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GRINS FOUNDATION

1.3.3 Environmental footprint national and regional datasets for the main Italian production systems – section c: aluminium foundries

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Executive summary

This deliverable presents the environmental footprint of aluminium production in 15 foundries located in Italy. This analysis has been conducted within the framework of the project GRINS – “*Growing Resilient, INclusive and Sustainable Extended Partnership”*. This is the third deliverable within Work Package 3 “WP 3 - To increase firms' efficiency in circular resource management along the whole value chain”, which in turn is part of Spoke 1 on Firm’s Sustainability. WP3 refers to companies' entire supply chains to assess the environmental impacts of specific sectors. e.g., agri-food and industrial clusters. It aims to support companies to adopt efficient and circular strategies/tools and sustainable, innovative solutions, facilitate the transition to industrial symbiosis models, and measure their local impacts by means of Life Cycle Assessment (LCA).

The analysis is based on primary data collected from 15 aluminium foundries. It has been carried out in accordance with the LCA methodology, as set out in ISO 14040 and ISO 14044 standards, and the Product Environmental Footprint guidelines of the European Commission.

The functional unit is defined as the production of 1 ton of aluminium, adopting cradle-to-gate system boundaries that include raw material acquisition, transport, and manufacturing processes. A total of 54 datasets were developed, covering material and energy flows, production stages, and complete production routes.

The environmental impact assessment was performed using the Environmental Footprint 3.1 life cycle impact assessment method, considering 16 impact categories and applying characterization, normalization, and weighting steps. The results show that:

- The most relevant impact categories are *Resource use, minerals and metals*, *Climate change, Particulate matter*, *Resource use, fossils*, and *Acidification*, which together account for approximately 80% of the total environmental impact.
- The melting phase represents the main environmental hotspot, dominating most impact categories.
- Among melting technologies, oxi-fuel furnaces show the lowest environmental impacts, while basin furnaces are generally more impactful.
- Differences among casting technologies are relatively limited for the majority of the impact categories, as well as for the single score indicator; high-pressure die casting overall tends to have higher impacts compared to the other solutions.
- The supply of aluminium ingots is the most significant contributor to the melting phase, and therefore to the overall environmental impacts.

The contribution analysis also highlights the importance of direct emissions (e.g., CO_2, SO_2) and critical raw materials (e.g., tellurium, copper, tin) across impact categories.

Overall, the results provide a robust and representative picture of the environmental performance of the Italian aluminium foundry sector, supporting the identification of key improvement strategies along the value chain.

List of Abbreviations

CFF	Circular Footprint Formula
EF	Environmental Footprint
ISO	International Organization for Standardization
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PEF	Product Environmental Footprint

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1 Introduction

This deliverable focuses on the life cycle impact assessment of the datasets developed in Deliverable 1.3.1 of the project GRINS, "*Growing Resilient, INclusive and Sustainable Extended Partnership*" (Grins Foundation, 2023). According to the standards ISO 14040 and ISO 14044 (International Organization for Standardization, 2022a, 2022b), which serve as the main reference framework for this study, Life Cycle Assessment (LCA) is a methodology structured into four phases: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) life cycle interpretation. In addition to the ISO standards, the Product Environmental Footprint (PEF) method developed by the European Commission is also adopted as a methodological guideline for this study (Zampori and Pant, 2019).

The goal of this study is to assess the environmental performance of aluminium production in Italy based on primary data collected from 15 foundries. Additionally, the study evaluates the environmental impacts associated with the different stages of the foundry process and identifies the main environmental hotspots within the production system.

The functional unit of this study is the production of 1 ton of aluminum. The system boundaries are defined as cradle-to-gate, encompassing raw material acquisition, transportation, and manufacturing, while excluding the use phase and end-of-life stages. This choice is justified by the fact that aluminum foundries produce intermediate products that undergo further processing in subsequent stages of the value chain. The manufacturing phase includes the following steps of the foundry process:

1. *Melting:* In the melting phase, primary or secondary aluminium alloys, in the form of ingots, are fed into a furnace powered by electricity or fuels (mainly natural gas). Internal returns of aluminium scrap (pre-consumer) are also reintroduced into the production line. The output of the furnace is molten metal ready for casting.
2. *Casting:* The molten metal exiting the furnace is cast into moulds, which may contain cores. Moulds can be either disposable or permanent. Lubricating fluids may be applied to facilitate the removal of the aluminium component from the mould. Two types of moulds are used in aluminium foundries, i.e., permanent and disposable moulds. Permanent moulds can be reused over several production cycles and are therefore considered part of the foundries' infrastructure; consequently, they are excluded from the LCIs. In contrast, disposable sand moulds are included in the analysis, as they are used only once and must be disposed of after each production cycle. Cores are also made of sand and are inserted into the moulds to create internal cavities in aluminium components.

3. *Removal:* The aluminium component is removed from the mould in which it has been cast. Removal from permanent moulds is relatively straightforward and can often be performed manually. In the case of disposable sand moulds, a vibratory machine is typically used to separate the aluminium component from the residual sand.
4. *Finishing:* Finishing operations aim to refine the surface of the aluminium component by removing irregularities and unwanted material. The finishing processes considered in this study include deflashing, deburring, and shot blasting.
5. *Quality checks*: penetrating liquids are used to detect cracks or incisions, also at the microscopic level.
6. *Thermal treatments*: Thermal treatments are performed to modify the properties of the aluminium to meet the requirements of the intended application of the component.

In this report, all post-casting operations (*Removal*, *Finishing*, *Quality checks*, *Thermal treatments*) are grouped as "Processing" steps.

Regarding the LCI phase, primary data collected from the 15 aluminium foundries that participated in the data collection campaign were used to quantify the materials and energy consumed, as well as the waste generated and direct emissions associated with each of the above-mentioned steps of the foundry process. By processing and aggregating these data, 54 datasets were generated, as described in the project Deliverable "1.3.1 LCI (Life Cycle Inventory) national and regional datasets for the main Italian production systems" and organized into three folders:

1. Materials and energy: This folder contains datasets related to material consumption, energy use, and waste management flows associated with all phases of the production process. In total, the folder includes 32 datasets.
2. Production stages: This folder contains 17 inventories associated with the different production stages of the foundry process.
3. Production process: This folder contains 5 datasets representing the overall aluminium production process as a combination of the different production stages.

Among all the datasets produced within GRINS, this report focuses on those related to the melting and casting stages, as well as on the complete production routes that incorporate melting, casting, and all subsequent processing operations. In addition, a contribution analysis is performed to identify the material and energy flows that contribute most significantly to the overall environmental impacts.

The list of datasets considered in this analysis is presented in Table 1.

Table 1: List of the datasets considered during the LCIA phase.

Dataset	**Description**
Melting process, basin melting furnace	This dataset focuses on the melting phase of aluminium ingots purchased by the foundries, considering a specific furnace technology, i.e., the "basin melting furnace."
Melting process, dry hearth furnace	This dataset focuses on the melting phase of aluminium ingots purchased by the foundries, considering a specific furnace technology, i.e., the "dry hearth furnace."
Melting process, oxi-fuel furnace	This dataset focuses on the melting phase of aluminium ingots purchased by the foundries, considering a specific furnace technology, i.e., the "oxi-fuel furnace."
Melting process, tower melting furnace	This dataset focuses on the melting phase of aluminium ingots purchased by the foundries, considering a specific furnace technology, i.e., the "tower melting furnace."
Melting process, average	This dataset focuses on the melting phase of aluminium ingots purchased by the foundries without considering a specific furnace technology. This dataset does not represent an average between the above-mentioned technologies, but rather a mix of all technologies deployed by the companies that provided data for the analysis.
Sand casting	This dataset focuses on aluminium casting, considering sand casting as a reference technology.
Gravity casting	This dataset focuses on aluminium casting, considering gravity casting as a reference technology.
Die casting, low-pressure	This dataset focuses on aluminium casting, considering low-pressure die casting as a reference technology.
Die casting, high-pressure	This dataset focuses on aluminium casting, considering high-pressure die casting as a reference technology.
Aluminium casting, average	This dataset focuses on aluminium casting, considering a weighted average across all the above-mentioned casting technologies.
Aluminium production, sand casting route	This dataset focuses on the full aluminium production process, including melting, sand casting, piece removal, shot blasting, deflashing, deburring, quality checks, and thermal treatment.
Aluminium production, gravity casting route	This dataset focuses on the full aluminium production process, including melting, gravity casting, shot blasting,

	deflashing, deburring, quality checks, and thermal treatment.
Aluminium production, low-pressure, die casting route.	This dataset focuses on the full aluminium production process, including melting, low-pressure die casting, shot blasting, deflashing, deburring, quality checks, and thermal treatment.
Aluminium production, high-pressure, die casting route.	This dataset focuses on the full aluminium production process, including melting, high-pressure die casting, shot blasting, deflashing, deburring, quality checks, and thermal treatment.
Aluminium production, average	This dataset focuses on the aluminium production process, considering a weighted average across the above-mentioned technologies differing in the casting phase.

