
PE INTERNATIONAL

Harmonization of LCA Methodologies for Metals

A whitepaper providing guidance for conducting LCAs for metals and metal products

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International Lead Management Center Site
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International Manganese Institute
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EXECUTIVE SUMMARY

The mining and metals industry adopted life cycle based tools and concepts over a decade ago. However, the market and regulatory demands for life cycle data from this sector are increasing as is sector activity in this field, particularly with regards to the development of life cycle inventory data.

Currently, various methodological approaches are used within the metals and mining industry for the life cycle inventory (LCI) and life cycle assessment (LCA) of metals and metal products. In January 2012, an initiative was launched to review the current practices and experience, and to develop new guidance on how to adopt a more harmonized approach to LCI and LCA methodologies within the metals and minerals industry.

This harmonization initiative was spearheaded by the International Copper Association (ICA) and brings together representatives of ten (10) metal commodities¹, as well as the International Council on Mining and Metals (ICMM), Eurometaux and Euromines. The participating organizations, supported by PE INTERNATIONAL, have created a new multi-metal guidance document, and have collated a set of recommendations for how to align these LCI and LCA methodologies.

The importance of having a consistent approach across the metals and minerals industry is also being driven by an increase in the life cycle based efforts of governments and regulators, the end-use market sectors, civil society, multi-lateral organizations (e.g. United Nations International Resource Panel, European Commission), and material suppliers. While the specific efforts of these groups vary, their objectives rely on having accurate and consistent information on the environmental impacts of their materials and products.

The main intent of this new guidance is to create a ‘common voice’ for the metals industry on life cycle methodologies when engaging with various stakeholders. This new guidance is intended for use by associations and companies within the metals and minerals industry to support engagement and communication with:

- Regulators;
- Life cycle database providers;
- LCA practitioners; and,
- Industry groups related to metals and minerals sector.

It is envisaged that this new guidance will inform the development of new or updated LCIs and LCAs. The approach and resulting recommendations of this effort answered the following key questions regarding life cycle activities within the metals and minerals industry.

¹ Associations participating in this initiative (listed by commodity they are representing) include: Copper (ICA, ECI), Nickel (NI), Zinc (IZA and ILZRO), Aluminum (AA and IAI), Steel (World Steel Association), Stainless Steel (ISSF), Molybdenum (IMOA), Cobalt (CDI), Lead (ILA and ILZRO, ILMC), Manganese (IMnI)

1. Which metals or minerals associations have done a life cycle assessment and, if so, are the methodologies aligned?

This harmonization effort began with a comparison of existing methodologies used by participating associations. Of the ten commodities represented in this effort, eight have already conducted LCAs while the other two commodities have either recently initiated these efforts or are currently planning their first such effort. The creation of a matrix of existing methodologies used by associations highlighted several areas of alignment in existing methodologies as well as areas which were either less aligned or could benefit from discussions and alignment across the associations.

2. What common issues or challenges are being faced by the metals and minerals industry with respect to conducting LCIs and LCAs?

Results of the comparison of existing efforts along with discussions regarding industry-wide challenges and opportunities for collaboration resulted in the focus of this effort being on the following topics: treatment of co-products; scoping; end-of-life recycling; and life cycle impact assessment (LCIA).

3. How can the metals and mining industry work to align their methodological approach to conducting LCIs and LCAs?

- *System boundaries should be set to include end-of-life disposal and recycling and, whenever possible, the product use phase;*
- *Co-product allocation methods should consider the type and properties of co-products being produced;*
- *Recycling allocation should use the end-of-life recycling approach, which accounts for the recyclability of the material; and,*
- *The life cycle impact assessment stage should report the well-established and scientifically-defensible impact categories, with the understanding that inclusion of other impact categories will be periodically reevaluated by the metals industry, or may be mandatory based on certain standards.*

Next Steps

The participating organizations in this effort have contributed a significant amount of time and effort to develop the guidance set out in this document. However, through the many discussions held by the group, a number of topics and potential activities were raised which the group was not able to address within the scope of this document. These potential next steps include, but are not limited to, the following:

- Creation of supplementary guidance documents which address metal-specific examples or best practices (e.g. examples of co-product allocation for a particular metal or group of metals); and,
- Creation of supplementary guidance documents on related key topics and identified areas of concern (e.g. communication of life cycle data and LCA results).

1 PURPOSE AND SCOPE

As an industry, metals constitute a major category of non-renewable resources extracted from the environment. Metals can be found in a vast range of product and economic sectors, ranging from buildings and infrastructure to automobiles and electronics. To foster the sustainable development of metal-containing products, the metals industry has embraced the use of life cycle assessment (LCA) to evaluate and communicate the environmental impacts of its products.

The purpose of this document is to provide guidance on a harmonized approach to life cycle inventory and assessment methodologies for the metals and minerals industry. The document offers guidance to align methodologies where appropriate, recognizing that complete alignment of all aspects of the methodologies is not feasible due to the broad range of metal- or mineral-specific issues which may require approaches unique to the given material and/or its downstream uses.

This document has been created through the cooperation of numerous commodity associations² with the intention that the guidance offered can be used by other metals and minerals commodity associations as well as life cycle practitioners within the industry. This document attempts to address the following concerns identified by the participating organizations:

- Strengthen the ability to have a ‘common voice’ on life cycle methodologies when engaging with regulators, life cycle database providers, and other external stakeholders; and,
- Agree on life cycle methodologies so that the industry can better align its practices.

This harmonization effort began with a comparison of existing methodologies used by participating associations, and discussions regarding industry-wide challenges and opportunities for collaboration and alignment of activities across the industry. The creation of a matrix of existing methodologies used by associations highlighted several areas of alignment in existing methodologies as well as areas which were either less aligned or could benefit from discussions and alignment across the associations. The topic areas identified for further discussion included: treatment of co-products; scoping; End-of-Life recycling; and life cycle impact assessment (LCIA). Through a series of teleconferences in 2012 and 2013 as well as a two-day face-to-face meeting in June 2012, the participating organizations shared experiences and insights on each of these topics resulting in the guidance provided in this document.

The participating associations acknowledge additional efforts to create common approaches to assessing the environmental impacts of materials, particularly the European Commission’s work on Product and Organizational Environmental Footprints. The Commission was asked by the European Council to develop a harmonized methodology characterized by the guiding principle of “comparability shall be given priority over flexibility”. This initiative follows a multi-criteria, life cycle based methodology, building upon the International Reference Life Cycle Data System (ILCD) Handbook as well as other relevant methodological standards and guidance documents (e.g., ISO 14040/44 and the GHG Protocol series). It is important to mention that a consortium of non-ferrous associations, single

² See Appendix for a list of participants and their contact information

companies, and ferrous companies are conducting a pilot project with the European Commission which has established a technical steering committee to develop and test product category rules and the content process. While this pilot project involves several of the associations participating in the creation of this harmonization document, it should be noted that these initiatives are not directly related. However, the Commission's efforts are being taken into consideration and monitored to assess the potential for considering footprinting methodologies developed in future versions of this report. There is also potential for the group of associations that participated in this harmonization effort to act as a stakeholder group for the metal technical steering committee within the Commissions pilot testing phase.

2 SYSTEM BOUNDARIES

Life cycle assessment requires establishing the system boundary of the study and is a key part of the LCA scoping phase. The system boundary is defined as the “set of criteria specifying which unit processes are part of a product system”³, where a unit process is the “smallest element considered in the life cycle inventory analysis for which input and output data are quantified.”⁴ System boundaries should be drawn to effectively support the goal of the study, ensuring that the results comprehensively characterize the life cycle of the product. This is particularly important for comparative assertions, where proper system boundary and functional unit definitions enable fair comparisons between alternatives.

This section describes system boundaries and their relevance for the metals industry. As with other steps of the LCA process, the development and application of system boundaries for metals differs amongst practitioners due to vague best practices and a general lack of an industry-wide and consensus-based procedure. This document will provide a background on system boundaries per the ISO standards, their importance and application in comparative assertions, information about the selection of environmental indicators, and guidance on system boundaries in LCI databases.

This document includes elements that are related to, but technically do not fall under the umbrella of system boundaries as defined in the ISO standards. Additional topics include the selection of environmental indicators and categories, and the importance of the functional unit in comparative assertions. These additional elements are part of the LCA scoping phase (along with system boundaries) and have similar influence regarding comprehensive and fair assessments.

2.1 Defining the System Boundary for Metals

The choice of the system boundary is a key methodological decision for any LCA. The inclusion or exclusion of individual processes and life cycle stages can have a large effect on the LCA results; in particular, the system boundary definition becomes imperative when comparing between alternatives for decision support. Both comparability and completeness are pivotal characteristics in this regard.

The following subsections provide an overview of current practice with regards to system boundary selection. Included is a description of the life cycle stages and individual unit processes, as well as recommendations on determining the system boundary for LCAs involving metals.

2.1.1 Life cycle stages

A product (or service) life cycle is typically broken into stages that are used to describe where environmental impacts occur. The stages of a product life cycle, for example, might include raw

³ ISO 14044, §3.32

⁴ ISO 14044, §3.34

materials extraction, production, use, and recycling/disposal. Combinations of the terms *cradle*, *gate*, and *grave* are often used to loosely define the system boundary of a given study. A *cradle-to-gate* study, for example, considers the life cycle from the raw materials' extraction (the "cradle") to the point of shipment of the final product (the "gate"), which may or may not include packaging. Similarly, *gate-to-gate* considers only the impacts from the facility itself, whereas *cradle-to-grave* includes the entire life cycle, from raw materials extraction to disposal and/or recycling. Figure 1 illustrates the product life cycle for a generic product.

The selection of life cycle stages for LCAs involving metals is of key importance. Although a metal may have relatively high potential impacts during production, the use phase and the recycling of the metal at end-of-life can help offset production impacts relative to competing non-metal products. Essentially, a cradle-to-gate study does not capture many of the benefits from using metals and usually a poor system boundary choice for an LCA involving metals. A cradle-to-grave study uses a more comprehensive system boundary and provides a more accurate reflection of the actual environmental impacts. In fact, per ISO definition, an LCA is always cradle-to-grave: "LCA addresses the environmental aspects and potential environmental impacts ... throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave)" (ISO 14040/44). Although omission of life cycle stages is tolerated in certain applications (e.g., some EPDs), it should be applied with caution and "only permitted if it does not significantly change the overall conclusions of the study" (ISO 14044).

Nonetheless, cradle-to-gate does have its place. Many of the metals associations involved with this white paper have produced cradle-to-gate studies of their metals in order provide the LCA community the necessary data for external, cradle-to-grave studies performed by other practitioners. Moreover, in some cases, it is understood that the use phase is uncertain; for instance, a metals fabricator may produce an intermediate product, such as a metal sheet, but not have influence on the exact application of that sheet in a larger product. In these circumstances, cradle-to-gate studies still provide important details about the environmental impact, but should be used with caution and should not be compared unless functional equivalency has been established.

Box 1: System Boundaries in ISO 14040 and 14044

Description of the System Boundary (ISO 14040, §5.2.3)

An LCA is conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the product system should be modeled in such a manner that inputs and outputs at its boundary are elementary flows. However, it is not necessary to expend resources on the quantification of inputs and outputs that will not significantly change the overall conclusions of the study.

