific robustness than CED, considered CEENE as (one of) the best thermodynamic-based LCIA methods. One of the differences among CEENE and CExD is the calculation approach used to account for the exergy of metals and minerals and for biotic resources (biomass and/or land use). The CEENE calculation approach accounts for land exergy terms through the accounting for quantity of photosynthetic solar exergy deprived from nature due to land use.

CEENE has some versions, the more recent one is 3.0 which has spatial differentiation for land use through the work.

CEENE is calculated as sum up all resource energy content (X_i) and cumulative amount from reference flow (a_{ij}). X factor is conversion factor which is defined as the energy content of the reference flow (**Equation 3**).

Calculation Formula:

$$CEENE_j = \sum_{i=1}^{184} (X_i \times a_{ij})$$

Equation 3: CEENE Calculation

- CEENE_j = the cumulative exergy extracted from the natural environment for a product j (in MJex)
 X_i = products energy content of the ith reference flow
 (X_i in MJ_{ex}/kg, MJ_{ex} /MJ, MJ_{ex} /Nm³, MJ_{ex} /m²a)
 a_{ij} = the cumulative amount a_{ij} from reference flow i (kg, MJ, Nm³, m²)

Table 2 provides an overview about CEENE factors for minerals and minerals aggregates (Dewulf et al., 2007)

Table 2: CEENE factors

Flow	Flow property	Factor	Unit
Anhydrite	Mass	0.158	MJex/kg
Basalt	Mass	0.31	MJex/kg
Clay	Mass	0.109	MJex/kg
Gravel	Mass	0.09	MJex/kg
Sand	Mass	0.031	MJex/kg

2.2.4. Solar Energy Demand (SED)

The Solar Energy Demand (SED) was developed by Rugani, Huijbregts, Mutel, Bastianoni, & Hellweg, 2011.

SED is a RAM that uses the Emergy concept as a baseline. “In Emergy, the cradle of an LCA is not in the boundary between the ecosphere and anthroposphere, as considered by several RAMs (e.g., CEENE), but within the limits of the geobiosphere, i.e., the Sun, tidal energy, and geothermal energy, aggregated into an indicator called solar energy equivalent” (Alvarenga et al., 2016). As shown in **Figure 5**, system boundaries for emergy and exergy-based RAMs are different.

In SED LCIA method, the authors concentrated on creating a high number of CFs for different natural resources. Concerning possible double-counting between biotic resources and land use, SED follows the approach of CEENE, which chooses to account for the use of the resource “land” (as opposed to the CED and CExD); for this reason, we can say that SED and CEENE are equivalent in this aspect.

According to Alvarenga et al., 2016, SED has a high number of CFs, but they are not regionalized. Emergy is an approach that is still disputed by scientific community, although there are some efforts to solve some of the problems and align to LCA, in which SED was a result of that effort.

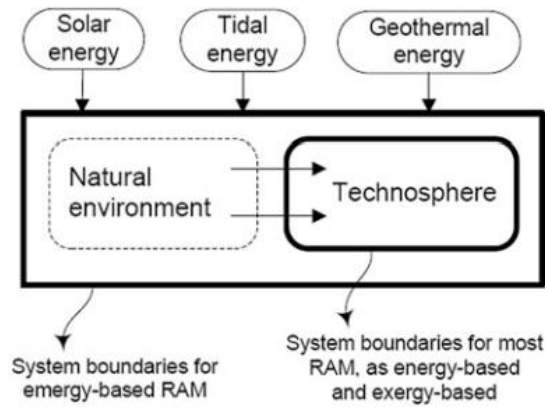


Figure 5: System boundaries of energy and exergy based RAMs (Swart et al., 2015)

As shown in **Figure 6** below, SED model evaluates minerals and mineral aggregates more than other models especially for building materials.

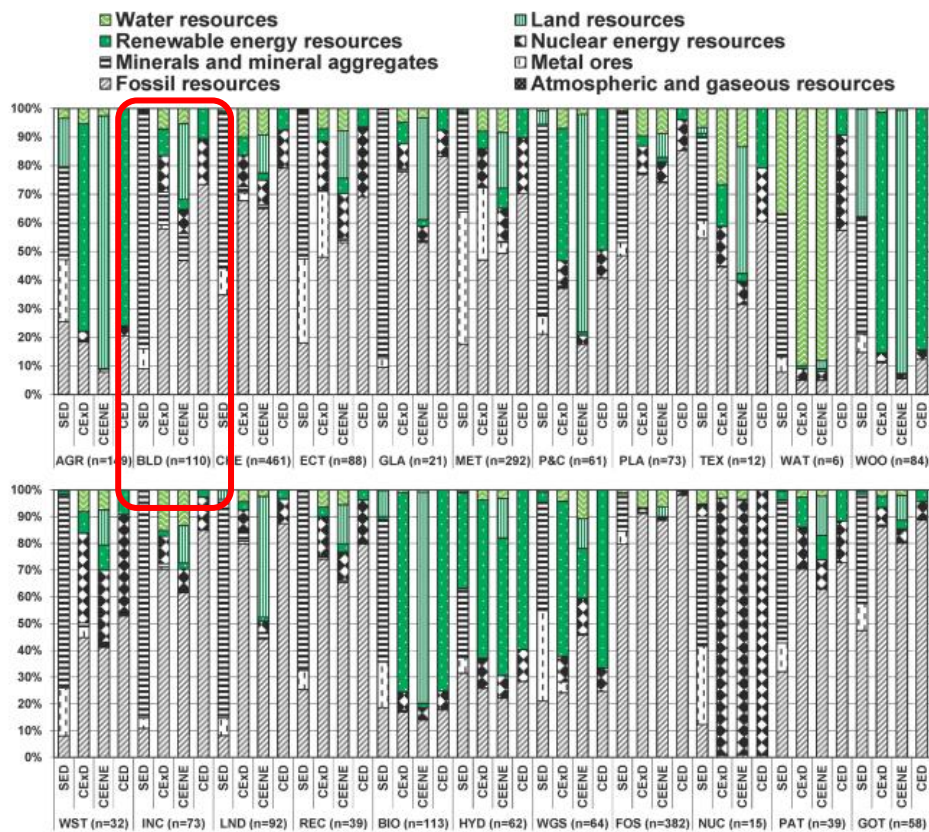


Figure 6: Comparison of the relative contribution of renewable and nonrenewable resources in SED, CExD, CEENE, and CED (Rugani et al., 2011)

Using energy as starting point, the SED accounts for the amount of solar energy needed to produce a certain product. However, it does not account for human labor and most of the ecosystem services: it accounts for provisioning services only (Swart et al., 2015).

Calculation formula of the SED represents total solar energy required to produce product or service (**Equation 4**). SEF is solar energy factor of the reference flow of resource which depends on the annual baseline of energy and annual flow of the resource (**Equation 5**) (Rugani et al., 2011).

Calculation Formula:

$$SED_p = \sum_i SEF_i \times M_{p,i} \quad \text{Equation 4: SED Calculation}$$

$$SEF_i = \frac{S}{F_i} \quad \text{Equation 5: SEF Calculation}$$

- SED_p = the solar energy demand (SED) of a given process
(SED_p in MJ_{se-equiv}, megajoules of equivalent solar energy)
- SEF_i = solar energy factor of the ith reference flow of resource
(SEF_i in MJ_{se}/kg, MJ_{se}/Nm³, MJ_{se}/m³, MJ_{se}/m²a, MJ_{se}/MJ)
- M_{p,i} = quantity of resource flow i (M_{p,i} in kg, Nm, m, m²a, MJ) involved as input in the production of p
- S = annual baseline of energy that flows in the geobiosphere, i.e., sum of energy in sun, tide, and crustal heat (from literature)
- F_i = annual flow of the resource i (e.g., kg/year), estimated by the ratio of the stored quantity and its turnover time.

Table 3 provides an overview about SEFs for minerals and minerals aggregates (Rugani et al., 2011).

Table 3: Solar Energy Factors (Rugani et al., 2011)

Key elementary flows and groups of resource	Units	Type*	SEF [MJ _{se.} unit ⁻¹]	Original source of minerals
Basalt	kg	N	1.46 x 10 ⁵	oceanic basalt
Granite	kg	N	4.90 x 10 ⁵	granitic rocks
n.15 flows (e.g., feldspar, gravel, kaolinite)	kg	N	1.25 x 10 ⁶	continental sediment
pyrite; metamorphous rock	kg	N	1.42 x 10 ⁶	metamorphic rock
clay (n.2 flows)	kg	N	1.98 x 10 ⁶	soil clay
Shale	kg	N	2.36 x 10 ⁶	shale
perlite; pumice	kg	N	4.45 x 10 ⁶	volcanic sediment
Sand	kg	N	4.95 x 10 ⁶	sandstone
calcite; dolomite	kg	N	5.50 x 10 ⁶	limestone
n.11 flows (e.g., anhydrite, borax, sodium chloride) ^f	kg	N	9.89 x 10 ⁷	evaporites
Stibnite	kg	N	2.47 x 10 ⁹	antimony

*N: Non-renewable resources
*R: Renewable
*f: Non carbonate salts

2.2.5. Abiotic Depletion Potential (ADP)

Abiotic Depletion Potential (ADP), originally developed by Guinée (1995), was later modified in van Oers (2002), and included in the LCIA methodology CML-IA (from the Institute of Environmental Sciences (CML), named CML-IA).

In order to compute the CFs, ADP uses a formulation that involves the extraction rate of a resource and the squared of the availability of this resource in deposits. All resources are normalized to the CF of antimony (Sb); for this reason, the indicator is expressed in antimony (Sb-eq) equivalent. Concerning deposits used to calculate the CFs, original ADP used the ultimate reserves, which may be defined as the total amount of a specific substance (e.g., Zinc) available in the Earth's crust, oceans and atmosphere. In this case, the ultimate reserve also contains deposits that are not economically or technically sufficient for extraction. Later on, ADP has set up a CF for other approaches as well, i.e., for reserve base and economic reserves (see **Table 4**). ADP has CFs for metals and minerals, and the total number of CFs is dependent on the method used (ultimate reserve, reserve base or economic reserve). For fossil fuels, ADP also has CFs, but in the latter versions of the ultimate reserve approach (e.g., v4.2) the CF are based on the net heating value of the fossil fuel, similar to CED (a RAM), therefore not providing a midpoint resource depletion assessment.

ADP has high scientific robustness according to the LCA community, and the approach based on the reserve base is recommended by ILCD (European Commission Joint Research Center, 2011) as the LCIA model to be used for midpoint assessment. In addition, the number of CFs provided by ADP model is quite high in comparison to other depletion LCIA models, even though the approach considered. In that sense, ADP received high scores for the criteria considered in Alvarenga study (Alvarenga et al., 2016).

Table 4: Types of reserves and definitions (van Oers & Guinée, 2016)

Terminology		Definition
(van Oers et al., 2002)	(Drielsma et al., 2016)	A Resource/ Reserve Classification for Minerals, United States Geological Survey (USGS)
Ultimate reserve	Crustal content	The quantity of a resource (like a chemical element or compound) that is ultimately available, estimated by multiplying the average natural concentration of the resource in the primary extraction media (e.g., the earth's crust) by the mass or volume of these media (e.g., the mass of the crust assuming a depth of e.g., 10 km)
Ultimately extractable reserve	Extractable global resource	Those reserves that can ultimately be technically extracted may be termed the “ultimately extractable reserves”. This ultimately extractable reserve (“extractable global resource”) is situated somewhere between the ultimate reserve and the reserve base
Reserve base	Mineral resource	Part of an identified resource that meets specified minimum physical and chemical criteria relating to current mining practice. The reserve base may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves) or marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources) (for further definitions see the original references)
Economic reserve	Mineral reserve	The part of the natural reserve base which can be economically extracted at the time of determination

The ADP characterization model is a function of the extraction rate of a resource and the extraction rate of the reference resource related to ultimate reserve of resource and reference resource (**Equation 7**). The CF is the abiotic depletion potential (ADP) which is obtained for antimony equivalent as a reference as mentioned above. Natural reserves of resources are based on “ultimate reserves”; that is, on concentrations of the elements and fossil carbon in the Earth's crust. “Antimony was chosen as a reference substance because it is the first element in the alphabet for which a complete set of necessary data (extraction rate and multimate reserve) is available, and aggregating the results of these multiplications in one score to obtain the indicator result (in kg antimony equivalents) ” (**Equation 6**) (van Oers & Guinée, 2016).

Calculation Formula:

$$Abiotic\ depletion = \sum_i ADP_i \times m_i \quad \text{Equation 6: Abiotic depletion calculation}$$

$$ADP_i = \frac{DR_i / (R_i)^2}{DR_{ref} / (R_{ref})^2} \quad \text{Equation 7: ADP Calculation}$$

- ADP_i = abiotic depletion potential of resource i (kg antimony equivalents/kg of resource i)
- m_i = quantity of resource i extracted (kg)
- R_i = ultimate reserve of resource i (kg)
- DR_i = extraction rate of resource i (kg yr⁻¹) (regeneration assumed to be zero)
- R_{ref} = ultimate reserve of the reference resource, antimony (kg)
- DR_{ref} = extraction rate of the reference resource R_{ref} (kg yr⁻¹)

2.2.6. Anthropogenic Stock Extended Abiotic Depletion Potential (AADP)

The Anthropogenic Stock Extended Abiotic Depletion Potential (AADP) can be considered a complementary method for the ADP, by including the depletion assessment resources that have already been extracted from their deposits and are now available in the anthroposphere (e.g., landfill), bringing an innovative concept. However, due to the difficulty of obtaining consistent data, it has CFs for solely 10 metals in Schneider, Berger, & Finkbeiner, 2011 version. But the number of CFs increased in Schneider, Berger, & Finkbeiner, 2015 version which includes 35 metals. Since it is a specific LCIA model for metals, it does not have CFs for fossil fuels and minerals (Alvarenga et al., 2016).

Calculation of the abiotic depletion potentials are defined according to existing definitions in the **Figure 7** which means were already explained in **Table 2**.

