Measuring circular economy through Life Cycle Assessment: challenges and recommendations based on a study on recycling of Al dross, bottom ash and shavings

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ABSTRACT

Metals are essential for the sustainability transition and decarbonisation of society. Yet, it will be paramount to produce them sustainably and minimise the affiliated resource and energy use, and the associated emissions. In the circular economy, the metallurgical industry should recycle existing material stocks, and improve its utilisation of wastes, residues and side streams. This increases the complexity of processes, as they become both (often multi-fraction) waste treatment as well as material production processes and brings complexity to the assessment of environmental benefits.

Assessing the environmental impact of technological developments frequently is supported by life cycle assessment (LCA). While the method is well documented, its implementation involves several methodological choices that deserve reasoning and analysis, such as how to define the product when former wastes are turned into new products, the selection of impact methodology when converting emissions to environmental indicators, the definition of system boundaries and co-product allocation, and the interpretation of sensitivity and uncertainty in final outcomes.

In this exploratory study, we investigate how the variation of LCA setup affects the environmental burden of the system. We consider a metallurgical process where a mix of hard-to-recycle aluminium-containing streams is used to produce aluminium cast alloys in a rotary furnace. Re-melting with salt-fluxes allows recovering metals from partly oxidised/contaminated streams, such as dross, bottom ash and industrial shavings, but at the expense of generating significant amounts of salt-slag/salt-cake hazardous waste. The study considers different system alternatives such as landfilling the salt-slag residues versus valorising them into salts, aluminium concentrates, ammonium sulphate and non-metallic-compounds to be used by the metallurgical, construction or chemical industries. Practical recommendations are outlined to facilitate the implementation of LCA in assessing the potential benefits of the circular economy in the metallurgical sector.

INTRODUCTION

Metals are critical for meeting the needs of our society, and we rely on them in multiple applications eg in the energy, transportation, packaging, construction, and communications industries. Applied ubiquitously across different sectors, some inherent sustainability implications are associated with their large lifespans and potential for recycling (Norgate and Rankin, 2002), in addition to being critical enablers of some relevant technologies for decarbonisation, such as renewable energy generation, batteries or electronics (World Energy Outlook, 2021).

Facing an unprecedented climate crisis, the demand for major metals might increase up to 6-fold over this century as the global population and living standards rise (Watari et al., 2021). Despite the economic and environmental benefits of metal production, sustaining the future provision of metals while considering the ecosystems' limited assimilation and provision capacity remains challenging. The production of metals alone entails resource use (2.8 billion tonnes of metal produced each year) (based on information from U.S. Geological Survey, 2023), energy-intensive processes (7-8% of the global energy consumption) (United Nations Environment Programme, 2017) and emissions of pollutants (among others, approx. 10% of global GHG emissions) (UN Environment and International Resource Panel, 2019). Some impacts derived from the extraction and processing of these metals are, for instance, climate change, biodiversity loss, and particulate matter health impacts (UN Environment and International Resource Panel, 2020).

With increasing environmental pressures to reduce the consumption of resources and generation of emissions in the production of metals, Life Cycle Assessment (LCA) has emerged as a method that quantifies the potential environmental burdens of a product system, identifying hotspots (or the parts of the system where environmental impacts are more significant) and possibilities for improvement. However, even though this method is well documented, its application involves several methodological choices that could significantly influence the results. Reasoning and consideration of these can be critical, especially when dealing with circular economy systems, in which material stocks are recycled and the utilisation of wastes, residues and side streams improved. The complexity of these systems lies in that they become both (often multi-fraction) waste treatment as well as material production processes.

Although LCA is a standard methodology to evaluate the impact through the life cycle of metallurgical systems, there is a lack of specific guidelines for the metallurgical industry that test the influence of methodological choices when implementing circular economy concepts. A study by PE International and Santero et al. (PE International, 2014; Santero and Hendry, 2016) highlights some methodological choices that affect the results of a metallurgical LCA, such as system boundaries, allocation, and impact categories. However, their influence has not been tested quantitatively in a case study. In addition, the present article expands on other relevant methodological choices.

Case study

The original model for this study is found in Vallejo Olivares *et al.* (2024). The system analysed considers the recycling of hard-to-recycle (partly oxidised or contaminated) aluminium-containing flows via a rotary furnace. This process allows, through re-melting with salt-fluxes and the rotational movement of the furnace, to separate the metal from the non-metallic contaminants (eg oxide layer, carbonaceous residues) and promote its coalescence, while also protecting the molten metal from oxidation during the high-temperature process (Milani and Timelli, 2023).