The choice of elements of the physical system to be modeled depends on: the goal and scope definition of the study; its intended application and audience; the assumptions made; data and cost constraints; and cut-off criteria. The models used within the LCA should be described and the assumptions underlying those choices should be identified. The cut-off criteria used within a study should also be clearly stated.

The criteria used in setting the system boundary are important for the degree of confidence in the results of a study and the possibility of reaching its goal.

System boundary procedure (ISO 14044, §4.2.3.3.2 and §4.2.3.3.2)

In accordance with section 4.2.3.3.1 of ISO 14044 “the selection of the system boundary shall be consistent with the goal of the study.” The criteria used in establishing the system boundary shall be identified and explained. “The deletion of life cycle stages, processes, inputs or outputs [from the scope of the study] is only permitted if it does not significantly change the overall conclusions of the study.”

During the scope definition, stakeholders should determine all unit processes throughout the product’s value chain. The following procedures are recommended:

A process flow diagram should be used to outline the unit processes and their inter-relationships. Each unit process should include the following definition from ISO 14044 §4.2.3.3.2:

- where the unit process begins, in terms of the receipt of raw materials or intermediate products
- the nature of the transformations and operations that occur as part of the unit process
- where the unit process ends, in terms of the destination of the intermediate or final products.

Identify what material inputs, energy inputs, and emission outputs will be studied based on identification of the inputs for each unit process identified. Define which inputs and outputs are traced to other product systems. Data should be collected using specific sites or published sources to quantify the identified inputs and outputs.

The system should be described in sufficient detail and clarity to allow another practitioner to duplicate the inventory analysis (ISO 14044 §4.2.3.3.3).

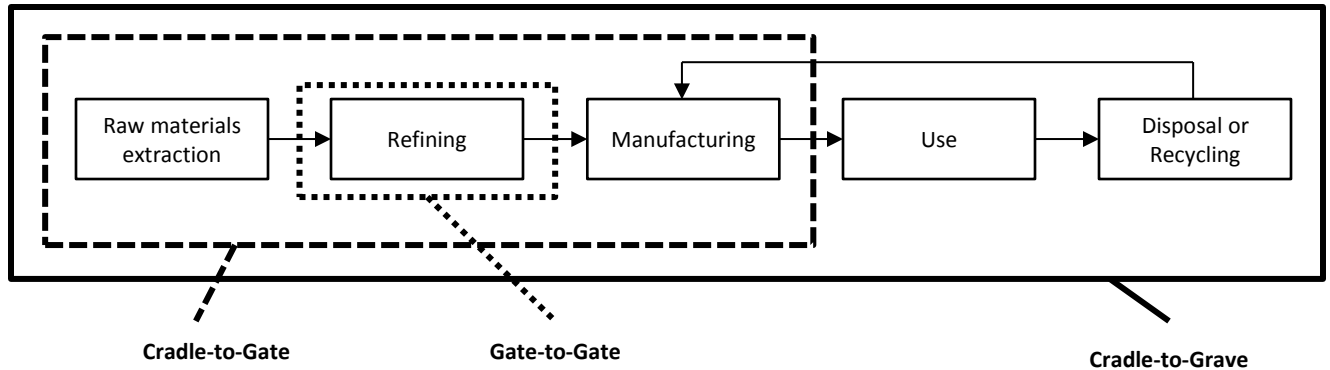


Figure 1. Life cycle phases for a generic product, illustrating *cradle-to-gate*, *gate-to-gate*, and *cradle-to-grave* system boundaries.

2.1.2 Information modules in EN15804

It may be advantageous to describe the system with more detail than the cradle-to-grave scheme in Figure 1. One example of a more granular approach is described in EN 15804⁵. This European standard is specifically designed to harmonize the creation of environmental product declarations (EPDs) in the building and construction sector, although the same principles can be applied to other LCA applications and economic sectors. EN 15804 breaks the product life cycle into a predefined set of information modules: A1-3 (product stage); A4-5 (construction process stage); B1-7 (use stage); C1-4 (end-of-life stage); and D (benefits and loads beyond the system boundaries). Figure 2 presents the life cycle modules defined by EN 15804. The modular breakdown of the life cycle (e.g., A1, B3) is part of the harmonized approach for EPD creation of building and construction products.

EPDs that comply with EN 15804 still may not include all modules, depending on the requirements set forth in the relevant product category rule (PCR). In these cases, EN 15804 suggests using a system boundary called “cradle-to-gate with options”; the options typically include impacts from end-of-life processes (e.g., landfilling) and credits received from recycling. Although this omits the use phase of the product, it accounts for end-of-life recycling, which is an important component of the metal life cycle.

⁵ EN 15804:2012, Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products. British Standards Institute (BSI)

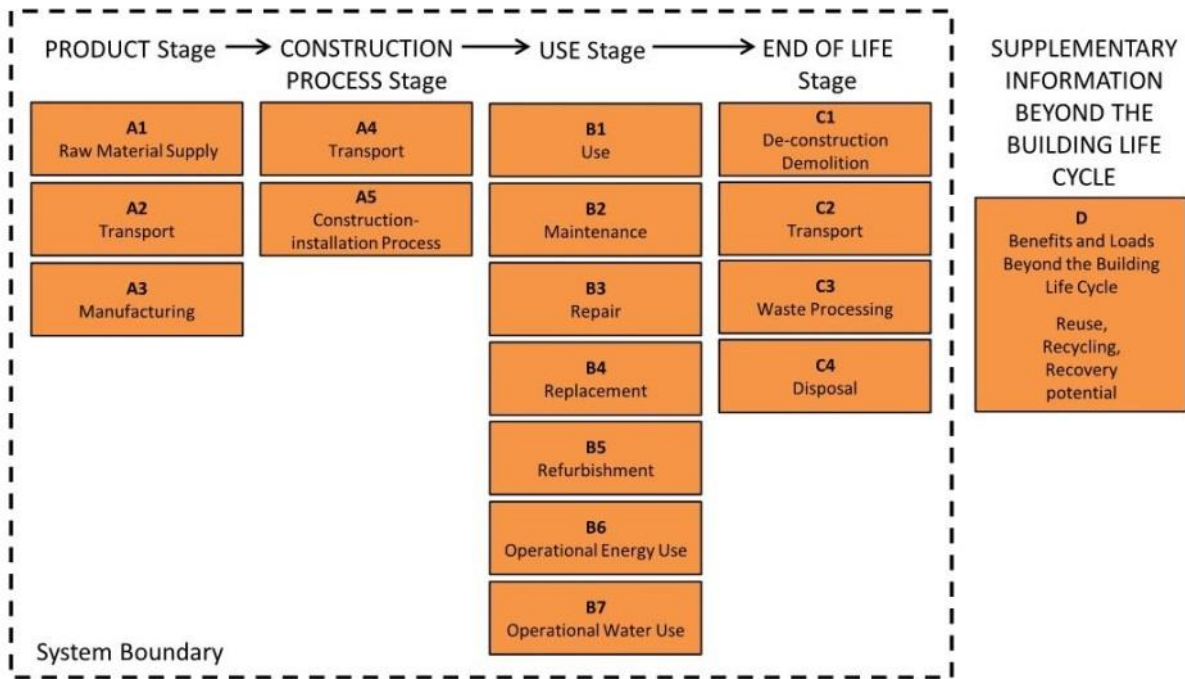


Figure 2. Life cycle stages per EN15804

2.1.3 Unit processes

The system boundaries need to establish the inclusion and exclusion of certain unit processes from the life cycle. In general, LCAs should include as much information as available in order to meet the goal of the study. For non-comparative studies, the goal is often to develop the most complete representation of the product life cycle. In practice, however, it is often necessary to exclude information, usually based on lack of data or budget. Good practice stipulates—and ISO 14044 mandates—that any exclusion should be disclosed in LCA documentation so that the audience knows which processes are excluded, as well as the governing rationale for excluding those processes. For comparative studies, identical processes may be excluded, as they do not contribute to the goal of the study (i.e., to compare the environmental impacts of alternative products).

The rationale for excluding unit processes is often defined through cut-off rules, which guide and set thresholds for omitting due to lack of relevance on the overall results. ISO 14044 helps to define this rationale (see Box 1), but does not provide guidance on actual thresholds. In practice, data gaps can often be addressed using proxy data, thus negating the need to set and use cutoff thresholds; this approach is recommended in favor of using cutoff thresholds.

Table 1 shows an example of inclusions and exclusions for a generic product. LCA of metals and metal products should follow the same approach. Using a cradle-to-gate system boundary that includes end-of-life recycling and disposal, the system boundary focuses on capturing all materials, processes, and energy flows needed to manufacture the product. Notable exclusions include the construction of capital equipment in the facility and the maintenance and support of that equipment.

Table 1. Typical inclusions and exclusions in the product life cycle (cradle-to-gate with end-of-life recycling and disposal)

Within the system boundaries	Outside the system boundaries
<ul style="list-style-type: none"> ✓ Raw materials production ✓ Auxiliaries and intermediates ✓ Manufacturing processes ✓ Electricity generation ✓ Fuel production & combustion ✓ Packaging materials ✓ Post-production recycling and waste disposal ✓ End-of-life recycling and waste disposal ✓ Transportation of materials, auxiliaries, intermediates, and waste 	<ul style="list-style-type: none"> ✗ Construction of capital equipment ✗ Maintenance and operation of support equipment ✗ Packaging materials not associated with the main product ✗ Human labor and employee commute

Box 2: Cutoff Rules in ISO 14044

Any flows that are “cut-off” from the system must be clearly described and the impact of these exclusions should be addressed in the final report. Cut-off criteria can be based on criteria of mass, energy or environmental significance. Mass contribution alone may help make initial cut-off decisions, but could lead to environmentally significant impacts being excluded from the study. Therefore, environmental relevance should always be tested with results documented in the final report.

In accordance with ISO 14044 §4.2.3.3.3 the following cut-off approaches may be used:

- a) **Mass:** an appropriate decision, when using mass as a criterion, would require the inclusion in the study of all inputs that cumulatively contribute more than a defined percentage to the mass input of the product system being modeled.
- b) **Energy:** similarly, an appropriate decision, when using energy as a criterion, would require the inclusion in the study of those inputs that cumulatively contribute more than a defined percentage of the product system’s energy inputs.
- c) **Environmental significance:** decisions on cut-off criteria should be made to include inputs that contribute more than an additional defined amount of the estimated quantity of individual data of the product system that are specially selected because of environmental relevance.

After the modeling is complete, the exclusions should be tested using sensitivity and scenario analysis to ensure the initial system boundary and cut-off criteria still meet the requirements of the study goal. This will ensure all inputs that cumulatively contribute more than a defined amount of the total burden are included in the study. In accordance with ISO 14044 4.2.3.3.2: Where the study is intended to be used in comparative assertions to be disclosed to the public, the final sensitivity analysis of the inputs and outputs data shall include the mass, energy and environmental significance criteria so that all inputs that cumulatively contribute more than a defined amount (e.g., percentage) to the total are included in the study.

2.2 Comparative Assertions and the Functional Unit

Life cycle assessment is routinely used as a method to compare the environmental impacts of two or more alternatives. When done correctly, comparative assertions support “environmental claim[s] regarding the superiority or equivalence of one product versus a competing product that performs the same function.”⁶ While comparative assertions are an important application of LCA, care must be taken in order to ensure that comparisons are fairly scoped and use comparable boundaries.

The following are two important considerations when developing comparative assertions:

- Functionally-equivalent systems; and,
- Characterization of impacts from all relevant life cycle stages.