It should be noted that all these datasets represent the foreground LCI of the study, while the background LCI is developed by linking all material and energy flows from the foreground model to secondary datasets from the ecoinvent 3.11 – cut-off database (Frischknecht and Rebitzer, 2005).

Regarding end-of-life modelling, this study follows the PEF approach (Zampori and Pant, 2019), which recommends the Circular Footprint Formula (CFF) and the allocation factor *A*. For intermediate products, the PEF methodology recommends setting the allocation factor to *A* = 1, thereby attributing the environmental impacts of recycling to the user of secondary resources. Consequently, the secondary resources consumed by the foundries carry the environmental impacts associated with their recycling processes, while the environmental burdens related to raw material extraction and primary production are attributed to virgin materials. Environmental burdens and credits are therefore linked to the recycling of output waste streams (e.g., scrap, dross, and slags). This assumption is consistent with the use of the ecoinvent 3.11 cut-off system model as the background database (Frischknecht and Rebitzer, 2005).

The LCIA phase translates the flows identified in the life cycle inventory into potential environmental impacts. During this phase, emissions to air, water, and soil, as well as resource consumption, are linked to specific environmental impact categories through scientifically established models. The LCIA phase consists of five steps: (i) selection of impact categories, category indicators and characterization models (ii), classification, and (iii) characterization, which are mandatory according to ISO 14040 and ISO 14044 (International Organization for Standardization, 2022a, 2022b), and (iv) normalization and (v) weighting, which are optional under ISO standards but recommended by the PEF guidelines (Zampori and Pant, 2019; Damiani et al., 2022).

The first step of the LCIA phase consists of selecting and justifying the impact categories, category indicators, and characterization models in alignment with the goal and scope of the study, which entails identifying the appropriate LCIA method and motivating this choice. Classification consists of assigning elementary flows from the LCI (e.g., emissions and resource uses) to the relevant environmental impact categories according to the type of environmental effect they contribute to. Characterization then quantifies potential environmental impacts by converting inventory flows into impact category indicators using characterization factors. Normalization expresses these impacts relative to a reference value, allowing the comparison of the relative magnitude of different impact categories. Finally, weighting assigns relative importance to each impact category and aggregates them into a single score to support interpretation and decision-making (International Organization for Standardization, 2022a, 2022b). Within the PEF method the normalization factors are expressed per capita based on a global value, meaning that these factors represent the total annual environmental impacts worldwide divided by the global population. Therefore, each normalization factor reflects the average yearly impact of one person for a given category (Crenna et al., 2019). On the other hand, the weighting factors applied to each impact category reflect their relative importance. In the PEF context, these factors are derived from policy priorities and expert judgment at the European level, and they express how much attention or concern is attributed to each environmental issue (Sala & Cerutti, 2018).

Since PEF is considered a reference guideline for this study, in this report, the LCIA is conducted using the Environmental Footprint (EF) 3.1 method (Zampori and Pant, 2019; Damiani et al., 2022), which considers 16 impact categories and a specific normalization and weighting set for the calculation of single score results. (Damiani et al., 2022). The LCIA results in this report are expressed in terms of characterization, normalization, and weighting.

Table 2: Impact categories included in EF method and details of the methods and indicators used to assess them. Adapted from (European Commission, 2021)

Impact category	Impact category Indicator (unit of measure)	Description
Acidification	Accumulated Exceedance – AE (mol H+ eq)	Acidification from air, water, and soil emissions (primarily sulfur compounds) mainly due to combustion processes in electricity generation, heating, and transport
Climate change	Radiative forcing as global warming potential – GWP100 (kg CO2 eq)	Increase in the average global temperature resulting from greenhouse gas emissions (GHG)
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	Impact of toxic substances on freshwater ecosystems
Particulate matter	Impact on human health (disease incidence)	Impact on human health caused by particulate matter emissions and its precursors (e.g. sulfur and nitrogen oxides)
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (kg N eq)	Eutrophication and potential impact on ecosystems caused by nitrogen and

Impact category	Impact category Indicator (unit of measure)	Description
		phosphorous emissions mainly due to fertilizers, combustion, sewage systems
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (kg P eq)	
Eutrophication, terrestrial	Accumulated Exceedance – AE (mol N eq)	
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	Impact on human health caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	
Ionising radiation	Human exposure efficiency relative to U-235 (kBq U-235 eq)	Impact of exposure to ionising radiations on human health
Land use	Soil quality index, representing the aggregated impact of land use on: Biotic production; Erosion resistance; Mechanical filtration; Groundwater replenishment (Dimensionless – pt)	Transformation and use of land for agriculture, roads, housing, mining or other purposes. The impact can include loss of species, organic matter, soil, filtration capacity, permeability
Ozone depletion	Ozone Depletion Potential – ODP (kg CFC-11 eq)	Depletion of the stratospheric ozone layer protecting from hazardous ultraviolet radiation
Photochemical ozone formation	Tropospheric ozone concentration increase (kg NMVOC eq)	Potential of harmful tropospheric ozone formation ("summer smog") from air emissions
Resource use, fossils	Abiotic resource depletion, fossil fuels – ADP-fossil (MJ)	Depletion of non-renewable resources and deprivation for future generations
Resource use, minerals and metals	Abiotic resource depletion – ADP ultimate reserves (kg Sb eq)	
Water use	Weighted user deprivation potential (m3 world eq)	Depletion of available water depending on local water scarcity and water needs for human activities and ecosystem integrity

Life cycle interpretation is the final phase of the LCA, as defined by ISO 14040 and ISO 14044 (International Organization for Standardization, 2022a, 2022b). Its purpose is to analyse and explain the results obtained from the LCI and LCIA phases in order to draw robust conclusions and support decision-making. During this phase, the results are examined to identify the main environmental hotspots, such as the most impactful processes, materials, energy flows, or life cycle stages. The interpretation also includes an evaluation of the consistency and completeness of the study, ensuring that the results are aligned with the defined goal and scope. In accordance with the ISO standards and the PEF methodology (Zampori and Pant, 2019; Damiani et al., 2022), the interpretation of the LCIA results in this study focuses on identifying the most relevant impact categories, life cycle stages, processes, and elementary flows (also called substances).

According to the PEF methodology, the most relevant impact categories shall cumulatively account for at least 80% of the total environmental impact, expressed as a single score (Zampori and Pant, 2019). In this study, the five most contributing impact categories were selected based on the dataset “Aluminium production, average”, which represents the average aluminium production route derived from the LCI modelling of all the foundries that participated in the project. These five impact categories were selected to ensure that, together, they account for at least 80% of the total environmental impact.

The most relevant life cycle stages should also be identified so that their cumulative environmental burden accounts for at least 80% of the total impact (Zampori and Pant, 2019). However, since only three life cycle stages are considered in this analysis - raw material acquisition, transport (when available), and manufacturing - the contribution analysis includes all of them. The raw material acquisition stage comprises the extraction and processing of all resources purchased by the foundries, such as ingots, minerals, additives, and gases (e.g., natural gas, argon, nitrogen, and oxygen). The transport stage includes the transportation of these materials from the producer to the foundries by lorry. The manufacturing stage encompasses all impacts directly attributable to the foundries’ activities, including direct emissions and the impacts associated with on-site electricity consumption. The contribution analysis is conducted considering only the most relevant impact categories. The most impactful processes and substances are also quantified, considering the most relevant impact categories. A contribution analysis is performed to ensure that the identified processes and substances together account for at least 80% of the overall environmental impact of the process (Zampori and Pant, 2019).

2 Life Cycle Impact Assessment

This section presents the LCIA results obtained for the datasets listed in Table 1. The results are reported in tabular form. In each table, the rows represent the different environmental impact categories corresponding to the 16 impact categories of the EF 3.1 method, listed in the first column. The second column reports the units of measurement associated with each impact category, while the remaining columns present the results for the different datasets.

For example, Table 2 reports the characterization results for the datasets "Melting process, basin melting furnace", "Melting process, dry hearth furnace", "Melting process, oxi-fuel furnace", "Melting process, tower melting furnace", and "Melting process, average". Using the same structure, Table 3 reports the characterization results for the different casting technologies, while Table 4 presents the results for the overall production routes considered in the study.