Even though from an environmental and economic perspective recycling aluminium is considered to be more sustainable than producing it anew (Olivieri, Romani and Neri, 2006; Damgaard, Larsen and Christensen, 2009), the use of salts has a significant downside in the generation of salt slag residues (a mix of salts, non-metallic compounds (NMCs) and entrapped metallic droplets), that are classified as hazardous waste (Environmental Protection Agency, 2002) and pose risks for landfilling (Office of Research & Development, 2015). Another option is to valorise these slags by crushing and dissolving them in water, obtaining both salts and aluminium concentrates that can be fed back into the rotary furnace, as well as ammonium sulphate and NMCs that the chemical and construction industries can benefit from. Various salt-slag recovery treatments are described in the non-ferrous industry's Best Available Techniques (BAT) reference document (Joint Research Centre, 2017).

The LCA methodology is applied to test the influence of relevant methodological choices in the environmental impact for this case study and draw practical recommendations for the use of LCA for the evaluation of metallurgical and circular economy systems for the industry.

LCA methodology

Life Cycle Assessment is described by the international standards ISO 14040 and 14044 as “the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (International Standard Organization, 2006a, 2006b).

The evaluation of environmental impacts through LCA is carried out in 4 iterative steps (Figure 1): (1) Goal and scope definition, where the methodological choices of the LCA are defined (2) Inventory analysis, or the calculation of all inputs (resources) and outputs (emissions) that pose a burden in the environment (3) Impact assessment, or the quantification of the environmental impact associated to the flows calculated during the inventory analysis, and (4) Interpretation, in which the outcomes of the previous phases are evaluated in accordance to the goal and scope.

While methodological choices affect the entire study of an LCA, they are broadly decided during the Goal and scope phase. However, as LCA is an iterative process, it allows for feedback loops between the different stages and correcting for these when necessary. That could be, for instance, if better information is available or if the application of the study has changed.

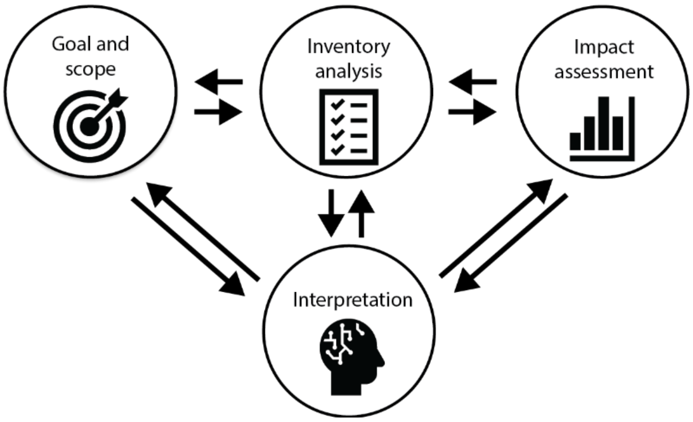


FIG 1 – Phases of an LCA.

The areas identified in the LCA methodology that significantly affect the assessment results are system boundaries; functional unit and allocation procedures; database, impact categories and impact method; and temporal, geographical and data quality considerations. These are thoroughly discussed and evaluated in the next sections.

EVALUATION OF METHODOLOGICAL CHOICES

System boundaries

ISO 14040 states that “The system boundary determines which unit processes shall be included within the LCA (…) The deletion of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study” (International Standard Organization, 2006a)”. The term “cradle to grave” involves considering a product's life cycle. However, the metallurgical industry produces many “cradle-to-gate” studies, ie from the extraction of raw materials to the semi-finished product, excluding its further transport, use and disposal, as these are often uncertain (PE International, 2014). For example, an aluminium sheet can be used in multiple applications (eg in construction, packaging or transport), over which the producer has no control. In contrast, when assessing finished products, such as home appliances, the LCA studies usually take a cradle-to-grave approach.