The second consideration when developing comparative assertions, characterization of impacts from all relevant life cycle stages, is discussed within Section 2.1. The first consideration, functionally-equivalent systems, is of equal (and related) importance to ensure comparability, but is often difficult to define for a metal product. ISO defines the functional unit as the “quantified performance of a product system for use as a reference unit.”⁷; Cooper (2003) expands on this definition, calling for the functional unit to include the magnitude of service, the duration of service, and the expected level of quality.⁸

Metals are typically used as input materials in downstream products, with their mass, geometry, and other specifications dependent upon their function within a specific product. Ultimately, the amount of required material is based on that material’s ability to perform a given function. For instance, a kilogram of metal may be able to provide the same function (e.g., structural support) as ten kilograms of plastic or wood. Similarly, one metal might perform at a higher per-mass rate than another metal; the only way to compare the two metals (or a metal and another material) is by scaling their inventories to identical functional units. The required mass of each material to provide that functional unit is then referred to as the ‘reference flow’ in LCA, defined as the measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit.”⁹

Unless the function of a product is properly represented by its mass (e.g., balancing weight in car wheels, counter weights in elevators or cranes), it is an inappropriate unit of comparison. In many applications, mass does not capture the relevant performance characteristics of that metal within the applied product or system. In Environmental Product Declarations (EPD), mass may be used as a ‘declared unit’ if “the precise function of the product or scenarios [...] is not stated or is unknown.”¹⁰

⁶ ISO 14044, §3.6

⁷ ISO 14044, §3.20

⁸ Cooper, JS. 2003. Specifying functional units and reference flows for comparable alternatives. *International Journal of Life Cycle Assessment*. 8(6): 337-349.

⁹ ISO 14044, §3.29

¹⁰ EN 15804, §6.3.2

However, declared units are not directly comparable to one another due to the lack of information regarding the function, and the proper scaling has to be performed by the user of the EPD information. Whenever metals are compared to one another or to other materials, it is imperative that identical functional units are used.

Similar to the in-depth deliberation of the functional unit, the system boundaries need to be consistently and comprehensively considered for all alternatives. The embodied impact of metal materials only considers cradle-to-gate system boundaries, thus ignoring the potential advantages (and disadvantages) of using one material over another. Impacts that occur outside of those boundaries (i.e., in a cradle-to-grave perspective) are also relevant for comparative assertions. In particular, the use and end-of-life stages for compared alternatives can widely vary. Impacts on energy performance and material recyclability, for instance, can be significant or dominant contributors to the overall life cycle impact. Omitting one or more of these stages can lead to unfair comparisons that do not accurately capture the life cycle impacts of the product.

Box 3: Example – Comparing Different Service Lives

The life cycle impacts of a product often depend on how long it is able to perform its intended function. Table 2 presents mass and GWP information for two products (A and B), each with a declared unit of a one meter tube with a 25 mm diameter. (The function of the tube is not stated, but is assumed to be equivalent between the two products. A functional unit for this comparison might be related to the volume of liquid transported under a given pressure and time.) For the same declared unit, Product A has a lower mass (0.30 kg versus 0.51 kg) and GWP per unit mass (0.76 kg CO₂-eq versus 0.98 kg CO₂-eq) than Product B.

At first glance, the comparison may appear clearly in favor of Product A. However, when considering the expected service lives of the products, the choice becomes less clear: Product B is in service for 25 years, while Product A needs to be replaced after 10 years. Note that end-of-life considerations are included in the impact factors.

The solution depends on the choice in analysis period. A cursory analysis of the two products is shown in Table 3, with a life cycle diagram shown in Figure 3. Over an analysis period of 50 years, Product B outperforms Product A due to their different service lives. The crossover point occurs at Year 40, where Product B is using only its second installment, but Product A requires a fifth installment.

This simple service life example illustrates the importance of the use phase of the life cycle. Similar anecdotes can be derived for instances where the performance (rather than the service life) differs between products. The key takeaway is that initial product impacts are not necessarily indicative of life cycle impacts.

Table 2. Characteristics of two tube products

	Product A	Product B
Declared unit	One meter length of tube with 25 mm diameter	One meter length of tube with 25 mm diameter
Mass	0.30 kg	0.51 kg
GWP per unit mass	0.76 kg CO ₂ -eq/kg	0.98 kg CO ₂ -eq/kg
Service life	10 years	25 years

Table 3. Global warming potential of two tube products

	Product A	Product B
GWP per product	0.23 kg CO ₂ -eq	0.50 kg CO ₂ -eq
Analysis period	50 years	50 years
Reference flow	1.50 kg (5 products)	1.00 kg (2 products)
GWP over analysis period	1.15 kg CO ₂ -eq/kg	1.00 kg CO ₂ -eq/kg

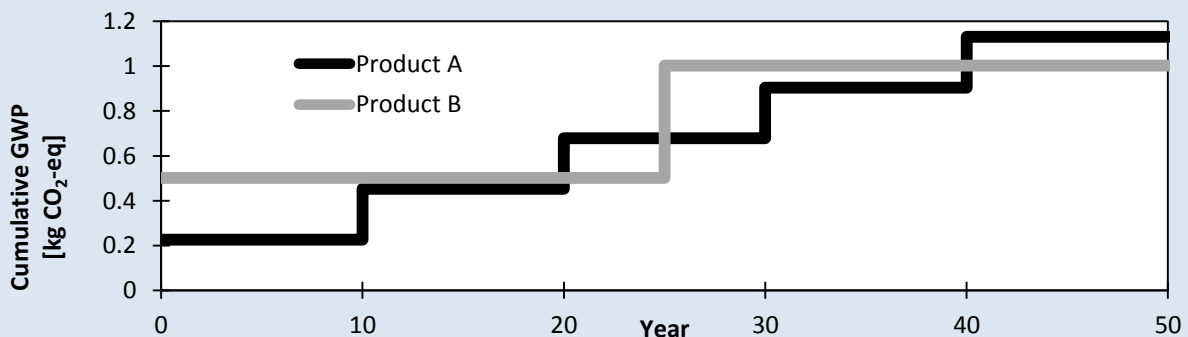


Figure 3. Comparison of tube products with different materials and service lives

3 CO-PRODUCTS

Life Cycle Inventory (LCI) assessment relies on the ability to link unit processes within a product system by single material or energy flows. Many industrial processes yield multiple products particularly if the generation of valuable scraps and other production residues is considered. The product outputs from these systems are called ‘co-products’, defined as “any of two or more products coming from the same unit process or product system.”¹¹ Co-products are distinguished from waste by their economic value; products and co-products are sellable, whereas waste has no economic value.¹² In co-product systems, the material and energy flows associated with these multi-output processes need to be assigned to the different co-products according to clearly stated procedures.

The following sub-sections discuss the treatment of multi-output processes for metal products. Basic background information is presented in order to establish a fundamental understanding of the co-product issue in life cycle assessment (LCA). Recommendations are then made as to preferred treatment of co-products in metal and metal product LCAs.

3.1 Co-Product Modeling in Life Cycle Assessment

The environmental impacts in a multi-output process are distributed between the co-products in one of three ways: (1) dividing the process into sub-processes that are specific to individual outputs (i.e., subdivision); (2) subtracting the inventories of functionally-equivalent products produced by mono-functional processes (i.e., system expansion by substitution); or, (3) allocating the process inventory amongst all co-outputs using a shared relationship, such as mass or economic value. Box 4 contains the guidance from ISO 14044 related to treatment of co-products in LCA studies.

3.1.1 Subdivision

When possible, the product system should be subdivided into the sub-processes that are specific to each co-product. This approach avoids allocation because the inputs and outputs are directly related to the manufacturing of the co-product and not shared with any other co-products. Subdivision may not be feasible for complex, multi-output processes, such as those found in many metal operations. In these circumstances, system expansion or co-product allocation should be considered per the guidance offered in Section 3.2.

3.1.2 System Expansion

System expansion considers alternative production routes for the co-products in a system. In practice, system expansion eliminates the co-products from the product system under study by subtracting the

¹¹ ISO 14044, §3.10

¹² The term “by-product” is sometimes also used to refer to supplementary outputs from multi-output systems. If the by-product is a sellable product, it is analogous to the term “co-product” (as used in this report) and would be subject to the same rules and guidance presented in this report.

inventory of a functionally-equivalent product produced by an alternative, mono-output process. Figure 4 illustrates system expansion using one main product and two co-products.

Because system expansion avoids the need for allocation, it is generally considered a preferred method of dealing with co-products in a system. However, for some co-products, no mono-output production routes are available, which makes it infeasible to apply this method as you cannot avoid allocation by using a process inventory that is based on allocation itself. Many metals are always produced in shared processes, so it is impossible to identify an alternative production route that is both independent of other metals and representative of industry production practices. In these cases, allocation must be used to distribute the impacts of the shared process.

Box 4: Co-Product Allocation in ISO 14044

The ISO standards provide a useful baseline for which to build an industry-specific set of best practices. The following sub-sections present the relevant information from ISO 14040 and ISO 14044 as they relate to co-product allocations.

General allocation procedure (§4.3.4.2)

The study shall identify the processes shared with other product systems and deal with them according to the stepwise procedure presented below:

Step 1 - Wherever possible, allocation should be avoided by:

- 1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes; or,
- 2) expanding the product system to include the additional functions related to the co products, taking into account the requirements of §4.2.3.3 ISO 14044.

Step 2 - Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

Step 3 - Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

Multifunctional Systems, Co-products and Recycling Systems (§4.3.4.1 and §4.3.4.3.4)

The sum of the allocated inputs and outputs of a unit process shall be equal to the inputs and outputs of the unit process before allocation. Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach. Consideration should be given to the need for allocation procedures when dealing with systems involving multiple products and recycling systems.

The allocation procedures for the shared unit processes mentioned should use as the basis for allocation, if feasible, the following order:

- a) physical properties (e.g., mass);
- b) economic value (e.g., market value of the scrap material or recycled material in relation to market value of primary material); or,
- c) the number of subsequent uses of the recycled material (see ISO/TR 14049).

It is relevant to note that system expansion is also used as a method for dealing with end-of-life recycling and reuse. LCA topics related to end-of-life scenarios for metals are discussed in Section 4.

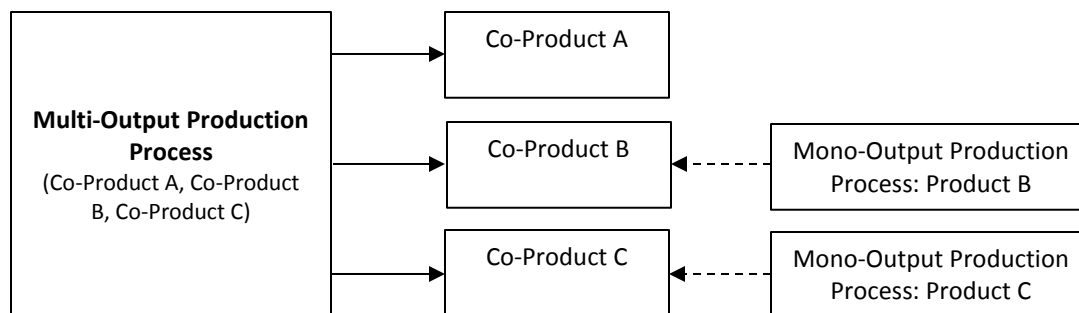


Figure 4. System expansion is applied in a generic system using two co-products. Solid arrows represent positive flows, while dashed arrows represent negative flows. The cradle-to-gate inventory of product A would be the cradle-to-gate inventory of the multi-output production process less the cradle-to-gate inventories from the mono-output production processes for co-products B and C.

