Critical Review Statement

of "Life Cycle Assessment of EGA's Primary Aluminium Ingot Production", 3rd version dated November 24, 2023, commissioned by Emirates Global Aluminium PJSC

DNV AS - Abu Dhabi ("DNV", "us" or "we") were engaged by Emirates Global Aluminium ("EGA") to provide limited assurance on the robustness of their methodology within Life Cycle Analysis (LCA) study conducted for Al Taweelah (AT), and Jebel Ali (JA) Aluminium plants, in accordance with requirements of the International Life Cycle Assessment Standards ISO 14040:2006 and ISO 14044:2006.

Our Conclusion: Based on the procedures we have performed and the evidence we have obtained, nothing has come to our attention that causes us to believe that the LCA methodology for Selected Information within EGA's LCA study is not fairly stated and has not been prepared, in all material respects, in accordance with the requirements of ISO 14040:2006 and ISO 14044:2006.

This conclusion relates only to the Selected Information, and it is to be read in the context of this Independent Limited Assurance Report, in particular the inherent limitations explained overleaf.

Our observations and areas for improvement will be raised in a separate report to EGA's Management. Selected observations are provided below. These observations do not affect our conclusion set out above.

- We recommend that EGA continues to their existing strong supplier engagement to provide primary data for unit processes in the further environmental assessment projects. A centralized data input platform for their suppliers, which enables EGA to compile, track and overview the inventory analysis for LCA model input would enhance the data quality, therefore the quality of assessments.
- We recommend that LCA model introduces a materiality assessment to decide, which transport activities to be excluded.
- We recommend that EGA considers system expansion in order to consider possible environmental credits from the utilization of pre-consumer scrap and salt slag for an improved environmental score.
- We recommend that LCA model introduces an extended sensitivity analysis over the allocation method adopted for scrap aluminum utilization.

Scope of work: Cradle to Gate (mining to casting) for aluminium products, covers the two production sites, which are located in the United Arab Emirates: EGA Jebel Ali and EGA Al-Taweelah.

- **Standard Aluminium Ingot**, three routes:
  - Total EGA Smelters (combined average of ATS and JAS),
  - ATS (site specific)
  - JAS (site specific)
- **CelestiAL Aluminium Ingot**, three routes:
  - Total EGA Smelters (combined average of ATS and JAS),
  - ATS (site specific)
  - JAS (site specific)
- **CelestiAL-R Aluminium Ingot**, three routes:
  - Total EGA Smelters (combined average of ATS and JAS),
  - ATS (site specific)
  - JAS (site specific)

System boundaries: Detailed cradle-to-gate LCA. It covers all stages of primary aluminium production (including alloys and scraps addition in casting process)

Impact Indicators:

The scope and boundary of our work is restricted to a review of the methodology within EGA's LCA system and LCA report (containing primary data for the calendar year 2022) for the Key Performance Indicators (the "Selected Information"), listed below:

- ADP (Abiotic Depletion Potential – fossil)
- EP (Eutrophication potential)
- POCP (Photochemical ozone creation potential)
- ODP (Ozone layer depletion potential)
- AP (Acidification potential)
- GWP100 (Global warming potential)

The methodology has been based on the LCA software GaBi with reference to ISO14044 principles, Aluminum sector GHG protocol and the IAI carbon footprint guidance 2018. This includes primary data from EGA sites and secondary data from upstream suppliers (with some limitations). To assess the robustness of the methodology within LCA report for the Selected Information, we reviewed EGA's LCA report system against the requirements of ISO 14040:2006 and ISO 14044:2006. We have not performed any work, and do not express any conclusion, on any other information that may be published or available on EGA's website.

Limitations: The system boundary ends after ingot casting unit process delivering primary aluminium ingot. Further shaping, dimensioning activities are out of scope of this project.

Our competence, independence and quality control

DNV established policies and procedures are designed to ensure that DNV, its personnel and, where applicable, others are subject to independence requirements (including personnel of other entities of DNV) and maintain independence where required by relevant ethical requirements. This engagement work was carried out by an independent team of sustainability assurance professionals. DNV holds other audit and assurance contracts with EGA, none of which conflict with the scope of this work. Our multi-disciplinary team consisted of professionals with a combination of environmental, LCA and sustainability assurance experience.

Standard and level of assurance

We performed a **limited** assurance engagement in accordance with the requirements of the International Life Cycle Assessment Standards ISO 14040:2006 and ISO 14044:2006. These standards require that we comply with ethical requirements and plan and perform the assurance engagement to obtain limited assurance.

DNV applies its own management standards and compliance policies for quality control, in accordance with ISO/IEC 17021:2015 - Conformity Assessment Requirements for bodies providing audit and certification of management systems, and accordingly maintains a comprehensive system of quality control including documented policies and procedures regarding compliance with ethical requirements, professional standards and applicable legal and regulatory requirements.

The procedures performed in a limited assurance engagement vary in nature and timing from, and are less in extent than for, a reasonable assurance engagement; and the level of assurance obtained is substantially lower than the assurance that would have been obtained had a reasonable assurance engagement been performed. We planned and performed our work to obtain the evidence we considered sufficient to provide a basis for our opinion, so that the risk of this conclusion being in error is reduced but not reduced to very low.