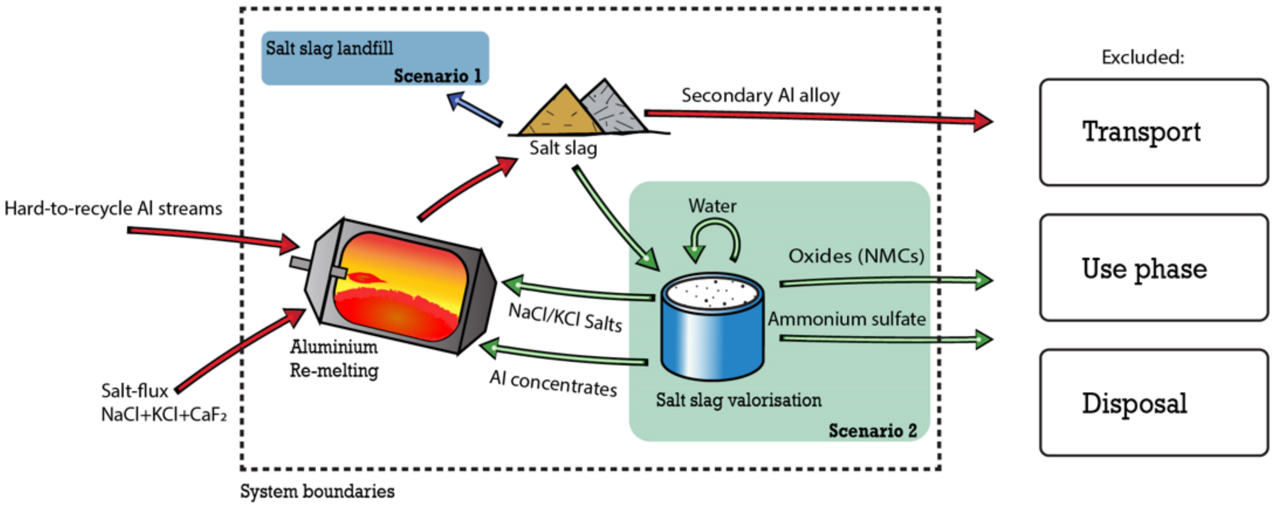


FIG 2 – The system boundaries for this study consider raw material extraction and production but exclude the use and final disposal of products. Modified from Vallejo Olivares et al. (2024).

Since this case study evaluates the production of a semi-finished product (aluminium ingots), a cradle-to-gate approach is preferred. Two different scenarios are considered:

- Scenario 1: salt slag residue is landfilled.
- Scenario 2: salt slag is processed into recycled salts recirculated in the process and NMCs and ammonium sulphates, which the cementitious and chemical industries can use further.

The inventory, or inputs and outputs translated to environmental impacts during the LCA, differs depending on the scenario and system boundaries considered and is displayed in Table 1. Note that the quantity of inputs needed when the system boundaries include the recycling of salts (Scenario 2) is generally higher. However, more by-products are also obtained by this process.

TABLE 1 – Life Cycle Inventory for treating 1 tonne of aluminium-containing waste streams.

Input/output	Unit	Scenario 1: salt slag landfill	Scenario 2: salt slag valorisation
Products			
Secondary cast aluminium product	tonne	0.70	0.72
By-product: oxides (NMCs)	tonne	-	0.35
By-product: Ammonium sulfate	tonne	-	0.033
Inputs			
Sodium chloride	tonne	0.098	0.01
Potassium chloride	tonne	0.042	0.0046
Calcium fluoride	tonne	0.0028	0.0029
Sulfuric acid	kg	-	10.22
Lime	kg	0.71	0.74
Liquid oxygen	kg	83.84	86.73
Nitrogen	kg	-	0.40
Water	m^3	0.5	1.07
Electricity	kWh	63.88	116
Heat from natural gas	kWh	670.72	917
Diesel	kg	1.04	1.41
Emissions and solid waste			
Carbon dioxide	tonne	0.170	0.233
Sulfur dioxide	tonne	0.21	0.21
Nitrogen oxides	kg	0.10	0.14
Particulates	kg	0.015	0.016
Hydrochloric acid	kg	0.019	0.020
Hydrogen fluoride	kg	0.004	0.004
Heavy metals	kg	0.0006	0.0007
Methane	kg	-	0.028
Dust	tonne	0.02	0.02
Sludge to landfill	tonne	0.53	-
Hard to recycle aluminium-containing streams	tonne	-1	-1

Regarding the last negative flow of hard-to-recycle aluminium, it implies that the evaluated process treats 1 tonne of material mix, which would otherwise be considered waste and end up handled by waste management systems. This is based on the assumption that the characteristics of the scrap mix (oxidation, contamination, low aluminium content) make it unsuitable for utilisation by other recycling processes. If treating scrap streams with a higher content of aluminium (eg used beverage containers), this flow should instead be replaced by an input of aluminium secondary material, partly decreasing the benefit of recycling aluminium through the current process. This is because the inherent value of the waste fraction makes it suitable for other recycling processes. There is also a third option, which involves the input of burden-free aluminum, leading to neither positive nor negative impacts. This is called the cut-off approach, in which only the impacts directly caused by a product are considered; in this case, the impacts caused by the collection and treatment of the scrap. The influence of these assumptions is studied later in the section “Temporal, geographical and data quality considerations”.

To compare the environmental performance of Scenario 1 and 2, the environmental burdens must be distributed among the different co-products through allocation procedures. This will be discussed in the next section, together with the functional unit.