3.1.3 Co-Product Allocation

Co-product allocation distributes the impacts of the multi-output process to the various outputs using a relationship between those products. ISO recommends that when allocation is necessary, it should be performed using the physical relationship between the co-products, such as mass or energy content. When physical relationships are unsuitable or unattainable for the purposes of allocation, other relationships (e.g., market value) can be used. For metals, mass and market value are the most common methods of allocation.¹³

Allocation is applied based on simple scaling of the multi-output process impacts by the chosen relationship. Box 5 shows an example of mass and market value allocation applied to the chlor-alkali electrolysis process. The inputs (electricity and salt) are allocated to the outputs (Cl_2 , NaOH , and H_2) using their relative contributions to the total mass or market value.

Due to the arbitrary selection process of the allocation relationship, it is encouraged to conduct a sensitivity analysis on alternative allocation methods. This will help communicate the range of values that can be expected based on the choice in allocation method.

The two primary approaches to co-product allocation in metals systems are described as follows.

Mass allocation

Allocation by mass is generally preferred when the economic value per unit of output between co-products is similar. This is due to the fact that mass remains relatively constant over time, while market value is subject to market fluctuations. As guidance, EN 15804 defines “small” as less than a 25%

¹³ Note that research is being performed to allocate metals impacts using energy-related metrics, such as enthalpy. Co-product allocation using alternative approaches can be considered as more information becomes available.

difference in value¹⁴. For metals, it is often appropriate to allocate on the basis of the mass of the metal content in the co-products (rather than the mass of the product as a whole) as the physical relationship between co-products. This allows the allocation to focus on the valuable products (the metals) and ignore the waste products (e.g., tailings).

Economic allocation

Revenue generation is the driving force behind industrial operations. Allocating based on the economic purpose of performing a given activity is known as economic (or market value) allocation. Using this approach, total impacts are allocated with respect to the economic value of the individual outputs. The market values of the outputs are averaged over a certain time period; longer periods are recommended in order to reduce the impact of random price spikes and drops. This harmonization document recommends that a 10-year average is used; other timespans can be used so long as the price data represents economically-current information that minimizes the effect of volatility. In metals systems where precious and base metals are mined as the same ore deposit, economic allocation is often the preferred allocation method. In these situations, mass allocation fails to adequately capture the main purpose of processing the ore and its downstream operations. Conversely, economic allocation captures the driver of this process (economic revenue) and uses that information to distribute the impacts.

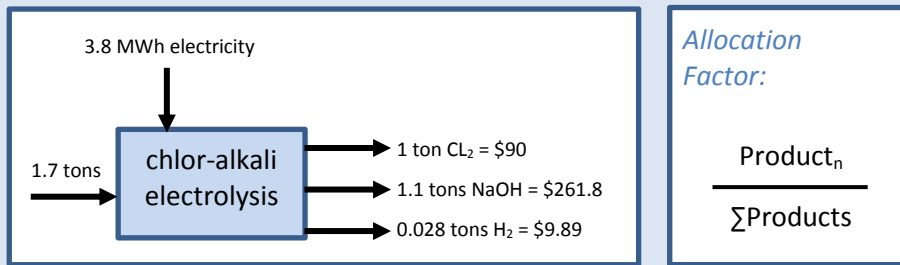
¹⁴ EN 15804:2012, Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products. British Standards Institute (BSI)

Box 5: Example – Co-Product Allocation

Co-product allocation is necessary for many different products, including both metals and non-metals. Figure 5 shows co-product allocation for a chlor-alkali electrolysis process—a non-metal application, but with a similar approach that can be applied to a metal.

The electrolysis process produces three outputs: sodium hydroxide, chlorine gas, and hydrogen gas. Impacts are distributed to the co-products either by the relative mass (mass allocation) or the market value (economic allocation). Given the wide price variation (the market value for the chlorine gas is nearly four times less than the hydrogen gas, and nearly three times less than the sodium hydroxide), the choice in allocation method is significant. Both allocation methods indicate that sodium hydroxide has the highest burden, but the magnitude of the difference varies significantly: using mass allocation, sodium hydroxide is only 10% higher than chlorine gas; using economic allocation, the sodium hydroxide is 190% higher than chlorine gas. Given the price differences and impact on the results, the practitioner should consider using economic allocation in the LCA and provide a sensitivity analysis for the alternative methods.

When the results from allocation are significant, it is good practice to conduct a sensitivity analysis to test the impact on the overall results. Regardless, the choice in allocation methodology should be transparent and defensible for any product.



Process Input	Total Process	Allocation Method	1 ton Cl ₂	1.1 tons NaOH	0.028 tons H ₂
Electricity	3800 kWh	Mass	1786	1965	50
		Economic	945	2750	105
Salt	1.7 tons	Mass	823	905	23
		Economic	435	1267	48

Figure 5. Co-product allocation as applied to the chlor-alkali electrolysis process. The inputs (electricity and salt) are allocated to the outputs (Cl₂, NaOH, and H₂) using their relative contributions to the total mass or market value.

3.2 Co-Products Methods in the Metals Systems

3.2.1 General recommendations for metals

Co-products are an important part of the metal production process. As illustrated in Figure 6, many metals are mined together and separated during the production process. Metal industries use various procedures to allocate environmental burdens of the various metal (and non-metal) co-products that are produced. The intent of this section is to establish consistency across metals industries through both mediation and scientific reasoning. However, it is understood that processes, data availability, and other relevant factors vary from industry to industry, as well as from facility to facility, thus making it difficult to draw sweeping, universal rules for dealing with co-products in metal and metal product LCAs.

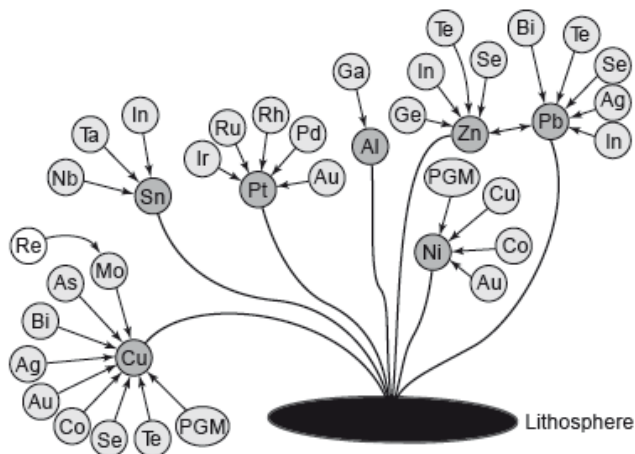


Figure 6. Example of linkages of different metals to one another, demonstrating potential co-products in the production processes (Graedel and van der Voet, 2010)¹⁵

Regardless, general guidance regarding co-product allocation provides movement towards harmonization. Table 4 through Table 6 provide a high-level overview of allocation procedures, recommendations, and rationales for base metals, precious metals, and non-metal co-products. Situations will call for deviations from the preferred approaches; in these cases, the rationale for deviation should be discussed within the LCA report. Note, the focus of these tables is primary metal production; secondary production is not discussed in this report, but will follow similar principles.

Metals are divided into two broad categories: base and precious. Definitions for these categories are not universal, are only loosely defined, and consider the economic value of the metal. In general, base metals have a relatively low economic value, whereas precious metals have a relatively high economic value. Even with uncertain definitions, the concept of high and low values provides useful guidance when choosing an allocation approach.

¹⁵ Graedel TE and van der Voet E (2010) Linkages of Sustainability. Strungmann Forum Report. MIT Press.

Table 4. Co-product approaches, recommendations, and rationales for base metals

Co-product type	Approach	Recommendation / Rationale
<p>Base metals (Co-products include only base metals that are found within the same mine)</p> <p>Examples: - copper - molybdenum - nickel - lead - zinc</p>	Mass allocation (metal)	Preferred approach
		Mass is a consistent physical property of the metal and allows for a geographic and temporal consistency. Although mass does not capture the economic purpose for extracting and refining metals, differences in market value between many base metals are generally relatively small. From a physical perspective, the same effort is needed to extract a unit mass of ore, regardless of the metal type or content. For base metal co-products with large market value differences, economic allocation should be considered.
	Mass allocation (total)	Use as appropriate
		Allocation by total mass (e.g., total ore) may be appropriate when various metals in the ore are combined are otherwise difficult to separate using other allocation methods. As with allocation by mass of metal, allocation by total mass captures the physical effort needed to extract a unit mass of ore. Allocation by total mass does not account for different quantities of the metal co-products in the ore; allocation by mass of metal is generally preferred due to this limitation.
	Economic allocation	Use as appropriate
		Economic allocation may be appropriate when there are relatively large differences in the market value of the base metals. In these cases, allocation by mass of metal does not adequately capture the economic purpose for extracting and refining the base metals. If chosen, market data should be averaged over a long timespan (10-year average is recommended) so as to minimize the effect of price volatility. Note: it may be appropriate to allocate upstream processes (e.g., mining and concentration) using mass of metal and downstream processes (e.g., smelting and refining) using economic allocation.
	System expansion ¹⁶	Preferred approach (when data is available)
		System expansion is preferred when LCI data for mono-output alternative routes are available for the co-products. In case of metals, mono-output alternative routes, or the LCI data associated with those routes, are often not available for the co-products; allocation should be used in these instances.

¹⁶ It is acknowledged that this is not an allocation method but rather a method of avoiding its application according to ISO standards.

Table 5. Co-product approaches, recommendations, and rationales for precious and rare metals

Co-product type	Approach	Recommendation / Rationale
<p>Precious metals (Co-products include precious metals that are found with other base or precious metals in the same mine)</p> <p>Examples</p> <ul style="list-style-type: none"> - silver - gold - platinum 	Economic allocation	Preferred approach
		Economic allocation accounts for the large disproportionately high market value of precious metals and the corresponding differences in price between metal co-products. Economic allocation captures the economic purpose for extracting and refining metals. If chosen, market data should be averaged over a long timespan (10-year average is recommended) so as to minimize the effect of price volatility.
	Mass allocation (metal)	Use as appropriate
		<p>Mass allocation does not account for the large differences in price between precious metals and base metals. However, in certain instances (e.g., where price is highly variable or uncertain), it may be necessary or useful to allocate co-products using the mass of metal content.</p> <p>Note: it may be appropriate to allocate upstream processes (e.g., mining and concentration) using mass of metal and downstream processes (e.g., smelting and refining) using economic allocation.</p>
	Mass allocation (total)	Use as appropriate
		<p>Similar to allocation by mass of metal, allocation by total mass may be necessary when economic allocation is not possible. Allocation by total mass (i.e., total ore) may be appropriate when various metals in the ore are combined are otherwise difficult to separate using other allocation methods. As with allocation by mass of metal, allocation by total mass captures the physical effort needed to extract a unit mass of ore. Allocation by total mass does not account for different quantities of the metal co-products in the ore. Allocation by mass of metal is generally preferred due to this limitation.</p>
	System expansion	Preferred approach (when data is available)
		System expansion is preferred when LCI data for mono-output alternative routes are available for the co-products. In case of metals, mono-output alternative routes, or the LCI data associated with those routes, are often not available for the co-products; allocation should be used in these instances.