Basis of our conclusion

We are required to plan and perform our work in order to consider the risk of material misstatement of the Selected Information; our work included, but was not restricted to:

- Reviewing that the methods used to carry out the LCA studies were consistent with ISO 14044 and ISO 14040 requirements;
- Reviewing that the methods used to carry out the LCA studies were scientifically and technically valid;
- Ascertaining that the database(s) used were appropriate and reasonable in relation to the overall goal of the studies;
- Confirming that the limitations of the model and the methodology were identified and assessed;
- Assessing that the LCA methodology documentation was transparent and consistent.
- Reviewing the methodological structure in terms of general LCA methods and relation with the specific animal production systems-related methodological documents;
- Reviewing the LCA system, including the review of a case-study with application of the methodology to model the effects of feed additives on the environmental footprint of animal production;
- Reviewing the data management processes;
- Reviewing a fully implemented client project, from background processes for data gathering and modelling to final outcomes; and
- Performing limited substantive testing on a selective basis of the Selected Information to check that methodology was appropriately robust.

DNV AS - Abu Dhabi
Abu Dhabi, UAE
29th November 2023

Lead Verifier   LCA Expert   Technical Reviewer

Inherent limitations

All assurance engagements are subject to inherent limitations as selective testing (sampling) may not detect errors, fraud or other irregularities. Non-financial data may be subject to greater inherent uncertainty than financial data, given the nature and methods used for calculating, estimating and determining such data. The selection of different, but acceptable, measurement techniques may result in different quantifications between different entities. Our assurance relies on the premise that the data and information provided to us by EGA have been provided in good faith. DNV expressly disclaims any liability or co-responsibility for any decision a person or an entity may make based on this Independent Limited Assurance Report.

Responsibilities of the Directors of EGA and DNV

The Directors of EGA have sole responsibility for:

- Preparing and presenting the Selected information in accordance with the ISO 14040 and ISO 14044 requirements;
- Designing, implementing and maintaining effective internal controls over the information and data, resulting in the preparation of the Selected Information that is free from material misstatements;

Our responsibility is to plan and perform our work to obtain limited assurance on whether the methodology that sits behind the Selected Information in LCA report has been prepared in accordance with the ISO 14040:2006 and ISO 14044:2006 requirements and to report to EGA in the form of an independent limited assurance conclusion, based on the work performed and the evidence obtained. We have not been responsible for preparing any information that may be found within LCA report.

DNV Business Assurance

DNV AS - Abu Dhabi is part of DNV – Business Assurance, a global provider of certification, verification, assessment and training services, helping customers to build sustainable business performance.

Chair of Sustainable Engineering (FG SEE), Technical University of Berlin

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Life Cycle Assessment of EGA's Primary Aluminium Ingot Production

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Life Cycle Assessment according to ISO 14040/14044

Version:	3rd version (24/11/2023)
Commissioner:	Emirates Global Aluminium PJSC
Authors:	Nicolas Hübner, Prof. Dr. Matthias Finkbeiner

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List of Acronyms

ADP	Abiotic Depletion Potential
AP	Acidification Potential
CP3	Co-Product allocation approach 3 (per-flow allocation)
EGA	Emirates Global Aluminium
EP	Eutrophication Potential
GWP100	Global Warming Potential, 100 Years
IAI	International Aluminium Institute
ISO	International Standard Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ODS	Ozone-depleting Substances
ODP	Ozone Depletion Potential
POCP	Photochemical Ozone Creation Potential
TUB	Technical University of Berlin
SPL	Spent Pot Lining
W	Cut-off approach (waste flow allocation)

1 Background and Introduction

Life cycle assessment (LCA) has proven to be a valuable tool for evaluating the environmental impacts of products, processes, or services and is a topic with constantly growing interest to the global aluminium industry. Following publications for the reference years 2000, 2005, 2010 and 2015, the International Aluminium Institute (IAI) has recently conducted its latest global life cycle inventory (LCI) update for the primary aluminium industry for the reference year 2019 (IAI, 2022). The report includes a cradle-to-gate impact assessment and provides an explanation of the methodology, results and interpretation of the LCI data for aluminium products. The study has been undertaken in accordance with ISO 14040 and ISO 14044 (ISO, 2006a, 2006b), and has been critically reviewed by an independent panel of experts.

In the context of increased global environmental awareness, Emirates Global Aluminium (EGA) has an interest in knowing the environmental impact of its products. Concurrently, customer expectations move away from industry average for aluminium to supplier-specific environmental impact data. In future, more and more primary data along the supply chain will be included in the life cycle assessments of products. In order to identify the environmental impacts of EGA major product lines, TU Berlin developed 2019 a detailed EGA LCA model according to ISO 14040/44 and under consideration of the guidelines from the IAI. The purpose of the model was to describe relevant resource inputs and emissions associated with the production of primary aluminium from bauxite mining to ingot casting. This allowed first insights into the environmental hotspots and helped to establish the data collection process.

Following the LCA projects of EGA's aluminium production for the reference years 2017, 2018 and 2019, this report presents an updated version of the EGA cradle-to-gate LCA model for the reference year 2022.

2 Goal and Scope definition

The following study and report are ISO 14040/44 (ISO, 2006a, 2006b) based and conform to their requirements. The report covers the four main phases of an LCA:

1. Goal and scope – definition of the framework and objectives of the study
2. Life cycle inventory – input/output analysis of mass and energy flows from operations along the product's value chain
3. Life cycle impact assessment – evaluation of the magnitude and significance of the potential environmental impacts, and
4. Life cycle interpretation – evaluation of both the inventory and impact assessment in order to reach conclusions and recommendations.