The characterized results indicate that, among the analysed melting technologies, the basin melting furnace and the dry hearth furnace generally show the highest environmental impacts across most of the impact categories. However, the relative differences between the individual technologies and the average melting process, which represents the average of all furnace types used by the participating foundries, vary considerably depending on the impact category (Table 2). As a result, more consistent comparisons between technologies can be obtained through the normalization and weighting of results. Regarding the casting phase, high-pressure die casting emerges as the most impactful technology, while sand casting generally shows the lowest environmental impact. An exception is observed for the water use impact category, which is strongly influenced by the water required for the production of sand moulds (Table 3). The aluminium production process, which includes the entire manufacturing chain, does not show significant differences among the production routes considered. This is mainly because the analysed production routes differ primarily in the casting technology, while the melting phase represents the main contributor to the overall environmental impact.

Following the same format used for the characterization results (Section 2.1), the results of the normalization (Section 2.2) and weighting (Section 2.3) are presented in Tables 5–10. The weighted results indicate that, among the specific melting technologies analysed, the oxi-fuel furnace shows the lowest overall environmental impact when expressed as a single score (Table 8). In contrast, the basin melting furnace shows comparatively higher impacts, particularly due to its high contribution to the *Eutrophication, freshwater* category. Nevertheless, the average melting process, representing the mix of all technologies used by the participating foundries, results in the lowest overall environmental burden (Table 8).

With respect to the casting phase, the analysed casting technologies show relatively similar environmental impact values, with the exception of high-pressure die casting, which exhibits higher impacts (Table 9).

Based on the "Aluminium production, average" dataset - representing the most comprehensive dataset, including data from all foundries and all process operations - the five most relevant impact categories are identified as follows:

- *Resource use, minerals and metals*
- *Climate change*
- *Particulate matter*
- *Resource use, fossils*
- *Acidification*

Together, these five impact categories account for approximately 80% of the total environmental impact of the foundry process, expressed as a single score.

2.1 Characterization

Table 3: Characterization results of aluminium melting technologies. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Melting process, basin melting furnace	Melting process, dry hearth furnace	Melting process, oxi-fuel furnace	Melting process, tower melting furnace	Melting process, average
Acidification	mol H+ eq	3.45E+01	5.50E+01	2.86E+01	4.20E+01	2.83E+01
Climate change	kg CO2 eq	5.11E+03	3.25E+03	3.21E+03	3.46E+03	2.70E+03
Ecotoxicity, freshwater	CTUe	2.14E+05	3.15E+04	2.44E+04	2.58E+04	2.26E+04
Particulate matter	disease inc.	3.21E-04	4.29E-04	2.43E-04	3.41E-04	2.43E-04
Eutrophication, marine	kg N eq	3.82E+01	4.01E+00	3.25E+00	3.61E+00	2.89E+00
Eutrophication, freshwater	kg P eq	5.81E+00	1.76E+00	1.82E+00	1.70E+00	1.61E+00
Eutrophication, terrestrial	mol N eq	5.32E+01	1.49E+02	3.73E+01	9.69E+01	3.76E+01
Human toxicity, cancer	CTUh	4.53E-06	3.13E-06	3.04E-06	3.13E-06	3.16E-06
Human toxicity, non-cancer	CTUh	3.02E-04	1.44E-04	1.48E-04	1.42E-04	1.41E-04
Ionising radiation	kBq U-235 eq	5.84E+02	2.42E+02	2.87E+02	2.17E+02	1.97E+02
Land use	Pt	2.67E+04	2.14E+04	2.09E+04	2.08E+04	1.98E+04
Ozone depletion	kg CFC11 eq	8.13E-05	8.53E-04	4.90E-04	8.06E-04	2.69E-05
Photochemical ozone formation	kg NMVOC eq	1.76E+01	1.35E+01	1.26E+01	1.32E+01	1.03E+01
Resource use, fossils	MJ	6.76E+04	4.08E+04	4.03E+04	4.37E+04	2.84E+04
Resource use, minerals and metals	kg Sb eq	1.96E-01	1.91E-01	1.87E-01	1.89E-01	1.84E-01
Water use	m3 depriv.	1.17E+03	1.60E+03	1.48E+03	1.48E+03	1.39E+03

Table 4: Characterization results of aluminium casting technologies. Referred to 1 ton of cast aluminium.

Impact category	Unit	Die casting, low-pressure	Die casting, high-pressure	Gravity casting	Sand casting	Aluminium casting, average
Acidification	mol H+ eq	8.25E-01	2.13E+00	1.03E+00	4.24E-01	1.14E+00
Climate change	kg CO2 eq	2.96E+02	5.21E+02	3.67E+02	9.03E+01	3.26E+02
Ecotoxicity, freshwater	CTUe	2.03E+03	7.50E+03	2.08E+03	6.52E+02	3.40E+03
Particulate matter	disease inc.	4.04E-06	1.87E-05	4.55E-06	5.23E-06	8.60E-06
Eutrophication, marine	kg N eq	1.90E-01	4.32E-01	2.34E-01	9.93E-02	2.46E-01
Eutrophication, freshwater	kg P eq	6.53E-02	1.20E-01	8.47E-02	3.05E-02	7.52E-02
Eutrophication, terrestrial	mol N eq	1.97E+00	3.99E+00	2.42E+00	9.54E-01	2.39E+00
Human toxicity, cancer	CTUh	9.14E-08	2.87E-07	9.32E-08	7.18E-08	1.46E-07
Human toxicity, non-cancer	CTUh	1.21E-06	8.84E-06	1.40E-06	1.66E-06	3.56E-06
Ionising radiation	kBq U-235 eq	1.38E+01	4.24E+01	1.80E+01	1.13E+01	2.19E+01
Land use	Pt	3.53E+02	1.72E+03	4.27E+02	7.08E+02	8.25E+02
Ozone depletion	kg CFC11 eq	9.93E-04	3.58E-03	9.95E-04	3.89E-05	1.59E-03
Photochemical ozone formation	kg NMVOC eq	9.82E-01	8.48E+00	1.15E+00	3.44E-01	3.09E+00
Resource use, fossils	MJ	7.19E+03	1.82E+04	8.23E+03	1.43E+03	9.41E+03
Resource use, minerals and metals	kg Sb eq	3.65E-04	3.71E-03	4.21E-04	4.28E-04	1.37E-03
Water use	m3 depriv.	1.59E+01	9.93E+01	1.95E+01	3.07E+03	6.00E+02

Table 54: Characterization results of aluminium production routes. Referred to 1 ton of aluminium product.

Impact category	Unit	Aluminium production, gravity casting route	Aluminium production, high-pressure, die-casting route	Aluminium production, low-pressure, die-casting route	Aluminium production, sand casting route	Aluminium production, average
Acidification	mol H+ eq	3.11E+01	3.22E+01	3.10E+01	3.05E+01	3.13E+01
Climate change	kg CO2 eq	3.44E+03	3.60E+03	3.38E+03	3.17E+03	3.41E+03
Ecotoxicity, freshwater	CTUe	2.60E+04	3.16E+04	2.61E+04	2.46E+04	2.75E+04
Particulate matter	disease inc.	2.62E-04	2.76E-04	2.62E-04	2.62E-04	2.66E-04
Eutrophication, marine	kg N eq	3.42E+00	3.62E+00	3.39E+00	3.28E+00	3.44E+00
Eutrophication, freshwater	kg P eq	1.81E+00	1.85E+00	1.80E+00	1.76E+00	1.81E+00
Eutrophication, terrestrial	mol N eq	4.33E+01	4.50E+01	4.31E+01	4.19E+01	4.34E+01
Human toxicity, cancer	CTUh	3.43E-06	3.63E-06	3.45E-06	3.41E-06	3.50E-06
Human toxicity, non-cancer	CTUh	1.49E-04	1.57E-04	1.49E-04	1.49E-04	1.51E-04
Ionising radiation	kBq U-235 eq	2.35E+02	2.60E+02	2.32E+02	2.29E+02	2.40E+02
Land use	Pt	2.12E+04	2.26E+04	2.13E+04	2.15E+04	2.17E+04
Ozone depletion	kg CFC11 eq	1.10E-03	3.76E-03	1.10E-03	1.17E-04	1.71E-03
Photochemical ozone formation	kg NMVOC eq	1.28E+01	2.04E+01	1.27E+01	1.20E+01	1.49E+01
Resource use, fossils	MJ	4.43E+04	5.45E+04	4.33E+04	3.74E+04	4.56E+04
Resource use, minerals and metals	kg Sb eq	1.91E-01	1.94E-01	1.92E-01	1.91E-01	1.92E-01
Water use	m3 depriv.	1.50E+03	1.58E+03	1.50E+03	4.64E+03	2.10E+03

