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Feasibility study to implement resource dissipation in LCA

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Authors

Luca Zampori, Serenella Sala

Abstract

The assessment of potential impacts associated to resource use in Life Cycle Assessment (LCA) is a highly debated topic. At present, there is neither a consensus on the safeguard subject of the natural resource Area of Protection (AoP), nor on the approach to use for modeling the impacts in the life cycle impact assessment (LCIA) step.

This technical report focuses on the aspects related to dissipative use of resources and explores the feasibility of its implementation for the assessment of abiotic resources.

One of the critical aspects of abiotic resource modelling is related to the concept of depletion. Depletion is currently one of the most common aspects taken into account among existing LCIA models addressing resources, assuming that once a resource is extracted from the Earth's crust, it is considered depleted. However, abiotic resources may remain in the anthropogenic system and may be available for further use for a long time after they have been extracted from the Earth's crust.

When assessing the dissipative use of resources, it is relevant to focus both on the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA): LCIs will require to be modified compared to current practise, in order to exploit the advantages that this new approach may provide.

Initial results form this study indicate that a dissipation approach is feasible and can have several advantages, e.g providing more detailed results for several life cycle stages, but also has some drawbacks, e.g. a higher data demand on the life cycle inventory side. Both, advantages and drawbacks of the dissipation modelling will have to be further explored.

1 Introduction

In 2011, the Joint Research Centre of the European Commission (EC-JRC) published the International Reference Life Cycle Data System (ILCD) Handbook recommendations on the use of Impact Assessment models for use in LCA (EC-JRC 2011). This created the basis for the Product and Organisation Environmental Footprint (PEF/OEF) recommendations for impact categories and models as per Recommendation 2013/179/EU on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (EC 2013b).

In 2016, the JRC reviewed the recommendation of four impact categories (land use, water depletion, resource depletion and respiratory inorganics) and provided a short analysis of future research needs for each of them. Regarding resource depletion, improvements and further research are needed for the assessment of biotic resources, recycling, implementation of the concept of dissipation and a dynamic approach to estimate future availability.

Experiences gathered in the EF pilots showed that the assessment of natural resources still needs improvement: aN alternative for a way forward to assess abiotic resources was suggested by the Technical Secretariat (TS) dealing with the Organisation Environmental Footprint Sector Rule (OEFSR) for the copper producing sector (TS of the OEFSR pilot on copper production, 2015). The proposal focused on the assessment of the dissipative use of resources; the TS suggested a two steps procedure: i) acting on the life cycle inventories, ii) acting on the life cycle impact assessment.

Currently there is no agreement in the scientific community on the most appropriate characterization models to address natural resources in LCA. Also the analysis carried out by JRC in 2016 showed a general low degree of consistency of the models investigated (25 models in total). The assessment of potential impacts associated to resource use in LCA is a highly debated topic. At present, there is still no consensus on the safeguard subject of the natural resource Area of Protection (AoP), neither on the approach to use for model the impacts in the life cycle impact assessment (LCIA) step (Klinglmair et al. 2013; Dewulf et al, 2015; Vadembo et al., 2014). It is also argued that natural resources availability should not be seen as an environmental issue, rather it best fits under economic considerations (Drielsma, 2016a); however the natural environment provides natural resources that human can use and changes on these provisions can therefore be considered an environmental impact (Sonderegger et al., 2017). In addition, lack of consistency when assessing the different types of resources (e.g. abiotics, biotics, ..) and risk of burden shifting across from one resource to the other (Sonderegger et al., 2017).

The work by Sonderegger et al. (2017), which summarizes the findings of an expert group under the umbrella of the United Nations Environment Program/Society of Environmental Toxicology and Chemistry (UNEP/SETAC) initiative proposing natural resources as an Area of Protection (AoP) in LCIA provides a good insight on what a natural resource is and how to categorize natural resources.

When assessing the resources, the different perspectives covered may be summarized as follows.

- **Resource accounting at the inventory**. Accounting for all resources (metals and minerals) needed for producing a certain product. The inventory of resources as metals and minerals from the LCI leads to an estimate of the overall materials needed trough the product life cycle.
- **Resource depletion.** Characterizing the resource based on either a reserve-based approach (as in ILCD 2011) or an ultimate resource perspective (based on the relative share of resource in earth crust) (as in EF 2017) addresses the perspective of the use of resources considering their scarcity as reserve or in terms of geological occurrence.

- **Resource criticality.** Several raw materials are classified as critical (e.g. see the critical material list for EU) based on a number of elements that put at risk their supply. Specifically for Europe, Raw Materials have been classified as critical due to reserve availability and geopolitical considerations. The inventory is multiplied by the supply risk characterisation factors as in Mancini et al. 2016. This unveils which are the materials used within the production and consumption of the representative products which are Critical Raw Materials (CRMs).
- **Resource dissipation.** Resource dissipation may be both a perspective on resource accounting and on resource characterisation, aiming at discounting the resources which have a potential to be kept in the technosphere, namely that could be recycled and used repeatedly.

One of the critical aspects of the discussion around abiotic resource modelling in LCA is related to the concept of depletion. Depletion is currently one of the most common aspects taken into account among existing LCIA models addressing resources, assuming that once a resource is extracted from the Earth's crust, it is considered depleted. However, abiotic resources may remain in the anthropogenic system and may be available for further use. Several authors (Yellishetty et al. (2011), Klinglmair et al. (2013), Frischknecht (2014), Schneider et al. (2011 and 2015) and van Oers and Guinée, 2016) already discussed the possibility to consider also the amount of resources in the technosphere (e.g. in the form of scraps or waste) as part of the stock potentially available, and to include them in the calculation of characterization factors for assessing resource depletion.

However, the quantification of the "anthropogenic stock" of resources (resources in the technosphere) poses some challenges. For instance, the quantification might be uncertain (e.g. due to the complexity of differentiating the recyclability potential of different metals) (Klinglmair et al., 2013) or there is the need to account for the time of residence in the products before the resources can be made available for reuse or recycling (Yellishetty et al., 2011).

The need to distinguish between borrowing and dissipative use of resources has been alredy put forward in scientific debates (Vadembo et al., 2014). Borrowing means that resources are extracted from nature to the technosphere, but it does not automatically imply that they will not be anymore available for human use in the future (e.g. because they are embedded in products in a way that allows their recovery through recycling). On the contrary, the dissipative use of resources implies an "irreversible loss", i.e. a depletion. The distinction between borrowing and dissipative use is not inherent in the resource itself but it is related to the typology of resource use. For example, Ciacci et al. (2015) provide an overview of dissipative uses of metals, distinguishing different materials streams (i.e. in-use dissipated, currently unrecyclable, potentially recyclable and unspecified).

As proposed by Frischknecht (2014) the amount of resources extracted from the natural environment and the amount of resources used in a dissipative could be considered separately. Furthermore, Drielsma et al. (2016a) reported that dissipative outflows from studied systems are the concern to address in order to maximize continued availability of raw materials. This concept could be developed further, if resources flows are tracked also within the technosphere: this means that we need to move from looking only at the interface between the ecosphere and the technosphere (by measuring the amount of resources extracted), to look at what happens within the technosphere, once the resources are available for (multiple) human uses, and to reflect this at the inventory stage.

Improving the way in which resources are modelled and accounted for is fundamental, also in light of supporting the assessment of products in the context of the circular economy principles. In the circular economy concept and policies (e.g. EC, 2015), resources are used efficiently within the life cycle of a product and the wastes generated along the supply chains are minimized and used as much as possible, directly or after transformation, as input to other products and systems.

This feasibility study focuses on the aspects related to dissipative use of resources and explores its implementation for the assessment of abiotic resources.

When assessing the dissipative use of resources, as discussed in this report, it is relevant to focus both on the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA): LCIs will require to be modified compared to current practice, in order to exploit the advantages that this new approach may provide. Indeed, within the life cycle of a product, the assessment of the dissipative use of resources in LCA allows to identify the processes and life cycle stages that are actually responsible for not making a resource available anymore. To do this, new inventory flows will need to be added to current inventories and characterized. The concept has also been used by the Technical Secretariat of the Organisation Environmental Footprint Sector Rule (OEFSR) on copper production, who included a possible way forward regarding dissipative use of resources in the OEFSR (Technical Secretariat OEFSR Copper, 2016).

The feasibility study on the application of the dissipation concept to resource in LCA is organized as follows:

- Illustration of the current state of the play of resource assessment in LCA and in the EF context.
- Focus on the possible applications of the dissipation concept to LCA.
- Description of possible alternatives for structuring life cycle inventories.
- Simplified case studies to illustrate the application of the concept and the added value.

2 The current status of play and current recommendation in an Environmental Footprint (EF) context

2.1 Current status of play in LCA

Consumption of natural resources has steadily grown in the past decades: different disciplines aim at assessing consumption or use of resources, LCA being one of them. The assessment of resources in an LCA framework has widely been debated, and there is no clear consensus on many of the basics concepts. Furthermore, it is seen by some as not belonging purely to the sphere of environmental issues, due to its interconnections with economics. In this context, the use or consumption of resources normally refer to the Area of Protection (AoP) "natural resources": it is worth noting that, recently, proposals for re-thinking the AoP of natural resources were brought forward by some researchers (Dewulf, 2015).

Different characterization models can be used to assess natural resources in LCA:

- Advanced accounting models,
- Abiotic Depletion Models (ADP),
- Models taking into account the variation of ore grade over time,
- Models based on the Distance-to-target concept,
- Model based on Willingness to Pay,
- Models accounting for criticality of resources.

A more elaborated description and analysis is available in (Sala et al 2017). Although many approaches have been discussed in scientific papers and are used also in LCA practice, none of the above-mentioned models is tackling the issue of assessing dissipation of resources. The only model which takes into account availability of resources within the technosphere is the anthropogenic stock extended abiotic depletion potential (AADP) (Schneider et al., 2011; Schneider et al., 2015).

2.2 Current Environmental Footprint (EF) recommendations for resources

In the context of the Environmental Footprint (EF), the recommendation in the PEF Guide (EC, 2013) was challenged by the results of many PEF and OEF screening studies, available at https://webgate.ec.europa.eu/fpfis/wikis/spaces/viewspace.action?key=EUENVFP.

Therefore, in 2016 the JRC reviewed the recommendation for resources and the EF recommendation now covers two levels: mandatory for impact assessment, split between abiotic resources (metals and minerals) and fossil (energy carriers) and foresees additional environmental information (Sala et al 2017). Table 1 summarizes the current recommendations and the level thereof.

Table 1. Current recommendations for resource use in EF pilots (Sala et al 2017).