The objective of this report is to provide the documentation for demonstrating that both the results and the procedure of their generation conform to these international standards, which is checked by a critical review conducted by an external independent expert.

In Section 2.1, the goal, the intended audience and intended application of the study are defined.

2.1 Goal of the study

The goal of the study is to assess the environmental impacts associated with the production of 1000 kilogram of primary aluminium ingot from cradle-to-gate, encompassing bauxite mining, alumina refining, electrolysis (including the production of prebaked anodes) and the ingot casting process. Primary aluminium serves as intermediate product used for diverse applications within the transportation (car, train and plane parts), construction (aluminium beams, window frames) and electrical sector (power lines) and other. They can be rolled, extruded or cast into various forms depending on the intended application. For this reason, the use phase and the End-of-Life (EoL) phase are not part of this study.

The results of the study include:

a. the inventory analysis (LCI) of primary aluminium production unit processes;
b. quantitative analysis of the environmental impacts by selected impact categories.

2.1.1 Reasons for carrying out the study

The primary reason for carrying out the study is to enable holistic quantification of the potential environmental impacts associated with the studied product. This should enable EGA to identify significant parameters influencing the environmental performance of its product and enable transparent communication with customers and the public, demonstrating the company's commitment to environmental responsibilities.

2.1.2 Intended audience

The main audience for the study results are expected to be senior management involved in decision making processes, engineers involved in research and development, the environmental department involved in the development of the LCA model and other internal EGA personnel. In addition, the study is addressed to external independent experts who perform the critical review, as well as to EGA customers and third parties who request supplier-specific environmental impact data.

EGA is responsible for passing on the study in full or in part, in response to specific requests. However, it must be ensured that the results are not detached from the context of this study, which includes its goal, scope, and methodological choices to avoid misinterpretation.

2.1.3 Intended application

The study is based on primary production data and secondary data. The results are intended to identify optimization and improvement opportunities for technology and product development within EGA. In addition to internal use, the results can also be used for external purposes outside EGA to support product level environmental reporting and as a basis for developing approaches to communicate the environmental performance of EGA aluminum to customers and other stakeholders. The present study is not intended to serve as a means for comparison and shall not be used in comparative assertions intended to be disclosed to the public.

2.2 Scope of the study

The following section describes the general scope of the study to achieve the stated goals. This includes description of the system, the functional unit and the methodological framework of the study.

2.2.1 System description

The studied product is primary aluminium ingot measured by mass, intended for further processing depending on the application. Pure aluminium is too soft and weak to act as a structural material for most purposes. To adjust its properties, aluminium is often alloyed with pure alloying elements, like magnesium or silicon, or master alloys, which consist of a base metal such as aluminium or copper combined with one or two other elements. Alloying additives are added directly to the molten metal during the ingot casting process.

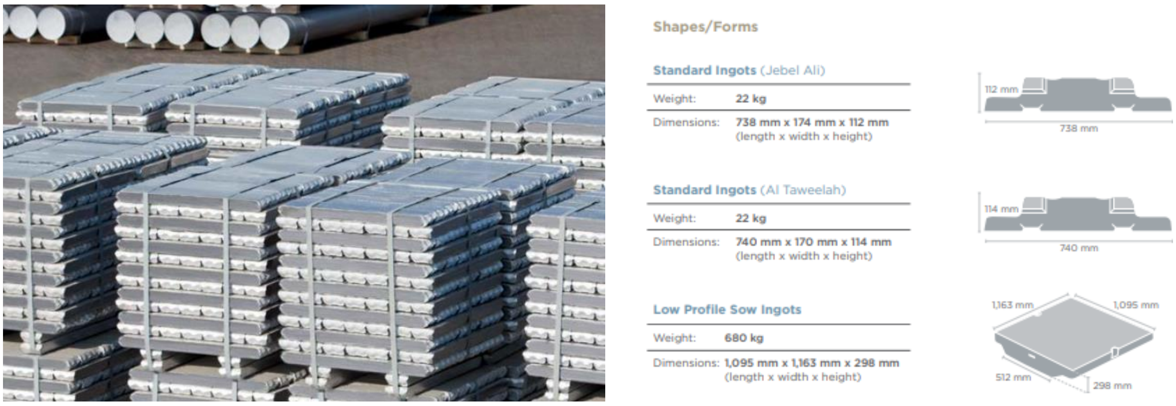

Figure 1: Primary aluminium ingot products, exemplary shapes (EGA, 2023)

The study is a cradle-to-gate LCA, that evaluates the potential environmental impacts associated with the production of primary aluminium at EGA. According to the IAI report (IAI, 2022) the primary aluminium production includes the following five unit processes:

1. Bauxite mining;
2. Alumina production (from bauxite);
3. Anode production (including production of *Prebake* anodes);
4. Electrolysis (*Prebake* technology);
5. Ingot casting (no differentiation is made between ingot forms).

There are two primary electrolysis processes used to extract aluminium from alumina: Prebake and Søderberg. The prebake process uses prebaked anodes, while the Søderberg process uses self-baking anode paste formed in the electrolysis cell during operation. Only the prebake process is used at the EGA sites.