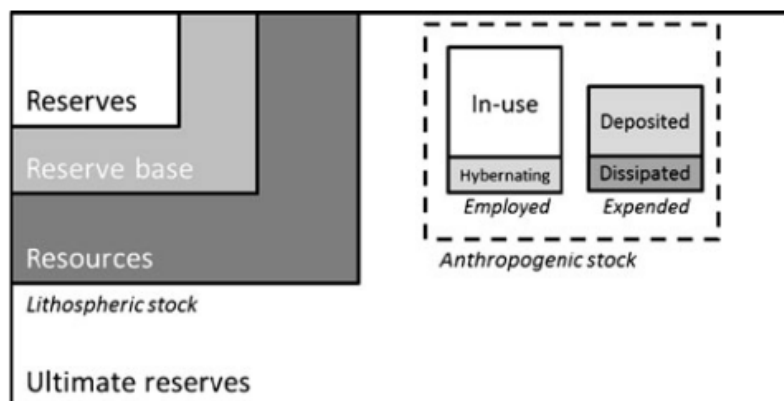


Figure 7: Types of lithospheric and anthropogenic material stock (Schneider et al., 2011)

ReCiPe 2016 Midpoint is an update of the method of 2008. ReCiPe has eighteen impact categories that are targeted at the midpoint level. Mineral resource scarcity is one of these impact categories (Goedkoop et al., 2009).

Recipe 2016 Midpoint has CFs for fossil fuels, metals and minerals, and the approach used is different for the types of resources. While fossil resources are examined under fossil resource scarcity impact category, metals and minerals are examined under mineral resource scarcity impact category. Recipe Midpoint considers the heating value for fossil fuels, i.e., a RAM approach, like CED. For metals and minerals, the approach is different, considering the depletion of those resources at midpoint level. Recipe Midpoint has an innovative approach, in comparison to ADP and EDIP, evaluated through the deposits of minerals, and not by the metals per se. According to the authors, in this way, the LCIA model better represents the reality of the metals' geological distribution, which enables them to cover a higher number of raw materials, especially those extracted as by-products. The model takes into account change in the ore grade, i.e., the decrease in the concentration of minerals in an ore due to extraction. Recipe 2016 Midpoint version has higher CFs than ADP and EDIP. Besides, Recipe Midpoint has some inconsistencies in the creation of CFs (e.g., allocation procedure) as stated in the Alvarenga study (Alvarenga et al., 2016).

2.2.9. Model in Ecological Scarcity 2013 (Swiss Eco-factors) method

The ecological scarcity method was introduced by Müller-Wenk (1978) and sophisticated for the first time by Braunschweig (1982). Then it was further developed in the context of the interpretation of the life cycle assessments for packaging materials published by BUWAL, the precursor agency from which the Swiss Federal Office for the Environment FOEN emerged, in 1984 (Rolf Frischknecht et al., 2013).

The ecological scarcity method is the “distance-to-target” method as defined by SETAC (Udo de Haes 1996). The method offers standardized, generic weights (Rolf Frischknecht et al., 2013).

National or international regulations and limit values are used to define the tolerance quantities. These can include intergovernmental agreements or targets set by national political bodies. In the example of climate gases, the Kyoto Protocol, the CO₂ Act and the “Sustainable Development Strategy” of the Swiss Federal Council are used to derive the Swiss eco-factors. The targets are aligned for the year 2030.

One of the problems of the ecological scarcity method is dealing with environmental pressures abroad. In cases where emissions and resource extractions are not always similarly relevant from region to region (such as freshwater consumption, land use or SO₂ emissions), they cannot always be effectively represented. Because the ecological scarcity method is based on limit values, it does not directly illustrate the damage potential.

The ecological scarcity method uses eco-factors to weight environmental impacts emissions of pollutants and noise as well as resource extractions – and expresses them in eco-points (UBP). The eco-factor is derived from environmental legislation or political targets which is results of calculation steps. These steps are characterization, normalization and weighting in accordance with ISO Standard 14044. Characterization factors are defined for pollutants and resources

allocated to an environmental impact (e.g. global warming or resource depletion). Normalization is used to adapt the scarcity condition to the actual emission and resource extractions in a geographic region. Pollutants, resources or characterized environmental impacts are finally weighted on the basis of their "distance to target" or "ecological scarcity." (Rolf Frischknecht et al., 2013).

Characterization factors (K) for mineral and metal resources are defined by antimony equivalent (kg/kg Sb-eq) regarding to ADP model, then characterization factor is normalized and weighted according to antimony flow per year (Sb-eq/year). **Table 5** provides an example of eco-factors for ecological scarcity model (Rolf Frischknecht et al., 2013).

The eco-factor is defined as follows (**Equation 10**):

$$Eco - factor = K \times \frac{1 \times UBP}{F_n} \times \left(\frac{F}{F_k}\right)^2 \times c$$

Equation 10: Eco-factor calculation

Characterization Normalization Weighting

- K = Characterization factor of an emission or resource
- F_n = Normalization quantity (technical term: normalization flow): current annual quantity (it is expressed as kg Sb-eq yr⁻¹ for mineral and metal)
- F = Current quantity (technical term: current flow): current annual quantity of the emission or of the consumption of that resource in the reference area
- F_k = Tolerance level (technical term: critical flow): statutory limit value in the reference region
- c = Constant: it serves to obtain readily representable numerical quantities
- UBP = Eco- point (the unit of environmental impact assessed; it does not have numerical number)

Table 5: Ecological Scarcity eco-factors (Rolf Frischknecht et al., 2013)

Flow	Flow property	Factor	Unit
Metals			
Copper	Mass	1100	UBP/kg
Chromium	Mass	4800	UBP/kg
Minerals			
Gypsum	Mass	6.3	UBP/kg
Phosphorus	Mass	62	UBP/kg
Gravel	Mass	0.029	UBP/g

2.2.10. Summary of the Methods

Models explained till now are summarized in **Table 6**.

There are also different LCIA methods that use one of the characterization models explained before (e.g ILCD, EF, Impact 2002 +).

In the document “ILCD recommendations for LCIA in the European context” the European Commission (EC-JRC-IES, 2011) analyzed several methods for LCIA and made some effort towards harmonization. Starting from the first pre-selection of existing methods and the definition of criteria, a list of recommended methods for each impact category at both midpoint and endpoint was produced. The recommendation presented for the impact category resource depletion is ADP model (EC-JRC-IES, 2011).

The Environmental Footprint (EF) is the impact assessment method introduced by the European Commission in the context of the Product Environmental Footprint initiative. It builds on existing approaches and international standards. For resources depletion at midpoint, the recommended model is the Abiotic Resource Depletion, “ultimate reserves” version, described in van Oers et al. (2002), based on the models of Guinée et al. (2002). The CFs are given as Abiotic Depletion Potential (ADP), quantified in kg of antimony-equivalent (Sb-eq) per kg extraction. The CFs recommended are the ones in the CML method, version 4.8 (2016) (Sala, Cerutti, & Pant, 2018).

The overall approach is not difference from ILCD. However, reference model for resource depletion of minerals and metals has changed from reserve base to ultimate reserves.

The IMPACT 2002+ LCIA method suggests feasible implementation of a combined midpoint/damage approach. It evaluates LCI results with 14 midpoint and 4 damage impact categories, one of them is mineral extraction midpoint impact category. Midpoint categories are adapted from existing CML 2002 method (Jolliet et al., 2003).

Table 6: Summary of characterization models for resource depletion impact category

Impact Category	Characterization Models	Characterization Methods	Impact Category Name Used in SimaPro	Impact Pathways	Approach	Unit	Reference	Updated Reference	
Resource Depletion	CED Cumulative Energy Demand		Fossil and renewable energy resources	RAM	Energy	MJ oil-eq or kWh oil-eq	Frischknecht et al., 2015		
	CExD Cumulative Exergy Demand		Non -renewable fossil, minerals, metals, nuclear, primary resources	RAM	Exergy	MJ/kg MJ/m3	Bösch et al., 2007		
	CEENE Cumulative Exergy Extraction from Natural Environment		Atmospheric, renewable energy, land, metal, minerals, nuclear and water resources	RAM	Exergy	MJ/kg MJ/m3	Dewulf et al., 2007	Dewulf et al., 2014	
	SED Solar Energy Demand		Atmospheric, renewable energy, land, metal, minerals, nuclear and water resources	RAM	Emergy	MJse/kg MJse/Nm3 MJse/m3	Rugani et al., 2011		
	Model in the EDIP method	EDIP 1997/ 2003 Environmental Design of Industrial Products	Resources (all)	Midpoint	Scarcity- Amount of available deposits	PR2004	Hauschild et al, 1998		
	Model in the ReCiPe method	ReCiPe Midpoint	Mineral Resource Scarcity	Midpoint	Grade decrease Deposits metal related extraction rate	kg Fe-eq kg Cu-eq	Goedkoop et al., 2009		
	ADP Abiotic Depletion Potential	Ecological Scarcity 2013 (Swiss Eco-scarcity)	Mineral Resources	Midpoint RAM	Distance to target	EP/MJ (or UBP) EP/kg	Frischknecht et al., 2013		
			IMPACT 2002 + Impact Assessment of Chemical Toxic	Mineral extraction	Midpoint	Scarcity- Related to Antimony (Sb) equivalent	MJ surplus	Jolliet et al., 2003	
			CML	Abiotic Depletion (elements, ultimate reserves, econ. reserves)	Midpoint	Scarcity- Related to Antimony (Sb) equivalent	kg Sb-eq	Guinée, 1995	Van Oers & Guinée, 2016
			PEF Product Environmental Footprint	Resource Use, Minerals and Metals ADP ultimate reserves	Midpoint	Scarcity- Related to Antimony (Sb) equivalent- Ultimate reserve base	kg Sb eq.	Fazio, Castellani, V. Sala, Schau, EM. Secchi, Zampori, L. 2018	Sala, Cerutti, & Pant, 2018
			ILCD Midpoint + International Life Cycle Data System	Mineral, Fossil & Ren Resource Depletion	Midpoint	Scarcity Related to Antimony (Sb) equivalent- Reserve base	kg Sb eq.	EC-JRC-IES, 2011	
	AADP Anthropogenic Stock Extended Abiotic Depletion Potential	CML	Abiotic Depletion for Metals	Midpoint	Scarcity- Related to Antimony (Sb) equivalent	kg Sb-eq	Schneider et al., 2011	Schneider et al., 2015	

2.3. SimaPro Software

The analysis was carried out by SimaPro software in this study. SimaPro is a software produced by the Dutch company Pré Consultant; it was first implemented more than 25 years ago. Nowadays it is main software for performing LCA, used by industry and academics in more than 80 countries. The software can be used for a variety of applications, such as sustainability reporting, carbon and water footprint, product design, generating environmental product declarations and determining key performance indicators.

3. CDW and Sustainability

The largest portion of energy is used during the operational phase of a building. In the manufacture and transport of materials, construction, maintenance and demolition, a smaller percentage of energy is consumed, usually 10 to 20 percent (UNEP, 2009). In addition to energy consumption, the point we should focus on is material conservation. As shown in **Figure 8** (UNEP, 2009), thanks to CDW recycling, material conservation can be achieved through waste management strategies.

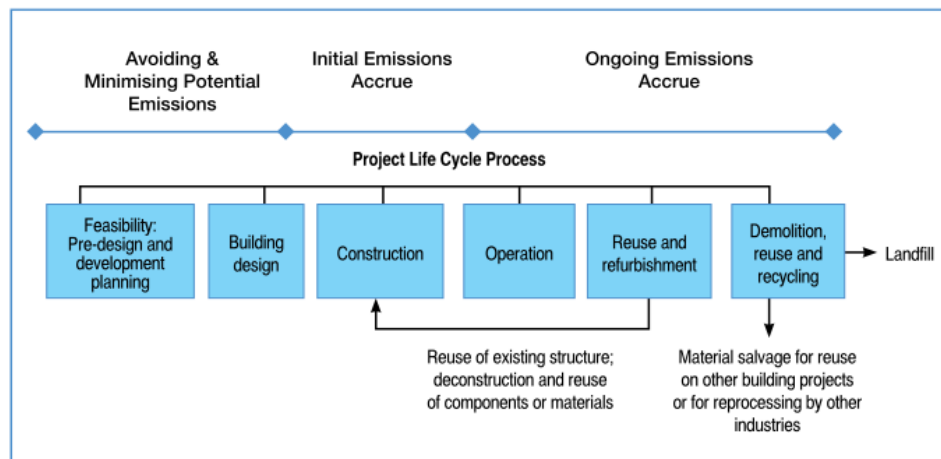


Figure 8: Life Cycle Phases of Building (UNEP, 2009)

3.1. Construction and Demolition Waste (CDW) Definitions

CDW is generally defined as the solid waste produced by construction, renovation and demolition. CDW is defined by Zhao et al.2010 “waste material generated from the process of renovation, construction and demolition of buildings. Structures comprise all types (both non-residential and residential) of buildings as well as bridges and roads. CDW or components generally include asphalt, wood, concrete, metals, wallboard gypsum and roofing materials”(Zhao, Leefink, & Rotter, 2010).

3.2. CDW Distribution in the Total Waste Generation

CDW is one of most plentiful waste stream generated in European Union (EU), accounting for approximately 36.4 % of the total waste production in EU-28 in 2016 as shown in **Figure 9** (Eurostat, 2016).