Impact category	**Mandatory for impact assessment**
Impact due to resource use, minerals and metals (short: "resource use, minerals and metals")	Mandatory indicator: - **"$ADP_{ultimate\ reserves}$"** for abiotic resources (metals and minerals) based on the models of van Oers et al. 2002 and van Oers and Guinée 2016. Level of recommendation III
Impact due to resource use, fossils (short: "resource use, fossils"	Mandatory indicator: - **"ADP_{fossil}"** for assessing depletion of energy carriers. based on the models of van Oers et al. 2002 and van Oers and Guinée 2016. Level of recommendation III
Requirements as additional environmental information	
A "should" requirement to report: - **"Biotic resource, use at inventory",** a mass accounting, of biotic resources (in kg) as for the LCI of the system under evaluation.	

3 Exploring the dissipative use of resources concept

3.1 Dissipative use of resources in LCA

The concept of dissipative use of resources is already dealt with in disciplines outside LCA (e.g. Material Flow Analysis (MFA)). When looking at studies in an LCA context, Stewart and Weidema (2005) proposed a first approach on how to assess dissipative losses to the environment. The concept was left aside for about ten years, until 2014 when Frischcknecht made a proposal on how to implement dissipative and borrowing use of resources (Vadenbo et al. (2014)).

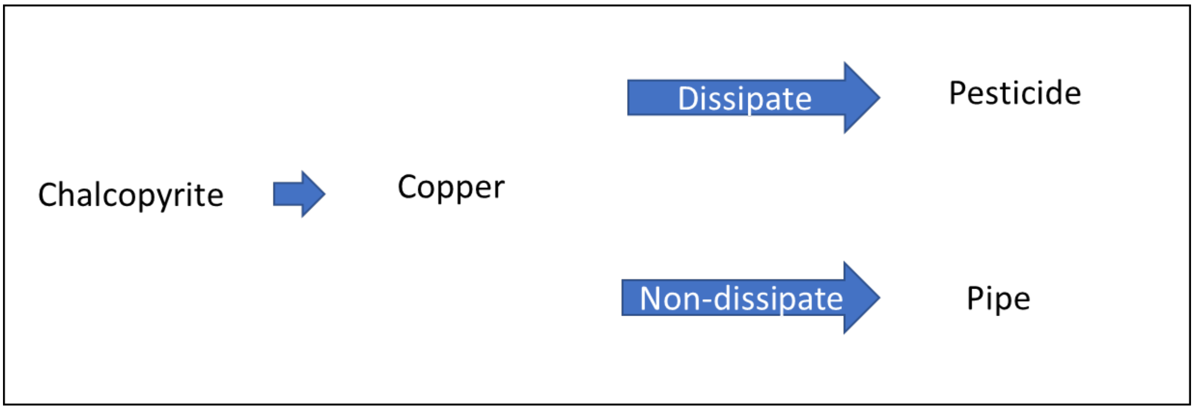
In the context of the Organisation Environmental Footprint Sector Rule (OEFSR) pilot on copper production, the Technical Secretariat (TS) proposed a way forward on how to deal with resource depletion, focusing on the dissipative use of resources (Technical Secretariat of the OEFSR pilot on Copper production, 2015). The novelties of the proposal were: i) tackling the issue first at Life Cycle Inventory level, ii) the identification of dissipative losses not only at the interface between ecosphere and technosphere, but also to other material uses and applications (i.e. within the technosphere).

This technical report builds on the proposal of the OEFSR pilot on copper production and tries to provide further insights on how to integrate dissipation of resources in LCA.

In contexts other than LCA, but still somehow complementary to it, Ciacci et al (2015) have quantified the "losses by design" of 56 metals and metalloids, assigning each use to one of three categories: in-use dissipation, currently unrecyclable when discarded, or potentially recyclable when discarded. This means that a dissipative use of a resource is **not inherent in the resource itself;** it is related to the **typology of resource use**.

For example, we can consider the resource "copper" (Figure 1): the diagram shows that it is the use of copper as a pesticide or as a pipe that determines the dissipation or non-dissipation of the resource.

Figure 1. The diagram shows that it is the use of copper as a pesticide or as a pipe that determines whether the resource "copper" is dissipated or non-dissipated.



Other studies, in the field of Material Flow Analysis (MFA) were conducted for example by Zimmermann (2016) where he focused on tracking dissipative losses of critical metals along the product life cycle: similar to the proposal of the copper pilot, the definition of dissipation proposed by Zimmermann considers dissipative losses not only to the environment, but also to other material flows and landfills.

Zimmermann and Gobling-Reisemann defined dissipative losses as "*losses of material into the environment, other material flows, or permanent waste storage that result in concentrations in the receiving medium, such that a recovery of these materials is technically or economically unfeasible*".

While the identification of dissipated resources may be seen as straightforward, simple examples show that the definition of a shared framework is necessary. Indeed, Figure 2 shows the transformation of different resources into concrete: to what extent can the original resources (sand, limestone…) be considered dissipated? To what extent should one evaluate the functionalities that a resource is able to provide?

Figure 2. Is the use of raw materials (e.g. limestone, sand,..) to produce concrete a dissipative use of resources?

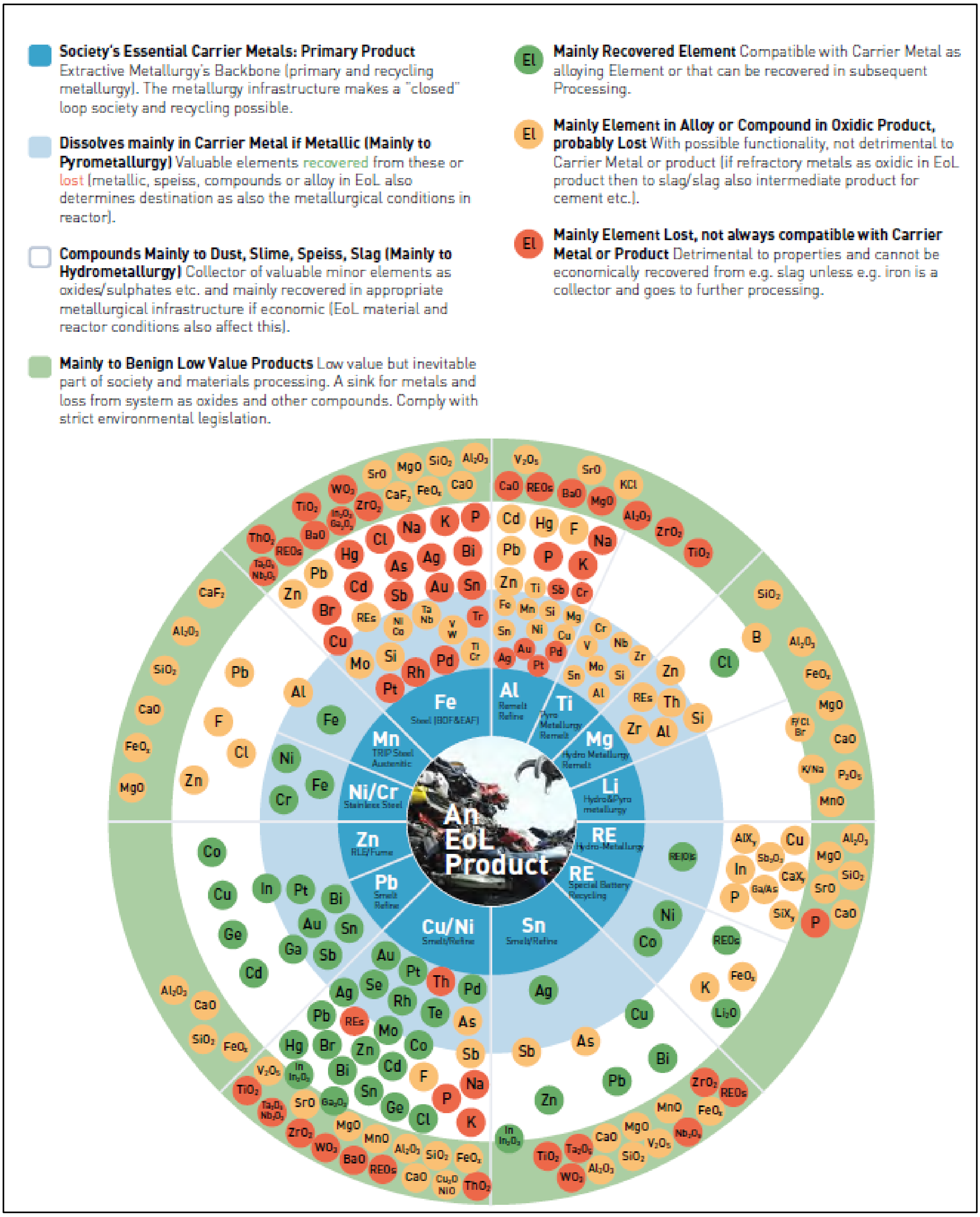
To show the complexity of identifying to what extent a resource can or cannot be considered lost/dissipated, in Figure 3 the "metal wheel" (UNEP, 2013) is reported. The metal wheel aims at reflecting the destination of different elements in base-metal minerals as a function of interlinked metallurgical process technology. Looking at the innermost blue circle one can find the carrier metal, while external circles identify elements that are dissolved mainly in carrier metal (light blue), compounds mainly to dust (white) or mainly to benign low value products (green). Within each circle, one can identify what is mainly recovered as element (green), what is in alloy or compound in oxidic product, probably lost (yellow) and what is not always compatible with carrier metal or product (red). It is not the intention to examine more in detail this graphic representation, however it can provide a useful picture to understand the underlying complexities linked to material recovery/losses.

This technical report aims at testing the feasibility of implementing the concept of dissipative use of resources in LCA. In view of a definition of a full methodology, tackling both the life cycle inventories and life cycle impact assessment, it is important to define a framework to assess the dissipative use of resources. This aspect is not within the scope of this feasibility study, nevertheless some key aspects that should be covered in further methodological developments are:

- Problem definition: what's the environmental issue that the methodology aims at addressing; what is it aiming at protecting;
- Definition of key concepts: for example, a unique definition of dissipation is needed. Indeed, there is not a universal definition of resource dissipation in the scientific literature;
- Multidisciplinary review of the state of the art: the coverage of disciplines beyond LCA is important to create a common understanding and to provide the proper information to a wide range of stakeholders;
- Scope of the method: how to take into account temporal aspects and technological aspects (e.g. a resource considered dissipated today, may be non-dissipated with evolving technologies), to what extent economic aspects may be integrated in the method;
- Requirement of cross-applicability to all abiotic resources, including fossil ones;
- Evaluation of cross-applicability to biotic resources.

The above points are key issues that need to be addressed to further progress in the implementation of dissipation of resources in LCA.