EGA operates three production facilities in the United Arab Emirates (UAE), two at Al Taweelah (AT), Abu Dhabi and one at Jebel Ali (JA), Dubai. The Jebel Ali Smelter (JAS) and Al Taweelah Smelter (ATS) sites each include the production of prebaked anodes, the electrolysis and ingot casting process. Recently, Al Taweelah alumina refinery (ATA) was built as part of EGA's upstream expansion strategy, supplying a substantial share of the feedstock for EGA's aluminium smelters. ATA is supplied with metallurgical-grade bauxite from EGA's bauxite mining subsidiary, Guinea Alumina Corporation (GAC) in Guinea. EGA operations are mainly powered by EGA's on-site power plants at ATS and JAS. Additionally, EGA purchases some electricity from photovoltaic sources.

The remaining alumina is sourced from various suppliers around the world, including Australia, India and Vietnam. Other raw materials used in electrolysis and anode production (calcined petroleum coke, bituminous coal pitch, aluminium flouride) or in the casting process (alloying additions) are also sourced from various global suppliers. Alumina and other raw materials are delivered by sea on bulk carriers.

2.2.2 Functional unit

The function of the aluminium product offered by EGA is to serve as an intermediate material for further processing, depending on the specific application.

The detailed study is based on the functional unit of 1,000 kg of aluminium ingot at the factory gate defined by IAI (IAI, 2022). The reference period for data collection and process modelling is 2022. The reference flows for each unit process correspond to 1,000 kg of primary aluminum ingot.

The FU is not specific to a particular application or ingot form and refers to the average metal composition of the product in 2022, including alloying additives and "cold metal". Cold metal refers to remelt aluminium ingots recovered from dross recycling, internal run-around scrap (e.g. from rodding) and purchased external pre-consumer and post-consumer aluminium scrap that are added to the hot electrolysis metal input in the ingot casting process. Further, the metal composition of the FU can be adjusted according to customer requirements, allowing results to be calculated for specific metal compositions.

This report presents the results for three products with three different production routes, i.e. EGA Total (combined weighted average of 58% ATS and 42% JAS aluminium based on production volumes) and site-specific results for aluminium from Al Taweelah (AT) and Jebel Ali (JA) production routes:

1. Standard Aluminium Ingot: This refers to the average of EGA production with average metal composition (cold metal and alloying additives), using the average electricity mix.
2. CelestiAL Aluminium Ingot: This specific product represents a certain part of the standard product, which is produced exclusively with solar energy in all EGA processes and the most efficient electrolysis technology/ potline (DX+ for ATS and D18+ for JAS) available. The alumina source is alumina from the ATA refinery (using solar electricity) in all cases. CelestiAL can serve as a case study to demonstrate the results of a low-carbon product produced using the best available technology and clean energy.
3. CelestiAL-R Aluminium Ingot: This specific CelestiAL product has a different metal composition with an increased recycled content, encompassing 16% post-consumer scrap, 10% internal run-around scrap and 0% pre-consumer scrap.

The specifications of the different products on process level are summarized in Table 1.

Table 1: Process specifications of different aluminium products

Process	Standard Aluminium	CelestiAL Aluminium	CelestiAL-R Aluminium
Bauxite Mining	Average 2022 Bauxite Supply Mix	Bauxite from GAC	Bauxite from GAC
Bauxite Transport	Weighted average mix of GAC bauxite transport and average IAI Glo data	GAC mine to ATA refinery	GAC mine to ATA refinery
Alumina Production	Weighted average mix of IAI Glo and ATA refinery using the standard electricity mix of EGA	ATA refinery with solar electricity	ATA refinery with solar electricity
Alumina Transport	Weighted average transport distance of EGA suppliers	On-site delivery to ATS, Truck transport to JAS	On-site delivery to ATS, Truck transport to JAS
Anode Production	Average anode production using the standard electricity mix of EGA	Average anode production using the standard electricity mix of EGA	Average anode production using the standard electricity mix of EGA
Electrolysis	Average electrolysis including all potlines using the standard electricity mix of EGA	Potline technology with highest electrical efficiency using solar electricity	Potline technology with highest electrical efficiency using solar electricity
Ingot Casting	Average process based on the average metal composition using the standard electricity mix of EGA	Average process based on the average metal composition using solar electricity	Adapted process to produce a product with higher recycled content using solar electricity

2.2.3 System boundaries

The present study represents a detailed cradle-to-gate LCA, covering all relevant individual life cycle stages of primary aluminium production in accordance with IAI (IAI, 2022). Simplified foreground system boundaries, including selected relevant material and energy flows, are illustrated in Figure 2, exemplary for the production route (values) of AT Standard Aluminium Ingots from ATA alumina. Only the main processes and inputs are shown. In the later modeling, many more processes, energy, waste and material flows were recorded and taken into account, as described in Chapter 3.