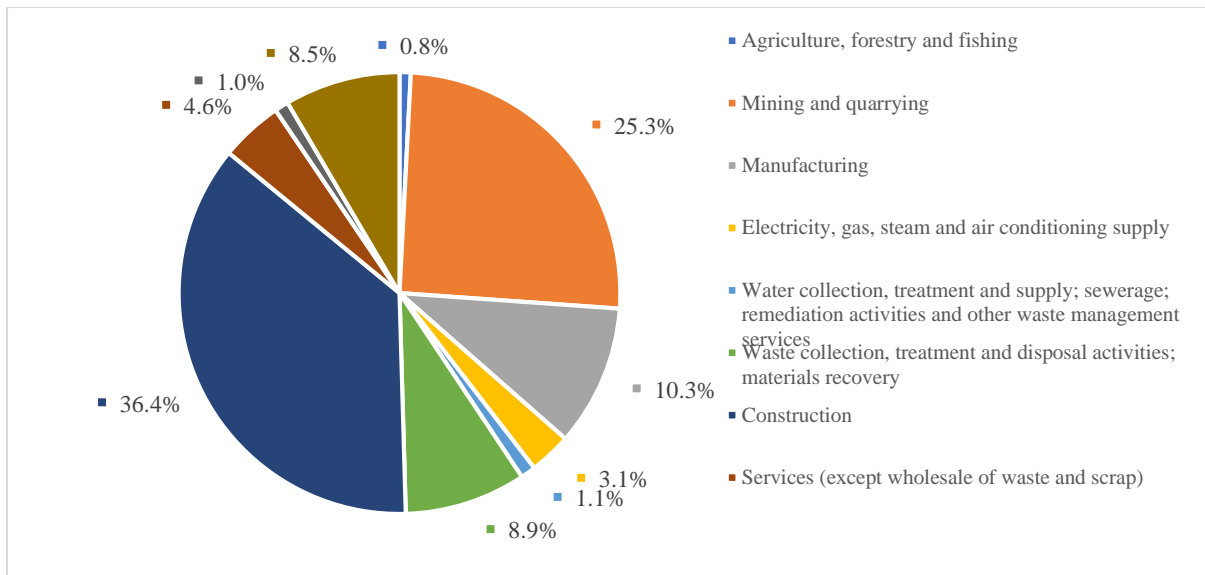


Figure 9: Waste generation by economic activities and households, EU-28, 2016 (%) (Eurostat)

CDW is also the largest percentage waste stream in Italy. It is about 55 Mt (33.3 %) of the total national production in 2016 as shown in **Figure 10**. Lombardy region is generating the largest amount of CDW in Italy (ISPRA, 2016).

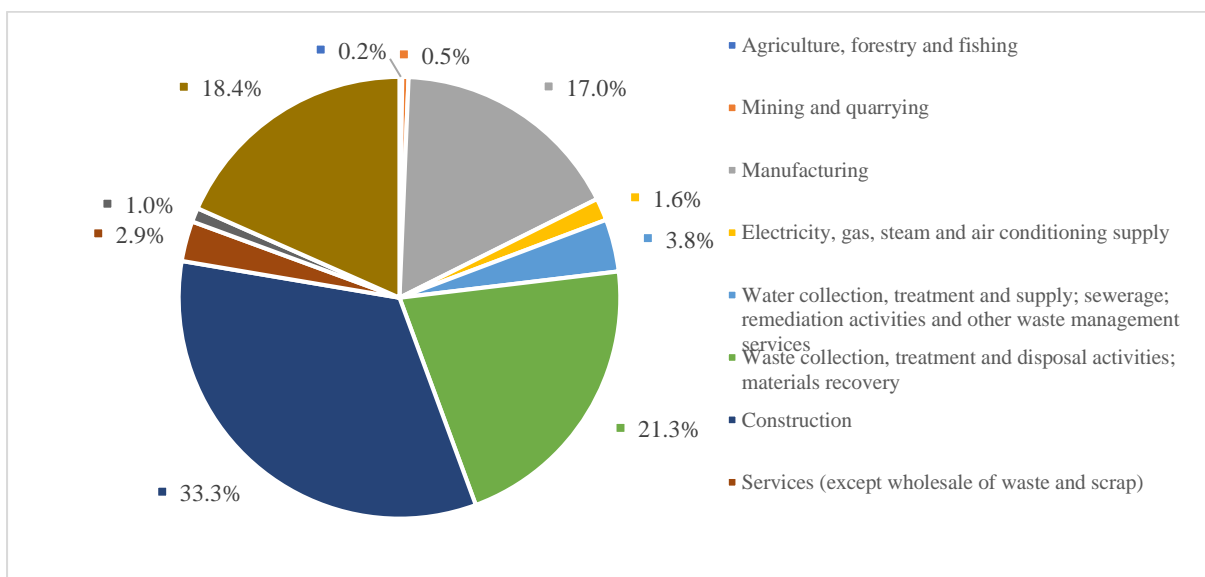


Figure 10: Waste generation by economic activities and households in Italy, 2016 (Eurostat)

Table 7 shows the CDW total generation (Mt) and per capita (kg/inhabitant) in the countries of the EU, in 2016, from the Eurostat database.

Table 7: CDW generation in the countries of the EU, in 2016, from the Eurostat database

Country	CDW [kg/ inhabitant]	CDW [Mt]
Austria	5.1	44.9
Belgium	1.7	19.6
Bulgaria	293	2.1
Croatia	310	1.3
Cyprus	1.0	0.9
Czechia	960	10.1
Denmark	2.1	12.2
Estonia	892	1.2
Finland	2.5	13.8
France	3.3	224.4
Germany (until 1990 former territory of the FRG)	2.7	220.5
Greece	57	0.6
Hungary	366	3.6
Iceland	129	0.0
Ireland	320	1.5
Italy	900	54.6
Kosovo (under United Nations Security Council Resolution 1244/99)	94	0.2
Latvia	57	0.1
Liechtenstein	11.7	0.4
Lithuania	176	0.5
Luxembourg	13.1	7.6
Malta	2.9	1.4
Montenegro	1.0	0.6
Netherlands	5.8	98.6
Norway	584	3.1
Poland	498	18.9
Portugal	166	1.7
Romania	16	0.3
Serbia	78	0.5
Slovakia	178	1.0
Slovenia	263	0.5
Spain	771	35.8
Sweden	989	9.8
United Kingdom	2.1	136.2

3.3. CDW Characterization

CDWs are classified in a variety of ways, defining specific waste composition and characteristics depending on each classification. There are three main factors that affect the characteristics of CDW; structure type, structure size and activity being performed. (Zhao et al., 2010). Structure type is related to be residential, commercial, or industrial building, road, bridge. Structure size can be explained as high-rise or low-rise buildings. Activity being performed is also defined as new construction, renovation, repair and demolition.

The European Waste Catalogue (EWC) categorizes CDW into nine major groups. The groups of CDW are defined in chapter 17 of EWC (**Table 8**).

Table 8: European Waste Catalogue and Hazardous Waste List for CDW

17 Construction and Demolition Wastes (Including Excavated Soil from Contaminated Sites)	
17 01	concrete, bricks, tiles and ceramics
17 02	wood, glass and plastic
17 03	bituminous mixtures, coal tar and tarred products
17 04	metals (including their alloys)
17 05	soil (including excavated soil from contaminated sites), stones and dredging spoil
17 06	insulation materials and asbestos-containing construction materials
17 08	gypsum-based construction material
17 09	other construction and demolition waste

In brief, CDW waste includes concrete, bricks, tiles, ceramics, bituminous mixtures, wood, glass, plastic, metals, soil, asbestos, gypsum and solvent.

3.4. CDW Treatment

The Waste Framework Directive (2008/98/CE) requires Member States to achieve at least 70% (by weight) of re-use, recycling and other material recovery, including backfilling operations, using non-hazardous CDW by 2020. For these purposes, public authorities are increasingly interested in ensuring a regional/local sustainable CDW management system, not only in reducing the environmental pressures associated with waste generation and landfilling, but also in minimizing the depletion of mineral resources caused by construction activities.

Figure 11 (Eurostat, 2016) shows waste management of CDW in EU according to the different operations; only non-hazardous waste is taken into account. Data shows that slightly more than 89 % of the non-hazardous mineral waste from construction and demolition waste was treated in recovery operations: recycling (83.24 % of the total treated), backfilling (5.7 %) or energy recovery (0.44 %) in EU-28 in 2016. According to data across Europe, it seems that it has achieved its goal for non-hazardous CDW. For some countries, as Germany and Luxembourg, data regarding the CDW management are not completely available yet, thus they are not reported.

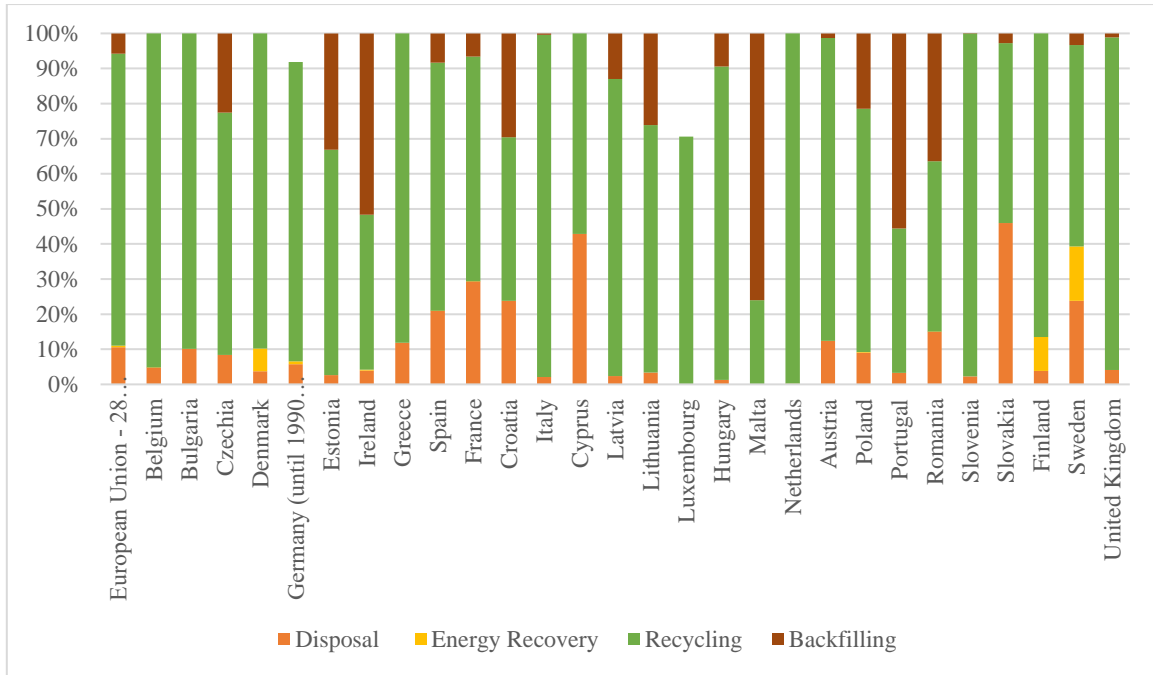


Figure 11: Waste management of non-hazardous CDW in the EU countries, 2016 (Eurostat, 2016)

One of the important steps to achieve the targets is to concentrate on the percentage of wastes streams generated that are the highest in quantity. As mentioned above, CDWs are the most abundant waste stream generated in EU. Standard life cycle flow chart of non-inert and inert waste is shown in **Figure 12** (Islam et al., 2019).

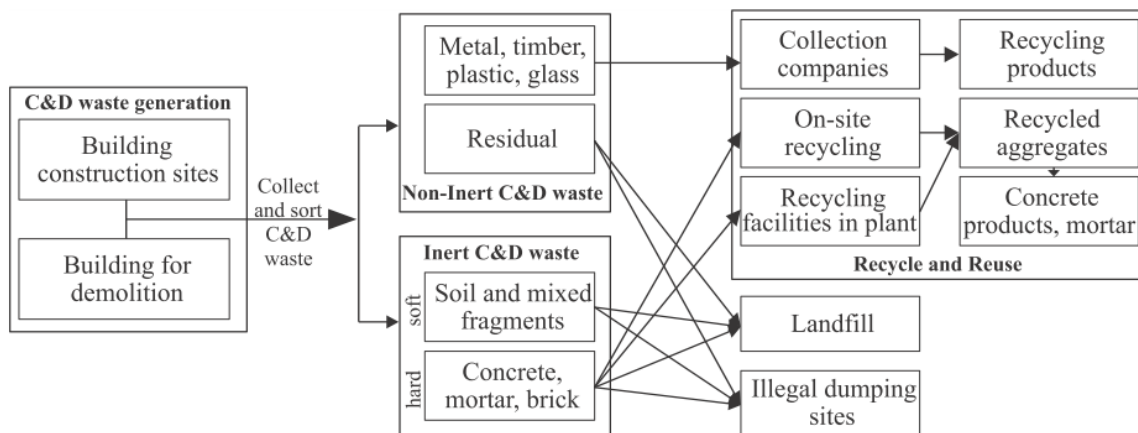


Figure 12: Typical life cycle flow chart of different types of CDW (Islam et al., 2019)

3.5. Sustainability of Aggregates

3.5.1. State of Aggregates

Aggregates is a generic term for crushed rock, sand and gravels, which can be sub-categorized by formation process (natural or manufactured), composition, and grain size distribution (UNEP, 2019). Three aggregates groups are defined:

Primary/Natural Aggregates (NAs): Crushed Rock, extracted in hard rock quarries by blasting and crushing; and sand and gravels, extracted from pits by excavation, crushing, screening and washing (if required), dredged or pumped from lakes and rivers, removed from coastal beaches, or dredged from the sea bed (also termed Marine Aggregates).

Recycled Aggregates (RAs): Crushed rock, sand and gravels produced by sorting, crushing and screening of construction and demolition materials.

Manufactured Aggregates: Crushed rock, sand and gravels substitutes produced from wastes from other industries.

Every year, an estimated 40-50 billion tons are extracted globally from quarries, mines, lakes, coasts and the marine environment (Peduzzi, 2014).

Aggregates are the largest concrete component, contributing between 60 to 75 percent of its weight, and are mainly obtained through raw material quarrying. **Figure 13** shows the development of the EU's material footprint or raw material consumption (RMC) over time. The RMC of non-metallic minerals is the major driver of the observed trend as it has the greatest impact on overall development over time. Non-metallic minerals consist mainly of construction minerals such as sand and gravel. According to (Eurostat, 2012) data, "Gross value added in construction increased by 12 % in the EU-28 from 2000 to 2007. Domestic extraction of non-metallic minerals increased by 16 % in the same period. Gross value added in construction decreased by 11 % during the economic crisis (2010 compared to 2007) and after a further decrease was back at 2010 levels in 2017. Domestic extraction of non-metallic minerals decreased by 25 % (2010 compared to 2007) and is still a bit lower (2 %) in 2017 compared to 2010".