Functional unit and allocation procedures

The functional unit (F.U.) is the reference flow to which all other inputs and outputs are scaled to.

It expresses the function of the system. For example, in a system where the production of a metal is assessed, it can relate to the mass of the product. In multi-output systems, however, selecting one functional unit is not straightforward. In our case study, the main product is the aluminium cast alloy; however, the treatment of the residue fraction is another function provided by this system.

In addition, the studied system produces other by-products: ammonium sulphates and NMCs. The inputs and outputs must be allocated among these co-products, to attribute the corresponding impact to each of them. Allocation is carried out in the following order of preference (International Standard Organization, 2006a):

1. Whenever possible, allocation should be avoided by subdividing the input and output data to each of the co-products, or by expanding the product system (system expansion approach). When two functions are provided in the same system, this last approach is equivalent to crediting the system with the impacts avoided by the alternative production of the secondary function, in the most likely way of producing it (Hauschild et al., 2018).
2. Mass allocation – allocating on a physical basis.
3. Economic allocation – allocating on a monetary basis.

The influence of selecting different functional units and allocation methods is tested in this study.

Functional unit

Regarding the functional unit, the results for the global warming impact when considering two functional units: one tonne of hard to recycle mixed scrap to treatment and one tonne of aluminium produced, are displayed in Figure 3. These functional units are tested for the two different scenarios of landfilling the salts (Scenario 1) vs. recycling them (Scenario 2).

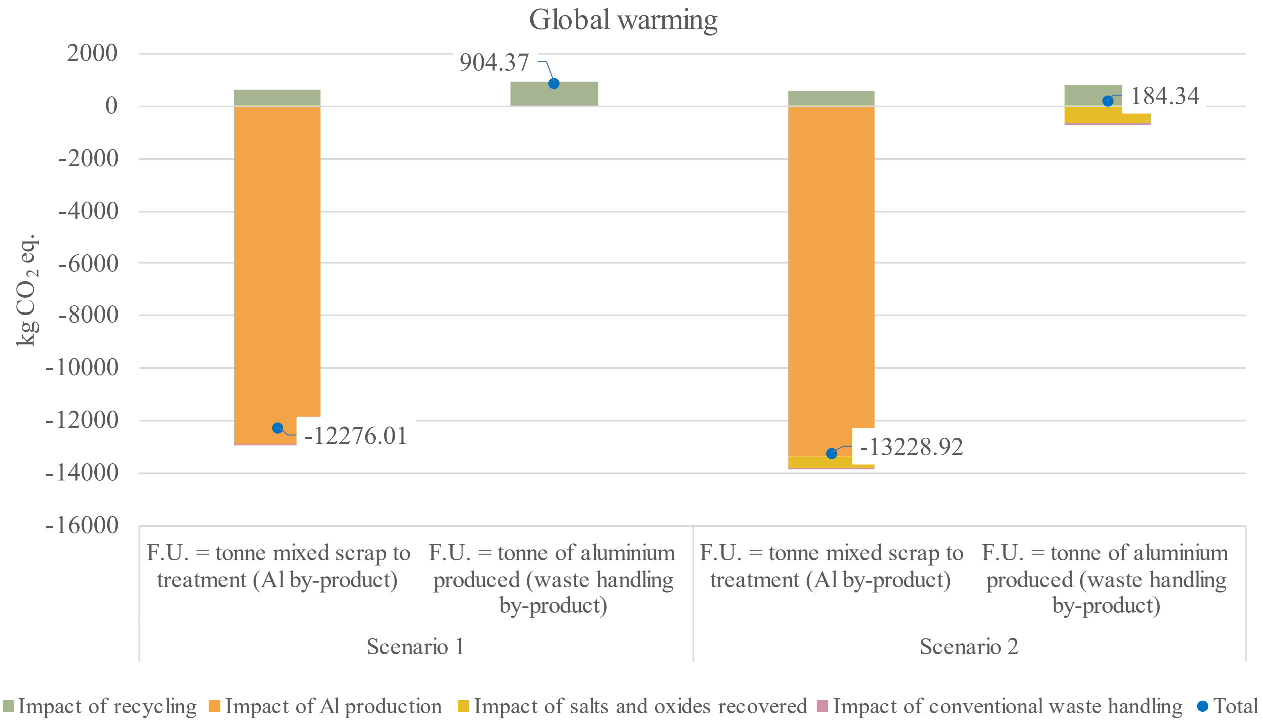


FIG 3 – Global warming impact (evaluated through ReCiPe 2016 Midpoint (H)).