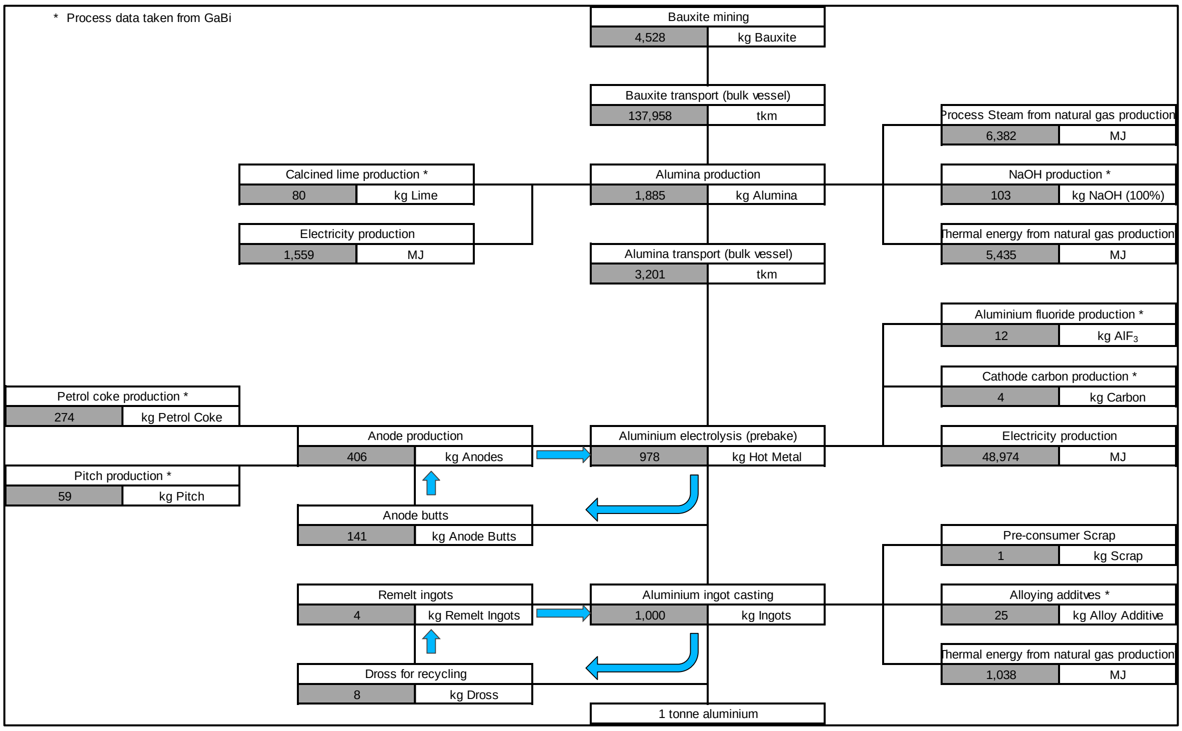

Figure 2 Simplified system boundaries, exemplary values for AT Standard Aluminium

All relevant sub-processes, i.e. production of energy, fuels and ancillary materials such as petcoke and pitch, of the life cycle phases are included in the system boundaries. In addition to the IAI report (IAI, 2022), this study also takes into account cold metal contributions and alloying additives for the ingot casting process. Dross recycling is considered based on a report by European Aluminium (EA, 2021), in which residual aluminium from the dross is separated from impurities and aluminium oxide and returned to the casting process as remelt ingot. In this process, salt is used to bind impurities and the generated salt slag can be recycled in another process, which is neglected in this study.

No specific cut-off criteria have been applied. All inputs and outputs (primary data collection) are considered according to the best knowledge. However, production equipment and infrastructure are not considered. Background data from LCA databases (GaBi and Ecoinvent) implicitly take into account the cut-off criteria used there, which is described accordingly in their public documentations (ecoinvent, 2021; Sphera, 2023).

2.2.4 Allocation procedures

There are no significant co-products associated with either of the main processes of the foreground system. Within the ingot casting process, however, the inclusion of scraps (cold metals) from other product systems leads to allocation issues.

In the dross recycling process, salt is used to bind impurities, producing significant amounts of salt slag in addition to the recovered remelted aluminium ingots. A subsequent salt slag recycling process typically recovers three value-added products, including recycled aluminium, fluxing salts, and aluminium oxide (EA, 2021). In this study, the recycling process is not modelled with regard to missing data and the environmental impacts associated with dross recycling are entirely attributed to the recovered remelt ingot. For future assessments, it is recommended that the salt slag recycling process be included through system expansion and that substitution benefits be considered to avoid the need for allocation.

For purchased pre-consumer scrap, the model considers different allocation approaches based on the unpublished "Reference document on how to treat pre-consumer scrap flows in carbon footprint calculations for aluminium products" prepared for IAI in 2022 (Solinnen, 2022), treating pre-consumer scrap either as a co-product of the semis production or as a secondary material recovered from another product system. The following 10 approaches for cradle-to-gate carbon footprint calculations are modelled:

1. **Co-product allocation:** pre-consumer scrap is treated as co-product and carries the emissions of the product it comes from based on:
    - Mass allocation (CP1)
    - Economic allocation (CP2)
    - Per-flow allocation (CP3)
2. **Cut-off approach:** pre-consumer scrap is considered burden-free, and the product which generated scrap carries the emissions of producing both the aluminium used in the product and the one ending up as scrap
    - Pre-consumer scrap is treated as a waste (W)
3. **Substitution approach:** a recycling credit is calculated when pre-consumer scrap is generated, and an equivalent burden is given to the scrap when used as an input for the next product:
    - Pre-consumer scrap can directly substitute primary aluminium:
        - Credit based on virgin aluminium used at scrap generator (SM1.1.)
        - Credit based on virgin aluminium used at scrap remelter (SM1.2.)
        - Credit based on average virgin production at global/continental/regional level depending on the scope of the study (SM1.3.)
    - Pre-consumer scrap must be remelted into an ingot before reaching the point of substitution with primary aluminium:
        - Credit based on virgin used at scrap generator (SM2.1.)
        - Credit based on virgin used at scrap remelter (SM2.2.)