Raw material consumption (RMC) by main material categories, EU-28, 2000-2017
(tonnes per capita)

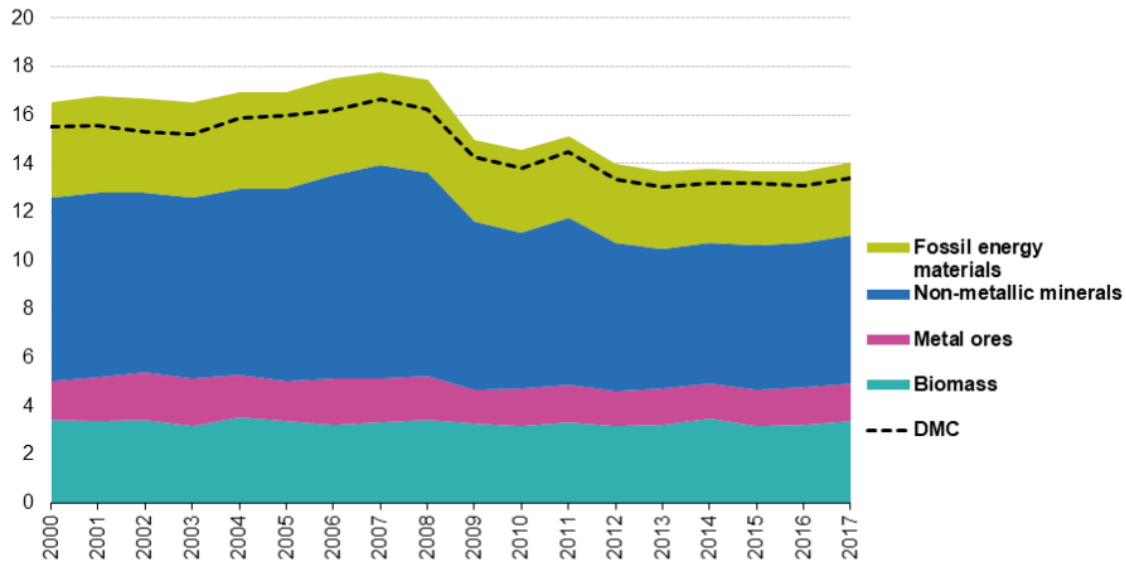


Figure 13: Raw Material Consumption (RMC) by Main Material Categories, EU-28, 2000-2017

Table 9 reports estimates of aggregates production data in 2017 for EU-28 and Italy.

Table 9: Estimates of Aggregates Production data in 2017 <http://www.uepg.eu/statistics/estimates-of-production-data/data-2017>

	Sand & Gravel [Mt]	Crushed Rock [Mt]	Marine Aggregates [Mt]	Recycled Aggregates [Mt]	Re-Used on Site [Mt]	Manufactured Aggregates [Mt]	Total [Mt]
Italy	65	91	0	4	0	0	160
EU-28	1282	60	266	91	64	2861	13906

As mention above, RAs can be used as secondary material in the construction industry. However, the usage of RAs as secondary material should provide legal requirements. According to Italian legislation, RAs can be classified as low (type C), medium (type B) and high (type A) quality type respect to their own technical requirements. Low quality (type C) RAs can be used for environmental reclamation and fillings. Medium quality (type B) RAs can be used in road sub-base, embankment body, in anti-freezing, anti-capillary and draining layers. High quality (type A) RAs can be used in road base and construction.

3.5.2. Aggregates Extraction Impacts on the Environment

All over the world, sand and gravel are mined and account for the world's largest amount of solid material produced. Sand extraction's environmental and social impacts are a global issue. According to (Peduzzi, 2014) data, extraction has an impact on biodiversity, water turbidity, water table levels and landscape and on climate through carbon dioxide emissions from transportation. There are also socio-economic, cultural and even political consequences.

Peduzzi et al. 2014 has made many suggestions to reduce these effects. For instance:

- Reducing consumption of sand and use renewable and recycled materials targets for building houses and roads
- Tax on aggregates extraction to create incentives on alternatives
- Reducing the negative consequences of extraction
- Policies

Usage of RAs as secondary material provides that NAs can be considered as avoided product in construction process. In addition to protection of NAs, the usage of RAs allows avoided energy and avoided material consumption during the extraction phases of NAs. Nevertheless, it is difficult to synchronize the usage of RAs as an avoided material in LCA with characterization models because most of these models does not include specific CFs for NAs such as sand and gravel. In general, models use some approaches to calculate CFs for substances such as exergy, energy, scarcity as mentioned in **Table 6**. There are some reasons which prevent proper calculation of CFs in LCA analysis; (i)the lack of adequate information of sand and gravel mining quantity, (ii) the lack of standardized data according to geographic condition of sand and gravel, (iii) difficulties of accessing data (Peduzzi, 2014).

4. Case Study on CDW Lombardy Region: Generation, Composition and Management

The LCA of the CDW Management system implemented in the Lombardy Region (Italy) and described by Borghi et al., 2018 was taken as a case study.

In the case study, non-hazardous CDW is considered, which is involved by cement, tiles, ceramics (EWC 1701), bituminous mixture (EWC 170302), gypsum (EWC 170702) and mixed waste (EWC 170904). The study was carried out within the year of 2014 data's (Borghi et al., 2018).

The amount of waste used in the analysis is given in the table below according to the waste codes (**Table 10**). High percentage of CDW (90.7 %) is recycled, limited percentage of waste is disposed of in landfill (3.3%), the remained waste is stored in transfer station (6%).

Total waste distribution is also given in **Table 10**. Cement, tiles, ceramics (EWC 1701) is 10.9 % of total waste, bituminous mixture (EWC 170302) is 8.4 % of the total waste, gypsum (EWC 170702) is 0.3 % of the total waste and mixed waste is 80.4 % of the waste which is one of the main flow of total managed waste.

Table 10: CDW managed in Lombardy region in 2014 for the European waste codes (EWC) of interest (Borghi et al., 2018)

Type of waste	%	Total Managed [t]	Storage [t]	Recycling [t]	Disposal [t]
EWC 1701 Cement, tiles and ceramics	10.9%	763.950	45.669	704.270	14.011
EWC 170302 Bituminous mixture	8.4%	589.168	68.502	510.465	10.201
EWC 170802 Gypsum	0.3 %	20.891	2.951	17.696	244
EWC 170904 Mixed waste	80.4%	5.625.978	303.243	5.119.930	202.805
Total	100 %	6.999.986	420.365	6.352.361	227.259
Total [%]	-	100%	6%	90.7%	3.3%

The main goal of the study was to evaluate the benefits and critical aspects related to the management system of non-hazardous CDW implemented in 2014 in Lombardy Region, focusing on the recycling of inert mineral fractions to produce mixed recycled aggregates (RAs).

The functional unit (FU) of the LCA was defined as one ton of non-hazardous CDW mixture managed in 2014, whose average composition is calculated from data reported in **Table 10**: 10.9% of cement, tiles and ceramics (EWC 1701), 8.4% of bituminous mixture (EWC 170302), 0.3% of gypsum-based waste (EWC 170802), and 80.4% of mixed waste (EWC 170904).

Figure 14 shows the current CDW flows distribution between the different treatment plants which reference data has been already summarized in **Table 10**.

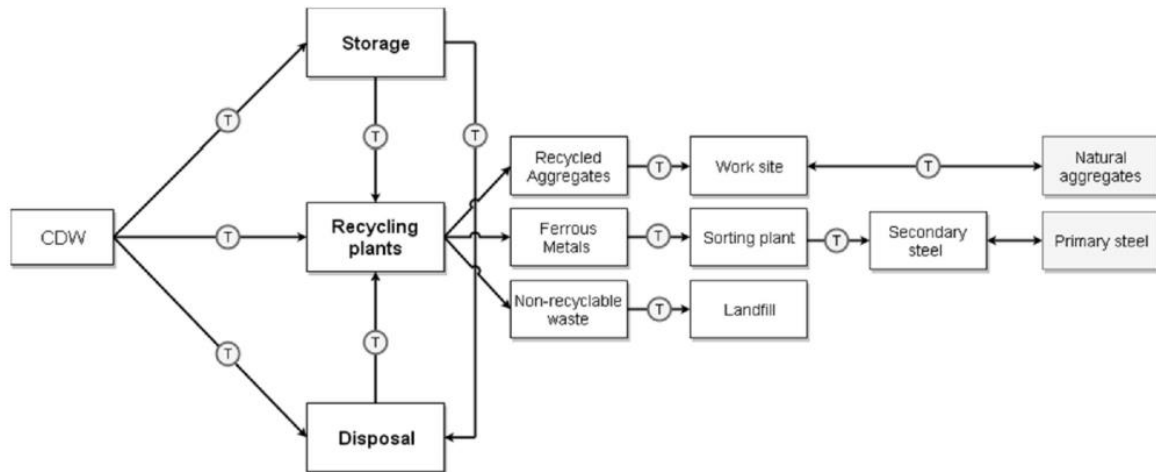


Figure 14: Reference system for the LCA analysis of the current CDW management in Lombardy Region (“T” on the arrows refers to transportation) (Borghi et al., 2018)

The system boundaries include following activities:

- Unloading, moving and uploading CDW in transfer stations,
- CDW recycling, including the treatment of the extraneous fractions separated from the inert mineral fraction (i.e. recycling of ferrous metals and landfilling of unrecoverable residues),
- CDW disposal,
- natural aggregates (NAs) avoided production,
- primary steel avoided production,
- transportation of CDW to plants, transportations of RAs from recycling plants to final users and transportation of natural raw material / NAs from quarries to final users.

“The natural aggregates” (NAs) is intended as sand and gravel with specific size distribution obtained from processing of the “natural raw material”. Natural raw material is intended as the unprocessed material extracted from quarries. Considering the possible applications of RAs of types B (medium quality) and types C (low quality), it follows that they are used in substitution of the unprocessed natural raw material (Borghi et al., 2018).

The following equation is used for the calculation of the replacement coefficient (**Equation 11**) which quantifies the amount of avoided material by considering quality and market demand of RAs. (Borghini et al., 2018).

$$R = Q_1 \times Q_2 \times M$$

Equation 11 : Replacement coefficient calculation

R = Replacement coefficient
Q₁ = Quality of RAs coefficient
Q₂ = Technical characteristic of RAs coefficient
M = Market coefficient

The coefficient Q₁ considers the quality of RAs. If there are impurities such as wood, plastic, Q₁ will be less than 1. Q₁ is defined as 0.97 for type B (medium quality) and type C (low quality) of RAs in Lombardy. The coefficient Q₂ considers technical characteristics of RAs regarding to specific application. Q₂ is defined as 1 for RAs type B, 0.89 for RAs type C in Lombardy. And lastly, market coefficient (M) is defined as ratio between the amounts of RAs sold and produced in recycling plant. If all the produced RAs are unsold, M is defined as 0. If all the produced RAs are sold, M is defined as 1. Market factor is given as 0.67 in Lombardy.

The overall impacts of the case study have been implemented associated with current scenario, best case scenario and landfill scenario. Differences between current scenario, best case scenario and landfill scenario are explained below (**Table 11**). In this study each scenario is taken into accounts for impact assessment and results are shown in Section 5 “Results and Discussion”.

The characterization models used in the impact assessment are those explained in Section 2 “Methodology” for the resource depletion impact category.

Table 11: Explanation of the current, best-case and landfill scenario assumptions

Current Scenario	Best- case Scenario	Landfill Scenario
Current management of CDW in Lombardy Region	Defined to understand the best performance that the CDW management system under study may achieve	All the managed waste is disposed of in landfill
96.7% of CDW is sent to recycling facilities and 3.3% of CDW is sent to disposal	All CDW waste (100 %) assumed as it is sent to recycling facilities	All CDW waste (100%) assumed as it is sent to disposal
11.6% of CDW is sent to storage. 86.1% of the recycling plants powered by diesel, 13.9% of the recycling plants powered by electricity	There is not storage operation. All the recycling plants powered by electricity	There is not storage operation. -
Transport distance have been evaluated according to MUD ¹ database of 2014. There are direct and secondary flow	CDW delivery distance to treatment plants are in the minimum value (20 km). There is not secondary flow	Transport distance of landfill has been assumed average transport distance (27.5 km)
High percentage (60%) of RAs of medium quality ² , remaining percentage of RAs of low quality ³ (40%)	90% of RAs are of high quality, 10% of RAs are of low quality	-
1. Modello Unico di Dichiarazione ambientale 2. Type B of RAs according to Italian legislation 3. Type C of RAs according to Italian legislation		

5. Results and Discussion

In this chapter, the results of the LCA analysis of the non-hazardous CDW, located in Lombardy region, are described and commented. According to the characterization models explained in Section 2 of “Methodology”, the results of LCA are evaluated for current, best-case and landfill scenario.

The results of the LCA analysis, shown in **Table 12**, depict the environmental burdens and benefits associated with the current CDW management system in Lombardy and refer to 1 t of CDW, in comparison with the best-case scenario and landfill scenario.

Table 12: Results for the resource depletion impact category: comparison between current CDW management system, best- case scenario and CDW landfill scenario.

Model	Method	Unit of Measure	Current Scenario	Best- case Scenario	Landfill Scenario
CED		MJ/t	65.29	-23.31	314.25
CExD		MJ/t	65.65	-25.45	341.23
CEENE		MJ/t	94.12	-31.28	649.65
SED		MJ/t	2.04E+07	6.27E+05	2.47E+08
Model in the EDIP method	EDIP 2003	PR2004/t	2.41E-04	-1.60E-04	1.52E-03
Model in the ReCiPe method	ReCiPe 2016 Midpoint (H)	kg Cu eq/t	-6.93E-02	-7.55E-02	3.28E-02
	Ecological Scarcity 2013	UBP/t	3.83E+02	-1.84E+01	5.60E+03
	IMPACT 2002+	MJ surplus/t	-2.27E-01	-2.80E-01	2.64E-01
ADP	CML-Ultimate	kg Sb eq/t	1.00E+00	4.40E-06	2.55E-05
	CML- Reserve b.	kg Sb eq/t	2.81E-04	9.16E-05	5.76E-04
	CML-Economic b.	kg Sb eq/t	5.17E-04	1.37E-04	1.17E-03
	EF Method	kg Sb eq/t	1.24E-05	4.40E-06	2.55E-05
	ILCD 2011 Midpoint+	kg Sb eq/t	2.82E-04	9.13E-05	5.81E-04
AADP	AADP	kg Sb eq/t	1.15E-04	3.63E-05	1.71E-02

The results of the analysis were evaluated under two headings: Evaluation of LCIA Models and Evaluation of the case study.