Figure 3. Metal wheel. Source UNEP (2013)



Regarding resource dissipation on a resource accounting perspective, an indirect way to address dissipation is to examine the level and quality of the recycling. Recycling rates have been defined in many different ways (e.g. considering product, metal, metals in product) and for different life cycle stages. According to UNEP, 2011, different type of recycling are related to the type of scrap and its treatment, namely: home scrap – generated during fabrication or manufacturing that could be reinserted in the process that generated it, usually excluded from recycling statistics; new or pre-consumer scrap

– generated during fabrication or manufacturing, usually at high purity and value; old or post-consumer scrap – referring to metals that have reached their end of life; functional recycling – metal coming from a product that leads to a recyclate that could be returned to raw material production processes that generate a metal or a metal alloy; non-functional recycling – metal is collected as old metals scrap and incorporated in a large magnitude material stream as impurity element or "tramp" leading to an open metal life cycle.

Dissipation may occur in all the above mentioned stages; however, dissipation could be linked also to specific recycling failures: i.e. a metal is not captured through any of the previous recycling streams, or is dissipated during use (e.g. corrosion, nanomaterials, etc.) or at the end of life.

3.1.1 Further explorations on the concept from resource depletion to resource dissipation

In LCA, depletion of resources is assessed as occurring at the interface between nature and technosphere. Resource depletion can be defined as the process of physically reducing the global amount of a specific resource. It refers to the reduction of geological/natural stocks over time (Drielsma et al, 2016b).

If the potential impact of resource depletion is only considered in relation to the exchanges of resources from the ecosphere to the technosphere, the information associated to what happens within the technosphere is irremediably lost. In other words, the burdens and benefits associated to depletion of resources are shifted exclusively to the life cycle stages where extraction of raw materials takes place and to the end-of-life in the case of recycling (e.g. through modelling of displaced primary resources due to recycling). By strictly looking at the physical element exchange between ecosphere and technosphere, one may observe that a resource is actually **transferred** from the natural environment to the man-made environment, therefore it cannot be considered **depleted**: actually the interface between ecosphere and technosphere is the point where a resource has been made **available** for human purposes.

Ignoring dissipation of resources along the life cycle of a product does not help in identifying those life cycle stage or processes where the major losses occur: as such, it does not help avoiding shifting of a potential environmental burden between life cycle stages or processes. In order to be able to capture dissipation of resources along the life cycle, and considering dissipation as occurring not only to the environment but also to other material flows, it is necessary to track resources also within the technosphere. Figure 4 and Figure 5 provide a graphical representation of the perspective adopted according to a resource depletion concept and to a dissipative approach.

To be able to capture flows of resources also within the technosphere, it is necessary to take the following steps:

1) Life Cycle Inventories need to be adapted by tracking flows of resources also within the technosphere.

2) A characterization model needs to be consistently associated to the new built inventories: this means that characterization factors will need to be provided to associate a potential impact to the resource flows occurring within the technosphere. Existing characterization models could also serve the purpose, however it is important that life cycle inventories and characterization models are designed to be consistent with each other.

An example of how the above concept could work is shown in the following sections.

"Depletion model" should be understood as the way Resource Depletion is assessed nowadays (i.e. flows of resources are tracked only at the interface between ecosphere and technosphere); "Dissipation Model" should be understood as the way forward explored here, with focus on the development of new life cycle inventories. The challenge of a suitable characterization model will have to be explored in further developments.

To allow tracking flows of resources within the technosphere, in addition to the existing elementary flows modelled from the ecosphere to the technosphere (e.g. “resource, raw”), at least two other type of flows should be considered:

- The share of extracted resource that has been used but is not irreversibly dissipated (e.g. it is within a product but can be still recovered at the end of life of the product) and can be considered part of the anthropogenic stock (i.e. still available for use, or “potentially recyclable” (Ciacci et al. (2015)).
- the share of the extracted resource that is dissipated, either because it is embedded in a product in a way that prevent any recovery or because it is irreversibly dispersed (e.g. “in-use dissipated”, (Ciacci et al. (2015)). Dissipation refers also to a resource that is physically in a product; however, its application in the product will prevent future recovery. For example, a specific design may not allow the future recovery of the resource; therefore, even if no resource losses to the environment can be observed in the production of the product, a dissipative use of the resource shall be captured in the inventory and assessed at the impact assessment level.

Figure 4. Perspective adopted according to resource depletion concepts: the potential impacts are calculated when a resource enter the technosphere.

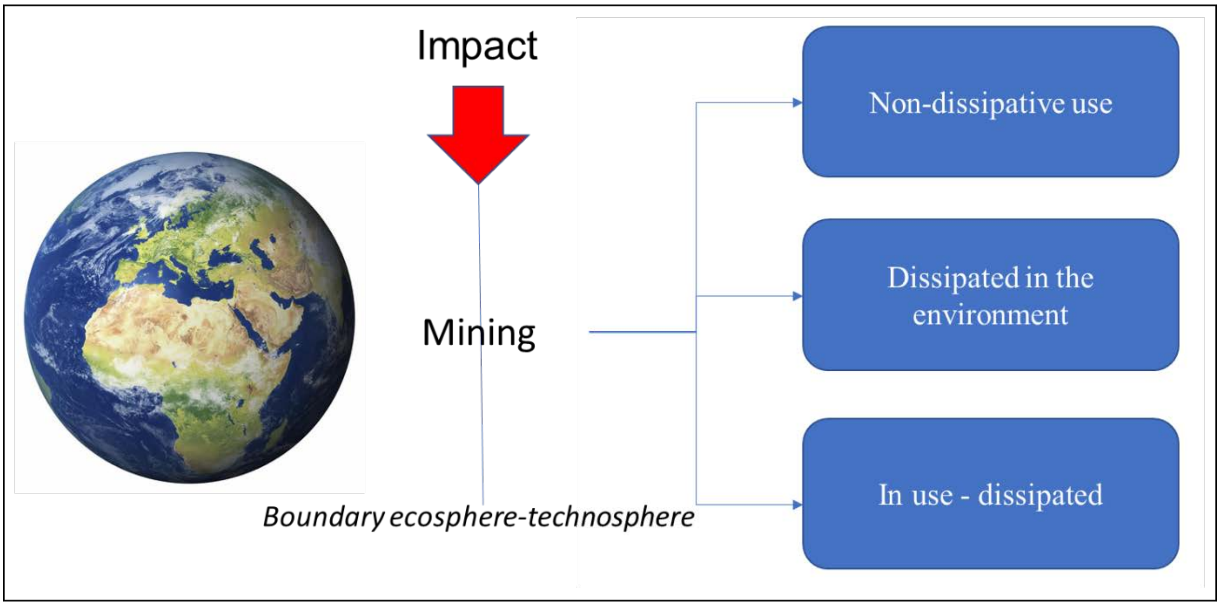
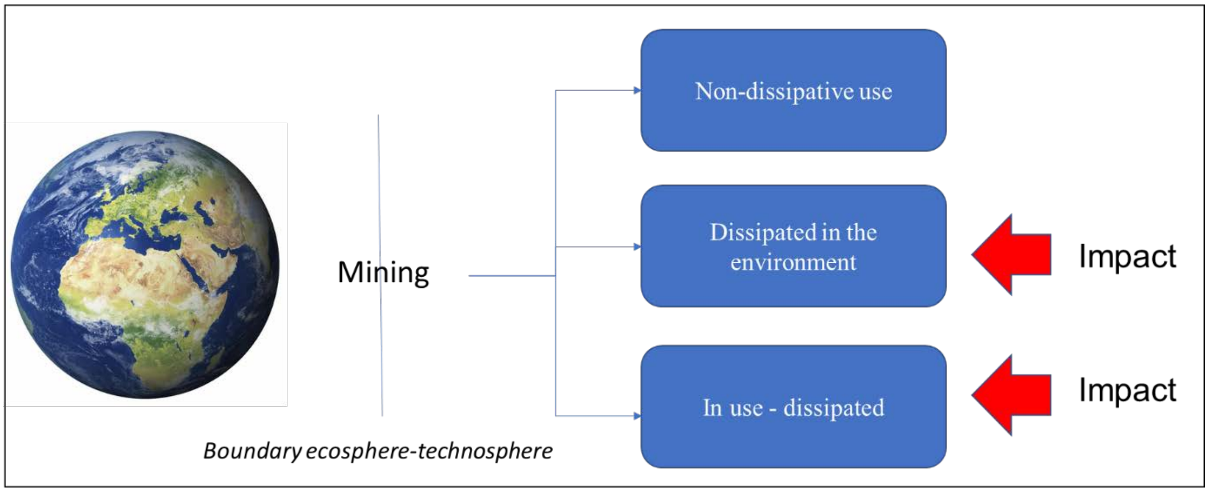


Figure 5. Perspective adopted according to a dissipation concept: the potential impacts are calculated when a resource is dissipated both in the technosphere and in the environment.



As mentioned in paragraph 2.1 it is sometimes argued that resource depletion/consumption/use poorly fits into environmental LCA. When assessing dissipation of resources the perspective adopted can be defined as: **additional resources that need to be extracted from the environment, due to dissipative use in the technosphere and dissipation from the technosphere to the environment.**

3.1.2 How to structure Life Cycle Inventories to capture dissipation of resources

To elaborate further on how to structure Life Cycle Inventories to capture dissipation of resources, we can use the schematic and simplified production of a generic product as an example (Figure 6). In the example in Figure 6 we show two ways of modelling a Life Cycle Inventory: i) according to a depletion approach and ii) according to the dissipation concept.

In the first case (depletion) to depict flows related to resource depletion, only the elementary flow *"resource, raw"* is modelled: this flow corresponds to an input to the production of the generic product and it represents the resource extracted from nature and provided to the technosphere.

In the second case, when applying a model based on dissipation, additional flows are needed: a flow "*resource, in technosphere"* has also to be considered as output to the generic product production, meaning that a certain amount of the resource incorporated in the product has not been dissipated; and a flow "*resource, dissipated*" which identifies the amount of resource which is dissipated in the unit process.

To assess the dissipative use of resources, a characterization factor shall be assigned also to the additional flows *"resource, in technosphere"*: several characterization models could be used, also building on existing ones, or new characterization models could be elaborated.

In this section, examples are built with the use of Characterization Factors with 0-1 values expressed as Arbitrary Units (AU): the use of 0-1 values is to be intended as an oversimplification to show the conceptual basis of the suggested way forward. When looking at the example in Figure 6 the CFs as AU 0-1 are applied. In the depletion approach, a CF (equal to 1) is assigned only to the elementary flow (*resource, raw*) at the interface between the ecosphere and the technosphere: this implies that the resource is completely depleted after its extraction (and eventually recovered at end-of-life during recycling). On the contrary, in the case of the dissipation model, it is acknowledged that only a fraction of the resource is really lost, whereas the majority of the amount extracted is still available within the technosphere (*resource, in technosphere*): the characterized amount of resource still available is therefore subtracted from the characterized amount of resource extracted. It is important to note that the dissipated fraction does not refer only to the portion of resource that is lost (e.g. in the environment), but it also refer to the amount of resource that is still within the technosphere, but its specific use, e.g. in a product, is recognized as a dissipative use.