- Credit based on average virgin production at global/continental/regional level depending on the scope of the study (SM2.3.)

Post-consumer scrap is considered as burden-free (zero burden allocation), following the recommendations of the IAI (Solinnen, 2022).

Internal scrap is recycled in a closed loop during the ingot casting process and does not require the definition of allocation approaches for the standard products. However, for CelestiAL-R Aluminium, a greater amount of internal scrap from EGA is used than is generated during their production. This additional internal scrap from the production of the Standard Aluminium is allocated a burden based on the respective Standard Aluminium ingot casting process impacts, which are allocated by mass to the scrap flow. This takes into account the increased throughput of the casting process, which in turn leads to a corresponding increase in environmental impacts.

For alumina production modeled with IAI data, the allocation procedure outlined in the IAI report applies, where data from refineries producing both metallurgical and non-metallurgical grade alumina are allocated on a mass basis (IAI, 2022).

For the allocation methods used in the generic datasets of LCA databases, see their respective documentation (ecoinvent, 2021; Sphera, 2023).

2.2.5 Life cycle impact assessment (LCIA)

During LCIA, inventory data is classified and characterized using LCIA methods to derive potential environmental impacts. The LCIA method for this study is CML 2001 (Jan 2016) created by the Centrum voor Milieukunde of the University of Leiden. Six midpoint impact categories according to recommendations of the IAI are selected as listed below.

Table 2: Selected LCIA categories

Impact category	Unit	Characterization factor	Abbreviation
Climate Change	[kg CO_2 eq.]	Global Warming Potential	GWP 100
Acidification	[kg SO_2 eq.]	Acidification Potential	AP
Ozone Layer Depletion	[kg R11 eq.]	Ozone Layer Depletion Potential	ODP
Photooxidant creation	[kg Ethene eq.]	Photochemical Ozone Creation Potential	POCP
Eutrophication	[kg Phosphate eq.]	Eutrophication Potential	EP
Abiotic Depletion (fossil)	[MJ]	Abiotic Depletion Potential (fossil)	ADP fossil

The optional components of the LCIA (normalization, weighting) are not performed in this study due to their subjective nature.

LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

2.2.6 Data requirements

The data requirements adopted in the study follow the guidelines provided by ISO 14044 and are listed in Table 3. The specific data sources and the procedures for data collection and for dealing with data gaps are described in detail in Section 3. The uncertainty of information is discussed within the context of assumptions in 2.2.7.

Table 3: Data requirements of the study based on ISO 14044 (ISO, 2006b)

Parameter	Description	Requirements
time-related coverage	age of data and the minimum length of time over which data should be collected	The reference year of the study is 2022. The data used is from 2015 to 2023. The primary data is collected for 2022 or for 2019. The generic data used are IAI data for the reference years 2019 and 2015 and data from Gabi (2023.2 version) and Ecoinvent (3.8) database. It has been ensured that the used datasets are not older than 10 years and that they are valid for the year 2022.
geographical coverage	geographical area from which data for unit processes should be collected to satisfy the goal of the study	The study relates to aluminium produced at the JAS site in Dubai and the ATS site near Abu Dhabi in the UAE. Nonetheless, the supply chain is globally distributed and EGA draws alumina and other intermediate materials from diverse sources worldwide. If possible, the secondary data selected reflects the respective geographical origin of the materials supplied. In case of no country-specific dataset being available, suitable proxies may be adopted, including cross-regional (GCC, GLO, EU) averages or data of other countries.
technology coverage	specific technology or technology mix	The datasets reflect the current state of the art aluminium production using prebake technology. For alumina production, process data is included for refineries only, that produce metallurgical grade alumina from bauxite ore, as described by IAI (IAI, 2022).
precision	measure of the variability of the data values for each data expressed	The highest level of precision is ensured by using specific primary data from EGA and suppliers, where available, and secondary data collected by IAI specifically for the primary aluminum industry. (IAI, 2022).
completeness	percentage of flow that is measured or estimated	All relevant, specific processes and flows according to the IAI and EA report are considered and modeled to represent the examined system.

		Simple data verifications, such as through mass balances, are conducted. The plausibility of the data is checked using data from the previous project for 2019 and IAI data.
representativeness	qualitative assessment of the degree to which the data set reflects the true population of interest (i.e., geographical coverage, time period and technology coverage)	The data meets the defined temporal, geographical, and technological scope and is collected in accordance with the IAI methodology.
consistency	qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis	The chosen methodology is consistently applied to all components of the analysis. Consistency of the primary data from EGA and suppliers was ensured through bilateral discussions between TU Berlin and EGA and by using only primary data with the same level of detail.
reproducibility	qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study	The data and methodology outlined in this report are intended to facilitate internal reproducibility for EGA, using the compiled data. It's important to note that due to confidentiality considerations, not all process data is fully disclosed. As a result, the general methodology, while transparent and reproducible, cannot be replicated in detail by external parties, but can certainly be replicated using the IAI data.
sources of the data		The data is sourced from EGA and suppliers, the IAI report and LCA databases.