2.2 Normalization

Table 65: Normalization results of aluminium melting technologies. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Melting process, basin melting furnace	Melting process, dry hearth furnace	Melting process, oxi-fuel furnace	Melting process, tower melting furnace	Melting process, average
Acidification		6.22E-01	9.89E-01	5.15E-01	7.55E-01	5.09E-01
Climate change		6.76E-01	4.30E-01	4.25E-01	4.58E-01	3.57E-01
Ecotoxicity, freshwater		3.77E+00	5.56E-01	4.31E-01	4.56E-01	3.99E-01
Particulate matter		5.39E-01	7.21E-01	4.08E-01	5.72E-01	4.08E-01
Eutrophication, marine		1.95E+00	2.05E-01	1.67E-01	1.85E-01	1.48E-01
Eutrophication, freshwater		3.61E+00	1.10E+00	1.13E+00	1.06E+00	9.99E-01
Eutrophication, terrestrial		3.01E-01	8.44E-01	2.11E-01	5.48E-01	2.13E-01
Human toxicity, cancer		2.62E-01	1.82E-01	1.76E-01	1.82E-01	1.83E-01
Human toxicity, non-cancer		2.35E+00	1.12E+00	1.15E+00	1.10E+00	1.10E+00
Ionising radiation		1.38E-01	5.74E-02	6.80E-02	5.15E-02	4.66E-02
Land use		3.26E-02	2.61E-02	2.55E-02	2.54E-02	2.42E-02
Ozone depletion		1.55E-03	1.63E-02	9.36E-03	1.54E-02	5.14E-04
Photochemical ozone formation		4.30E-01	3.30E-01	3.08E-01	3.23E-01	2.53E-01
Resource use, fossils		1.04E+00	6.28E-01	6.20E-01	6.73E-01	4.36E-01
Resource use, minerals, and metals		3.08E+00	3.01E+00	2.94E+00	2.97E+00	2.90E+00
Water use		1.02E-01	1.39E-01	1.29E-01	1.29E-01	1.21E-01

Table 76: Normalization results of aluminium casting technologies. Referred to 1 ton of cast aluminium.

Impact category	Unit	Die casting, low-pressure	Die casting, high-pressure	Gravity casting	Sand casting	Aluminium casting, average
Acidification		1.48E-02	3.83E-02	1.85E-02	7.63E-03	2.05E-02
Climate change		3.93E-02	6.90E-02	4.86E-02	1.20E-02	4.32E-02
Ecotoxicity, freshwater		3.58E-02	1.32E-01	3.66E-02	1.15E-02	6.00E-02
Particulate matter		6.78E-03	3.13E-02	7.64E-03	8.78E-03	1.44E-02
Eutrophication, marine		9.73E-03	2.21E-02	1.20E-02	5.08E-03	1.26E-02
Eutrophication, freshwater		4.06E-02	7.44E-02	5.27E-02	1.90E-02	4.68E-02
Eutrophication, terrestrial		1.11E-02	2.26E-02	1.37E-02	5.40E-03	1.35E-02
Human toxicity, cancer		5.30E-03	1.66E-02	5.40E-03	4.16E-03	8.46E-03
Human toxicity, non-cancer		9.37E-03	6.87E-02	1.09E-02	1.29E-02	2.76E-02
Ionising radiation		3.27E-03	1.00E-02	4.25E-03	2.69E-03	5.18E-03
Land use		4.31E-04	2.10E-03	5.21E-04	8.64E-04	1.01E-03
Ozone depletion		1.90E-02	6.83E-02	1.90E-02	7.44E-04	3.03E-02
Photochemical ozone formation		2.40E-02	2.08E-01	2.81E-02	8.42E-03	7.57E-02
Resource use, fossils		1.11E-01	2.80E-01	1.27E-01	2.21E-02	1.45E-01
Resource use, minerals and metals		5.74E-03	5.83E-02	6.62E-03	6.72E-03	2.15E-02
Water use		1.38E-03	8.66E-03	1.70E-03	2.68E-01	5.23E-02

Table 87: Normalization results of aluminium production routes. Referred to 1 ton of aluminium product.

Impact category	Unit	Aluminium production, gravity casting route	Aluminium production, high-pressure, die-casting route	Aluminium production, low-pressure, die casting route	Aluminium production, sand casting route	Aluminium production, average
Acidification		5.60E-01	5.80E-01	5.58E-01	5.49E-01	5.63E-01
Climate change		4.56E-01	4.77E-01	4.48E-01	4.19E-01	4.51E-01
Ecotoxicity, freshwater		4.59E-01	5.58E-01	4.60E-01	4.33E-01	4.84E-01
Particulate matter		4.39E-01	4.64E-01	4.40E-01	4.41E-01	4.47E-01
Eutrophication, marine		1.75E-01	1.85E-01	1.73E-01	1.68E-01	1.76E-01
Eutrophication, freshwater		1.13E+00	1.15E+00	1.12E+00	1.09E+00	1.12E+00
Eutrophication, terrestrial		2.45E-01	2.54E-01	2.44E-01	2.37E-01	2.46E-01
Human toxicity, cancer		1.99E-01	2.11E-01	2.00E-01	1.98E-01	2.03E-01
Human toxicity, non-cancer		1.16E+00	1.22E+00	1.16E+00	1.16E+00	1.18E+00
Ionising radiation		5.57E-02	6.16E-02	5.49E-02	5.42E-02	5.68E-02
Land use		2.59E-02	2.76E-02	2.59E-02	2.63E-02	2.65E-02
Ozone depletion		2.10E-02	7.18E-02	2.11E-02	2.23E-03	3.27E-02
Photochemical ozone formation		3.14E-01	4.99E-01	3.11E-01	2.94E-01	3.64E-01
Resource use, fossils		6.81E-01	8.38E-01	6.67E-01	5.75E-01	7.01E-01
Resource use, minerals and metals		3.00E+00	3.05E+00	3.01E+00	3.00E+00	3.02E+00
Water use		1.30E-01	1.38E-01	1.31E-01	4.05E-01	1.83E-01

2.3 Weighting

Table 98: Weighting results of aluminium melting technologies. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Melting process, basin melting furnace	Melting process, dry hearth furnace	Melting process, oxi-fuel furnace	Melting process, tower melting furnace	Melting process, average
Acidification	mPt	3.46E+01	3.60E+01	3.47E+01	3.41E+01	3.49E+01
Climate change	mPt	9.43E+01	1.00E+02	9.60E+01	8.83E+01	9.51E+01
Ecotoxicity, freshwater	mPt	8.83E+00	1.07E+01	8.81E+00	8.32E+00	9.29E+00
Particulate matter	mPt	3.95E+01	4.16E+01	3.94E+01	3.95E+01	4.01E+01
Eutrophication, marine	mPt	5.13E+00	5.48E+00	5.18E+00	4.97E+00	5.21E+00
Eutrophication, freshwater	mPt	3.13E+01	3.22E+01	3.16E+01	3.06E+01	3.15E+01
Eutrophication, terrestrial	mPt	9.04E+00	9.44E+00	9.10E+00	8.80E+00	9.11E+00
Human toxicity, cancer	mPt	4.26E+00	4.49E+00	4.24E+00	4.21E+00	4.32E+00
Human toxicity, non-cancer	mPt	2.13E+01	2.24E+01	2.13E+01	2.13E+01	2.17E+01
Ionising radiation	mPt	2.75E+00	3.09E+00	2.79E+00	2.71E+00	2.84E+00
Land use	mPt	2.06E+00	2.19E+00	2.06E+00	2.09E+00	2.10E+00
Ozone depletion	mPt	1.33E+00	4.53E+00	1.33E+00	1.41E-01	2.06E+00
Photochemical ozone formation	mPt	1.49E+01	2.38E+01	1.50E+01	1.41E+01	1.74E+01
Resource use, fossils	mPt	5.55E+01	6.97E+01	5.66E+01	4.79E+01	5.83E+01
Resource use, minerals and metals	mPt	2.27E+02	2.31E+02	2.27E+02	2.27E+02	2.28E+02
Water use	mPt	1.11E+01	1.17E+01	1.11E+01	3.44E+01	1.56E+01

Table 109: Weighting results of aluminium casting technologies. Referred to 1 ton of cast aluminium.