Two levels of consistency are needed:

- Consistency between inventory and characterization model: e.g. the distinction of different levels of dissipation, by distinguishing and potentially breaking-down to a more detailed level the "potentially recyclable", and "currently unrecyclable" fractions, shall be done consistently with the possibility to actually characterize them. For instance, the differentiation between functional and non-functional recycling could be further explored.
- Consistency with perspectives identified in Dewulf et al. (2015) is also recommended.

Figure 7 to Figure 10 provide generic examples on how a model based on dissipation of resources can be applied over the full life cycle of a product. The examples discussed in this section do not aim at depicting real case study and they are only an illustration to show how the methodology works over a complete life-cycle. Examples based on real case studies will be discussed in next sections.

In Examples A and B (Figure 7 and Figure 8), we discuss the case of a resource that is not recovered at end-of-life and which is not possible to be recovered even in the future. Example A illustrates how this is dealt with according to a depletion approach, while Example B shows how the LCI is built according to a dissipation approach.

As it can be seen by comparing Examples A and B:

- Impacts over the full life cycle are the same: in both cases the Potential Impact (PI) = 1 Arbitrary Units (AU).
- Example A associates all burdens of depletion of resources to the "extraction of raw materials": at that stage the resource could be used in a product in a way that it still allows its recovery at end-of-life through a recycling process or lost.
- Example B associates burdens (i.e. potential impacts) to those life cycle stages which prevent the recovery of the resource (in-use dissipation) or to those life cycle stages which physically lose part of the resource (dissipation back to the environment). The "Production, Use, …" life cycle stage becomes the "hotspot" of the life cycle, meaning that an improvement in this area is needed to keep resources in the loop.

In examples C and D (Figure 9 and Figure 10) we show the case of a life cycle with recycling at End-of-Life. Example C illustrates how this is dealt with according to a depletion approach, Example D shows it according to a dissipation approach. It is worth noting that in the dissipation model the new flows "*resource, in technosphere*" and "*resource, dissipated*", output of the first unit process are used as input in the following unit process: this allows to track the flows of resources within the tecnosphere. A further distinction between resource dissipated as a waste and a resource dissipated in-use (i.e. still within the product) is also made, to enable a better understanding of the concept.

Examples C and D are built to be compared with A and B. When comparing A and C, burdens are always associated only with "Extraction of raw materials", while processes occurring between this life cycle stage and the end-of-life (disposal or recycling) are always burden free, while they could actually influence the end-of-life destiny of the product.

When comparing B and D a more accurate depicting of resource flows is inventoried and the impacts associated to the different life cycle stages actually allow to focus where improvement is needed. Modeling the inventories as proposed in the dissipation model can help identifying the weak points in the value chain: these results could constitute the starting point for a more in depth analysis, thus being a bridge to other disciplines which focus on some steps of the value chains, to a higher level of detail (Reuter et al., 2015).

From the examples provided it can be observed that the dissipation model allows to identify the life cycle stages, which are actually contributing to a non-availability of resources due to their dissipative use. Indeed, the real difference between the scenario “recycling at EoL” and “disposal at EoL” has to be searched for in the “production, use,...” and “EoL” life cycle stage. Therefore, improvements need to be made in the production and use step and recycling can also be improved. This information is not visible when a depletion model like the ones currently used is applied.

Figure 6. Fictive unit process "extraction of raw materials" modelled according to a Depletion approach and to a Dissipation approach. In the former case only the elementary flow "resource, raw" from nature is modelled. In the second case, also flows within the technosphere are modelled "resource, in technosphere" and "resource, dissipated". The flow "resource, dissipated" may be used both to capture in-use dissipation and dissipation into the environment.

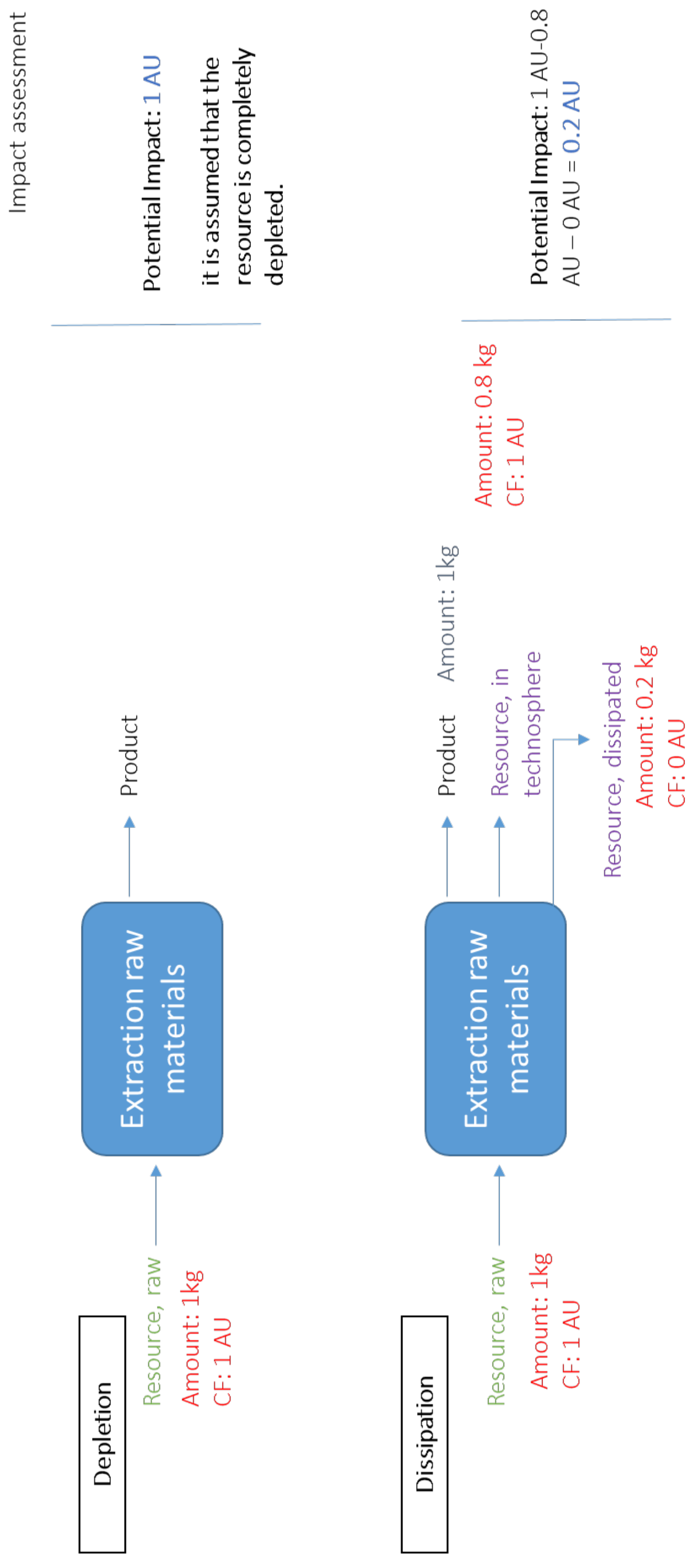
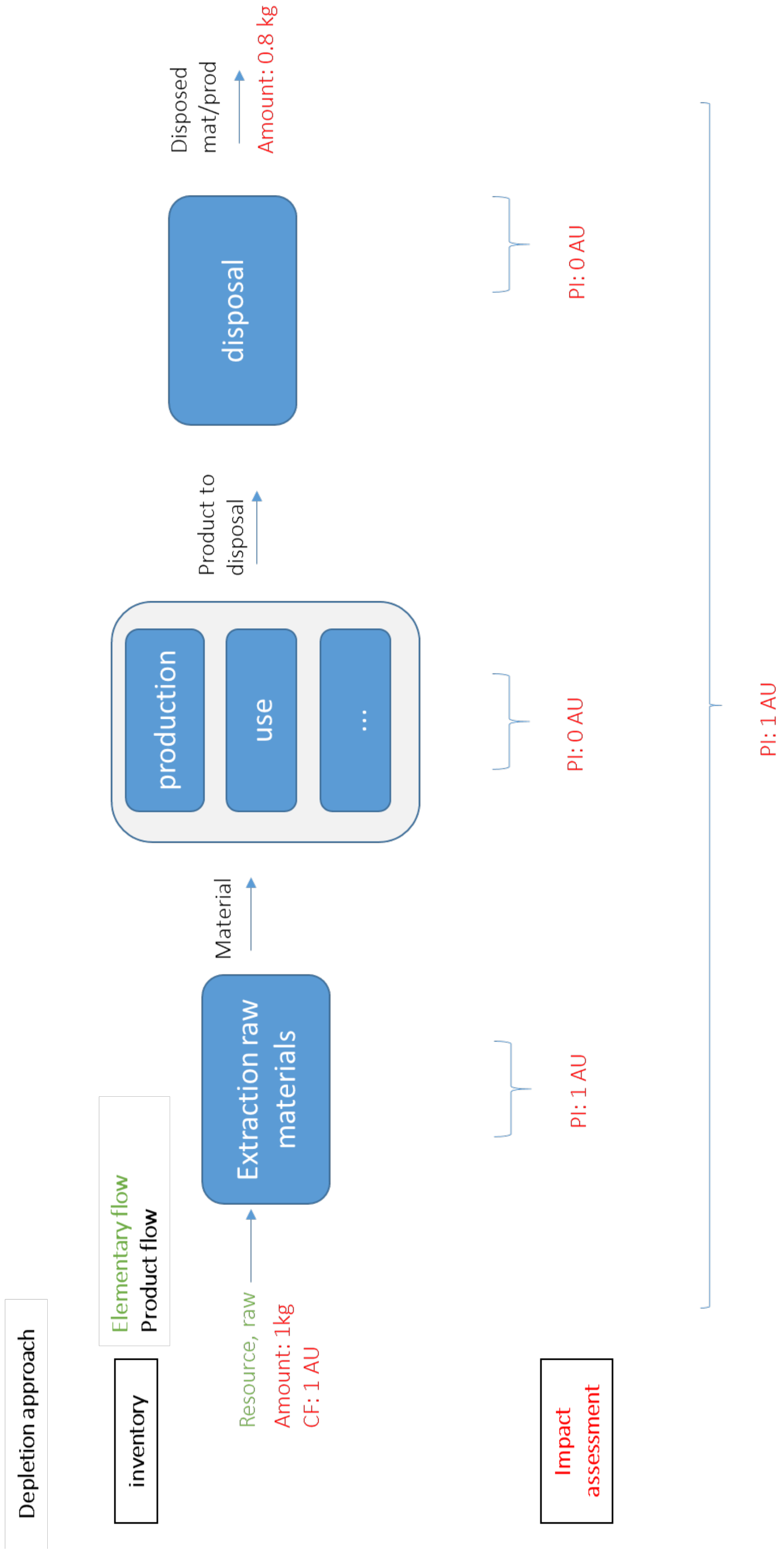


Figure 7. Example A: life cycle of a resource within a product, which is landfilled at end-of-life, using a depletion approach.