Table 6. Co-product approaches, recommendations, and rationales for non-metal co-products

Co-product type	Approach	Recommendation / Rationale
Non-metals (Metals with production of non-metal products)	System expansion	Preferred approach
		Alternative production routes are often available for non-metal co-products, making this a preferred approach for dealing with co-products. System expansion can be used for slags, process gases, and other non-metal co-products.
	Mass allocation (total)	Use with caution
		Allocation of non-metal co-products by total mass may be appropriate when information (e.g., LCI data) for the co-product is unavailable. It is assumed that allocation by total mass does not account for economic purpose for generating co-products; thus, the market value should be similar between co-products so as to avoid unfair impact allocation.
	Economic allocation	Use with caution
		Allocation of non-metal co-products by market value may be appropriate when information (e.g., LCI data) for the co-product is unavailable. Economic allocation accounts for the economic purpose for generating co-products. If chosen, market data should be averaged over a long timespan (10-year average is recommended) so as to minimize the effect of price volatility.
Mass allocation (metal)	n/a	

3.2.2 Multiple allocation approaches in a single product system

Multiple different allocation approaches can be used in a single product system when distinct sets of processes and products (e.g., upstream versus downstream) can be identified. For metals, upstream processes (e.g., mining and concentration) are sometimes best characterized using mass allocation, while downstream processes (e.g., smelting and refining) are best characterized using economic allocation for the metal co-products. The rationale is that the upstream processes needed to produce the concentrate are independent of the type of metal in the ore, while the downstream processes needed to extract the metal co-product from the concentrate are dependent on the metal in the ore.

The copper industry employed this technique in their 2011 LCI report. The report argues that for mining, "ore (containing a mix of metals) is considered to be mining's only product, so no allocation is made. However, if two different ores are mined, a total mass allocation is used. There is no difference in process effort or yield for different grades of metal ores." Subsequently, for the refining processes, the reports argues that "since the precious metal outputs have such disparate economic value and mass outputs compared to copper cathode, using the transparent market prices of the commodities copper, gold, silver and nickel sulphate to reflect the society value, is a substantial and appropriate approach for the treatment of the metal co-products → market value allocation."

3.2.3 Ferroalloys

Ferroalloys occur where ferrous and non-ferrous products are produced together as a single material. A common use of ferroalloys is in the production of stainless steel. The iron in the ferroalloy substitutes the need for other iron inputs; the substitution should be accounted for appropriately in the LCI calculations.

The following bullets summarize the recommended treatment of ferroalloys in a metal system:

- Ferroalloys are often best viewed as single, aggregated material and, ideally, their environmental impacts will not be broken down to the constituent elements.
- The elemental ratio (e.g., x% Fe and y% Ni) should be reported when presenting environmental impact results.
- If it is necessary to breakdown impacts into the constituent elements, the impacts need to be fairly distributed across both the ferrous and non-ferrous components. It is recommended that the impacts from the ferrous component are credited to the non-ferrous component using system expansion. Practitioners should be careful to apply the credit using an equivalent ferrous product, such as scrap, rather than sinter, pellet, hot metal or finished steel products. System expansion is justified here because iron is predominately produced in isolation from other metals.

4 RECYCLING

Recycling is a key consideration in the metal life cycle due to metals' high recycling potential. Unlike some other materials, metals can be recycled over and over again if their pollution with foreign materials is avoided. It is important to capture this feature of the metal life cycle when evaluating the environmental impacts of the raw materials themselves or the products that they form.

This section describes background information on recycling in LCAs and presents state-of-the-practice recycling in the metals industry. The discussion is limited to attributional life cycle assessment; consequential analyses are not considered within the scope of this document.

4.1 Background Information

4.1.1 Closed Loop and Open Loop Recycling

Recycling processes can be described based on how the recycled material is used at the end-of-life: closed loop recycling; open loop recycling with downcycling; and open loop recycling without downcycling (also called semi-closed loop recycling).

Closed loop recycling (Figure 7) occurs when the materials associated with a product are recycled back into the same product system. The material properties are not changed in comparison to the original primary material. For example, the lead used in lead based batteries operate in a closed loop, with nearly 100% of a battery's lead being recovered and used in new batteries.

Open loop recycling occurs when the material is recycled into another product system.

- **Downcycling** (Figure 8) occurs when the inherent material properties are changed to such an extent that the recycled material cannot be used in its original application. For alloyed metals, downcycling may take place when different alloy grades are mixed in the scrap or when the scrap is polluted with foreign materials that are unwanted in the recycling process. Downcycling can be accounted for by crediting the system based on the quality of the scrap or the quality of the recycled material relative to virgin alternatives. One method of accounting for scrap quality is through the use of value-corrected substitution.¹⁷
- **Without downcycling** (Figure 9) occurs when the material is recycled into another product system, without the material's inherent properties undergoing any change. In practice, this type of recycling loop is treated identically as a closed loop recycling system; ISO considers these two systems to be analogous to one another. This approach is also referred to as *closed material loop recycling*.

¹⁷ Koffler C and Florin J (2013) Tackling the Downcycling Issue—A Revised Approach to Value-Corrected Substitution in Life Cycle Assessment of Aluminum (VCS 2.0). Sustainability (5): 4546-4560.

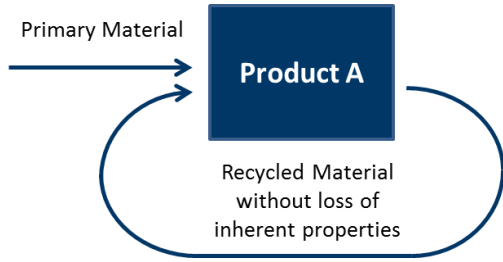


Figure 7. Closed loop recycling

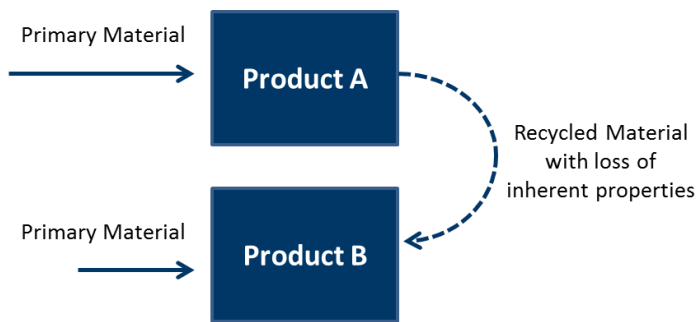


Figure 8. Open loop recycling with downcycling

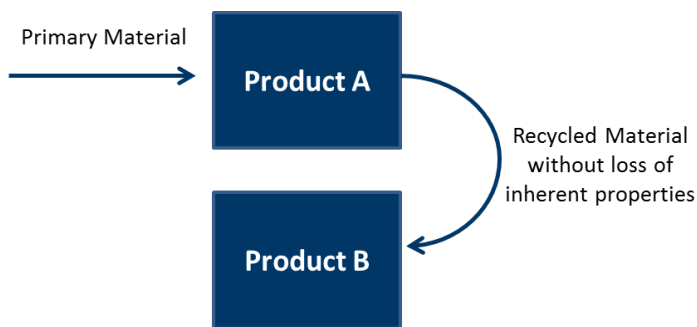


Figure 9. Open loop recycling without downcycling

4.1.2 LCI Modeling Approaches to Recycling

Life cycle inventory modeling for recycling of materials, particularly of metals, is currently very much debated.¹⁸ The proposed methodologies can roughly be classified into two distinctly different approaches that are currently used in life cycle assessment practice:

1. Recycled content approach (also known as the cut-off approach or 100:0); or,
2. End-of-life recycling approach (also known as the avoided burden approach or 0:100).

A description of each of these modeling approaches is outlined below.¹⁹ Note that there are a number of associated methodologies that are hybrids or derivatives of these basic approaches. For instance, the so-called 50/50 approach is a hybrid of the recycled content and end-of-life recycling approaches. The 50/50 approach distributes burdens and credits equally between the first and last products in the life cycle cascade. More information about various recycling approaches can be found in Nicholson et al. (2009)²⁰ and other recycling allocation articles.

Recycled content (or cut-off) approach

The recycled content approach considers the share of recycled metal in the manufacture of a product. System boundaries are drawn upstream at the point of scrap generation and downstream at the point of collection. The environmental impacts of extraction, beneficiation, and refining of primary metal are attributed to the first use of that metal product. The second use of the metal bears the environmental impacts of collection, beneficiation and refining of scrap. In some cases, collection is attributed to the first use and the collection and recycling steps need to be clearly separated. Scrap does not bear any environmental load from the primary metal production activities.

End-of-life recycling (or avoided burden) approach

The end-of-life recycling approach considers the end-of-life fate of the metal. The overall recycling efficiency (i.e., collection rate plus recycling yield) is used to characterize the quantity of material that is allocated to the next life cycle. Under this approach, end-of-life scrap is first balanced out with any open scrap inputs into production. Only the remaining *net scrap* is then modeled as being sent to material recycling in order to avoid double-counting the benefits of using recycled content. If more scrap is recovered at product end-of-life than is required in the manufacturing stage, the product system receives a credit equal to the burden of primary material production minus the burden of recycling scrap into secondary material based on the mass of secondary material produced. This credit represents the avoided burden of primary material production.

¹⁸ A list of the recent publications on this issue is found in Frischknecht (2009).

¹⁹ Definitions from Frischknecht (2009).

²⁰ Nicholson, A., E.A. Olivetti, J.R. Gregory, F.R. Field, and R.E. Kirchain . (2009). "End-of-life LCA allocation methods: open loop recycling impacts on robustness of material selection decisions." Proceedings from the International Symposium on Sustainable Systems and Technology.

4.2 State of the Practice: Recycling Approaches

4.2.1 Metals Industry Consensus: End-of-Life Recycling Approach

In 2006, the metals industry published its *Declaration by the Metals Industry on Recycling Principles*, in which it strongly endorses the end-of-life recycling approach:

“For purposes of environmental modeling, decision-making, and policy discussions involving recycling of metals, the metals industry strongly supports the end-of-life recycling approach over the recycled content approach.

...Of particular concern, pursuit of recycled content may generate market distortions and result in environmental and economic inefficiencies.”

This declaration represents a consensus metals industry position, as it was endorsed by all the major global metals commodity associations, as well as national/regional metals associations.²¹ Notable research institutions such as Yale University’s Stocks and Flows Project and the UNEP International Resource Panel’s Working Group on Global Metal Flows also endorse taking an end-of-life recycling approach.^{22,23}

4.2.2 Recycling in EN 15804

EN 15804 requires that the recycled content input is characterized in Module A1 (raw materials supply). The recyclability of metals can still be accounted for through the use of Module D, where credits can be applied to the system based on avoided burden. In order to avoid double-counting of recycling benefits from both recycled content and end-of-life recycling, the avoided burdens are calculated in Module D based on the net flow of secondary materials (i.e., scrap in the case of metals) exiting the product system. This is calculated as the flow of collected end of life scrap minus the flow of scrap used at the production stage. This approach ensures that only the net recycling is accounted for, which is consistent with the avoided burden allocation approach.

The following are notes from EN15804 that apply to recycling and end of life.