Impact category	Unit	Die casting, low-pressure	Die casting, high-pressure	Gravity casting	Sand casting	Aluminium casting, average
Acidification	mPt	9.20E-01	2.37E+00	1.15E+00	4.73E-01	1.27E+00
Climate change	mPt	8.27E+00	1.45E+01	1.02E+01	2.52E+00	9.09E+00
Ecotoxicity, freshwater	mPt	6.87E-01	2.54E+00	7.03E-01	2.21E-01	1.15E+00
Particulate matter	mPt	6.07E-01	2.81E+00	6.85E-01	7.87E-01	1.29E+00
Eutrophication, marine	mPt	2.88E-01	6.54E-01	3.54E-01	1.50E-01	3.72E-01
Eutrophication, freshwater	mPt	1.14E+00	2.08E+00	1.48E+00	5.32E-01	1.31E+00
Eutrophication, terrestrial	mPt	4.14E-01	8.37E-01	5.08E-01	2.00E-01	5.01E-01
Human toxicity, cancer	mPt	1.13E-01	3.54E-01	1.15E-01	8.86E-02	1.80E-01
Human toxicity, non-cancer	mPt	1.72E-01	1.26E+00	2.00E-01	2.38E-01	5.08E-01
Ionising radiation	mPt	1.64E-01	5.03E-01	2.13E-01	1.35E-01	2.60E-01
Land use	mPt	3.42E-02	1.67E-01	4.14E-02	6.86E-02	7.99E-02
Ozone depletion	mPt	1.20E+00	4.31E+00	1.20E+00	4.69E-02	1.91E+00
Photochemical ozone formation	mPt	1.15E+00	9.92E+00	1.34E+00	4.03E-01	3.62E+00
Resource use, fossils	mPt	9.21E+00	2.33E+01	1.05E+01	1.84E+00	1.20E+01
Resource use, minerals and metals	mPt	4.34E-01	4.40E+00	5.00E-01	5.07E-01	1.62E+00
Water use	mPt	1.18E-01	7.37E-01	1.44E-01	2.28E+01	4.45E+00

Table 1110: Weighting results of aluminium production routes. Referred to 1 ton of aluminium product.

Impact category	Unit	Aluminium production, gravity casting route	Aluminium production, high-pressure, die casting route	Aluminium production, low-pressure, die-casting route	Aluminium production, sand casting route	Aluminium production, average
Acidification	mPt	3.47E+01	3.60E+01	3.46E+01	3.41E+01	3.49E+01
Climate change	mPt	9.60E+01	1.00E+02	9.43E+01	8.83E+01	9.51E+01
Ecotoxicity, freshwater	mPt	8.81E+00	1.07E+01	8.83E+00	8.32E+00	9.29E+00
Particulate matter	mPt	3.94E+01	4.16E+01	3.95E+01	3.95E+01	4.01E+01
Eutrophication, marine	mPt	5.18E+00	5.48E+00	5.13E+00	4.97E+00	5.21E+00
Eutrophication, freshwater	mPt	3.16E+01	3.22E+01	3.13E+01	3.06E+01	3.15E+01
Eutrophication, terrestrial	mPt	9.10E+00	9.44E+00	9.04E+00	8.80E+00	9.11E+00
Human toxicity, cancer	mPt	4.24E+00	4.49E+00	4.26E+00	4.21E+00	4.32E+00
Human toxicity, non-cancer	mPt	2.13E+01	2.24E+01	2.13E+01	2.13E+01	2.17E+01
Ionising radiation	mPt	2.79E+00	3.09E+00	2.75E+00	2.71E+00	2.84E+00
Land use	mPt	2.06E+00	2.19E+00	2.06E+00	2.09E+00	2.10E+00
Ozone depletion	mPt	1.33E+00	4.53E+00	1.33E+00	1.41E-01	2.06E+00
Photochemical ozone formation	mPt	1.50E+01	2.38E+01	1.49E+01	1.41E+01	1.74E+01
Resource use, fossils	mPt	5.66E+01	6.97E+01	5.55E+01	4.79E+01	5.83E+01
Resource use, minerals and metals	mPt	2.27E+02	2.31E+02	2.27E+02	2.27E+02	2.28E+02
Water use	mPt	1.11E+01	1.17E+01	1.11E+01	3.44E+01	1.56E+01

3 Life cycle interpretation

The life cycle interpretation phase focuses on identifying the environmental hotspots of the aluminium production process.

Regarding the contribution analysis of the most relevant life cycle stages, the results indicate that raw material acquisition represents the most critical stage, followed by manufacturing. This observation holds true considering the characterization results for the most relevant impact categories (Tables 11 - 24) as well as the single score indicator (Tables 40 -53). The manufacturing stage is particularly relevant for energy-intensive processes that consume significant amounts of electricity, such as casting operations (Tables 16 – 19, 45 - 49). Conversely, raw material acquisition is the most critical life cycle stage for melting processes (Tables 11 -15, 40 - 44). Melting processes also have a considerable impact on the manufacturing stage due to direct emissions to the environment resulting from the combustion of natural gas and other fuels.

The transport stage has a low, but non-negligible, impact, relevant especially to the sand-casting phase, due to the massive amount of sand purchased from external producers and transported onsite (Tables 16, 45). The impact categories for which transport and manufacturing are most relevant are mainly those associated with energy demand, such as *Particulate matter*, *Resource use, fossils*, and *Climate change* (Table 16).

With respect to the most impactful processes, the contribution analysis clearly shows that the melting phase represents the main environmental hotspot of the production system, both considering the characterization results (Tables 30 -33) and the single score indicator (Tables 59 - 62). This phase is the largest contributor among all stages of the manufacturing chain across the most relevant impact categories, both at the characterization level and when considering the single-score indicator.

Focusing on the main sources of impact within the melting phase, the supply of aluminium ingots is by far the dominant contributor compared with other impact sources, as highlighted by Tables 25 (characterization results) and Table 54 (single score indicator) for the dataset "Melting stage, average", but the same considerations are valid for all melting technologies considered in this study. This evidence suggests that foundries should prioritize the selection of suppliers producing ingots with high recycled content to reduce the environmental impacts of the overall process.

Excluding melting, the casting phase also represents a significant contributor to the overall environmental impact, while the processing stages (e.g., deburring, deflashing, and shot blasting) generally represent minor contributors. Among these processing operations, thermal treatment shows the highest environmental impacts across the analysed categories as they figure among the most relevant contributors (Tables 30 -33, 59-62). Other notable sources of impact include the production of moulds and cores for sand casting (Tables

26, 55), as well as the consumption of lubricating oils and release agents required for die casting (Tables 29, 58).

The most impactful substances vary depending on the impact category (Table 64). For instance, tellurium, copper, and tin are the main contributors to the Resource use, minerals and metals category, while direct emissions of carbon dioxide and methane are particularly relevant for the Climate change indicator. It should be noted that this contribution analysis considers not only direct emissions but also emissions occurring throughout the entire supply chain and upstream processes. Similar considerations apply to sulphur dioxide, which is a key contributor to the Acidification impact category. Overall, tellurium, carbon dioxide, and sulphur dioxide are identified as the most impactful substances when considering the single-score indicator, which aggregates the environmental impacts across all impact categories.

3.1 Contribution analysis of the most burdening life cycle stages to the most relevant impact categories

Table 1112: Melting process, basin melting furnace. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	1.96E-01	4.96E-04	1.90E-04	1.96E-01
Climate change	kg CO2 eq	5.11E+03	1.20E+03	5.81E+01	3.84E+03
Resource use, fossils	MJ	6.76E+04	1.88E+04	8.38E+02	4.80E+04
Particulate matter	disease inc.	3.21E-04	4.19E-06	5.73E-06	3.11E-04
Acidification	mol H+ eq	3.45E+01	7.81E-01	2.67E-01	3.35E+01

Table 1213: Melting process, dry hearth furnace. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	1.91E-01	1.79E-04	2.09E-04	1.91E-01
Climate change	kg CO2 eq	3.25E+03	5.21E+02	6.39E+01	2.67E+03
Resource use, fossils	MJ	4.08E+04	2.45E+03	9.23E+02	3.74E+04
Particulate matter	disease inc.	4.29E-04	1.89E-04	6.30E-06	2.34E-04
Acidification	mol H+ eq	5.50E+01	2.76E+01	2.94E-01	2.71E+01

Table 1314: Melting process, oxi-fuel furnace. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	1.87E-01	3.33E-04	2.01E-04	1.87E-01
Climate change	kg CO2 eq	3.21E+03	5.45E+02	6.15E+01	2.60E+03
Resource use, fossils	MJ	4.03E+04	4.59E+03	8.88E+02	3.48E+04
Particulate matter	disease inc.	2.43E-04	8.18E-06	6.07E-06	2.29E-04
Acidification	mol H+ eq	2.86E+01	1.59E+00	2.83E-01	2.67E+01