In both scenarios it is observed that, when the F.U. refers to the treatment of scrap, the impact is negative, meaning an avoided impact on the environment or benefit. Following the system expansion approach, the impacts avoided are more significant than the impacts produced because the impact of the conventional means of producing aluminium (orange bar) outweighs the impact of recycling itself (green bar). Similarly, the impact of producing one tonne of aluminium is still credited with the avoided waste handling (pink bar). However, this is almost inappreciable compared to the impact of producing aluminium. When LCAs are used for comparative assertions, as is the case, the selection of the functional unit must be equivalent for all systems studied. The first F.U. could be used to compare different waste handling processes for the same waste mix, and the second F.U. could be used to compare different processes that produce a tonne of cast aluminium.

In addition, and regardless of the functional unit considered, the comparison between Scenario 1 and 2 always results in a higher benefit for the second one: the recovery of salts and oxides contributes to the negative (avoided) impact of the second scenario, being also the process yields higher, with more aluminium produced, and lowering the impact per functional unit.

Another important consideration in metallurgical systems when dealing with the functional unit is that, in many cases, we cannot compare the same material of two different qualities. For instance, we cannot develop an LCA comparing high-purity alumina extracted from bauxite through the Bayer process to the lower-purity alumina in the NMC fraction recovered from the salt-slag valorisation because their functions differ. It is also relevant to note that in many applications, mass is not a suitable unit for comparison, especially when comparing two different materials with the same functionality: in the example of producing beverage packaging, the functional unit could be set to eg a container holding half a litre of fluid. If we assess two options, aluminium and glass containers, the mass required to perform this function is not equivalent. In addition, we need to take into account that the lifetime of these containers is not equal; if, for instance, there was a return scheme in place to collect glass containers and refill them again, the same container could be used more than once, which would certainly decrease its impact over its life cycle.

When insufficient data is available, system expansion is not possible, and allocation is applied to multi-functional systems. In the next section, allocation methods are discussed.

Allocation method

As explained before, system expansion, such as in Figure 3, is prioritised by the ISO when sufficient data is available.

Whenever system expansion is not possible, the LCA practitioner can apply either mass or economic allocation, where the last is recommended for eg precious metals (PE International, 2014; Santero and Hendry, 2016). The reason behind this is that, in the case of precious metals, these are the ones driving demand and not the other co-products, and it could be unfair to credit the impact on a mass basis, given that, frequently, the less valuable co-products are found in a larger proportion.

TABLE 2 – Results for three different allocation methods (Scenario 2 – evaluated through ReCiPe 2016 Midpoint (H), for global warming impact).

Product	Mass output (per tonne mixed scrap to treatment)	Unit price	100% allocation to aluminium	Mass allocation	Economic allocation
F.U.	-	-	Aluminium cast alloy, 1 tonne	Production of 1 tonne (per product)	Production of 1 tonne (per product)
Aluminium cast alloy	0.72 tonne	1150 $	813 kg CO2 eq per tonne aluminium	533 kg CO2 eq	696 kg CO_2 eq
Oxides (NMCs)	0.35 tonne	375 $	0	533 kg CO2 eq	227 kg CO^2 eq
Ammonium sulphate	0.033 tonne	300 $	0	533 kg CO2 eq	182 kg CO_2 eq

In Table 2, it can be observed how the impact of the aluminium produced decreases when by-products are considered. The aluminium cast alloy has the lowest impact when applying mass allocation. Since it is also considered more valuable in the market, this material increases its carbon footprint with economic allocation. When a material is driving demand, one could argue economic allocation is preferable to mass allocation, especially if the difference in mass is substantial.

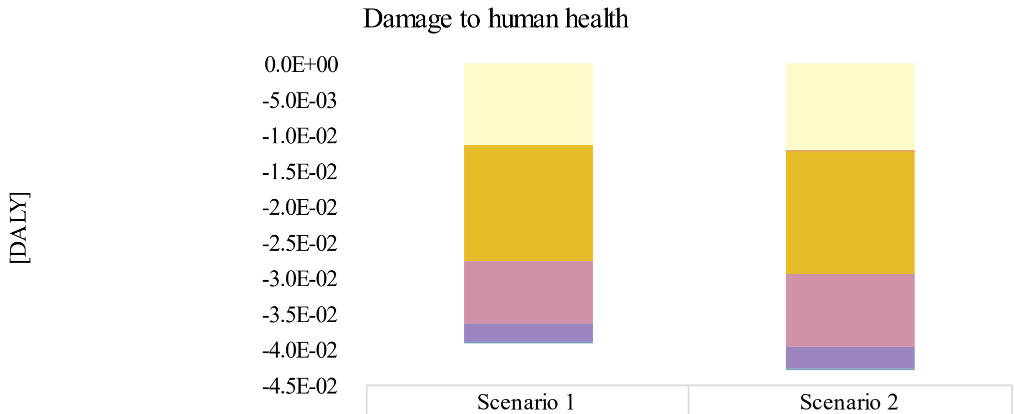
In addition to differences in the allocation method, the results of an LCA will depend on the impact categories and impact methods considered. These are treated in the next section.