- A1 input side: Recycling processes of materials used as input for the manufacture of the product, but not including those processes that are part of the waste processing in the previous product system.
- C3-4: The end-of-life stage of the construction product starts when it is replaced, dismantled or deconstructed from the building and does not further provide any functionality to the building. The end-of-life system boundary of the construction product system is set where outputs, e.g.,

²¹ Atherton J et al. (2007). Declaration on recycling principles. *International Journal of Life Cycle Assessment*. 12(1): 59-60.

²² Reck BK and Graedel TE (2012) Challenges in Metal Recycling. *Science* 337, 690.

²³ UNEP (2011). Recycling Rates of Metals – A Status Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Available at: http://www.unep.org/resourcepanel/Portals/24102/PDFs/Metals_Recycling_Rates_110412-1.pdf.

materials, products or building elements, have gained an economic value or where the “end-of-waste” stage is reached, whichever occurs first. The “end-of-waste” status is reached when it complies with the following conditions:

- the material, product or building element is commonly used for specific purposes
- a market or demand exists for such a material, product or building element
- the material, product or building element fulfills the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products
- the use of the material, product or building element will not lead to overall adverse environmental or human health impacts.

The goal of EN 15804 was to ensure that national schemes be based on a common European program founded upon European or International standards for EPDs. EPD schemes in Germany (IBU), Sweden (International EPD System), and the UK (BRE) have revised their scheme rules to align with EN 15804. National standards in the Netherlands and France have also been revised accordingly.

4.2.3 Recommendations for Recycling Allocation

The recyclability of metals is a key material property. The recycled content methodology neglects this property and is thus not the preferred approach to end-of-life allocation. Rather, the avoided burden methodology is the preferred allocation approach due to its inclusion of recycling rate, as well as the ability to account for downcycling and recycling efficiencies. Care should be taken to establish accurate recycling rates and sensitivity analyses should be used to capture uncertainty and/or variability in these rates.

5 LIFE CYCLE IMPACT ASSESSMENT

Life cycle impact assessment (LCIA) "aims at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO 14044). Whereas the life cycle inventory considers emissions and other flows from or to the environment, LCIA accounts for the potential impacts of those flows on humans, ecosystems and resources. Due to the relative approach of LCA, which is based on a functional unit rather than on total environmental loads, LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

LCIA metrics are reported through various impact categories, such as global warming potential, acidification potential, or human toxicity potential. ISO 14044 provides the following guidance to selecting impact categories for an LCA:

- the impact categories, category indicators and characterization models should be internationally accepted, i.e., based on an international agreement or approved by a competent international body;
- the impact categories should represent the aggregated impacts of inputs and outputs of the product system on the category endpoint(s) through the category indicators;
- value-choices and assumptions made during the selection of impact categories, category indicators and characterization models should be minimized;
- the impact categories, category indicators and characterization models should avoid double counting unless required by the goal and scope definition, for example when the study includes both human health and carcinogenicity;
- the characterization model for each category indicator should be scientifically and technically valid, and based upon a distinct identifiable environmental mechanism and reproducible empirical observation;
- the extent to which the characterization model and the characterization factors are scientifically and technically valid should be identified; and,
- the category indicators should be environmentally relevant.

In general, when defining the goal of an LCA, it is necessary to state the reasons for carrying out the study and its application(s). In some circumstances, certain impact categories are required by standards or guidelines. For example, for environmental product declarations, the impact categories and indicators are defined by the product category rule; the same applies for the European Union product environmental footprint.

The ISO standards do not define which methodology, impact, or indicators must be used. The decision of which impact categories to include is left to the discretion of the practitioner, who may rely on individual expertise, accepted best practices, and/or conformance to relevant supporting standards or guidelines (e.g., ILCD Handbook, PAS 2050).

This chapter provides an overview of LCIA methodologies and impact categories, and provides recommendations on which impact categories to use within LCAs of metals and metal products. Note that this chapter only discusses midpoint categories; end points are not discussed within this document.

5.1 Impact Assessment Methodologies

LCIA can be conducted using various established methodologies. These methodologies define the characterization factors that are used to convert inventories into potential impacts. The background science that supports the development of characterization factors considers: geography; population densities; chemistry; emission rates; and other technical characteristics that link the generation of environmental flows with the potential impact from these flows. Due to the complexity of the environmental mechanisms underlying the different impacts, the characterization models and factors are continuously evolving as the research advances.

Various LCIA methodologies are used in LCAs. The most commonly used sets of LCIA methodologies are TRACI, CML, and ReCiPe. These approaches differ through their choice of characterization models that are specific to certain regions or based on distinct methodologies. Some methods, such as global warming potential and ozone depletion potential, are universal, while others will produce different values depending on the chosen method. Regardless of the methodology, emissions are compartmentalized into air, water and soil, which are then divided into sub-compartments, as shown in Figure 10.

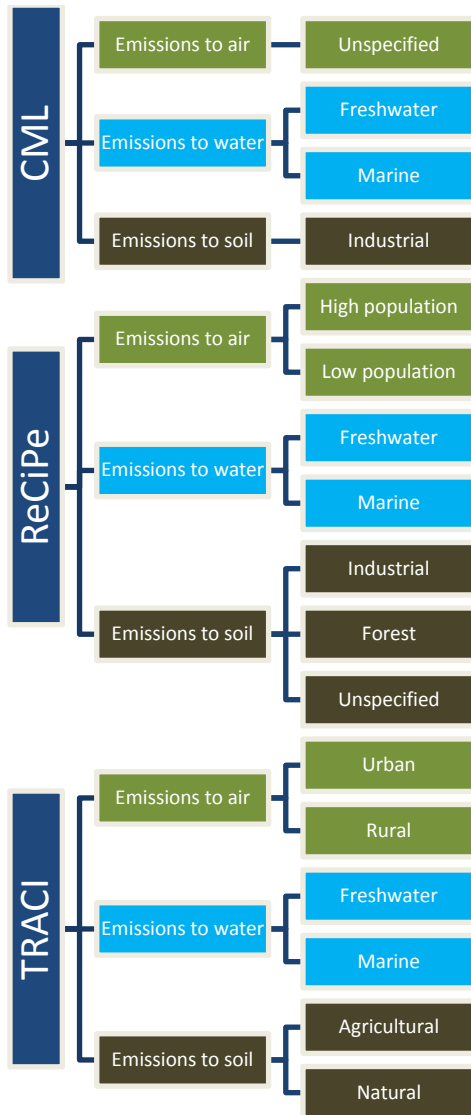


Figure 10. Emission sub-compartments for the CML, ReCiPe, and TRACI impact assessment methodologies

Substances are modeled on air, water, and soil emissions. This results in an estimation of what impact the product will have on humans and the environment. An overview of this process is shown in Figure 11.

The metals industry recommends using TRACI for North American-based LCAs and either CML or ReCiPe for European or globally-based LCAs.

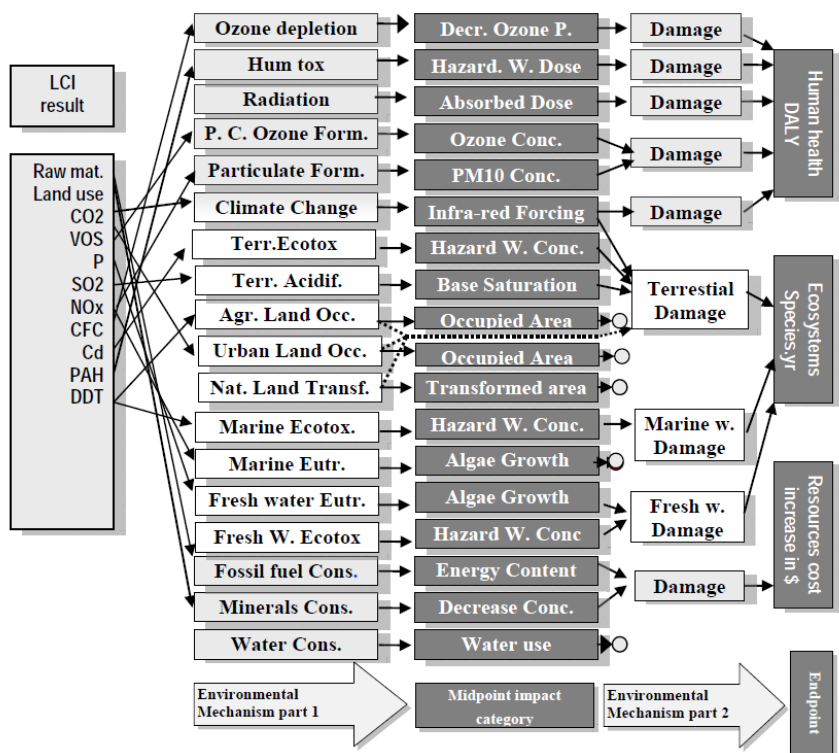


Figure 11. Illustration of inventory flows, midpoints, and endpoints in life cycle impact assessment (Goedkoop et al. 2009)²⁴

5.2 Overview of Impact Assessment Categories

The science that supports the characterization of impacts varies in quality from category to category. Some categories, such as global warming potential, are well-established and have a high level of consensus in the LCA community. Other categories, such as toxicity, biodiversity or resource depletion, rely on more controversial assumptions and methods and are thus less widely used and accepted in LCAs. The following set of impact categories are recommended for use in LCAs involving metals:

- Global warming potential
- Acidification potential
- Eutrophication potential
- Smog potential (e.g., photochemical oxidant creation potential)
- Ozone depletion potential

²⁴ Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, and van Zelm R (2009) ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition. Report I: Characterisation.

In addition to these categories, certain life cycle inventory metrics should be reported. In particular, primary energy demand (total, fossil, and renewable) and net water consumption should be part of the LCA reporting. Although these inventory metrics do not measure impact (as do LCIA categories), they are important parts of the environmental profile and have become commonly reported in most LCAs.

There are a number of additional LCIA categories available to LCA practitioners, including methods to measure the impact from resource depletion, toxicity to humans and ecosystem, land use change, and water scarcity (a weighted measure of water consumption). The metals industry does not recommend reporting the impact from these methods at this time. Although these impacts are relevant environmental concerns, it is the position of the metals industry that the characterization of these impacts from the inventory data does not adequately support decision-making. As the supporting science improves and the LCI data becomes more robust (e.g., higher spatial resolution), inclusion of these impact categories should be periodically reconsidered.

As discussed in section 5.1, the selection of impact categories should meet the product and the goals of the study, as well as follow any relevant standards or guidelines, such as those found in product category rules when developing environmental product declarations. Thus, certain impact categories may need to be included, regardless of recommendations from the metals industry.

The following subsections provide an overview of the aforementioned LCIA categories. The intent is to introduce the theory behind the characterization models and describe any caveats and limitations, as appropriate. A more thorough review of the impact categories can be found in the scientific literature, LCA guidelines (e.g., ILCD), and the LCIA methodology documentation.

5.2.1 Recommended LCIA Categories

5.2.1.1 Global warming potential (GWP)

The short-wave radiation from the sun comes into contact with the earth's surface and is partially absorbed (leading to direct warming) and partially reflected as infrared radiation. The reflection is absorbed by greenhouse gases in the troposphere and is re-radiated in all directions, including back to earth. This results in a warming effect at the earth's surface.