Table 1415: Melting process, tower melting furnace. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	1.89E-01	1.24E-04	2.09E-04	1.88E-01
Climate change	kg CO2 eq	3.46E+03	7.02E+02	6.39E+01	2.69E+03
Resource use, fossils	MJ	4.37E+04	1.70E+03	9.22E+02	4.11E+04
Particulate matter	disease inc.	3.41E-04	1.01E-04	6.30E-06	2.34E-04
Acidification	mol H+ eq	4.20E+01	1.47E+01	2.94E-01	2.70E+01

Table 16: Melting process, average. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	1.84E-01	1.47E-05	2.14E-04	1.84E-01
Climate change	kg CO2 eq	2.70E+03	2.69E+02	6.53E+01	2.36E+03
Resource use, fossils	MJ	2.84E+04	2.03E+02	9.43E+02	2.72E+04
Particulate matter	disease inc.	2.43E-04	1.56E-05	6.44E-06	2.21E-04
Acidification	mol H+ eq	2.83E+01	2.38E+00	3.00E-01	2.56E+01

Table 1617: Sand casting. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	4.28E-04	1.91E-04	2.01E-05	2.17E-04
Climate change	kg CO2 eq	9.03E+01	4.45E+01	6.14E+00	3.97E+01
Resource use, fossils	MJ	1.43E+03	7.39E+02	8.86E+01	6.07E+02
Particulate matter	disease inc.	5.23E-06	9.43E-07	6.05E-07	3.68E-06
Acidification	mol H+ eq	4.24E-01	1.45E-01	2.82E-02	2.51E-01

Table 1718: Gravity casting. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	4.21E-04	2.98E-04	N.A.	1.23E-04
Climate change	kg CO2 eq	3.67E+02	2.89E+02	N.A.	7.86E+01
Resource use, fossils	MJ	8.23E+03	4.12E+03	N.A.	4.11E+03
Particulate matter	disease inc.	4.55E-06	3.40E-06	N.A.	1.15E-06
Acidification	mol H+ eq	1.03E+00	8.29E-01	N.A.	1.98E-01

Table 1819: Die casting, low-pressure. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	3.65E-04	2.21E-04	N.A.	1.44E-04
Climate change	kg CO2 eq	2.96E+02	2.15E+02	N.A.	8.18E+01
Resource use, fossils	MJ	7.19E+03	3.06E+03	N.A.	4.14E+03
Particulate matter	disease inc.	4.04E-06	2.53E-06	N.A.	1.51E-06
Acidification	mol H+ eq	8.25E-01	6.15E-01	N.A.	2.10E-01

Table 1920: Die casting, high-pressure. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	3.71E-03	7.18E-05	N.A.	3.64E-03
Climate change	kg CO2 eq	5.21E+02	6.99E+01	N.A.	4.51E+02
Resource use, fossils	MJ	3.71E-03	7.18E-05	N.A.	3.64E-03
Particulate matter	disease inc.	1.87E-05	8.44E-07	N.A.	1.78E-05
Acidification	mol H+ eq	2.13E+00	1.84E-01	N.A.	1.94E+00

Table 2021: Aluminium production, sand casting route. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of aluminium product.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	1.91E-01	2.26E-04	2.41E-04	1.90E-01
Climate change	kg CO2 eq	3.17E+03	4.88E+02	7.39E+01	2.61E+03
Resource use, fossils	MJ	3.74E+04	3.11E+03	1.07E+03	3.32E+04
Particulate matter	disease inc.	2.62E-04	1.88E-05	7.28E-06	2.36E-04
Acidification	mol H+ eq	3.05E+01	3.10E+00	3.40E-01	2.71E+01

Table 2122: Aluminium production, low-pressure die casting route. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of aluminium product.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	1.92E-01	4.32E-04	2.22E-04	1.91E-01
Climate change	kg CO2 eq	3.38E+03	6.89E+02	6.78E+01	2.63E+03
Resource use, fossils	MJ	4.33E+04	5.96E+03	9.79E+02	3.64E+04
Particulate matter	disease inc.	2.62E-04	2.12E-05	6.69E-06	2.34E-04
Acidification	mol H+ eq	3.10E+01	3.68E+00	3.12E-01	2.70E+01

Table 2223: Aluminium production, high-pressure die casting route. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of aluminium product.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	1.94E-01	2.77E-04	2.21E-04	1.94E-01
Climate change	kg CO2 eq	3.60E+03	5.38E+02	6.76E+01	3.00E+03
Resource use, fossils	MJ	5.45E+04	3.72E+03	9.75E+02	4.98E+04
Particulate matter	disease inc.	2.76E-04	1.94E-05	6.66E-06	2.50E-04
Acidification	mol H+ eq	3.22E+01	3.22E+00	3.11E-01	2.87E+01

Table 2324: Aluminium production, gravity casting route. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of aluminium product.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	1.91E-01	5.10E-04	2.21E-04	1.90E-01
Climate change	kg CO2 eq	3.44E+03	7.63E+02	6.76E+01	2.61E+03
Resource use, fossils	MJ	4.43E+04	7.04E+03	9.75E+02	3.62E+04
Particulate matter	disease inc.	2.62E-04	2.21E-05	6.66E-06	2.33E-04
Acidification	mol H+ eq	3.11E+01	3.89E+00	3.11E-01	2.69E+01

Table 2425: Aluminium production, average. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of aluminium product.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Resource use, minerals and metals	kg Sb eq	1.28E+01	1.96E-01	3.43E-02	1.26E+01
Climate change	kg CO2 eq	2.53E+03	4.47E+02	4.93E+01	2.04E+03
Resource use, fossils	MJ	2.90E+04	3.62E+03	6.96E+02	2.47E+04
Particulate matter	disease inc.	2.91E-02	2.96E-03	1.03E-03	2.51E-02
Acidification	mol H+ eq	6.02E+01	2.54E+01	7.93E-01	4.09E+01

3.2 Contribution analysis of the most burdening processes to the most relevant impact categories

Table 2526: Melting, average. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of aluminium product.

Impact category	Unit	Total	Ingots	Direct emissions	Pre-consumer scrap	Fuels, average
Resource use, minerals and metals	kg Sb eq	1.84E-01	1.80E-01	0.00E+00	4.21E-03	1.74E-05
Climate change	kg CO2 eq	2.70E+03	2.35E+03	2.55E+02	5.45E+01	1.15E+01
Resource use, fossils	MJ	2.84E+04	2.67E+04	0.00E+00	6.19E+02	6.61E+02
Particulate matter	disease inc.	2.43E-04	2.21E-04	1.54E-05	5.13E-06	1.47E-07
Acidification	mol H+ eq	2.83E+01	2.52E+01	2.34E+00	5.87E-01	2.75E-02

Table 26: Sand casting. Contribution analysis of the most burdening processes to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Disposable moulds	Cores	Electricity
Resource use, minerals and metals	kg Sb eq	4.28E-04	2.12E-04	1.97E-04	1.27E-05
Climate change	kg CO2 eq	9.03E+01	4.54E+01	3.11E+01	1.23E+01
Resource use, fossils	MJ	1.43E+03	7.07E+02	5.32E+02	1.75E+02
Particulate matter	disease inc.	5.23E-06	2.98E-06	1.98E-06	1.45E-07
Acidification	mol H+ eq	4.24E-01	2.39E-01	1.44E-01	3.53E-02

Table 27: Gravity casting. Contribution analysis of the most burdening processes to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Electricity	Natural gas
Resource use, minerals and metals	kg Sb eq	4.21E-04	2.98E-04	1.06E-04
Climate change	kg CO2 eq	3.67E+02	2.89E+02	6.96E+01
Resource use, fossils	MJ	8.23E+03	4.12E+03	4.00E+03
Particulate matter	disease inc.	4.55E-06	3.40E-06	8.92E-07
Acidification	mol H+ eq	1.03E+00	8.29E-01	1.66E-01

Table 28: Die casting, low-pressure. Contribution analysis of the most burdening processes to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Electricity	Natural gas
Resource use, minerals and metals	kg Sb eq	3.65E-04	2.21E-04	1.05E-04
Climate change	kg CO2 eq	2.96E+02	2.14E+02	6.96E+01
Resource use, fossils	MJ	7.19E+03	3.05E+03	4.00E+03
Particulate matter	disease inc.	4.04E-06	2.52E-06	8.92E-07
Acidification	mol H+ eq	8.25E-01	6.15E-01	1.66E-01

Table 29: Die casting, high-pressure. Contribution analysis of the most burdening processes to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Lubricating oil	Electricity	Releasing agent
Resource use, minerals and metals	kg Sb eq	3.71E-03	3.56E-03	6.27E-05	6.34E-05
Climate change	kg CO2 eq	5.21E+02	4.13E+02	6.08E+01	3.26E+01
Resource use, fossils	MJ	1.82E+04	1.67E+04	8.67E+02	3.95E+02
Particulate matter	disease inc.	1.87E-05	1.68E-05	7.15E-07	9.35E-07
Acidification	mol H+ eq	2.13E+00	1.81E+00	1.74E-01	1.17E-01

Table 30: Aluminium production, sand casting route. Contribution analysis of the most burdening processes to the most relevant impact categories. Referred to 1 ton of aluminium product.