5.1. Evaluation of LCIA Models

Resources are examined under 8 main headings: mineral, metal, fossil resource, nuclear energy resource, renewable energy resource, land resource, atmospheric and gaseous resource and water resources. **Table 13** compares the number of CFs of a selected type of resources for each model. A high number of resources covered are clearly more desirable to render a complete picture than a more limited scope.

Regarding to **Table 13 and Figure 15**, ILCD Midpoint +, PEF and SED have higher total number of CFs for resource depletion. ILCD Midpoint + method is the most comprehensive one with 156 CFs in resource depletion category.

SED has the highest number of CFs (39) for mineral resources. CEENE (38) and CExD (34) are the following ones. ILCD Midpoint Method has the highest number of CFs (57) compared to the other models for Metal resources. For fossil resources, IMPACT 2002+ has the highest number of CFs (9). Renewable energy resources are not evaluated in all models. However, ILCD Midpoint + method has a far higher renewable energy resource (11) CFs than the others.

Evaluation of land and water resources is difficult to classify for impact category of natural resource depletion, because land and water are accepted as a resource by some of the models (e.g CEENE and SED). On the other hand, some of the models (e.g Ecological Scarcity, IMPACT 2002+) accept them as different impact category such as land occupation and water scarcity. In our study (**Table 13**), CFs of land occupation and water scarcity are counted as a resource, and not as a different impact category.

When considering the CDW management, minerals are very significant as resources. The aggregates are composed of minerals. As mentioned above (3.5.1 State of aggregates), aggregates are the largest concrete component, contributing between 60 to 75 percent of its weight, and are mainly obtained through raw material quarrying. Non-metallic minerals consist mainly of construction minerals such as sand and gravel. According to our study, it is needed to focus on mineral resources. In the case of minerals, SED, CEENE and CExD have much more CFs than the other models. Moreover, in addition to having few CFs of minerals, the other models (e.g. CML, EDIP 2003, AADP, PEF and ILCD midpoint) do not include the CFs of gravel and sand.

Considering the LCIA of current scenario, the contribution of the resource categories to the impact for SED, CEENE and CExD is shown in **Figure 16, Figure 17 and Figure 18**. Impact assessment of SED contains 86.4% of minerals and mineral aggregates whereas CEENE 0.8% and CExD 1.1%. Therefore, based on this resource categories distribution, SED is more reasonable to apply on LCA for CDW. However, it should be noted that SED use approach of “emergy” resource accounting method (RAM). “Emergy” is criticized by scientific community, as combining disparate time scales, allocation problems and lack of uncertainty quantification (Swart et al., 2015).

According to Hayes & Mccullough, 2018, critical minerals are reviewed related to recent studies. This study shows us 13 critical minerals which are the rare-earth element (REE), the platinum- group metals (PGM), indium (In), tungsten (W), germanium (Ge), cobalt (Co), niobium (Nb), tantalum (Ta), gallium (Ga), antimony (Sb), bismuth (Bi), thallium (Tl) and magnesium (Mg). In **Figure 19**, critical elements are given by number of studies (n) regarding to geographic comparison. For instance, while Europe and United Kingdom have 11 studies in total, United States and Japan have 7 and 5 studies, respectively. In **Figure 20** the usage of critical element as a primary and by-product is examined by number of studies. Considering critical elements, CFs are analyzed for each model in **Table 14**. This examination shows us that AADP includes CFs for all critical minerals. Moreover, Recipe 2016 midpoint method has higher number CFs (12) for critical minerals compared to evaluated model.

Table 13: Number of CFs for each resource category and each characterization model / method

Numbers	CED	CExD	CEENE	SED	Model in the EDIP method	Model in the ReCiPe method	Ecological Scarcity	IMPACT 2002 +	CML Ultimate reserve	CML Reserve Base	CML Economic Base	PEF	ILCD Midpoint +	AADP
Mineral	0	34	38	39	3	20	19	3	2	2	2	2	9	0
Metal	0	30	17	30	31	42	32	12	44	39	39	46	57	35
Fossil resources	7	5	5	5	3	4	3	9	5	0	0	4	5	0
Nuclear energy resources	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Renewable energy resources	9	7	2	3	0	0	6	1	0	0	0	0	11	0
Land resources	0	0	9	13	0	25	13	25	0	14	14	50	58	0
Atmospheric and gaseous resources	0	0	0	0	0	0	1	0	0	1	0	0	0	0
Water resources	0	9	5	5	0	14	12	0	0	0	0	15	15	0
Total	17	86	77	96	38	106	87	51	52	57	56	118	156	35

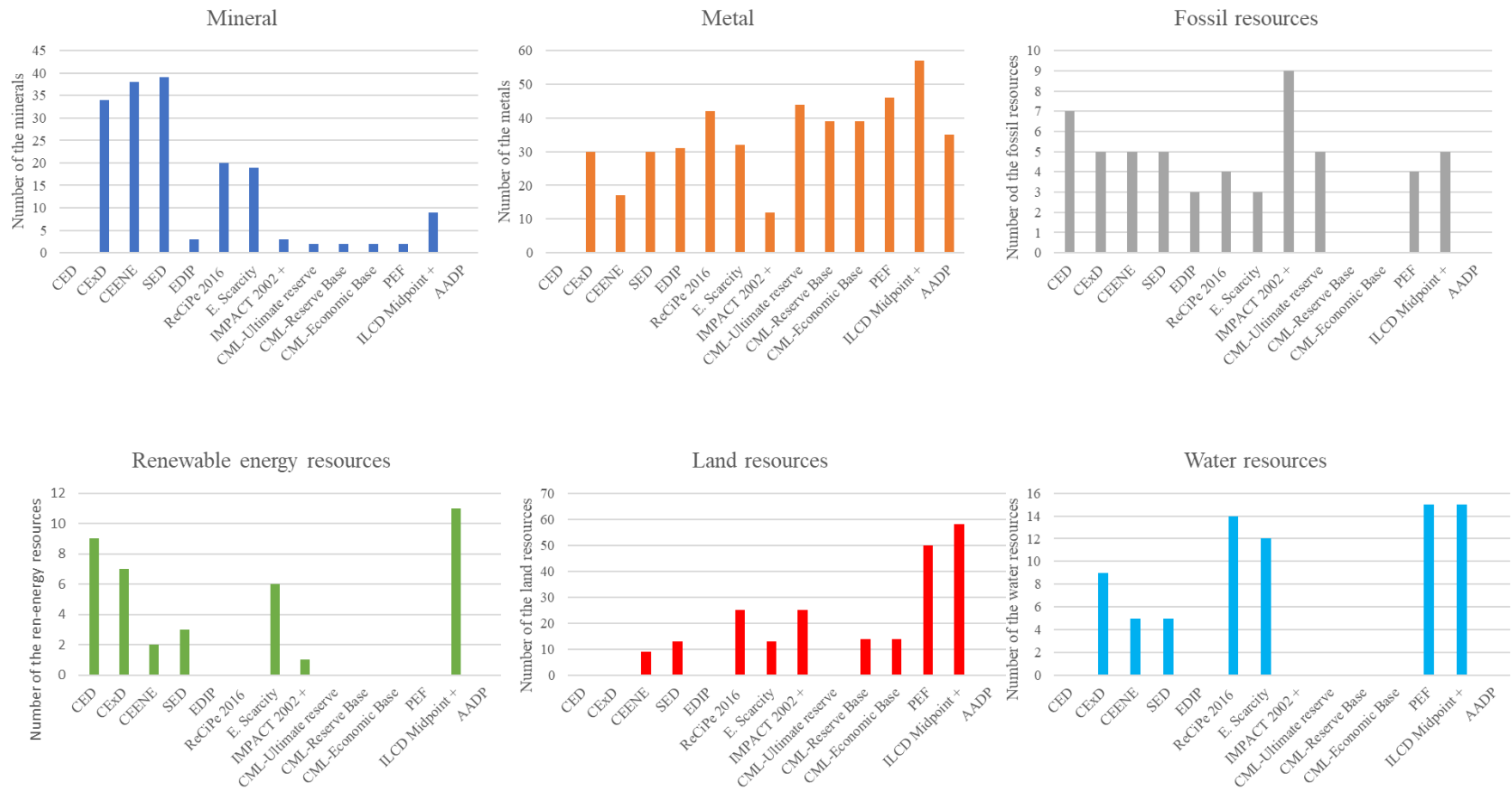


Figure 15: Numbers of CFs for each resource category and each characterization model /method

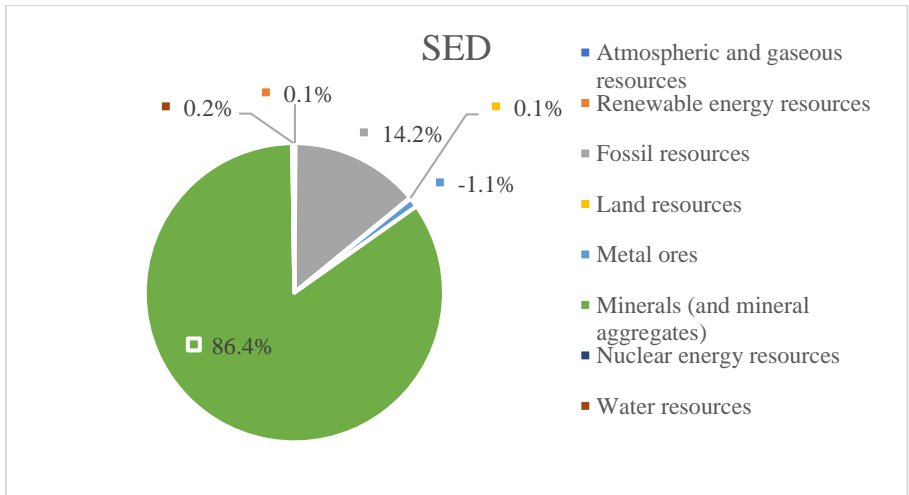


Figure 16: Resource distribution of SED in current scenario regarding to impact assessment

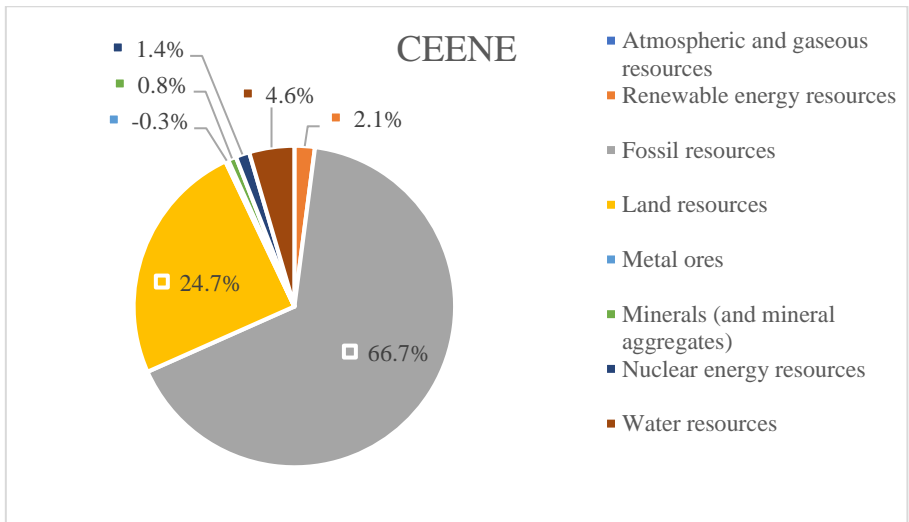


Figure 17: Resource distribution of CEENE in current scenario regarding to impact assessment

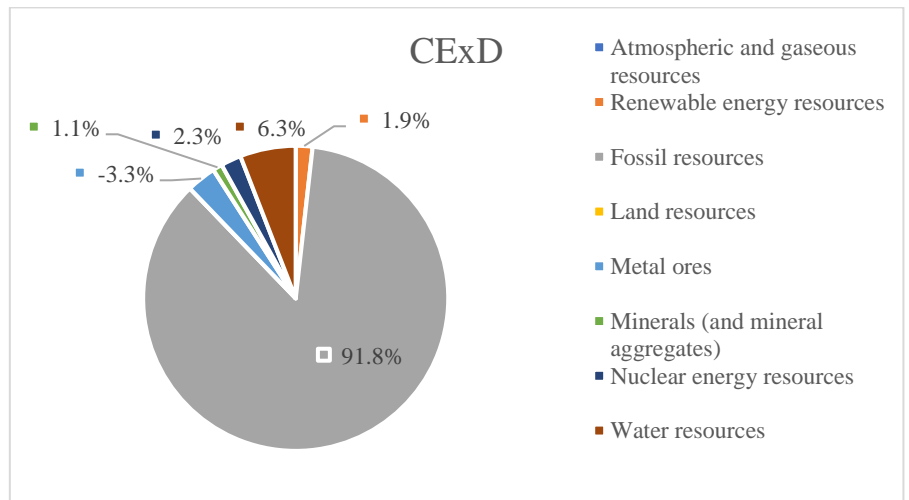


Figure 18: Resource distribution of CExD in current scenario regarding to impact assessment