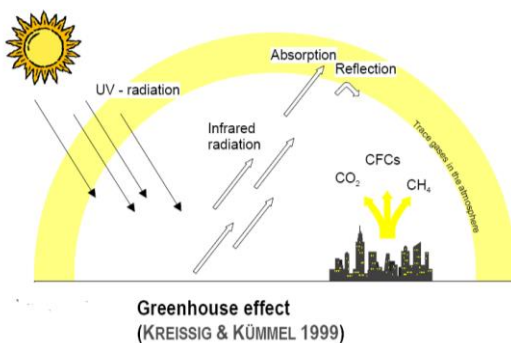


Figure 12. Impact mechanism for global warming potential

The global warming potential is calculated in carbon dioxide equivalents (CO₂-eq), meaning that the greenhouse potential of an emission is given in relation to CO₂. Since the residence time of gases in the

atmosphere is incorporated into the calculation, a time range for the assessment must also be specified. It is common practice to use a period of 100 years taken from the main reports of the Intergovernmental Panel on Climate Change (IPCC), which also includes factors for 20 and 500 years.

IPCC published an errata document of the Fourth Assessment Report (AR4) in June 2012. This added GWP factors for a few more substances from the original AR4. These factors yield the best combination of international consensus and quantity of substances evaluated.

As the name global warming indicates, this is a global impact and the recommendation for LCIA category is therefore independent of the geographical scope of the LCA.

5.2.1.2 Acidification potential (AP)

The acidification of soils and waters occurs predominantly through the transformation of air pollutants into acids. This leads to a decrease in the pH-value of rainwater and fog from 5.6 to 4 and below. Sulphur dioxide, nitrogen oxide and their respective acids (H_2SO_4 und HNO_3) produce relevant contributions. Forest dieback is the most well-known impact of acidification.

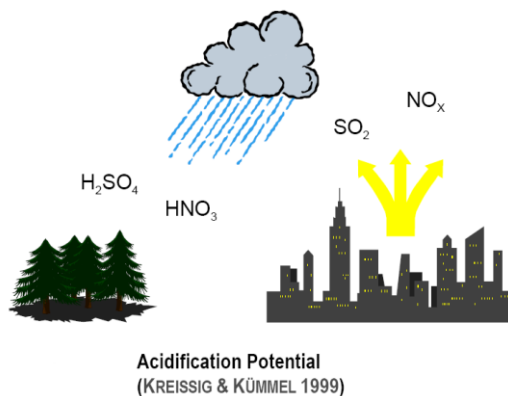


Figure 13. Impact mechanism for acidification potential

Acidification has direct and indirect damaging effects (such as nutrients being washed out of soils or an increased solubility of metals into soils). This can cause damage to buildings and building materials. Examples include metals and natural stones which are corroded or disintegrated at an increased rate.

AP is traditionally divided into aquatic and terrestrial acidification. The terrestrial acidification covers both effects towards the environment (e.g., animals and plants) and towards human structures (e.g., statues and buildings).

ReCiPe covers change in base saturation (BS) in forest ecosystems only, not all ecosystems include aquatic as in CML. In TRACI 2.1, the various acidification effects are merged into one acidification category. The notation of 'Acidification air' and 'Acidification water' relates to the emission compartment only, and not to a specification of the effect. ILCD recommends a method of accumulated exceedance of the neutralization capacity of the receiving soil for terrestrial acidification, i.e., how much more do we surpass the capacity of the receiving environment.

Problematic issues with the ILCD approach are as follows:

- It covers only Europe and surrounding countries. North and South America, Africa, Asia and the Pacific regions are not included.
- Site-specific impact categories cannot yet be implemented.

As the acidification potential can be considered a regional impact, the recommendation will differ depending on the geographical reference of the LCA.

CML and TRACI cover approximately the same effect compartments. TRACI is recommended for use in North America, whereas CML is recommended for use in Europe and the rest of the world, as it has slightly more international recognition. However, when the supply chain of a North American product (for example) extends beyond the region, it is acceptable to use TRACI in parallel with CML.

5.2.1.3 Eutrophication potential (EP)

Eutrophication is the enrichment of nutrients in a certain environmental compartment. Eutrophication can be divided into freshwater, marine and terrestrial. Air pollutants, wastewater and fertilization in agriculture all contribute to eutrophication.

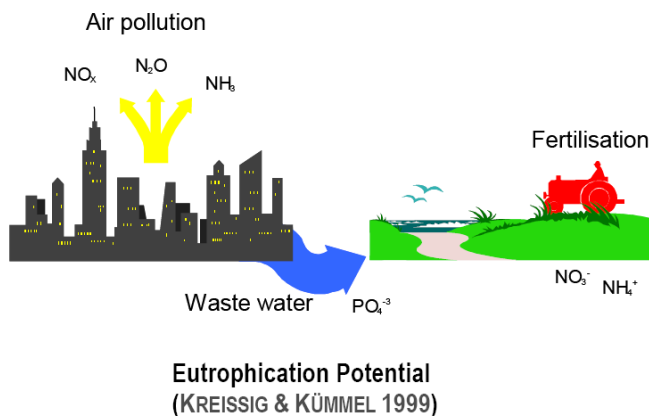


Figure 14. Impact mechanism for eutrophication potential

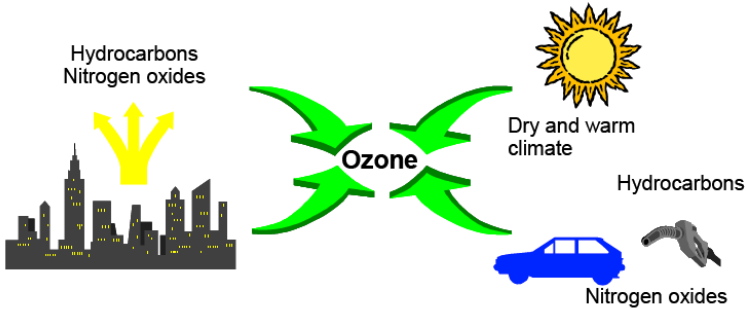
The result in water is an accelerated algae growth, preventing sunlight from reaching the lower depths, leading to a decrease in photosynthesis and less oxygen production. Phosphorus (P) is the limiting nutrient for algae growth in freshwater systems. Hence, adding more nitrogen (N) will itself not lead to increased growth in freshwater systems. The opposite is taking place in marine environment where nitrogen is the limiting nutrient. Conversion between phosphorus and nitrogen equivalents is done via the concentration of nitrogen and phosphorus in standard algae specie.

On eutrophicated soils, an increased susceptibility of plants to diseases and pests is often observed, as is degradation of plant stability. If the nitrification level exceeds the amounts of nitrogen necessary for a maximum harvest, it can lead to an enrichment of nitrate. This can cause, by means of leaching, increased nitrate content in groundwater, which can end up in drinking water.

ILCD recommends a method of accumulated exceedance of the neutralization capacity of the receiving soil for terrestrial eutrophication, as is the case with acidification, and also with the same drawbacks.

5.2.1.4 Photochemical Ozone Creation Potential (POCP)

Despite playing a protective role in the stratosphere, ozone at ground level is classified as a damaging trace gas. Photochemical ozone production in the troposphere, also known as ‘summer smog’²⁵, will damage vegetation and materials and is toxic to humans.



Photochemical Ozone Creation Potential (
KREISSIG & KÜMMEL 1999)

Figure 15. Impact mechanism for photochemical ozone creation potential (smog)

Radiation from the sun and the presence of nitrogen oxides and hydrocarbons incur complex chemical reactions, producing aggressive reaction products, one of which is ozone. Nitrogen oxides alone do not cause high ozone concentration levels.

Hydrocarbon emissions occur from incomplete combustion and from evaporation of petroleum products or solvents. High concentrations of ozone arise when temperature is high, humidity is low, air is relatively static and there are high concentrations of hydrocarbons.

TRACI is based on an approach that has more substances evaluated than CML and ReCiPe. However, which substances have a high characterization factor and which have a low compared to the average within each methodology seems to show the same pattern. The characterization factors for ReCiPe and CML are in principle identical, only differing in reference substance: Ethylene (C₂H₄) for CML and NMVOC for ReCiPe. A direct conversion reveals exact matches with only two exceptions (NO_x and NO₂), plus that NO is not included in ReCiPe.

While NO and NO₂ have the same characterization factors in TRACI 2.1, the CML characterization factor for NO emission is negative leading to the narrow conclusion that driving a diesel truck through the city will improve the local air quality. This seems to be caused by some extreme assumptions on the weather pattern, i.e., assuming that “the sun always shines”.

As the TRACI methodology is modeled for North American conditions and CML/ReCiPe for European conditions, this will also determine the recommendation for use.

²⁵ As opposed to ‘winter smog’, which used to be a major problem caused by particle / soot emissions from coal heating in 19th and 20th century London.

If using CML or ReCiPe, it is the current recommended approach to conduct a sensitivity analysis showing two different POCP categories or as a minimum step, explain the ongoing issue that NO_x and NO_2 show highly different values, and that NO has a negative characterization factor for NO emissions.

5.2.1.5 Ozone depletion potential (ODP)

Ozone is created in the stratosphere by the disassociation of oxygen atoms that are exposed to short-wave UV-light. This leads to the formation of the ozone layer in the stratosphere (15-50 km high). About 10% of this ozone reaches the troposphere through mixing processes. In spite of its minimal concentration, the ozone layer is essential for life on earth as it absorbs the short-wave UV-radiation and releases it in longer wavelengths. As a result, only a small part of the UV-radiation reaches the earth.

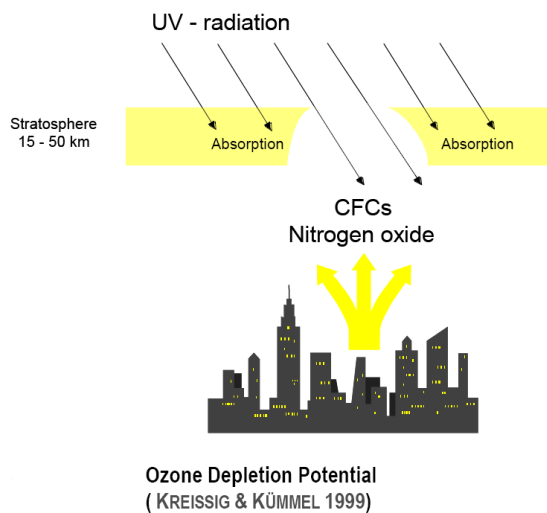


Figure 16. Impact mechanism for ozone depletion potential

The characterization factors for ozone depletion have been standardized and do not differ between the methodologies. Furthermore, it is considered a global problem. Which methodology is used is therefore not important. Also considering that the emission of ozone depleting CFCs seem to be decreasing and rarely present the tipping point of an analysis.

5.2.2 LCIA Categories Not Currently Recommended for LCAs Involving Metals

5.2.2.1 Resource depletion

The abiotic depletion potential (ADP) covers some selected natural resources as metal-containing ores, crude oil and mineral raw materials. Non-renewable means a time frame of at least 500 years. The abiotic depletion potential is split into two sub-categories: elements and fossil.

5.2.2.1.1 ADP elements

Abiotic depletion potential (elements) covers an evaluation of the availability of natural elements in minerals and ores, including uranium ore. Two calculations of ADP (elements) from CML are in common use: one based on ultimate resources (i.e., the total mineral content in the earth crust) and one based on what is evaluated as being economically feasible to extract (economic reserves).

Both approaches are controversial. Varying definitions of “resources” and “reserves” are known to contribute to variable results. Where definitions are harmonized, estimates of resource and reserve quantities also vary amongst experts and significantly over time. Additionally, the metals industry argues that existing characterization models are based on assumptions that do not hold in reality.