Impact category	Unit	Total	Melting process, average	Sand casting	Thermal treatments
Resource use, minerals and metals	kg Sb eq	1.91E-01	1.90E-01	4.40E-04	1.59E-04
Climate change	kg CO2 eq	3.17E+03	2.80E+03	9.30E+01	1.27E+02
Resource use, fossils	MJ	3.74E+04	2.95E+04	1.48E+03	4.31E+03
Particulate matter	disease inc.	2.62E-04	2.51E-04	5.38E-06	1.56E-06
Acidification	mol H+ eq	3.05E+01	2.92E+01	4.37E-01	3.37E-01

Table 31: Aluminium production, low-pressure die casting route. Contribution analysis of the most burdening processes to the most relevant impact categories. Referred to 1 ton of aluminium product.

Impact category	Unit	Total	Melting process, average	Die casting, low-pressure	Thermal treatments
Resource use, minerals and metals	kg Sb eq	1.92E-01	1.91E-01	3.78E-04	1.59E-04
Climate change	kg CO2 eq	3.38E+03	2.81E+03	3.07E+02	1.27E+02
Resource use, fossils	MJ	4.33E+04	2.97E+04	7.44E+03	4.31E+03
Particulate matter	disease inc.	2.62E-04	2.52E-04	4.17E-06	1.56E-06
Acidification	mol H+ eq	3.10E+01	2.93E+01	8.53E-01	3.37E-01

Table 32: Aluminium production, high-pressure die casting route. Contribution analysis of the most burdening processes to the most relevant impact categories. Referred to 1 ton of aluminium product.

Impact category	Unit	Total	Melting process, average	Die casting, high-pressure	Thermal treatments
Resource use, minerals and metals	kg Sb eq	1.94E-01	1.90E-01	3.82E-03	1.59E-04
Climate change	kg CO2 eq	3.60E+03	2.80E+03	5.37E+02	1.27E+02
Resource use, fossils	MJ	5.45E+04	2.95E+04	1.87E+04	4.31E+03
Particulate matter	disease inc.	2.76E-04	2.51E-04	1.92E-05	1.56E-06
Acidification	mol H+ eq	3.22E+01	2.92E+01	2.19E+00	3.37E-01

Table 33: Aluminium production, gravity casting route. Contribution analysis of the most burdening processes to the most relevant impact categories. Referred to 1 ton of aluminium product.

Impact category	Unit	Total	Melting process, average	Gravity casting	Thermal treatments
Resource use, minerals and metals	kg Sb eq	1.91E-01	1.90E-01	4.33E-04	1.59E-04
Climate change	kg CO2 eq	3.44E+03	2.80E+03	3.78E+02	1.27E+02
Resource use, fossils	MJ	4.43E+04	2.95E+04	8.47E+03	4.31E+03
Particulate matter	disease inc.	2.62E-04	2.51E-04	4.68E-06	1.56E-06
Acidification	mol H+ eq	3.11E+01	2.92E+01	1.06E+00	3.37E-01

Table 34: Aluminium production, average. Contribution analysis of the most burdening processes to the most relevant impact categories. Referred to 1 ton of aluminium product.

Impact category	Unit	Total	Aluminium production, low-pressure, die casting route	Aluminium production, high-pressure, die casting route	Aluminium production, sand casting route
Resource use, minerals and metals	kg Sb eq	1.92E-01	9.81E-02	5.76E-02	3.49E-02
Climate change	kg CO2 eq	3.41E+03	1.73E+03	1.07E+03	5.80E+02
Resource use, fossils	MJ	4.56E+04	2.22E+04	1.62E+04	6.84E+03
Particulate matter	disease inc.	2.66E-04	1.34E-04	8.20E-05	4.80E-05
Acidification	mol H+ eq	3.13E+01	1.59E+01	9.57E+00	5.59E+00

3.3 Contribution analysis of the most burdening substances to the most relevant impact categories

Table 35. Aluminium production, routes. Contribution analysis of the most burdening substances to the impact category Resource use, minerals, and metals. Referred to 1 ton of aluminium product.

Substances	Unit	Aluminium production, gravity casting route	Aluminium production, high-pressure, die casting route	Aluminium production, low-pressure, die-casting route	Aluminium production, sand casting route	Aluminium production, average
Tellurium - raw	kg Sb eq	1.91E-01	1.94E-01	1.92E-01	1.91E-01	1.92E-01
Copper - raw	kg Sb eq	1.00E-01	1.02E-01	1.01E-01	1.00E-01	1.01E-01
Tin - raw	kg Sb eq	2.63E-02	2.66E-02	2.64E-02	2.62E-02	2.64E-02
Silver - raw	kg Sb eq	1.95E-02	1.96E-02	1.96E-02	1.95E-02	1.96E-02

Table 36: Aluminium production routes. Contribution analysis of the most burdening substances to the impact category Resource use, minerals, and metals. Referred to 1 ton of aluminium product.

Substances	Unit	Aluminium production, gravity casting route	Aluminium production, high-pressure, die-casting route	Aluminium production, low-pressure, die-casting route	Aluminium production, sand casting route	Aluminium production, average
Carbon dioxide - air	kg CO2 eq	3.07E+03	3.16E+03	3.01E+03	2.85E+03	3.03E+03
Methane - air	kg CO2 eq	3.26E+02	3.85E+02	3.20E+02	2.75E+02	3.31E+02

Table 37: Aluminium production routes. Contribution analysis of the most burdening substances to the impact category Resource use, fossils. Referred to 1 ton of aluminium product.

Substances	Unit	Aluminium production, gravity casting route	Aluminium production, high-pressure, die casting route	Aluminium production, low-pressure, die casting route	Aluminium production, sand casting route	Aluminium production, average
Gas, natural, 36 MJ per m3 - raw	MJ	1.96E+04	1.66E+04	1.90E+04	1.36E+04	1.73E+04
Coal, hard-raw	MJ	1.23E+04	1.21E+04	1.21E+04	1.15E+04	1.20E+04
Oil, crude, 43.4 MJ per kg- raw	MJ	6.98E+03	1.98E+04	6.93E+03	6.97E+03	1.08E+04

Table 38: Aluminium production routes. Contribution analysis of the most burdening substances to the impact category, Particulate matter. Referred to 1 ton of aluminium product.

Substances	Unit	Aluminium production, gravity casting route	Aluminium production, high-pressure, die casting route	Aluminium production, low-pressure, die-casting route	Aluminium production, sand casting route	Aluminium production, average
Particulates, < 2.5 um - air	disease inc.	1.86E-04	1.96E-04	1.87E-04	1.88E-04	1.90E-04
Sulfur dioxide - air	disease inc.	3.93E-05	4.25E-05	3.91E-05	3.88E-05	4.01E-05

Table 39: Aluminium production routes. Contribution analysis of the most burdening substances to the impact category Acidification. Referred to 1 ton of aluminium product.

Substances	Unit	Aluminium production, gravity casting route	Aluminium production, high-pressure, die-casting route	Aluminium production, low-pressure, die casting route	Aluminium production, sand casting route	Aluminium production, average
Sulfur dioxide - air	disease inc.	3.11E+01	3.22E+01	3.10E+01	3.05E+01	3.13E+01
Nitrogen oxides - air	disease inc.	2.31E+01	2.39E+01	2.31E+01	2.28E+01	2.33E+01

3.4 Contribution analysis of the most burdening life cycle stages to the single score indicator

Table 40: Melting process, basin melting furnace. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	8.79E+02	6.47E+01	5.26E+00	8.09E+02

Table 41: Melting process, dry hearth furnace. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	6.33E+02	1.06E+02	5.79E+00	5.21E+02

Table 42: Melting process, oxi-fuel furnace. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	5.41E+02	3.07E+01	5.57E+00	5.05E+02

Table 43: Melting process, tower melting furnace. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	5.95E+02	6.95E+01	5.78E+00	5.20E+02

Table 44: Melting process, average. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	4.97E+02	1.62E+01	5.91E+00	4.75E+02

Table 45: Sand casting. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	3.10E+01	3.56E+00	5.55E-01	2.69E+01

Table 46: Gravity casting. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	2.94E+01	1.86E+01	N.A.	1.08E+01

Table 47: Die casting, low-pressure. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	2.49E+01	1.38E+01	N.A.	1.11E+01

Table 48: Die casting, high-pressure. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	7.07E+01	4.17E+00	N.A.	6.66E+01

Table 49: Aluminium production, sand casting route. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	5.68E+02	3.01E+01	6.68E+00	5.31E+02

Table 50: Aluminium production, low-pressure die-casting route. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	5.63E+02	4.30E+01	6.14E+00	5.14E+02

Table 51: Aluminium production, high-pressure die casting route. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	6.08E+02	3.30E+01	6.11E+00	5.69E+02

Table 52: Aluminium production, gravity casting route. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	5.66E+02	4.78E+01	6.11E+00	5.12E+02

Table 53: Aluminium production, average. Contribution analysis of the most burdening life cycle stages to the most relevant impact categories. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Manufacturing	Transport	Raw material acquisition
Single score	mPt	5.73E+02	3.39E+02	4.37E+00	3.61E+02

3.5 Contribution analysis of the most burdening processes to the single score indicator

Table 54: Melting process, average. Contribution analysis of the most burdening processes to the single score. Referred to 1 ton of liquid aluminium.