Depletion approach
inventory
Elementary flow
Product flow
Resource, raw
Amount: 1kg
CF: 1 AU
Extraction raw materials
Material
production
use
...
Product to disposal
disposal
Disposed mat/prod
Amount: 0.8 kg
Impact assessment
PI: 1 AU
PI: 0 AU
PI: 0 AU
PI: 1 AU

Figure 8. Example B: life cycle of a resource within a product, which is landfilled at end-of-life, using a dissipation approach.

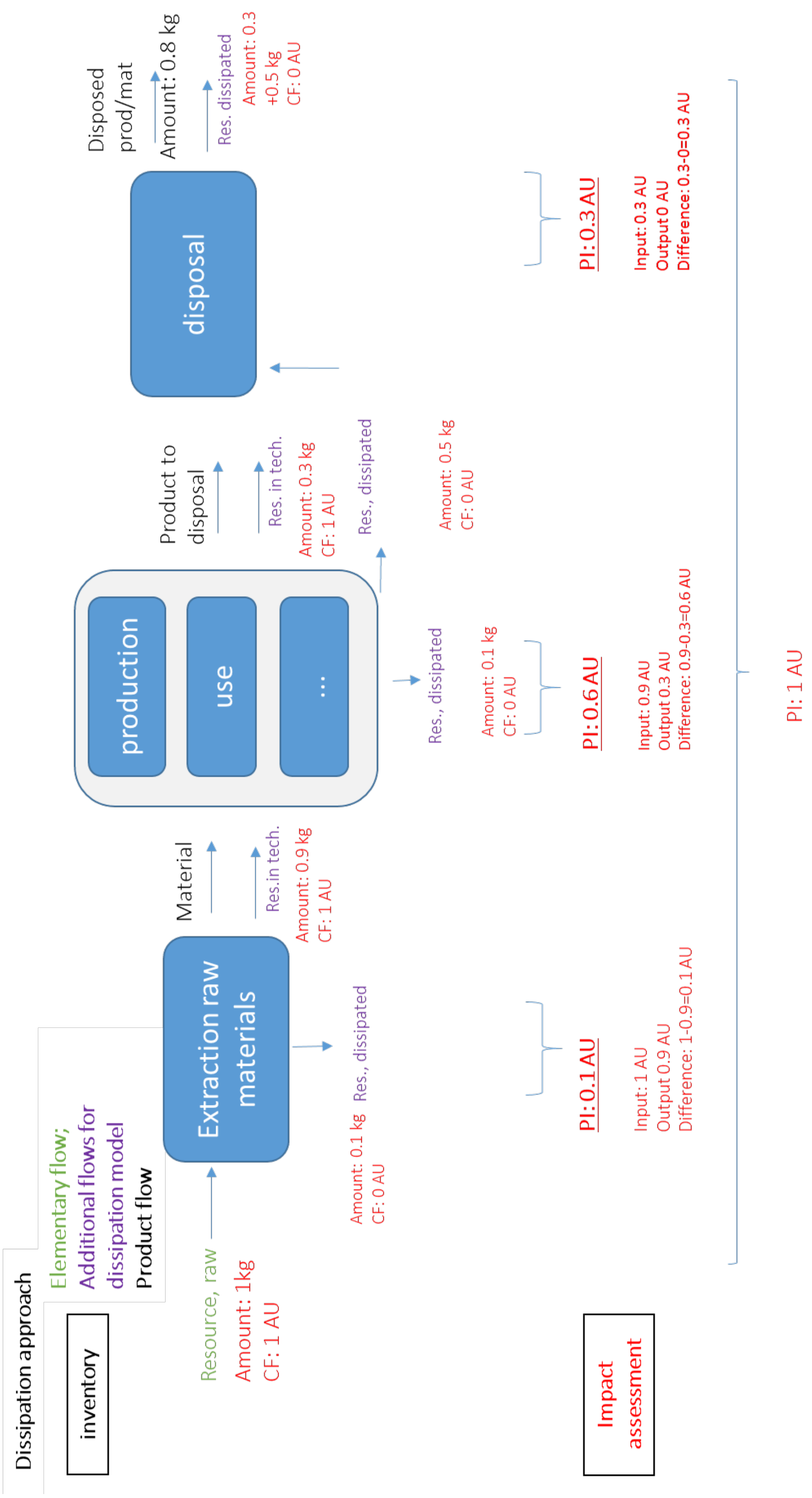


Figure 9. Example C: life cycle of a resource within a product, which is recycled at end-of-life, using a depletion approach.

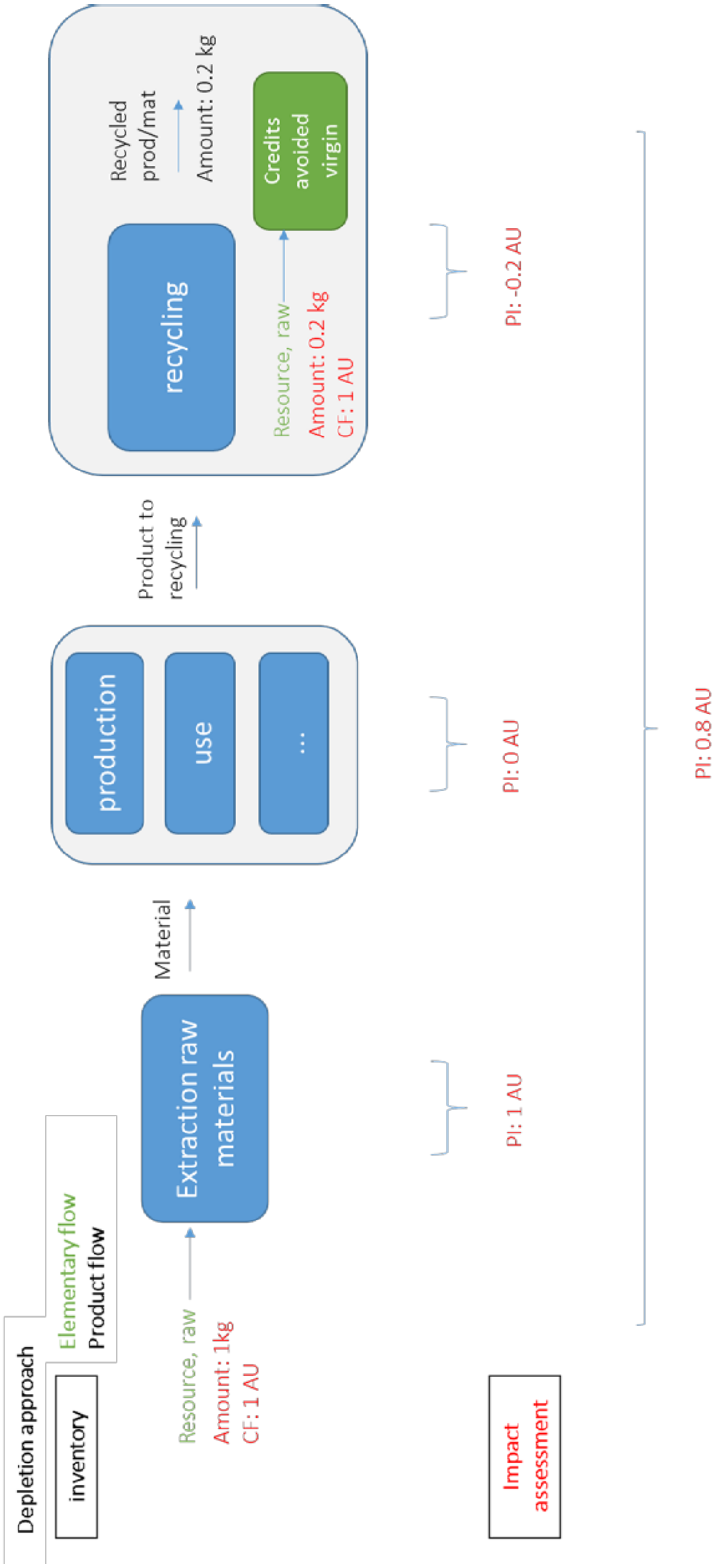
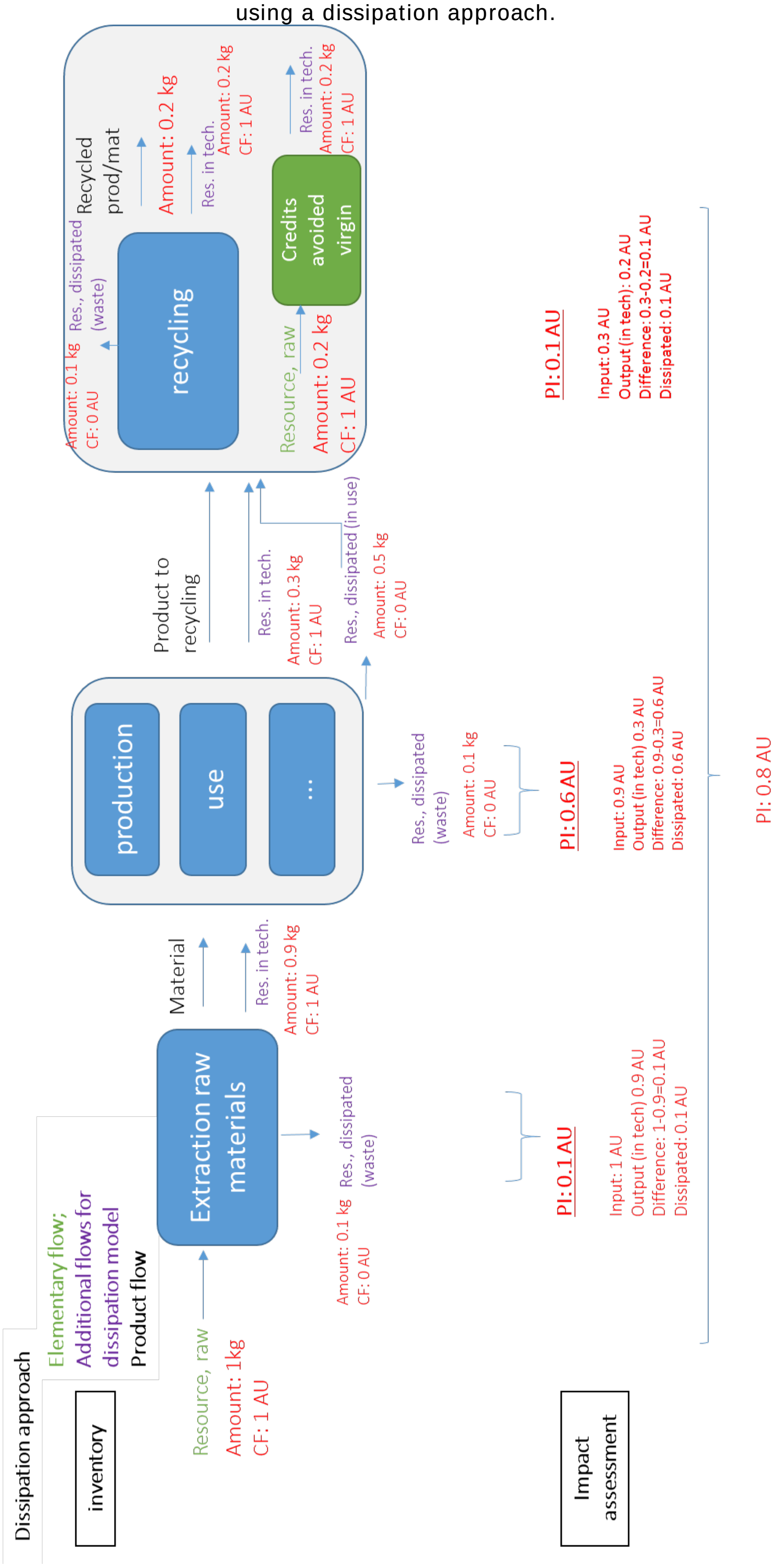


Figure 10. Example D: life cycle of a resource within a product, which is recycled at end-of-life, using a dissipation approach.