2.2.7 Assumptions and limitations

The assumptions and limitations of the IAI model and guidelines apply to this study as well (e.g. data quality, reporting rates, modeling and background data). See the IAI report for details (IAI, 2022). Uncertainties arise from the use of average secondary data due to a lack of primary data for certain suppliers and auxiliary processes.

It is important to acknowledge that these assumptions and limitations may have significant implications for the results and the results are only valid for this specific study.

Limitations:

Neglected processes due to missing primary data and non-coverage of IAI guidelines/data include filter dust recycling and salt slag recycling in the dross recycling model for the ingot casting unit process and Spent Pot Lining (SPL) recycling for the electrolysis unit process.

Transport of several auxiliary materials, i.e. steel, aluminium fluoride, pitch, caustic soda, calcined lime and refractory, and of alloying additives (except for silicon and magnesium, which represent 90% by weight of alloying additives) is neglected due to a lack of exact supply origin information.

While the impacts of these processes are expected to be small, it is recommended to consider them in future projects.

<u>Data quality:</u>

Primary Data:

All reported survey data was checked systematically, comparing it to data from the 2019 project and with IAI data, data with significant deviations from one of those was queried and rechecked with suppliers or EGA for confirmation.

Secondary data:

For secondary data from Sphera and Ecoinvent databases, result accuracy is related to the quality and robustness of these datasets.

Proxy datasets were used when required datasets were unavailable. Some processes had to use regional data sources with limited regional representativeness (e.g. Glo, RER, DE), as indicated when occurred. *RER: Tap water from groundwater* is utilized as a proxy dataset for modelling the freshwater from desalination for the ATA refinery, as no LCA dataset was available for fresh water from desalination. This may not reflect the full environmental impact. Groundwater and desalinated water are distinct water sources with different environmental implications and desalination may have higher energy requirements and associated emissions.

Further, there are inconsistencies between Sphera and Ecoinvent datasets; some Ecoinvent datasets used to model certain alloying components have ODP values several orders of magnitude higher than comparable Sphera datasets. Small quantities of titanium salt and strontium therefore contribute to a significant ODP increase compared to 2019 project data. It should be noted that international agreements like the Montreal Protocol eliminated many ozone-depleting substances (ODS) (UNEP, 2023). Therefore, even minor increases can lead to substantial relative ODP increases due to the low baseline values resulting from the Protocol's success in reducing ODS.

2.2.8 Interpretation

The interpretation of the results was conducted using the following steps recommended by the ISO standard. Significant aspects were identified based on life cycle inventory and life cycle impact assessment results. A data quality discussion, completeness assessment, sensitivity analysis and consistency check are also presented and discussed in this report. Conclusions are presented, along with study limitations and recommendations.

2.2.9 Critical review

The study has undergone a third-party critical review according to ISO 14040/14044 (ISO, 2006a, 2006b) and ISO TS 14071 (ISO, 2014), carried out by independent external experts from DNV Group, to ensure the consistency and validity of this report.

The review was performed upon submission of a first draft of the report. The review includes a review of data and methodology. The review statement is included in the Appendix of this report.

2.3 Type of the report

The current report serves as a documentation of the described LCA study, as a basis for the critical review, as well as a technical report for internal use within EGA. If applicable, extracts and results of the report can be edited in accordance to target groups' requirements and further published. The results and conclusions are only valid for the specific LCA study performed.

3 Life Cycle Inventory (LCI)

The following chapters provide information on the modelling of the differentiated process modules, the process/inventory data used, and the life cycle inventory results of relevant subprocesses.

3.1 Data basis

For the purposes of the present study, data used includes a mixture of measured, calculated and estimated data. The primary data collection procedure was established in previous projects. The main data sources are primary data directly provided by EGA and suppliers.

The study object represents a state-of-the-art primary aluminium production. Along the presented life cycle in chapter 2.2.1 EGA is directly involved in all steps 1-5 from bauxite mining to ingot casting. Primary process data for EGA operations encompassing GAC bauxite mining, ATA alumina refining, ATS/JAS power generation, electrolysis (including anode production) and ingot casting, are reported by EGA. This includes the products and by-products generated, consumptions of materials and energies, emissions to water and air, and generation of waste.

Detailed data collection sheets for Life Cycle Inventory (LCI) were developed by TU Berlin considering the goal and scope (functional unit, systems boundaries) and data requirements defined.