Impact category	Unit	Total	Ingot	Melting process, average	Pre-consumer scrap	Fuels, average
Single score	mPt	4.97E+02	4.64E+02	1.52E+01	1.08E+01	1.40E+00

Table 55: Sand casting. Contribution analysis of the most burdening processes to the single score. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Disposable moulds	Cores	Electricity
Single score	mPt	3.10E+01	2.70E+01	3.07E+00	7.90E-01

Table 56: Gravity casting. Contribution analysis of the most burdening processes to the single score. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Electricity	Natural gas
Single score	mPt	2.94E+01	1.86E+01	8.47E+00

Table 57: Die casting, low-pressure. Contribution analysis of the most burdening processes to the single score. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Electricity	Natural gas
Single score	mPt	2.49E+01	1.38E+01	8.47E+00

Table 58: Die casting, high-pressure. Contribution analysis of the most burdening processes to the single score. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Lubricating oil	Electricity	Releasing agent
Single score	mPt	7.07E+01	5.64E+01	3.91E+00	8.54E+00

Table 59: Aluminium production, sand casting route. Contribution analysis of the most burdening processes to the single score. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Melting process, average	Sand casting	Thermal treatments
Single score	mPt	5.68E+02	5.14E+02	3.19E+01	1.15E+01

Table 60: Aluminium production, low-pressure die-casting route. Contribution analysis of the most burdening processes to the single score. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Melting process, average	Die casting, low-pressure	Thermal treatments
Single score	mPt	5.63E+02	5.16E+02	2.58E+01	1.15E+01

Table 61: Aluminium production, high-pressure die casting route. Contribution analysis of the most burdening processes to the single score. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Melting process, average	Die casting, high-pressure	Thermal treatments
Single score	mPt	6.08E+02	5.14E+02	7.28E+01	1.15E+01

Table 62: Aluminium production, gravity casting route. Contribution analysis of the most burdening processes to the single score. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Melting process, average	Gravity casting	Thermal treatments
Single score	mPt	5.66E+02	5.14E+02	3.03E+01	1.15E+01

Table 63: Aluminium production, average. Contribution analysis of the most burdening processes to the single score. Referred to 1 ton of cast aluminium.

Impact category	Unit	Total	Aluminium production, low-pressure, die casting route	Aluminium production, high-pressure, die casting route	Aluminium production, sand casting route
Single score	mPt	5.78E+02	2.88E+02	1.81E+02	1.04E+02

3.6 Contribution analysis of the most burdening substances to the single score indicator

Table 64: Aluminium production routes. Contribution analysis of the most burdening substances to the impact category, Single score indicator. Referred to 1 ton of aluminium product.

Substances	Unit	Aluminium production, gravity casting route	Aluminium production, high-pressure, die casting route	Aluminium production, low-pressure, die casting route	Aluminium production, sand casting route	Aluminium production, average
Tellurium - raw	Pt	1.19E+02	1.21E+02	1.20E+02	1.19E+02	1.20E+02
Carbon dioxide - air	Pt	7.81E+01	8.06E+01	7.65E+01	7.19E+01	7.69E+01
Sulfur dioxide - air	Pt	3.34E+01	3.48E+01	3.33E+01	3.29E+01	3.37E+01
Copper - raw	Pt	3.12E+01	3.15E+01	3.13E+01	3.11E+01	3.13E+01
Phosphate - Water	Pt	3.15E+01	3.21E+01	3.13E+01	3.06E+01	3.14E+01
Particulates, <2.5 um - air	Pt	2.80E+01	2.95E+01	2.81E+01	2.82E+01	2.86E+01
Nitrogen oxides - air	Pt	2.86E+01	3.00E+01	2.84E+01	2.75E+01	2.87E+01
Tin - raw	Pt	2.32E+01	2.32E+01	2.33E+01	2.32E+01	2.33E+01
Gas, natural, 36 MJ per m3 - raw	Pt	2.51E+01	2.12E+01	2.44E+01	1.75E+01	2.22E+01

4 Conclusions

This deliverable provides a comprehensive set of LCIA results representing the environmental footprint of the aluminium production in Italy based on the data from 15 foundries, presented following the ISO 14040-44 standards and the PEF guidelines.

The results clearly indicate that environmental impacts are largely driven by raw material acquisition, particularly the production of aluminium ingots, critical for the melting phase, which is the main hotspot within foundry operations. This confirms the critical role of upstream processes and the energy-intensive nature of aluminium foundries' operations.

The analysis further shows that:

- Differences among production routes are relatively limited, as they mainly vary in the casting phase, while the melting phase remains the dominant contributor.
- Among melting technologies, oxi-fuel furnaces provide better environmental performance, suggesting potential opportunities for technological optimization.
- Casting processes contribute to overall impacts but to a lesser extent compared to melting; however, high-pressure die casting is associated with higher environmental burdens.
- Downstream processing steps (e.g., finishing operations) generally have a minor impact, except thermal treatments, which can be more relevant due to energy consumption.
- Transport plays a secondary but non-negligible role, particularly due to the large volumes of materials handled (e.g., the sand used for producing moulds and cores in sand casting operations).

The contribution analysis of processes and substances highlights that:

- The production and supply of aluminium ingots dominate most impact categories.
- Direct emissions (especially carbon dioxide and sulphur dioxide) are key contributors to the impact categories *Climate change* and *Acidification* during the melting phase.
- Certain elementary flows extracted from the ground (e.g., tellurium, copper, tin) significantly influence the *Resource use, minerals and metals* category.

From a practical perspective, the findings suggest that the most effective strategies for reducing the potential environmental impacts of aluminium production include:

- Increasing the use of secondary (recycled) aluminium in input materials;
- Improving the energy efficiency of melting processes;
- Optimizing fuel use and electrification strategies;

- Enhancing process integration and material efficiency within foundries.

In conclusion, this study provides a solid scientific basis for supporting decision-making, policy development, and future research aimed at improving the environmental sustainability of aluminium production systems in Italy.

5 References

Crenna, E., Secchi, M., Benini, L., & Sala, S., 2019. Global environmental impacts: data sources and methodological choices for calculating normalization factors for LCA. International Journal of Life Cycle Assessment, 24(10), 1851–1877. https://doi.org/10.1007/s11367-019-01604-y

Damiani, M., Ferrara, N., Ardente, F., 2022. Understanding Product Environmental Footprint and Organisation Environmental Footprint methods. https://doi.org/10.2760/11564

Frischknecht, R., Rebitzer, G., 2005. The ecoinvent database system: A comprehensive web-based LCA database. J. Clean. Prod. 13, 1337–1343. https://doi.org/10.1016/j.jclepro.2005.05.002

Grins Foundation, 2023. Growing Resilient, Inclusive and Sustainable. URL https://grins.it/ (accessed 3.11.24).

International Organization for Standardization, 2022a. ISO 14040:2006 - Environmental management, Life cycle assessment, Principles and framework. URL https://www.iso.org/standard/37456.html (accessed 4.11.24).

International Organization for Standardization, 2022b. ISO 14044:2006 - Environmental management, Life cycle assessment, Requirements and guidelines. URL https://www.iso.org/standard/38498.html (accessed 4.11.24).

Sala, S., & Cerutti, A. K., 2018. Development of a weighting approach for the Environmental Footprint. https://doi.org/10.2760/446145

Zampori, L. and Pant, R., 2019. Suggestions for updating the Product Environmental Footprint (PEF) method, EUR 29682 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76- 00654-1, doi:10.2760/424613, JRC115959.