3.1.3 Possible alternatives on how to structure Life Cycle Inventories

In this report we have identified 5 different alternatives on how to structure Life Cycle Inventories. They are described in the following paragraphs, with identification of main pros and cons.

3.1.3.1 Alternative 1 (A1): Classes of dissipation

This approach is based on the identification of different classes of dissipation (e.g.: total, partial (eventually further split into high, medium, low), null). *Table 2* provides an example.

Resource flows are modelled at both the input and the output of a unit process, following the generic example discussed in Figure 6.

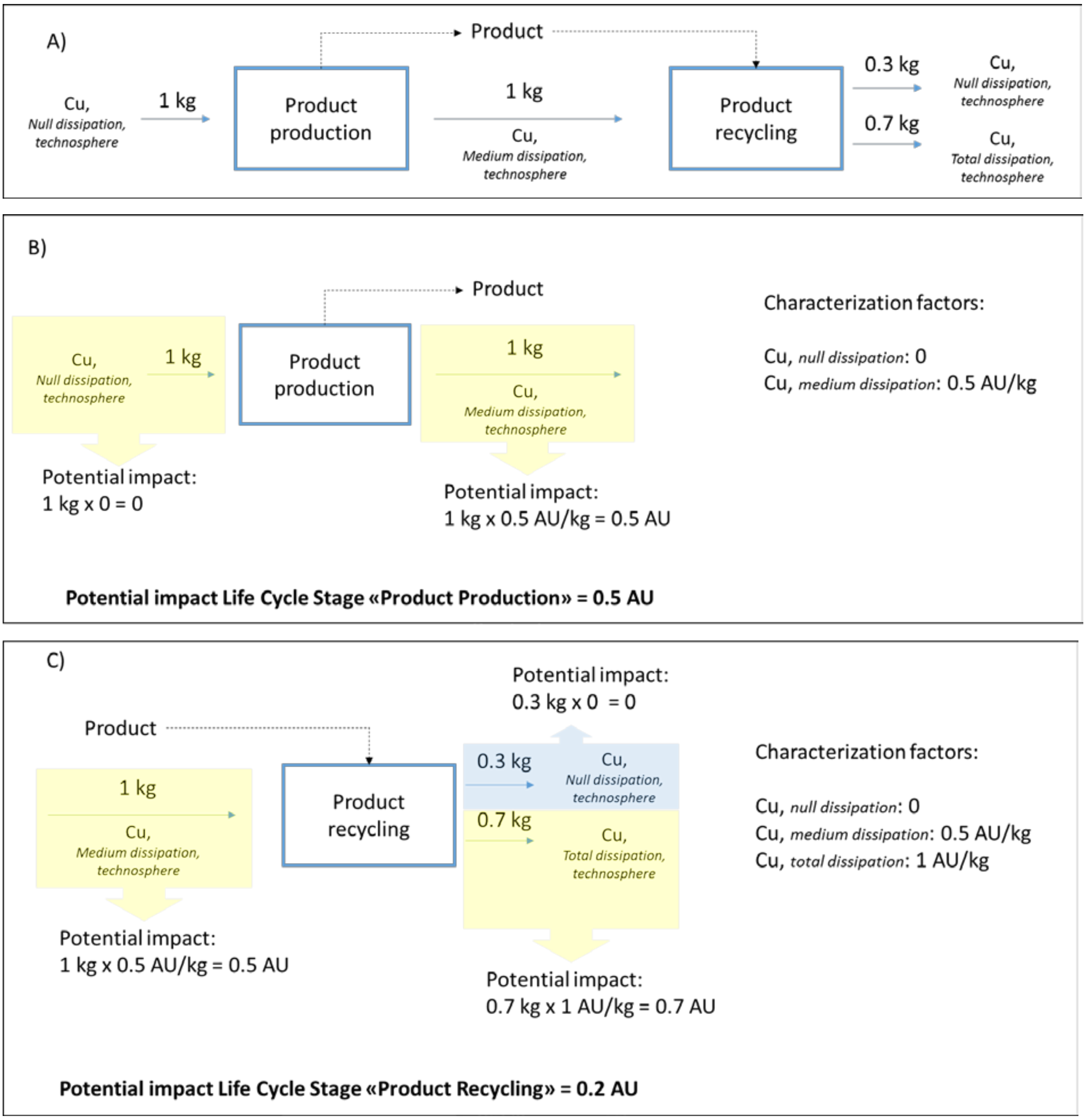
- Pros: detailed mass flows; transparency; granularity of dissipation classes allows for higher flexibility: with evolving technological and economic conditions, an application can be moved to a different dissipation class.
- Cons: granularity of dissipation classes increases the complexity in modelling; data availability. One of the flows, or one of the characterization factors, at the input or output needs to carry a negative sign: higher complexity in terms of hotspot analysis and interpretation.

Table 2. Example of scheme to define dissipative losses (fictive example)

Resource	**Application**	**Dissipation classes**					**Media**	
		Total	High	Medium	Low	Null	Environment	Technosphere
	Pipes					x		X
	Tubes					x		X
Copper	Wasted during mining			x			X	
	Landfilled		x					X
	PCBs			x				X

Figure 11 provides a graphical example (fictive) to show how to model the life cycle inventory using the approach proposed in this paragraph. While being highly detailed, the need to always report flows at input and output and the different dissipation classes make the modeling quite complex.

Figure 11. Fictive example on how to model the life cycle inventory using the approach named Way 1. Potential impacts are, at this stage, defined as AU = Arbitrary Units.



3.1.3.2 Alternative 2 (A2): A 0-1 model based on classes of dissipation

A second alternative is to consider resources as either "dissipated" or "non-dissipated" (here defined as a 0-1 model), without displaying the classes of dissipation in the Life Cycle Inventory. The "dissipated" and "non-dissipated" flows would still be based on classes of dissipation: the partial (or high, low, average) class of dissipation would need to be aggregated at inventory level into a "dissipated" or "non-dissipated" class to define the 0-1 classes. For example, if 1 kg of a substance is "average dissipated", it will be modelled as 0.5 kg non-dissipated and 0.5 kg dissipated.

- Pros: easier to display and model in a LCI compared to A1
- Cons: granularity of dissipation classes increases the complexity in modelling; data availability. One of the flows, or one of the characterization factors, at the input or output needs to carry a negative sign: higher complexity in terms of hotspot analysis and

interpretation (same as A1). In addition, despite the apparent easiness, it is less transparent compared to A1.

3.1.3.3 Alternative 3 (A3). Net approach

A third option is to avoid the modelling of resource flows both at input and output of each unit process, to avoid complicated LCA modelling.

This third alternative is compatible both with A1 and A2, because the input and output resource flows are still calculated in the background, however they are not shown in the inventory which is modelled as a flow of net dissipation. Therefore the calculated “resource dissipated”, based on the scheme at A1 or A2, can be inserted in the LCI as an input flow.

- Pros: easy in software and modelling, no flows (or characterization factors) carry negative signs.
- Cons: less transparent to check mass balances and detailed flows.

3.1.3.4 Alternative 4 (A4): 0-1 model not based on classes of dissipation

A fourth alternative is to identify for each resource flow in a specific application and unit process the share which is on average dissipated and the share that is not dissipated. With this alternativealternative, classes of dissipation are not identified (*Table 3*), due to two main reasons: i) data availability, ii) it may actually be not meaningful to identify different classes of dissipation. It is a simplification of A1, and it is similar to A2; however, compared to A2 classes of dissipation are not needed neither as background information. Flows are modelled at both the input and output of each unit process.

- Pros: Partially solves data availability issues of A1. Easier to model.
- Cons: Less accurate compared to A1. One of the flows, or one of the characterization factors, at the input or the output needs to carry a negative sign: higher complexity in terms of hotspot analysis and interpretation.

Table 3. Example of scheme to define dissipative losses, with no intermediate classes. Fictitious example

Resource	Application	Dissipation classes		Media	
		Total	Null	Environment	Technosphere
		[%]	[%]		
Copper	Pipes	0	100		X
	Tubes	0	100		X
	Wasted during mining	85	15	X	
	Landfilled	50	50		X
	PCBs	80	20		X

3.1.3.5 Alternative 5: Net approach not based on classes of dissipation

A last alternative is to structure the inventories based on a net approach (as in A3), without inventorying resource flows at both input and output of a unit process, and to use a 0-1 approach starting from A4 to model dissipative losses to be characterized. Therefore, according to A5, flows named "resource, dissipated" are the only ones characterized.

Pros: very practical and easy to handle conceptually and in software

Cons: less accurate compared A1 and potentially less transparent

3.1.3.6 Choice of the most suited approach to structure Life Cycle Inventories for further explorations

Table 4 provides a summary of aspects included in each alternative.

Table 4. Summary of aspects included in each alternative

	Alternative				
Aspect	**A1**	**A2**	**A3**	**A4**	**A5**
Modelling of input and output flows	X	X	-	X	-
Net approach	-	-	X	-	X
Classes of dissipation	X	X (in the background)	X	-	-
0-1 model	-	X	-	X	X

A5 is the chosen approach to be further investigated for the goal of this feasibility study, due to its practicality and to data availability.

3.2 Case studies

3.2.1 Modelling the copper supply chain

The first case study focuses on only one resource (copper), for sake of simplicity. Using a model on copper stocks, flows and recycling rates developed by the Fraunhofer Institute, for the International Copper Alliance (http://copperalliance.org/), the dissipation rates related to year 2010 have been estimated, and they are summarized in *Table 5*.