Impact categories and impact methods

Previously we have been describing the different methodological choices using global warming and the ReCiPe method (2016) as an example. However, LCA is a methodology intended to study more than one environmental impact, to avoid burden shifting between impact categories, such as eg acidification or human toxicity potentials.

Impact methods are defined as the specific methodologies to convert inventory data into environmental impacts, with different spatial coverage (eg European, global…). Impact methods also look at a wide range of environmental impacts. ReCiPe, the impact method considered in this study, involves the assessment of 13 impact categories (midpoints), which are aggregated in 3 areas of protection (AoPs) or endpoints: human health, ecosystems, and resources (Huijbregts et al., 2017). In the white paper of PE International, later published by Santero et al. (PE International, 2014; Santero and Hendry, 2016), some categories such as global warming potential, acidification potential, eutrophication potential, smog potential and ozone depletion potential are recommended to be assessed by metallurgical industry, while others such as resource depletion, toxicity, land use change, and water scarcity are considered still too uncertain for the decision-making processes. However, standards and guidelines, the interest of the stakeholders, or the specific case study might broaden the consideration of impact categories.

Another way of considering impact categories is by starting the analysis with areas of protection, and then deciding which environmental impacts to include based on the impacts that have a higher effect on these. An example for the human health impact is shown in Figure 4.



	Scenario 1	Scenario 2
Water consumption, Human health	-6.52E-05	-7.27E-05
Human non-carcinogenic toxicity	-2.58E-03	-2.98E-03
Human carcinogenic toxicity	-8.68E-03	-1.04E-02
Fine particulate matter formation	-1.62E-02	-1.70E-02
Ozone formation, Human health	-2.89E-05	-3.10E-05
Ionizing radiation	-1.80E-06	-1.94E-06
Stratospheric ozone depletion	-1.64E-06	-1.80E-06
Global warming, Human health	-1.14E-02	-1.23E-02

FIG 4 – Endpoint analysis, and midpoint contribution, in ReCiPe 2016 (H). Example for human health endpoint, F.U. = tonne mixed scrap to treatment.

It is observed that the categories of global warming, fine particulate matter, and human carcinogenic toxicity significantly impact human health. Therefore, this is a relevant manner of selecting impact categories for the study. While endpoints give an overview of the impacts, the decision-maker might prefer midpoints as they are easier to communicate because these show more primary effects. It is important to emphasise that the selection of impact categories should be justified to avoid falling into greenwashing practices by just showing some impact categories that are beneficial to a process or product, especially in comparative assertions.

When midpoint categories have been selected, an in-depth analysis, also called contribution analysis, is developed in Figure 5.