Figure 17, from the ReCiPe main report from 2008, shows that the ReCiPe authors are aware of the problems. Many studies published in 2000’s tried to develop a better approach, including Society of Environmental Toxicology and Chemistry (SETAC) (e.g., Udo de Haes et al. 1999²⁶, 2002²⁷) and the UNEP-SETAC Life Cycle Initiative (e.g., Jolliet et al. 2004²⁸). None resulted in a uniform globally accepted set of characterization models and factors. As a result, ADP is not consistently included in LCIA or environmental product declarations.²⁹ Hauschild et al. (2013) recently highlighted again the need for ADP models to be further refined.³⁰

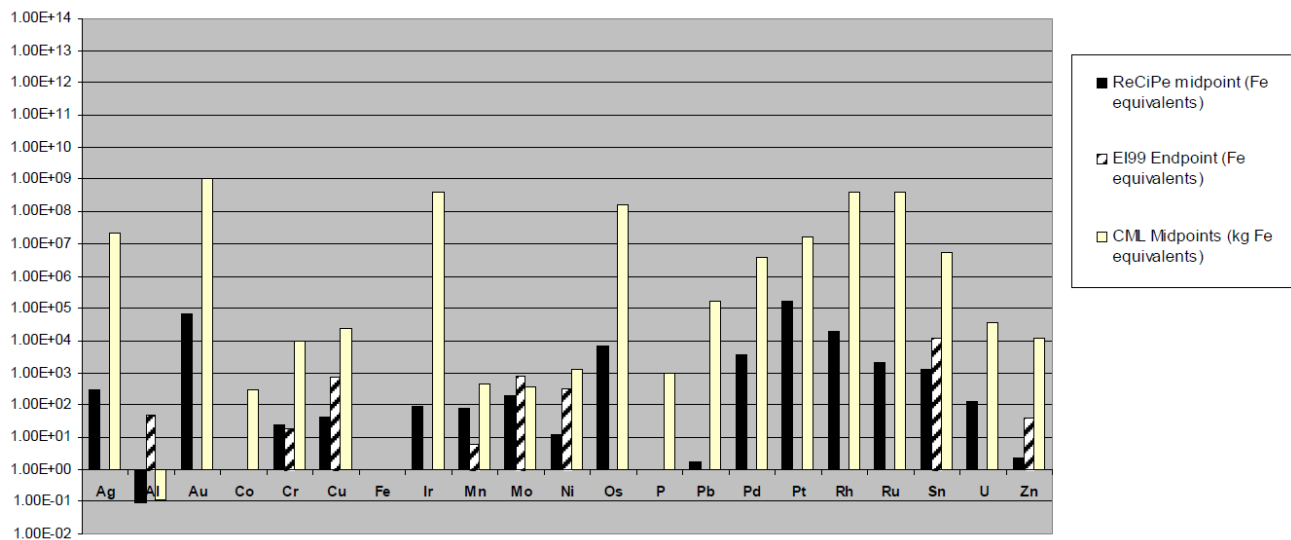


Figure 17. Illustration of different characterization factors for ADP (elements). Differences in methodological approaches and assumptions are the root causes of discrepancy.

²⁶ Udo de Haes HA, Jolliet O, Finnveden G, Hauschild M, Krewitt W, Müller-Wenk R (1999) Best available practice regarding impact categories and category indicators in life cycle impact assessment. *International Journal of Life Cycle Assessment*. 4:66-74.

²⁷ Udo de Haes HA, Jolliet O, Norris G, and Saur K (2002) UNEP/SETAC life cycle initiative: background, aims and scope. *International Journal of Life Cycle Assessment*. 7:192-195.

²⁸ Jolliet O, et al. (2004). The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. *International Journal of Life Cycle Assessment*. 9:394-404

²⁹ Environdec.com – General Programme Instructions, 2008 Version 1.0

³⁰ Hauschild M, et al. (2013) Identifying best existing practice for characterization modeling in life cycle impact assessment. *International Journal of Life Cycle Assessment*. 18:683-697

As the issue of potential resource depletion can be considered a global problem, the geographical location of the resource consumption should be of low importance. However, with current model and data uncertainties the determination of an internationally accepted baseline for “world total resources (or reserves)” of a mineral commodity is most likely not achievable.

5.2.2.1.2 ADP fossil

The second sub-category is abiotic depletion potential (fossil), which includes the fossil energy carriers (crude oil, natural gas, coal resources). MJ is the respective reference unit.

Fossil depletion has recently been incorporated into TRACI with the approach originating from ecoinvent. Here, the effect of using one energy resource is the difference towards the next-best alternative, i.e., “*when I use this energy resource, then ‘next person’ will have to use another one.*”

ADP fossil usually closely correlates with global warming potential, as both are heavily dominated by the use of fossil energy resources. Apart from not adding much insights, this poses a problem in decision-making based on LCA results as the decision criteria (i.e., the impact categories), which should be independent of each other.

5.2.2.2 Water

Recent water initiatives on ISO level have specified the difference between water use and water consumption. All freshwater intakes are considered freshwater *use*. Freshwater that leaves the watershed is considered to be consumed (e.g., by evaporation, evapotranspiration, integration into products, or release into sea). This is the fraction that is most interesting regarding the environmental impacts as this water is lost to downstream ecosystems and human consumption. An example is hydropower that has a very high water use, but a low consumption as the water is released within the same watershed. Water that is evaporated from a hydropower reservoir, however, would be included in water consumption.

Blue water refers to surface and ground water only (excluding rain water, green water). Rain water is typically excluded from the assessment of freshwater consumption and one focuses on blue water consumption only, as this is the relevant part which can be assessed with current impact assessment methods.

Several methodologies are incorporating characterization factors to account for the difference in water scarcity. Logically, this is specific to a region and not currently implemented consistently across databases. Therefore using water scarcity indices can currently be recommended as a sensitivity approach only.

5.2.2.3 Land use

Several methods exist for evaluating land use.

The method LANCA includes a set of environmental indicators that are not considered midpoint impact categories, but rather a step between elementary flows and midpoints: biotic production, erosion resistance, groundwater replenishment, land occupation, mechanical filtration, and physicochemical filtration. All these factors are evaluated towards a ‘natural background state’ which for Europe is interpreted as forest. This background state is implemented to avoid giving credit for using an already used or polluted piece of land.

Soil organic matter as recommended by ILCD requires determination of a balance of soil organic matter on field level. This is extremely site-specific and not practical in LCAs that span global production networks.

5.2.2.4 Toxicity

USEtox is a scientific consensus model developed by the researchers behind the CalTOX, IMPACT 2002, USES-LCA, BETR, EDIP, WATSON and EcoSense.³¹ USES-LCA is currently used by ReCiPe and CML, and CalTOX was used in earlier versions of TRACI. The later versions of TRACI have directly incorporated USEtox to account for toxicity effects and TRACI is therefore not evaluated separately for toxicity.

USEtox was initiated in 2005 by the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC), directly involving the model developers of CalTOX, IMPACT 2002, USES-LCA, BETR, EDIP, WATSON and EcoSense. Based on a referenced database, it has now been used to calculate characterization factors for several thousand substances.

The model provides both recommended and interim (not recommended and to be used with caution) characterization factors for human health and freshwater ecotoxicity impacts. An overview of the toxicity categories in CML, ReCiPe and USEtox is shown in the Table 7. Note that experts from the CML group participated in the development of USEtox, but CML still operates with their specific set of toxicity indicators.

Table 7. Toxicity categories in CML, ReCiPe, and TRACI

	CML and ReCiPe [1,4-dichlorobenzene]	USEtox (TRACI)
Human toxicity, cancer	Human toxicity (HTP)	Human tox, cancer [CTUh]
Human toxicity, non-cancer		Human tox, non-cancer [CTUh]
Freshwater ecotoxicity	Freshwater aquatic ecotoxicity (FAETP)	Ecotoxicity [CTUh]
Marine ecotoxicity	Marine aquatic ecotoxicity (MAETP)	n/a
Terrestrial ecotoxicity	Terrestrial ecotoxicity (TETP)	n/a

If the toxicity impact category is a required part of an LCA (e.g., requested by a downstream user or material, included in product category rules) practitioners should use the USEtox methodology. The precision of the current USEtox characterization factors is within a factor of 100–1,000 for human health and 10–100 for freshwater ecotoxicity.³² This is a substantial improvement over previously available toxicity characterization models³³, but still significantly higher than for other impact categories. Given the limitations of the characterization models for each of these factors, if toxicity is reported, the level

³¹ Rosenbaum et al. (2008). USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *International Journal of Life Cycle Assessment*. 13:532–546.

³² *ibid*

³³ *ibid*

of precision (i.e., reliability of two to three orders of magnitude) should be considered during the interpretation phase of the LCA. In particular, comparative assertions should not rely on toxicity results from USEtox or other toxicity models.

The USEtox model is helpful in identifying potentially important toxics in the life cycle. Using the USEtox results, practitioners can isolate the top chemicals of concern, and then use more specific evaluations (e.g., risk assessment) to better ascertain the toxicity risk in the given application.

In summary, toxicity is not recommended for decision-making processes, but could be used for 'order of magnitude' estimates and for sensitivity analysis. The suggested approach is for practitioners is as follows: (a) look for existing risk assessments for the metals; (b) use the current LCA toxicity models with caution; (c) make sure the most recent data/models are being used; and, (d) consider toxicity separately from other environmental indicators.

6 SUMMARY AND NEXT STEPS

This guidance document has reviewed a number of methodological topics relevant to LCAs involving metals. Key takeaways are summarized as follows:

- System boundaries should be set to include end-of-life disposal and recycling and, whenever possible, the product use phase, particularly for material and product comparison
- Co-product allocation methods should consider the type of co-products being produced and should follow the recommendations listed in Tables 4–6
- Recycling allocation should follow the recommendations from Atherton et al. (2007) and use the end-of-life recycling approach
- The life cycle impact assessment stage should report the impact categories listed in Section 5.2, with the understanding that inclusion of other impact categories will be periodically reevaluated by the metals industry, or may be mandatory based on certain standards.

The participating organizations in this effort have contributed a significant amount of time and effort to develop the guidance set out in this document. However, through the many discussions held by the group a number of topics and potential activities were raised which the group was not able to address within the scope of this document. These potential next steps include, but are not limited to, the following:

- Create supplementary guidance documents which address metal specific examples or best practices (e.g., specific examples of co-product allocation for a particular metal or group of metals)
- Create a common set of ‘talking points’ for the participating associations to use with respect to use and dissemination of this document
- Create supplementary guidance documents on related topics / areas of concern among participating associations, e.g., communication of life cycle data and results.
- Create supplementary guidance, within the report or as an addendum to the report, on some or all of the following topics:
 - Performing comparative assertions;
 - Conducting a critical review, choosing a panel for external review, critical review steps, etc.;
 - Reporting requirements, LCA phases documentation;
 - Communicating the impacts/benefits from LCA studies; and
 - Alignment with other tools (e.g., material flow analysis (MFA), sustainable development indicators).

APPENDIX

Participation and Contact Information

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Errata

Version 1.01

Changed discussion on closed loop recycling without downcycling (§4.1.1) to reflect the acceptance of this recycling option in the ISO standards.

Added “Errata” section to the Appendix