Figure 12. Global copper stocks and flows in 2010 (source: International Copper Alliance).

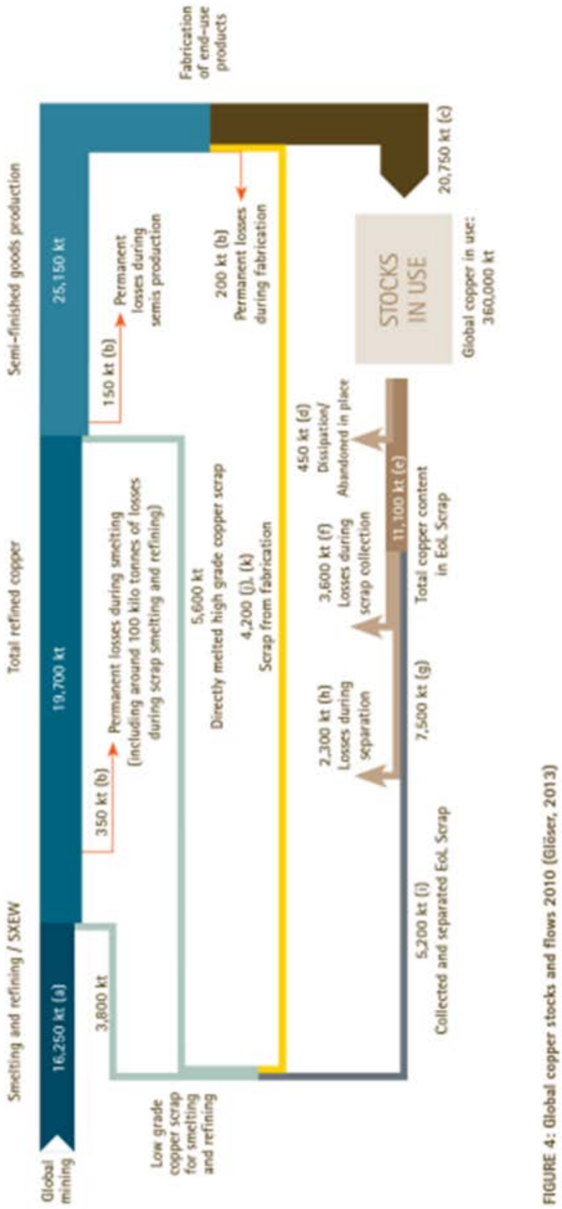


Table 5. Global dissipation rates of copper calculated based on data in Figure 12.

Dissipation rates
Smelting and refining
2%
Semi-finished products
0.6%
end use products
0.8%
EoL
3.9%
32.4%
30.7%

In addition, considering Ciacci et al. (2015), the dissipation rates of copper depending on specific applications were quantified as the ratio between the sum of in-use dissipation+currently unrecyclable+unspecified and the application specific market share. The market average is 5%; results are shown in *Table 6*.

Table 6. Dissipation rates of copper per application.

Application	**Dissipation rate per application* [%]**	**Potentially recyclable [%]**
Electrical	0	100
Industrial	0	100
Transportation	0.8%	99.2%
Cooling	0	100
Plumbing	1.7%	98.3%
Communications	0	100
Electronics	0%	100%
Architecture	5.0%	95.0%
Building plant	0	100
Other		
Dissipative uses	100	0
Pigments &CCA	100	0
Miscellanoeous	15.2%	84.8%
Average market	*5%*	*95%*

Based on the dissipation rates calculated in *Table 5* and considering also the amount related to "average market" in *Table 6* a Life Cycle Inventory, for the average copper market was compiled, as shown in *Table 7*. The two sources are heterogeneous and may be based on different starting data, however no better data were found to attempt the modelling of all the life cycle stages of the copper supply chain. The sources can be considered a reasonable proxy for the goal of this feasibility study. It was assumed an initial extraction of 1 kg of *copper, raw* from nature, which is progressively dissipated in subsequent processes.

Table 7. Life Cycle Inventory, related to 1 kg of copper extracted at a mining site, for the average copper market using the "dissipation model".

Dissipation approach			Life Cycle Inventory		
life cycle stage / process	**Dissipation rate**	**Application**	**Copper, in technosphere**	**Copper, dissipated**	**Copper, raw**
			[kg]	[kg]	[kg]
Raw materials input			*0*	0	1
Smelting and refining	1.7%		*0.983*	**0.0175**	0
Semi-finished good	0.6%		*0.977*	**0.0058**	0
Fabrication end-use product	0.8%		*0.969*	**0.0078**	0
Application specific	5.0%	Average sector	*0.921*	**0.048**	0
End-of-life					
abandoned in place	3.9%		*0.885*	**0.036**	0
losses during collection	32.4%		*0.598*	**0.287**	0
losses during separation	30.7%		*0.414*	**0.183**	0

As a comparison, Table 8 shows how the inventory would look like when modelling according to a Depletion approach: in this last case, the only flows that are considered are the ones occurring during the process of extracting copper from the lithosphere and the avoided copper extracted from the lithosphere thanks to the amount of copper actually recycled at end-of-life.

Table 8. Life cycle inventory for the average copper market according to a depletion modelling.

Depletion approach		Inventory
life cycle stage	Recovery rate	**Copper, raw**
	[%]	[kg]
Raw materials input	0	1
Smelting and refining	0	0
Semi-finished good	0	0
Fabrication end-use product	0	0
Application	0	0
End-of-life	41.4%	-0.414

LCIs in *Table 7* and *Table 8* where characterized using the current recommendation in an Environmental Footprint (EF) context (Table 1. Current recommendations for resource use in EF pilots (Sala *et al 2017).*).

When the inventories in *Table 7* and *Table 8* are characterized, they show large differences. Indeed in the first case, inventory flows related to dissipative losses are characterized, while in the second case the elementary flows related to copper either extracted from nature (production) or avoided to be extracted from nature (credit at end-of-life) are characterized.

Results are shown in Figure 13 and Figure 14, using the characterization factors of the current EF recommendation ($ADP_{ultimate}$).

Figure 13. Characterized results for the average copper market, using the dissipation model.

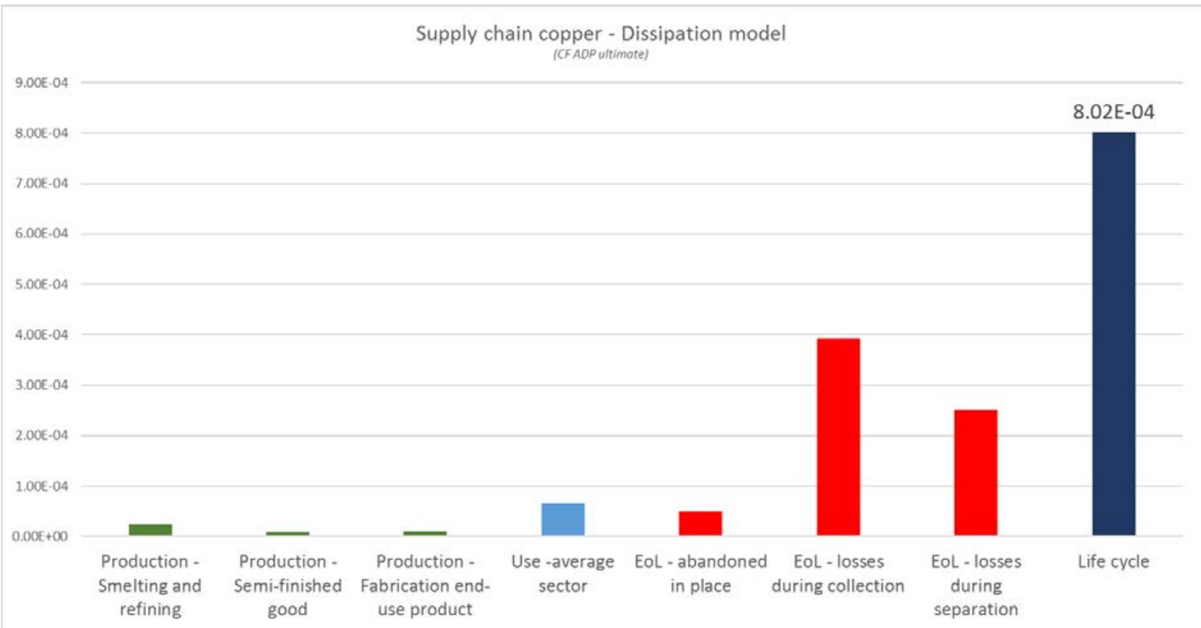


Figure 14. Characterized results for the average copper market, using the depletion modelling.

When comparing the results in Figure 13 and Figure 14 key points are:

1. The overall results, over the complete life cycle, using the two methodologies to construct the LCIs and using the same set of CFs, are the same.
2. The dissipation model has a higher resolution compared to the depletion modelling. The latter shows impacts (positive or negative) only at the first and the last life cycle stage, while the dissipation model can in principal identify shares of impacts for each life cycle stage or process (depending on data availability).
3. The interpretation of results allows for more accurate and detailed conclusions using the dissipation model: in the example that highest inefficiencies, and therefore the highest impacts in terms of loss of resources, are related to end-of-life operations during collection and separation. The use phase has also some shares of burdens, while the processes at the beginning of the life cycle are actually the ones that are affected by the lowest impacts. On the contrary, the depletion modelling attributes all impacts to the first life cycle stage and all benefits to the end-of-life stage: these results suggest that the first process is the one where the biggest improvement can be made, which however does not correspond to reality, because it is the end-of-life stage where most losses occurs.
4. In the depletion modelling, in contrast to the dissipation modelling, the use stage carries no burdens (and no benefits either).
5. The dissipation model, in contrast to the depletion model, does not display negative impacts (<0) for any life cycle stage.

3.2.2 Modelling copper in a specific application

Following the example presented in the previous section, the life cycle inventories of copper used in plumbing applications are shown in Table 9 (dissipation model) and Table 10 (depletion inventory). The end-of-life values still refer to the average copper sector, while depending on data availability they should be application-specific.

Table 9. Life Cycle Inventory for copper in plumbing applications using the "dissipation model".