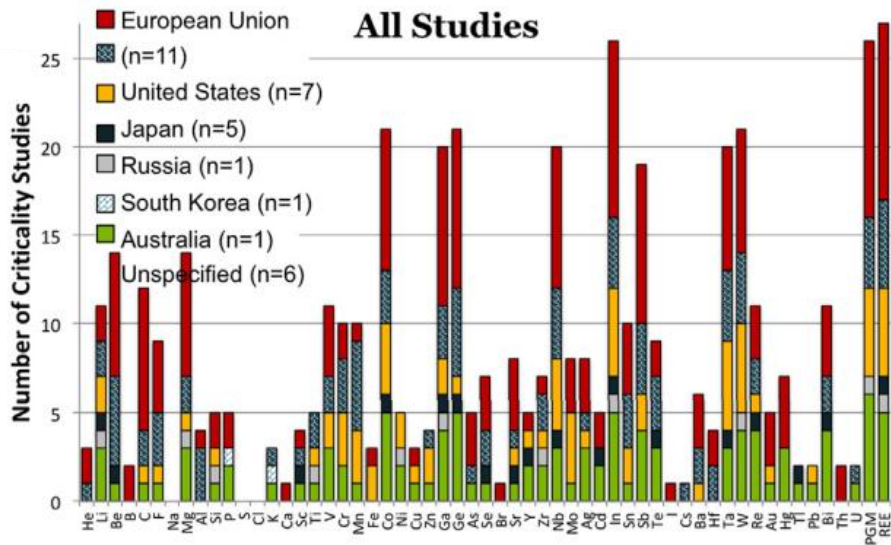


Figure 19: Geographic comparison of critical element by number of studies (Hayes & Mccullough, 2018)

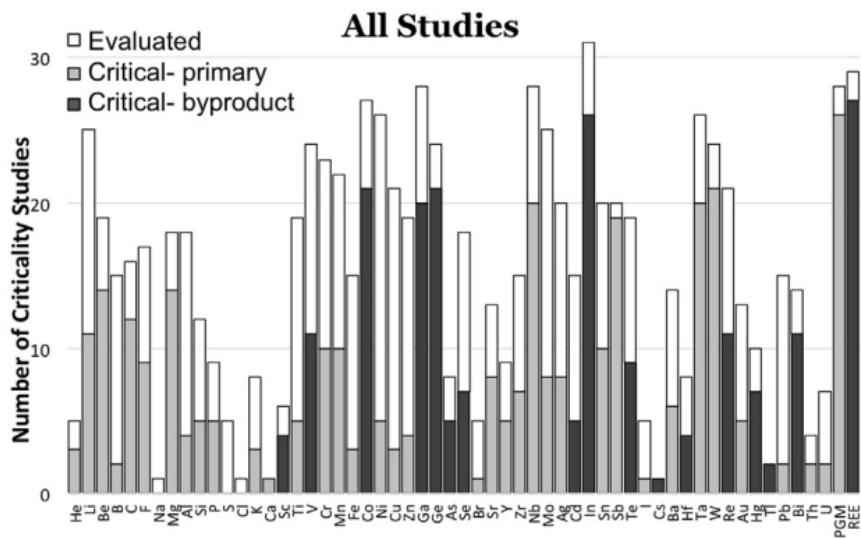


Figure 20: Summary of studies for critical elements (Hayes & Mccullough, 2018)

Table 14: Examination of CFs of critical elements regarding to evaluated models

		CED	CExD	CEENE	SED	EDIP	ReCiPe 2016	E. Scarcity	IMPACT 2002 +	CML- Ultimate reserve	CML- Reserve Base	CML- Economic Base	PEF	ILCD Midpoint +	AADP
		MJ/kg	MJ/kg	MJ/kg	MJ/kg	PR2004/ kg	kg Cueq/kg	UBP /kg	MJ _{surplus} /kg	kgSbeq/kg	kgSbeq/kg	kgSbeq/kg	kg Sbeq/kg	kg Sbeq/kg	kg Sbeq/kg
The rare-earth element	REE	-	-	-	-	-	-	-	-	-	-	-	-	-	1.2E-05
The platinum- group metals	PGM	-	-	-	-	1.3E+02	3.8E+03	-	-	-	-	-	-	-	6.9E+00
Antimony	Sb	-	-	-	-	3.6E+00	5.7E-01	1.1E+06	-	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00
Bismuth	Bi	-	-	-	-	-	3.2E+00	-	-	4.5E+00	4.1E-02	1.1E+01	4.1E-02	4.5E+00	8.4E-01
Cobalt	Co	-	1.9E+02	1.2E+00	7.9E+07	9.1E-01	6.6E+00	4.4E+04	-	2.6E-02	1.6E-05	4.9E-02	1.6E-05	2.6E-02	1.0E-03
Gallium	Ga	-	4.5E+03	-	1.0E+07	-	8.4E+01	2.8E+07	-	-	1.5E-07	-	1.5E-07	6.3E-03	3.8E-06
Germanium	Ge	-	-	-	-	-	3.2E+02	-	-	2.0E+04	6.5E-07	1.0E+04	6.5E-07	2.0E+04	1.8E-04
Indium	In	-	2.8E+03	-	2.4E+08	-	1.0E+02	1.3E+08	-	5.6E+02	6.9E-03	1.2E+03	6.9E-03	5.6E+02	7.5E-01
Magnesium	Mg	-	-	-	-	-	7.9E-01	-	-	-	2.0E-09	-	2.0E-09	2.5E-06	8.6E-10
Niobium	Nb	-	-	-	-	-	5.2E+00	-	-	6.6E-02	1.9E-05	7.0E-02	1.9E-05	6.6E-02	1.1E-03
Tantalum	Ta	-	8.2E+05	-	9.9E+07	1.5E+02	5.3E+01	1.5E+06	-	1.2E+01	4.1E-05	2.3E+01	4.1E-05	1.2E+01	2.5E-03
Thallium	Tl	-	-	-	-	1.7E+04	1.2E+03	-	-	3.0E+03	2.4E-05	3.8E+03	2.4E-05	3.0E+03	3.8E-05
Tungsten	W	-	-	-	-	2.2E+00	7.8E+00	-	9.3E-01	2.5E-01	4.5E-03	2.8E-01	4.5E-03	2.5E-01	5.5E-02

5.2. Evaluation of the Case Study

In this section, LCA results of current, best-case and landfill scenario are explained.

5.2.1. Current Scenario

Examination of the current scenario shows that the most beneficiary process is the recycling one even if the benefits are not enough to balance the burdens generated from the other management phases (mainly arising from CDW transport). In fact, transportation, storage and landfill processes have positive sign, recycling process has negative sign for each model (**Table 15**).

However, it should be noted that the net environmental impacts of the current scenario are much lower than those associated to the worst scenario (landfill scenario) in which all CDW are landfilled (last column in **Table 12**).

CDW transport (both direct and secondary flows) has the most contribution regarding to total impacts in CDW management. According to Borghi et al., 2018, this is due to the fact that, in the current scenario, the avoided impacts associated with recycling operations are quite low due to many reasons: “i) recycling facilities are mostly mobile (higher impacts associated to diesel consumption than electricity consumption); ii) plants produce medium-low quality RA: the avoided primary resource is the natural raw material, whose production impacts are less than the production of natural aggregates; iii) the replacement coefficient between RA and natural raw material is limited by the market factor.”

Recipe 2016 Midpoint and IMPACT 2002 + methods have higher benefits from recycling process compared to other models (**Figure 21**). The substances contributions are shown in **Figure 22**, to understand which substances are included for each model and which one is beneficial for recycling process. This figure shows us the most effective and beneficiary substances for recycling process. For instances, benefits of Recipe 2016 Midpoint and IMPACT 2002 + methods mostly come from iron and nickel. The percentages of beneficiary substances for Recipe 2016 Midpoint were approximately 75% of iron and 27% of nickel. Besides, they were 16% of iron, and 83% of nickel for IMPACT 2002 +.

SED model and Ecological scarcity method have higher burden related to landfill disposal compared to other models because of having high CFs (e.g. chromium, magnesite and manganese) compared to other models. Except ReCiPe 2016 Midpoint and IMPACT 2002+ methods, transportation burdens distribution can be considered similar for other models (**Figure 21**).

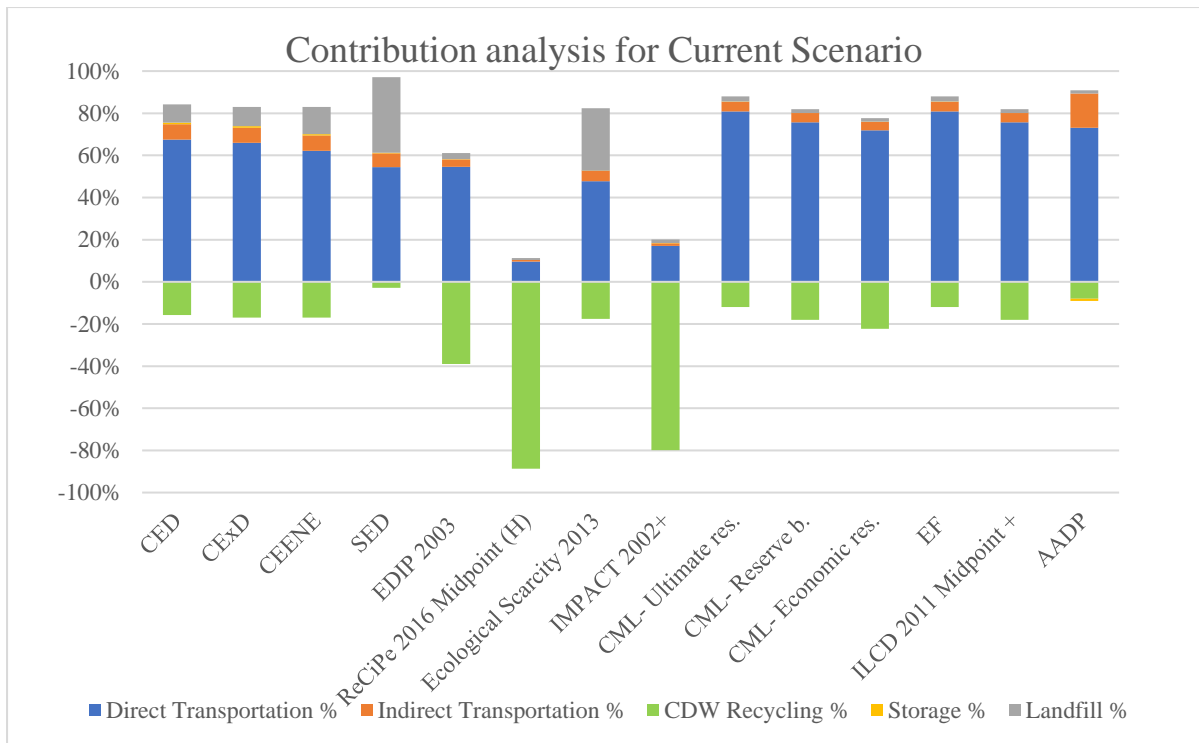


Figure 21: Contribution analysis of the impacts associated with the current CDW management in Lombardy.

Table 15: Contribution analysis of the impact of 1 tonne of CDW managed in the current scenario

Model	Method	Impact Category	Unit of Measure	Total	Direct Transportation	Secondary Transportation	CDW Recycling	Storage	Landfill
CED			MJ/t	65.3	64.3	7.0	-15.0	0.8	8.2
CExD			MJ/t	65.6	65.6	7.1	-16.9	0.8	9.1
CEENE			MJ/t	94.1	88.6	10.3	-24.1	0.8	18.5
SED			MJ/t	2.04E+07	1.2E+07	1.4E+06	-6.3E+05	5.9E+04	7.8E+06
Model in the EDIP method	EDIP 2003	Resources (all)	PR2004/t	2.4E-04	6.0E-04	3.9E-05	-4.3E-04	2.0E-06	3.1E-05
Model in the ReCiPe method	ReCiPe 2016 Midpoint (H)	Mineral resource scarcity	kg Cu eq/t	-6.9E-02	8.6E-03	6.7E-04	-7.9E-02	7.9E-05	8.0E-04
ADP	Ecological Scarcity 2013	Mineral resources	UBP/t	3.8E+02	2.8E+02	2.9E+01	-1.0E+02	3.9E-01	1.8E+02
	IMPACT 2002+	Mineral extraction	MJ surplus/t	-2.3E-01	6.5E-02	4.7E-03	-3.0E-01	4.5E-04	6.6E-03
	CML-IA baseline	Abiotic depletion (elem., ultimate reserves)	kg Sb eq/t	1.0E+00	1.1E+00	6.1E-02	-1.6E-01	1.3E-03	3.3E-02
	CML-IA non-baseline	Abiotic depletion (elem., reserve base)	kg Sb eq/t	2.8E-04	3.3E-04	1.9E-05	-8.0E-05	2.0E-07	8.0E-06
	CML-IA non-baseline	Abiotic depletion (elem., econ. reserve)	kg Sb eq/t	5.2E-04	6.7E-04	3.8E-05	-2.1E-04	4.6E-07	1.6E-05
	EF Method	Resource use, mineral and metals	kg Sb eq/t	1.2E-05	1.3E-05	7.6E-07	-2.0E-06	1.6E-08	4.1E-07
	ILCD 2011 Midpoint+	Mineral, fossil & ren resource depletion	kg Sb eq/t	2.8E-04	3.3E-04	1.9E-05	-8.0E-05	2.1E-07	8.1E-06
AADP	AADP	Abiotic Depletion for Metals	kg Sb eq/t	1.2E-04	1.0E-04	2.3E-05	-1.1E-05	-1.6E-06	2.2E-06