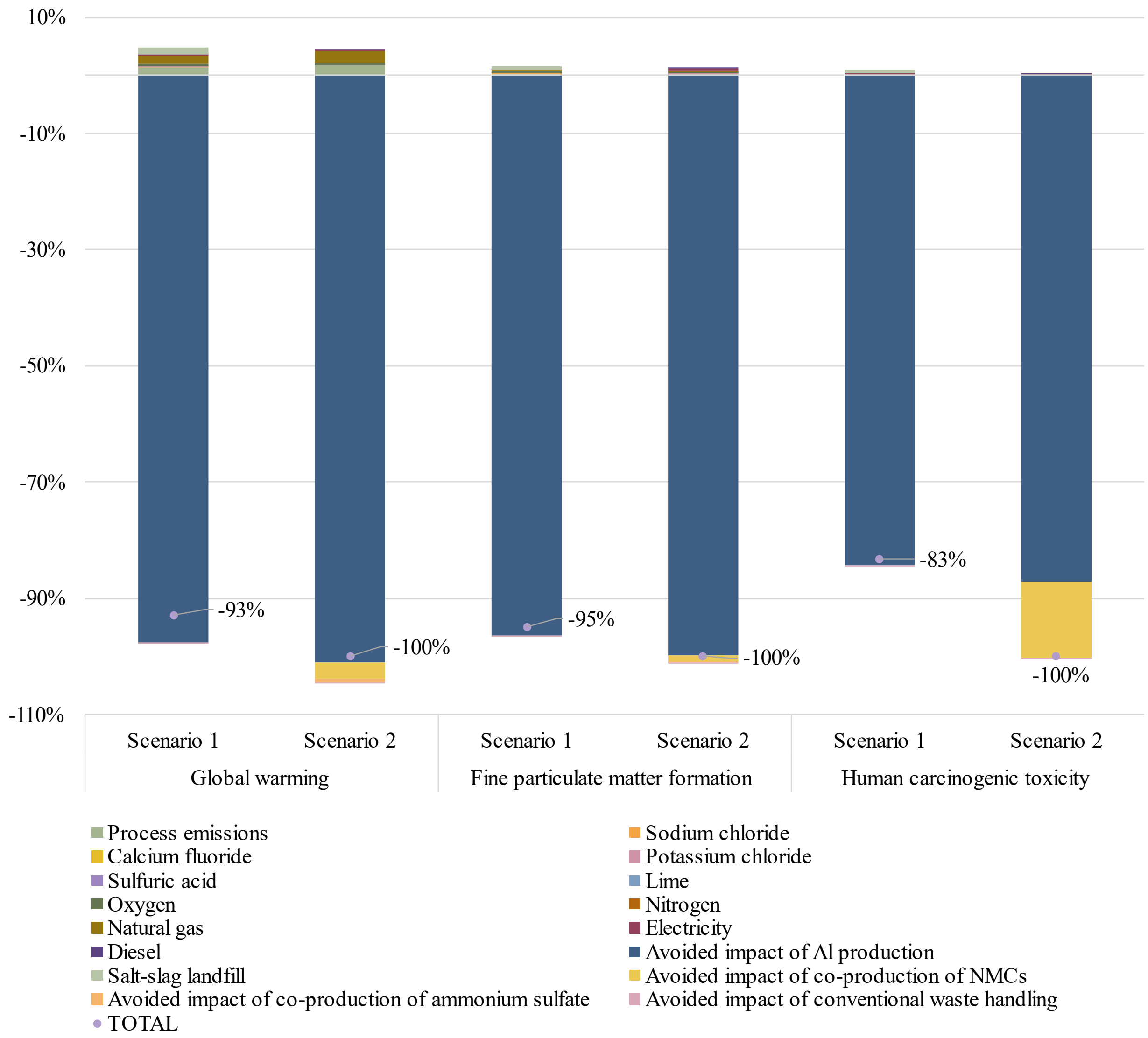


FIG 5 – Contribution analysis (ReCiPe 2016 Midpoint (H)), F.U. = tonne mixed scrap to treatment. Results are analysed further in Vallejo Olivares et al. (2024).

Temporal, geographical, and data quality considerations

In Figure 5, the avoided impacts of aluminium production stand out in all impact categories studied. Therefore, to truly understand what is driving the environmental impact, the conventional production of aluminium (cast alloy) should be analysed more closely. The initial LCA of this system (Vallejo Olivares et al., 2024) considered aluminium from the global market, and this flow was chosen in the ecoinvent 3.6 database. Running an analysis of this process in SimaPro, electricity, specifically from China, makes up for more than 44% of this material's global warming environmental impact, evidencing its reliance on the electricity mix of the country of origin. Considering China accounts for almost 90% of coal thermal power, shifting towards producing low-carbon energy sources remains one of the most significant opportunities for reducing its carbon footprint (Saevarsdottir et al., 2021).

In this regard, the geographical scope is highly relevant to determine the impact of the process. As mentioned in the previous example, the electricity source is a dominant parameter in the environmental impact of this and other production systems. Other important parameters could be related to eg the supply chain. In addition, the vulnerability of the ecosystem varies for each location; for instance, regarding water consumption, water scarcity in each territory will affect how sensitive each area is to water use. Spatial-explicit LCA, or regionalised LCA, is a growing field that, over the last decade, has assessed regional impact categories such as air pollution, particulate matter, or land use (Mutel et al., 2019).

Temporal data is also relevant in that, for instance, the average electricity mix changes and is predicted to become greener in the future (International Energy Agency, 2023). With a less carbon-intensive electricity mix, the global warming potential from processes that are dependent on energy will also decrease. Investments, the alternative use of waste materials, market considerations, and the vulnerability of the ecosystems, all might be subject to changes in the future. These are studied in different ramifications of LCA (prospective, consequential, dynamic LCAs…), which are not inside the scope of this paper but hold a significant influence in the environmental assessments of metal production and could be analysed further in future research.

Last but not least, data quality should be evaluated regarding eg the age of the data, adequacy of the process, or representativeness. Uncertainty and sensitivity analysis are crucial for assessing the effects of data quality on the LCA results. For instance, as discussed during the "System boundaries", the input of secondary aluminium could be considered of different qualities, both a material to waste management and an input of secondary aluminium to the process, considering the system expansion approach. Sensitivity to the type of aluminium input is tested in Figure 6.