Dissipation approach		LCI		
life cycle stage	**Dissipation rate**	**Copper, in technosphere**	**Copper, dissipated**	**Copper, raw**
		[kg]	[kg]	[kg]
Raw materials input		0	0	1
Smelting and refining	1.7%	0.983	0.0175	0
Semi-finished good	0.6%	0.977	0.0058	0
Fabrication end-use product	0.8%	0.969	0.0078	0
Application specific (Plumbing)	1.7%	0.953	0.016	0
End-of-life				
abandoned in place	3.9%	0.916	0.037	0
losses during collection	32.4%	0.619	0.297	0
losses during separation	30.7%	0.429	0.190	0

Table 10. Life cycle inventory for copper in plumbing applications according to a *depletion model.*

life cycle stage	Recovery rate	Copper, raw
	[%]	[kg]
Production	0.0%	1
End-of-life	42.9%	-0.429

3.2.3 Modelling silver and aluminium in photovoltaic panels

The previous example on the copper supply chain was not focusing on a specific product and it was dealing with one single resource flow. To improve the understanding of how the dissipation model works when more than one resource is modelled, we now consider the case of silver and aluminium in photovoltaic panels. The inventory flows were taken from the PEF screening study of the PEF pilot on photovoltaic electricity generation for the production of micro-Si photovoltaic panels in China (Technical Secretariat of the PEFCR pilot on photovoltaic electricity generation, 2015).

We focus on silver and aluminium for two reasons:

1) Silver has a high CF in the default characterization model used, while its relevance in terms of mass is very low. On the opposite, aluminium is highly relevant in terms of mass, while its CF is low. While for the copper example the inventory flows had a one to one correspondence with the characterized results, because only one resource was considered, in this case potential impacts over the life cycles cannot be gathered directly by looking at the inventory alone.
2) When looking at the recycling rate of the mass of two metals summed up together, it can be quantified in about 95%. Intuitively this is a satisfying result. However, the Silver Scrap Report (2015) warns that the volume of contained silver per cell is generally too small and also difficult to separate from the rest of the cell to make the recovery of the metal economically viable (because the focus now is on recovering aluminum from spent PV cells). As a result, unless government subsidies emerge to fund silver recycling, it appears unlikely that silver contained in end-of-life PV cells will find its way back into the supply chain.

This means that the use of silver in PV cells is currently a dissipative use, and it will be treated as such in this example. The life cycle inventories using the dissipation model and the depletion model are available in Table 11 and Table 12.

The LCIA results, using the current EF recommended model, are available in Figure 15 and Figure 16.

Table 11. Life cycle inventory of aluminium and silver in micro-Si photovoltaic panels according to the dissipation model.

	Dissipation rates		**Life Cycle Inventory**			
life cycle stage	Silver	Aluminium	Silver, raw	**Silver, dissipated**	Aluminium, raw	**Aluminium, dissipated**
	[%]	[%]	[kg]		[kg]	**[kg]**
Production	0.0%	0.0%	1.64E-04	**0**	2.67	**0**
Use	100.0%	0	0	**1.64E-04**	0	**0**
Recycling	0.0%	5%	0	**0**	0	**0.1335**

Table 12. Life cycle inventory of aluminium and silver in micro-Si photovoltaic panels according to a depletion model.

	Recovery rates		**Life Cycle Inventory**	
life cycle stage	Silver	Aluminium	**Silver**	**Aluminium**
	[%]	[%]	**[kg]**	**[kg]**
Production	0.0%	0.0%	**1.64E-04**	**2.67**
Use	0.0%	0.0%	**0**	**0**
Recycling	0.0%	95%	**0**	**-2.5365**

Figure 15. Characterized results for the photovoltaic panel, using the dissipation model.

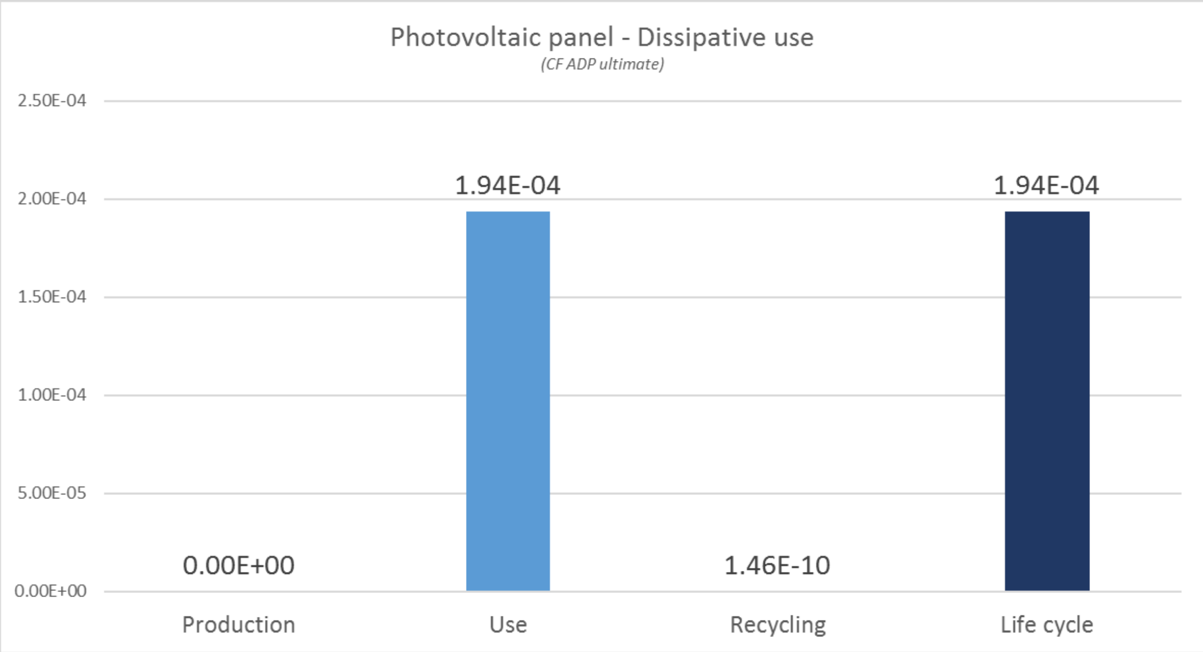
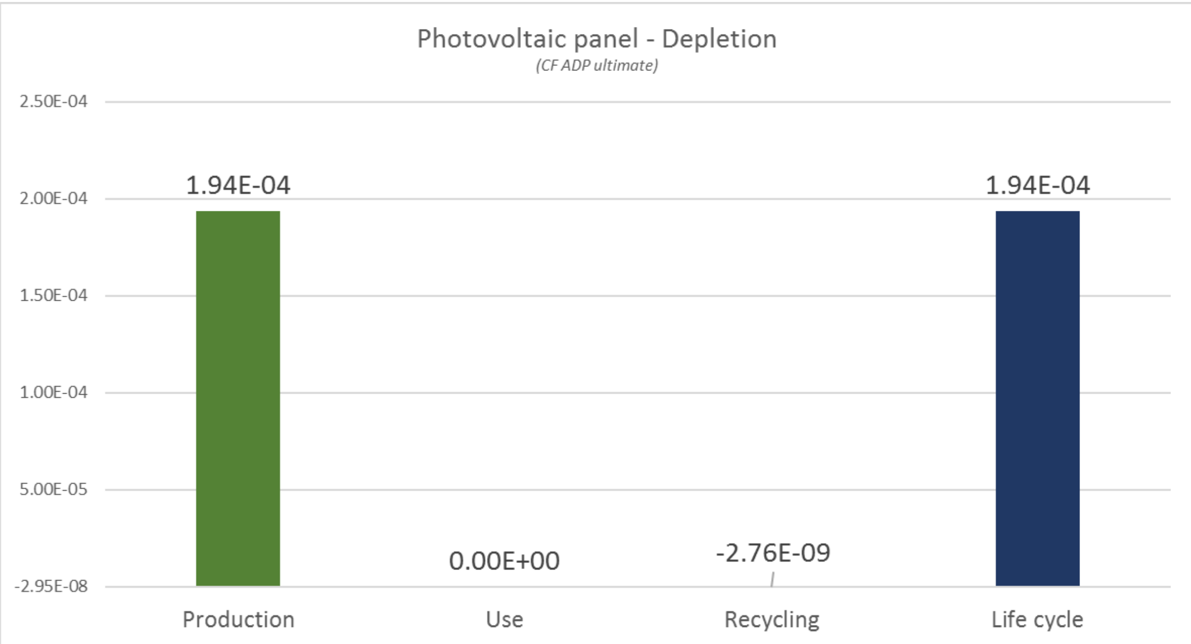


Figure 16. Characterized results for the photovoltaic panel, using the depletion model.



When comparing the results in Figure 15 and Figure 16 some key observations can be made:

1. The overall results, over the complete life cycle, using the two methodologies to construct the two LCIs and same characterization model, are the same.
2. The depletion model attributes all impacts to the production stage (meaning extraction of silver from nature) and some credits to the recycling stage (due to recycling 95% of aluminium).
3. The dissipation model identifies the use phase as the one responsible for causing the greatest impacts: indeed, when silver is used in the specific application it is

actually made unavailable. Thus, it is correct to identify the Use stage as a burden, instead of the production stage, where silver availability is still independent from the downstream application.

4. The dissipation model attributes no credits, while the depletion model always associates credits with recycling. Instead, the dissipation model attributes a small share of burdens during recycling due to the (small) amount of aluminium that is dissipated during the recycling operations.

4 Conclusions

In this feasibility study, a possible way forward to implement the assessment of dissipative use of resources within LCA is explored. This approach has the potential of providing a more accurate assessment of resource use in LCA and, by focusing on where dissipation of resources takes place, it helps identifying the life cycle stages and processes where resources are turned from being available for human uses to be unavailable.

The report focus is on how to structure the Life Cycle Inventory, while the Life Cycle Impact Assessment is not discussed. A general framework to structure the LCI and five different alternatives are presented and discussed: a compromise between accuracy and operability in LCA practice is recommended.

Simplified case studies were performed: results using an approach based on dissipation were compared to results based on a depletion approach. The key points are:

1. The overall results, over the complete life cycle, using the two methodologies to construct the LCIs and using the same set of CFs, are the same.
2. The dissipation model has a higher resolution compared to the depletion modelling. The latter shows impacts (positive or negative) only at the first and the last life cycle stage, while the dissipation model identifies shares of impacts for each process.
3. The interpretation of results allows for more accurate and detailed conclusions using the dissipation model.
4. In the depletion modelling, in contrast to the dissipation modelling, the use stage carries no burdens (and no benefits either).
5. The dissipation model, in contrast to the depletion model, does not display negative impacts (<0) for any life cycle stage.

Further work is needed beyond this feasibility study, to make a dissipation approach more operational in an LCA context. The main limitations for now is the availability of data, which could be addressed with a broad involvement of stakeholders.

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List of abbreviations and definitions

AADP	Anthropogenic stock extended Abiotic Depletion Potential
ADP	Abiotic Depletion Potential
AoP	Area of Protection
AU	Arbitrary Units
EF	Environmental Footprint
ILCD	International Reference Life Cycle Data System
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MFA	Material Flow Analysis
OEF	Organisation Environmental Footprint
OEFSR	Organisation Environmental Footprint Sector Rule
PEF	Product Environmental Footprint
TS	Technical Secretariat

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