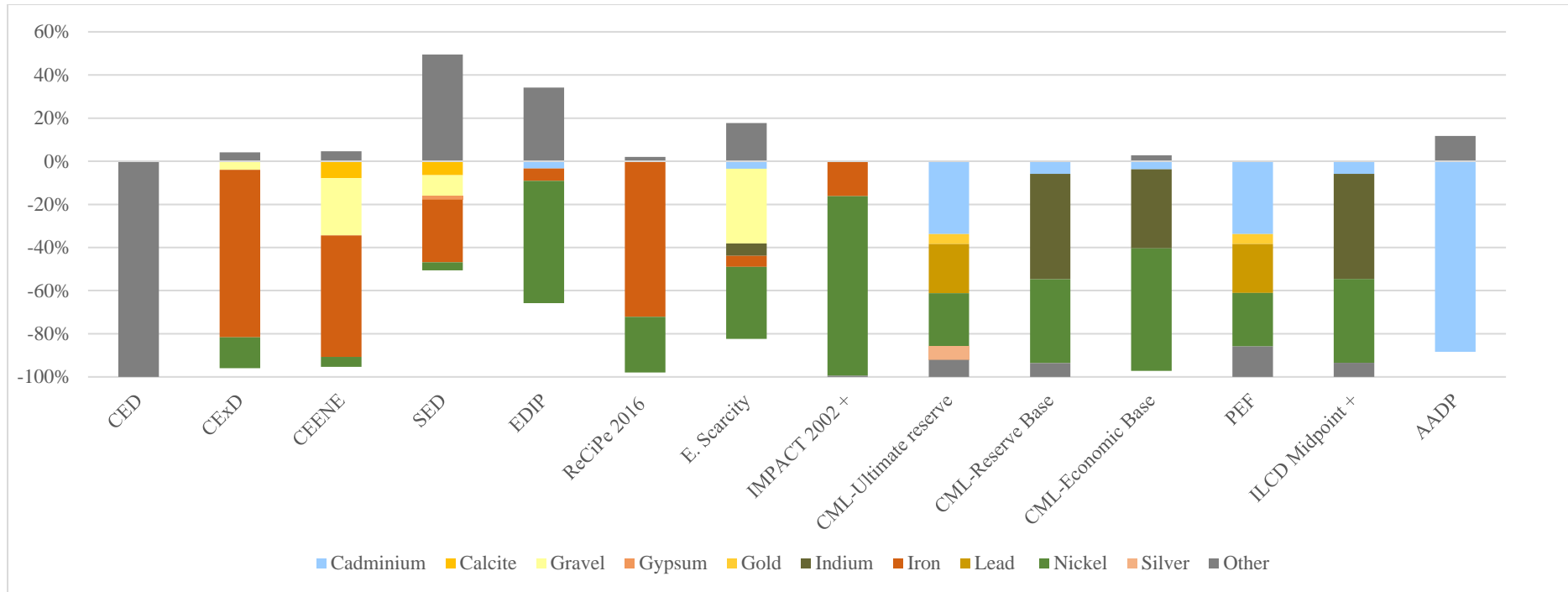


Figure 22: Substances giving benefits and burdens from recycling process for current scenario

5.2.2. Best-case scenario

In best-case scenario, it is observed that recycling process has a negative sign, transportation process has a positive sign (Figure 23). The benefits arising from CDW recycling process are higher than in the current scenario and, at the same time, the added impacts are minimized. In this scenario, in fact, there is no storage, no direct disposal, recycling plants are powered by electricity and transportation distances are reduced.

Differences between current and best-case scenarios are important. For instance, impact assessment of CED model is evaluated as 65.29 MJ/t and -23.31 MJ/t for current and best-case scenario, respectively. The impact assessment of EF method is estimated 1.24E-05 kg Sb eq/t for current scenario and 4.40E-06 kg Sb eq/t for best-case scenario (**Table 16**).

According to the contribution analysis, SED model has lower benefits from recycling process because high burdens come from other substances such as chromium, magnesite, and manganese. The highest benefit of recycling process is observed on the ReCiPe 2016 Midpoint and IMPACT 2002 + methods.

The substances contributions are shown in **Figure 24**, that helps to understand which substances are included for each model and which one is beneficial for recycling process. This figure shows the most effective and beneficiary substances for recycling process. For instances, the benefits of Recipe 2016 Midpoint and IMPACT 2002 + methods mostly come from iron and nickel. The percentages of beneficiary substances for Recipe 2016 Midpoint were approximately 75% of iron and 27% of nickel. Besides, they were 15% of iron, and 78% of nickel for IMPACT 2002 +. Unlikely current scenario, barite and zinc are also considered as beneficial substances for recycling process in best-case scenario.

SED model has higher burden regarding to direct transportation compared to CED, CExD and CEENE models. Besides, it has higher CFs for some substances (e.g. chromium, magnesite, manganese). On the other hand, ReCiPe 2016 Midpoint and IMPACT 2002+ methods have lower burden regarding to direct transportation process because nickel and iron are main contributors of both models.

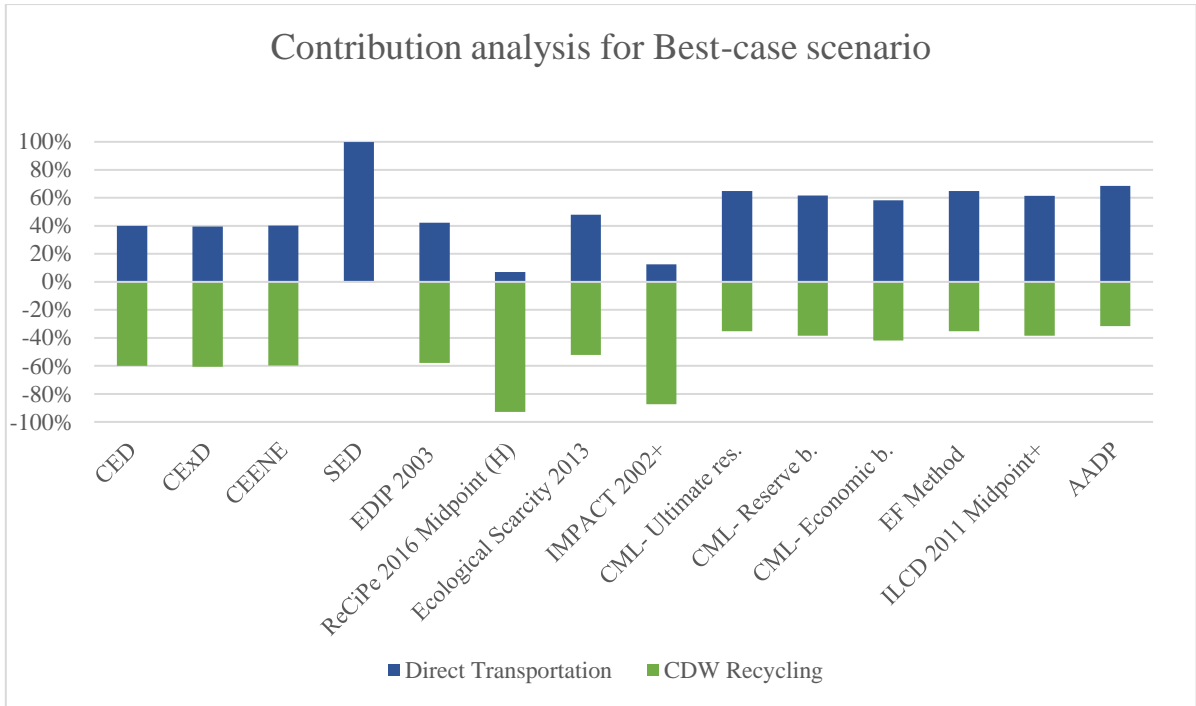


Figure 23: Contribution analysis of the impacts associated with the best- case scenario.

Table 16: Environmental and energetic impacts of the management of 1 tonne of CDW in the best- case scenario

Models	Method	Impact Category	Unit of Measure	Total Impact Value	Direct Transportation	CDW Recycling
CED			MJ/t	-23.31	46.75	-70.06
CExD			MJ/t	-25.45	47.69	-73.14
CEENE			MJ/t	-31.28	64.44	-95.72
SED			MJ/t	6.27E+05	8.56E+06	-2.15E+04
Model in the EDIP method	EDIP 2003	Resources (all)	PR2004/t	-1.60E-04	4.33E-04	-5.93E-04
Model in the ReCiPe method	ReCiPe 2016 Midpoint (H)	Mineral resource scarcity	kg Cu eq/t	-7.55E-02	6.23E-03	-8.17E-02
	Ecological Scarcity 2013	Mineral resources	UBP/t	-18.45	205.81	-224.26
	IMPACT 2002+	Mineral extraction	MJ surplus/t	-2.80E-01	4.72E-02	-3.27E-01
	CML-IA baseline	Abiotic depletion (elem., ultimate reserves)	kg Sb eq/t	4.40E-06	9.62E-06	-5.22E-06
ADP	CML-IA non-baseline	Abiotic depletion (elem., reserve base)	kg Sb eq/t	9.16E-05	2.43E-04	-1.51E-04
	CML-IA non-baseline	Abiotic depletion (elem., econ. reserve)	kg Sb eq/t	1.37E-04	4.87E-04	-3.50E-04
	EF Method	Resource use, mineral and metals	kg Sb eq/t	4.40E-06	9.61E-06	-5.21E-06
	ILCD 2011 Midpoint+	Mineral, fossil & ren resource depletion	kg Sb eq/t	9.13E-05	2.43E-04	-1.52E-04
AADP	AADP	Abiotic Depletion for Metals	MJ/t	3.63E-05	6.74E-05	-3.11E-05

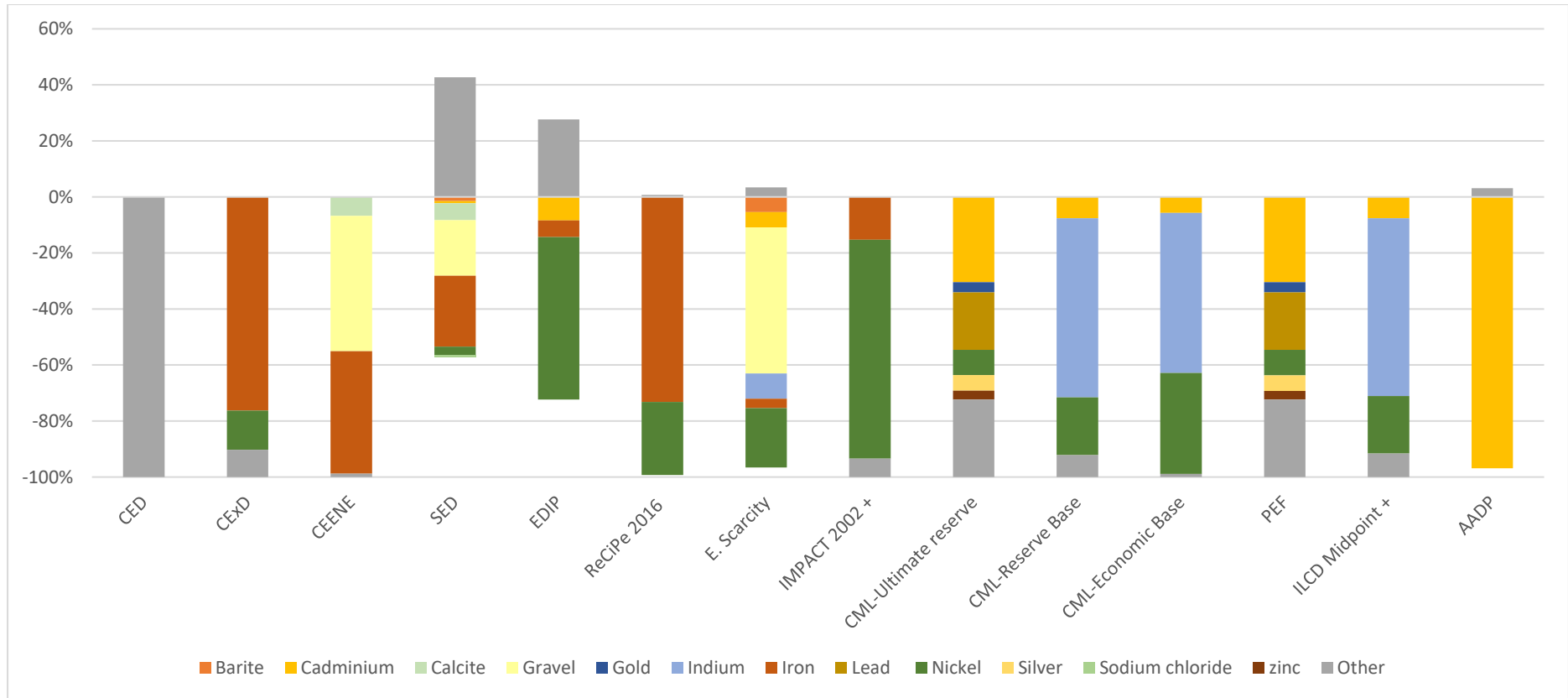


Figure 24: Substances giving benefits and burdens from recycling process for best-case scenario

5.2.3. Landfill Scenario

In landfill scenario, all processes have a positive sign which means all the process have burdens coming from landfill disposal. It signifies all the substances are lost.

There is no recycling process in this scenario because it is assumed that all CDW waste is sent to disposal. There are only direct transportation and landfill disposal process. Differences between current and landfill scenarios are significant. For instance, impact assessment of CED model is calculated as 65.3 MJ/t and 314.2 MJ/t for current scenario and landfill scenario, respectively. On the other hand, it is also calculated that impact assessment of EF method has values of 1.2E-05 kg Sb eq/t and 2.5E-05 kg Sb eq/t for current scenario and landfill scenario, respectively. Environmental impacts of 1 t of CDW in the landfill scenario have been shown in **Table 17**.

According to the contribution analysis, methods/models have higher burdens from transportation and landfill disposal compared to current and best-case scenario. SED, Ecological scarcity and AADP models have not only lower burdens from transportation process but also have higher burdens from landfill disposal due to having higher effectiveness of CFs for iron and nickel compared to evaluated models. When the models of CML, EF and ILCD Midpoint are examined in **Figure 25**, it is observed that contribution analysis is almost evenly distributed in terms of direct transportation and landfill processes.