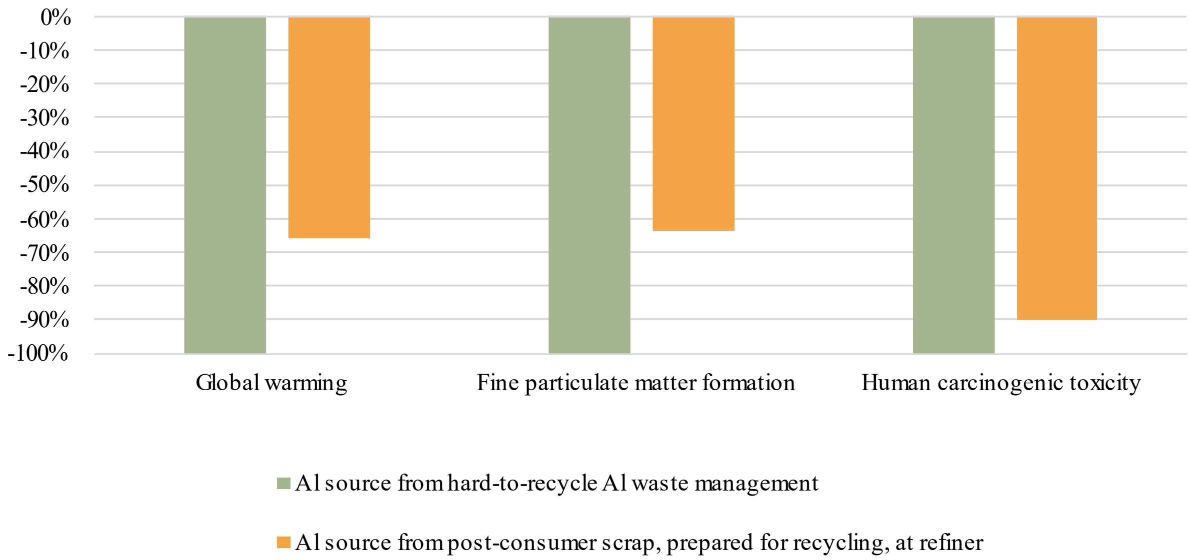


FIG 6 – Effect of different aluminium input considerations (evaluated through ReCiPe 2016 Midpoint (H)).

Even though all impact categories studied still benefited from the recycling of the waste stream, the advantage was smaller when considering an input of post-consumer Al scrap than when considering a flow of hard-to-recycle aluminium-containing streams to waste management. When considering post-consumer Al scrap, it is assumed that this flow is taken from other processes in the technosphere, and the impact of taking out this material from circulation is then added to the process under study because of the system expansion approach. When considering a waste material that is hard to recycle and assumed not currently being used by other processes, then the benefit is higher given that there is no alternative use of this material, highlighting the importance of choosing the correct data and assumptions when developing an LCA assessment of any waste flow.

CONCLUSIONS

The main conclusions and recommendations of this article are summarised below:

TABLE 3 – Relevant methodological choices recommendations summary.

System boundaries	• Depends on the object of study:
	  ○ Product oriented → usually cradle-to-grave.
	  ○ Material oriented → usually cradle-to-gate.
	• Possible to use scenario analysis to assess different configurations of the processes included in the system boundaries.

Functional unit	• Depends on the function of the system:
	  ○ Single-function, eg mass of product.
	  ○ Multifunction: F.U. accounting for material(s) produced or waste management. A key point is to always take the same functional unit for comparative assertions.
	  ○ Always comparing materials that are able to provide the same function, and that often means they present similar quality.
	  ○ Lifetime can be relevant in the comparison among products.

Allocation procedures	• Allocation can be done by:
	  ○ System expansion: prioritised, when enough data.
	  ○ Mass allocation: generally all other metals, or when the objective is assessing co-products separately.
	  ○ Economic allocation: mainly for precious metals, or if a material is driving demand.

Impact categories and impact method	• Various impact methods, depending on eg spatial coverage.
	• Selection of impact categories:
	  ○ Low uncertainty.
	  ○ Standards and guidelines.
	  ○ Interest of stakeholders.
	  ○ Effect on AoPs.

Temporal, geographical and data quality considerations	• Geographical scope: changes regarding electricity source and supply chain dominant parameters, and vulnerability of ecosystems.
	• Temporal data: influenced by future-dependant process impacts, market conditions and ecosystems changes.
	• Other data quality considerations:
	  ○ Age of data.
	  ○ Adequacy to the process.
	  ○ Representativeness.

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