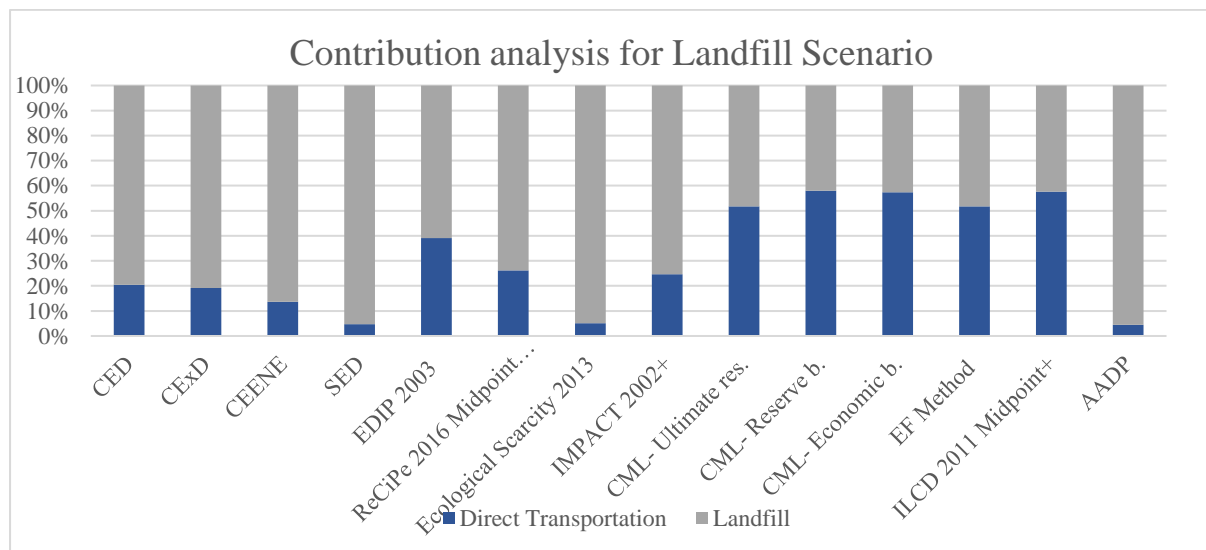


Figure 25: Contribution analysis of the impacts associated with the landfill scenario.

Table 17: Environmental and energetic impacts of the management of 1 tonne of CDW in the landfill scenario

Models	Method	Impact Category	Unit of Measure	Total Impact Value	Direct Transportation	Landfill
CED			MJ/t	314.25	64.28	249.97
CExD			MJ/t	341.23	65.58	275.65
CEENE			MJ/t	649.65	88.59	561.05
SED			MJ/t	2.47E+08	1.18E+07	2.35E+08
Model in the EDIP method	EDIP 2003	Resources (all)	PR2004/t	1.52E-03	5.95E-04	9.26E-04
Model in the ReCiPe method	ReCiPe 2016 Midpoint (H)	Mineral resource scarcity	kg Cu eq/t	3.28E-02	8.57E-03	2.42E-02
AADP	Ecological Scarcity 2013	Mineral resources	UBP/t	5.60E+03	2.83E+02	5.32E+03
	IMPACT 2002+	Mineral extraction	MJ surplus/t	2.64E-01	6.49E-02	1.99E-01
	CML-IA baseline	Abiotic depletion (elem., ultimate reserves)	kg Sb eq/t	2.55E-05	1.32E-05	1.23E-05
	CML-IA non-baseline	Abiotic depletion (elem., reserve base)	kg Sb eq/t	5.76E-04	3.34E-04	2.42E-04
	CML-IA non-baseline	Abiotic depletion (elem., econ. reserve)	kg Sb eq/t	1.17E-03	6.69E-04	4.98E-04
	EF Method	Resource use, mineral and metals	kg Sb eq/t	2.55E-05	1.32E-05	1.23E-05
	ILCD 2011 Midpoint+	Mineral, fossil & ren resource depletion	kg Sb eq/t	5.81E-04	3.35E-04	2.46E-04
AADP	AADP	Abiotic Depletion for Metals	kg Sb eq/t	1.71E-02	7.58E-04	1.63E-02

5.3. Possible Future Developments for the Methodology

Although ISO standards have listed the use of resources regarding to the impact categories for LCA, there is no agreement in the scientific community on the way of resources accounting (Ardente, Beylot, & Zampori, 2011).

There are different perspectives for assessing resource such as resource accounting at the inventory, resource depletion, resource criticality and resource dissipation. Perspective of resource dissipation is defined as “both a perspective on resource accounting and on resource characterization, aiming at discounting the resources which have a potential to be kept in the technosphere, namely that could be recycled and used repeatedly”(EC-JRC-IES, 2017). Although, none of mentioned models are tackling the issue of assessing dissipation of resources for now, this perspective is accepted as possible future development in LCA.

According to Ardente et al., 2011, resources are linked to their function. For this reason, approaches should provide a systematic framework for the accounting of resource function or ability of dissipated resource. Different approaches to account dissipated resources are suggested by Ardente et al., 2011: (i) specific description of resource based on potential applications (e.g. minerals in fertilizer, metals in alloys), (ii) ultimate quality limit (e.g. purity of metals).

Secondly, European Commission published a technical report with the title of “feasibility study to implement resource dissipation in LCA” (EC-JRC-IES, 2017). In this report, simplified case studies were examined based on dissipation approach. The key points are given in conclusion: (i) dissipation model has higher resolution compared to depletion model, (ii) the results of dissipation model are more accurate and detailed.

Moreover, potential developments for dissipation of resources are discussed in short-term including development and test of possible approaches, mid-term including towards satisfactory robustness, and consensus and long-term including large scale changes of LCI databases (Beylot, Ardente, Sala, & Zampori, 2020). However, the main limitation is data availability of resource dissipation.

6. Conclusion

The aim of this study was to evaluate the impact of resource depletion associated with the non-hazardous construction and demolition waste (CDW) management by applying different LCIA models. The LCA of the CDW management system is implemented in Lombardy region (Italy) and it is described by Borghi et al., 2018. This research has chosen as a case study.

Identification of differences between characterization models and understanding which characterization model is proper for current system assessment are explained with numerical data.

The study focuses on impact characterization models and characterization factors (CFs) for resource depletion. Abiotic resource use in LCA is discussed by use of resources such as metals, minerals, fossil energy, nuclear energy, atmospheric resources, land resources, renewable energy resources and water resources. Mineral aggregates (e.g. gravel and sand) have been examined in detail regarding to its significance in the construction industry. Moreover, the different LCIA models were analyzed considering the impact pathways, indicators, characterization factors, calculation ways and CFs units.

In conclusion, SED model is suggested as the best one to evaluate the impact of resource depletion in LCA of CDWs management. This suggestion is evaluated by CFs number and CFs effects on resource depletion of SED model.

In order to be able to evaluate construction wastes from the natural resource depletion point of view, the most of models must determine an effective CF for minerals. Thus, the models will enable the evaluation of minerals, which are the most effective natural source in the impact category of resource depletion in every aspect. In addition, perspective of resource dissipation should be improved as a possible future development in LCA.

Bibliography

- Alvarenga, R. A. F., Lins, I. de O., & Neto, J. A. de A. (2016). Evaluation of abiotic resource LCIA methods. *Resources*, 5(1), 1–21. <https://doi.org/10.3390/resources5010013>
- Ardente, F., Beylot, A., & Zampori, L. (2011). *Towards the accounting of resource dissipation in LCA*. 202–208.
- Beylot, A., Ardente, F., Sala, S., & Zampori, L. (2020). Accounting for the dissipation of abiotic resources in LCA : Status , key challenges and potential way forward. *Resources, Conservation & Recycling*, 157(July 2019), 104748. <https://doi.org/10.1016/j.resconrec.2020.104748>
- Borghi, G., Pantini, S., & Rigamonti, L. (2018). Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy). *Journal of Cleaner Production*, 184, 815–825. <https://doi.org/10.1016/j.jclepro.2018.02.287>
- Bösch, M. E., Hellweg, S., Huijbregts, M. A. J., & Frischknecht, R. (2007). Applying Cumulative Exergy Demand (CExD) indicators to the ecoinvent database. *International Journal of Life Cycle Assessment*, 12(3), 181–190. <https://doi.org/10.1065/lca2006.11.282>
- Dewulf, J., Bösch, M. E., De Meester, B., Van Der Vorst, G., Van Langenhove, H., Hellweg, S., & Huijbregts, M. A. J. (2007). Cumulative exergy extraction from the natural environment (CEENE): A comprehensive life cycle impact assessment method for resource accounting. *Environmental Science and Technology*, 41(24), 8477–8483. <https://doi.org/10.1021/es0711415>
- Drielsma, J. A., Russell-Vaccari, A. J., Drnek, T., Brady, T., Weihed, P., Mistry, M., & Simbor, L. P. (2016). Mineral resources in life cycle impact assessment—defining the path forward. *International Journal of Life Cycle Assessment*, 21(1), 85–105. <https://doi.org/10.1007/s11367-015-0991-7>
- EC-JRC-IES. (2011). International Reference Life Cycle Data System (ILCD) Handbook- Recommendations for Life Cycle Impact Assessment in the European context. In *European Commission*. <https://doi.org/10.1017/CBO9781107415324.004>
- EC-JRC-IES. (2017). Feasibility study to implement resource dissipation in LCA. In *Publications Office of the European Union*. <https://doi.org/10.2760/869503>
- European Commission Joint Research Center. (2011). International Reference Life Cycle Data System (ILCD) Handbook- Recommendations for Life Cycle Impact Assessment in the European context. *Publications Office of the European Union*. <https://doi.org/10.278/33030>
- Eurostat. (2012). *Material flow accounts - Statistics Explained*. (October 2019), 1–8. Retrieved from http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Material_flow_accounts
- Eurostat. (2016). *Waste statistics*. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics
- Frischknecht, R., Wyss, F., Büsler Knöpfel, S., Lützkendorf, T., & Balouktsi, M. (2015). Cumulative energy demand in LCA: the energy harvested approach. *International*

- Journal of Life Cycle Assessment*, 20(7), 957–969. <https://doi.org/10.1007/s11367-015-0897-4>
- Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., & Zelm, R. Van. (2009). ReCiPe 2008. A life cycle assessment method which comprises harmonized category indicators at the midpoint and the endpoint level. Report I: characterisation. *Ministry of Housing, Spatial Planning and Environment, Amsterdam*. <https://doi.org/10.029/2003JD004283>
- Hayes, S. M., & Mccullough, E. A. (2018). Critical minerals : A review of elemental trends in comprehensive criticality studies. *Resources Policy*, 59(June), 192–199. <https://doi.org/10.1016/j.resourpol.2018.06.015>
- Islam, R., Nazifa, T. H., Yuniarto, A., Shanawaz Uddin, A. S. M., Salmiati, S., & Shahid, S. (2019). An empirical study of construction and demolition waste generation and implication of recycling. *Waste Management*, 95, 10–21. <https://doi.org/10.1016/j.wasman.2019.05.049>
- ISPRA. (2016). *Rapporto Rifuti Speciali*. Retrieved from <http://www.isprambiente.gov.it/it/pubblicazioni/rapporti/rapporto-rifiuti-speciali-edizione-2016>
- Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., & Rebitzer, G. (2003). IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. *Industrial Ecology & Life Cycle Systems Group*, 13. https://doi.org/10.1093/pch/16.suppl_a.47ab
- Peduzzi, P. (2014). *Sand, rarer than one thinks*. *United Nations Environment Program (UNEP)*. 2012(March), 1–15. Retrieved from https://wedocs.unep.org/bitstream/handle/20.500.11822/8665/GEAS_Mar2014_Sand_Minig.pdf?sequence=3&isAllowed=y
- Rolf Frischknecht, A., Büsser Knöpfel, S., Ltd, T., Flury, K., Stucki, M., Wädenswil, Z., ... von Arx, R. (2013). *Methodological fundamentals and their application in Switzerland Author of Part 1: Life cycle assessments in short Markus Ahmadi, ideja – Agentur für Kommunikation*. Retrieved from <http://eicca.recnnet.org/uploads/resource/c5e6b4cfb572cc6f97d69393085f8192.pdf>
- Rugani, B., Huijbregts, M. A. J., Mutel, C., Bastianoni, S., & Hellweg, S. (2011). Solar energy demand (SED) of commodity life cycles. *Environmental Science and Technology*, 45(12), 5426–5433. <https://doi.org/10.1021/es103537f>
- Sala, S., Cerutti, A. K., & Pant, R. (2018). *Development of a weighting approach for the Environmental Footprint*. <https://doi.org/10.2760/945290>
- Schneider, L., Berger, M., & Finkbeiner, M. (2011). The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterisation to model the depletion of abiotic resources. *International Journal of Life Cycle Assessment*, 16(9), 929–936. <https://doi.org/10.1007/s11367-011-0313-7>
- Schneider, L., Berger, M., & Finkbeiner, M. (2015). Abiotic resource depletion in LCA—background and update of the anthropogenic stock extended abiotic depletion potential (AADP) model. *International Journal of Life Cycle Assessment*, 20(5), 709–721. <https://doi.org/10.1007/s11367-015-0864-0>
- Swart, P., Alvarenga, R. A. F., & Dewulf, J. (2015). Abiotic Resource Use. In M. A. J. H.

- Michael Z. Hauschild (Ed.), *Life Cycle Impact Assessment* (1st ed., pp. 247–269).
<https://doi.org/10.1007/978-94-017-9744-3>
- UNEP. (2009). Buildings and Climate Change – Summary for Decision-Makers. *SBCI (Sustainable Buildings & Climate Initiative)*.
<https://doi.org/10.1017/S0035336100129600>
- UNEP. (2019). *Sand and Sustainability: Finding New Solutions for Environmental Governance of Global Sand Resources*. Retrieved from
<https://wedocs.unep.org/handle/20.500.11822/28163>
- van Oers, L., & Guinée, J. (2016). The abiotic depletion potential: Background, updates, and future. *Resources*, 5(1). <https://doi.org/10.3390/resources5010016>
- van Oers, L., Koning, A. De, Guinée, J. B., Huppes, G., de Koning, A., Guinée, J. B., ... Huppes, G. (2002). *Abiotic resource depletion in LCA. Improving characterisation factors for abiotic resource depletion as recommended in the new Dutch LCA Handbook*. (June), 1–75. Retrieved from depletion; LCA; materials, minerals
- Zhao, W., Leefink, R. B., & Rotter, V. S. (2010). Evaluation of the economic feasibility for the recycling of construction and demolition waste in China-The case of Chongqing. *Resources, Conservation and Recycling*, 54(6), 377–389.
<https://doi.org/10.1016/j.resconrec.2009.09.003>