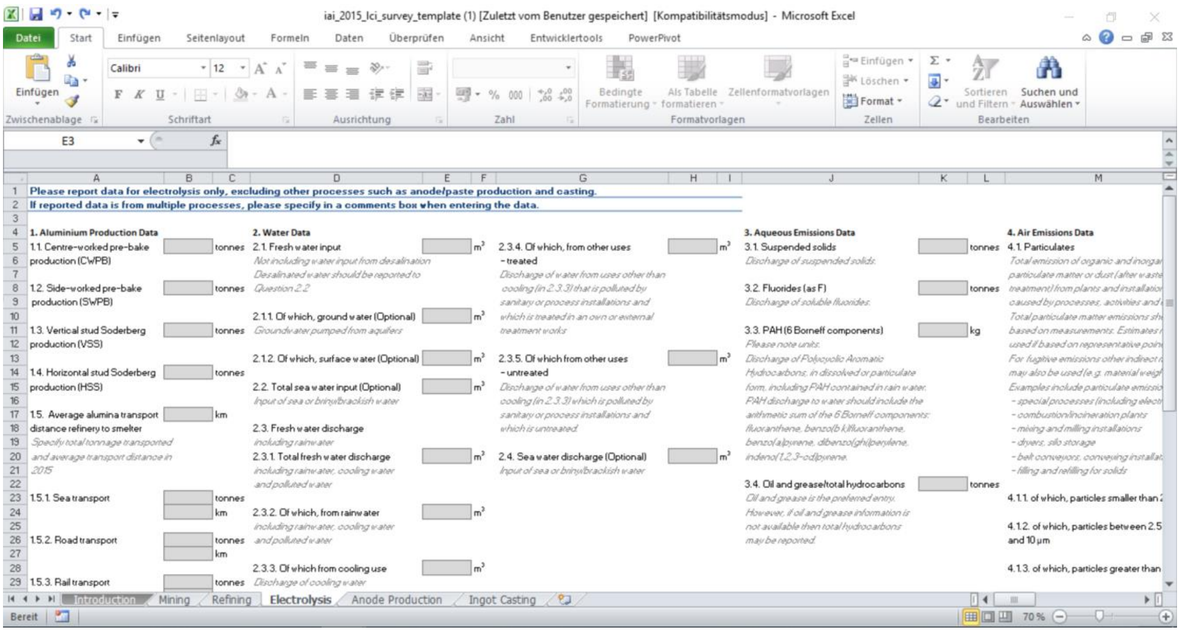

Figure 3 Exemplary data collection sheet

The templates include the input and output data of the respective unit process in 2022 and are based on the following surveys from IAI (see Figure 3):

- IAI LCI Survey
- IAI Smelter Anode Energy Survey
- PFC Survey
- Energy Survey (Energy generation including all turbines)

Incomplete data is supplemented by IAI average 2019 LCI data from the 2022 report (IAI, 2022), with priority given to the Gulf Cooperation Council (GCC) region, followed by global (GLO) averages (IAI, 2022). For the extension of the ingot casting process, data was collected for the following input materials with specific surveys:

- Run-around/internal scrap refers to scrap generated at the same process that consumes the scrap (e.g., cast house scrap),
- Pre-consumer scrap refers to scrap within the supply chain after the smelter/casthouse, includes scrap from fabrication and manufacturing,
- Aluminium remelts recovered from Dross/skimmings,
- Post-consumer scrap refers to scrap resulting from collection systems after an aluminium product has been used and scrapped.

In addition, a detailed data collection sheet for the origin and exact compositions of purchased alloying elements and master alloys (metals and metalloids) was elaborated by TU Berlin.

The production of auxiliary materials and purchased alumina is performed by suppliers. Primary data from suppliers was requested using data collection surveys developed by TU Berlin. As part of the data collection hierarchy, if no new data was available, primary data from the previous project in 2019 was utilized, as it was assumed that processes had not undergone significant changes. When responses were lacking, data for bauxite mining and alumina production and industry-specific energy mixes was sourced from IAI Global (GLO) average data. Several background processes (indirect upstream and downstream processes) including the production of the certain auxiliary materials, alloying elements and energy carriers as well as transport and disposal processes are modelled using GaBi (content version: 2023.2) and Ecoinvent (3.8) database (ecoinvent, 2021; Sphera, 2023).

The comprehensive LCI data, detailing inputs, outputs, and their respective data sources for each process, can be found in the enclosed Appendix A. The following chapter discusses the modelling in LCA software.

3.2 Modelling

The LCA model and the calculation have been performed using Sphera's LCA for Experts 10.7.1.28 software system (Sphera, 2023). The process modules distinguished in chapter 2.2.1 are considered. The modelling of the individual subprocesses was implemented based on all available information (secondary and primary data). The following chapters explain the modelling of the subprocesses in the different process modules. There are 4 connected plans for the general life cycle stages of EGA Total Aluminium products: (1) Bauxite mining and alumina production, (2) Transport of Alumina, (3) Prebake Electrolysis, (4) Ingot casting. Each plan is a mix of sub-plans for different production pathways scaled by production volume, e.g. the electrolysis plan contains one plan for each site (42% JAS and 58% ATS), and each pathway contains further sub-plans with processes, e.g. the ingot casting plan for ATS contains plans for the production of master alloys, external dross recycling, electricity from EGA power plant or pre-consumer scrap.

3.2.1 Energy production

The EGA JAS and ATS production facilities are powered by on-site combined cycle gas turbine plants and minor shares (3.3% for ATS and 0.3% for JAS) of purchased electricity from photovoltaic sources. The ATA refinery is also powered by the ATS power plant. Combined heat and power (CHP) turbines along with heat recovery units (steam turbines) are utilized to generate electricity from natural gas. CelestiAL products are produced using exclusively solar electricity as power source for EGA facilities.

Primary data has been collected for all electricity-producing turbines, including the units gas consumption, electrical output, and fuel combustion emissions to air (Carbon dioxide CO2, Carbon monoxide CO, Nitrogen oxide NOx and Sulphur dioxide SO2). Using this data, the turbines are modelled by adapting the parameters of the Sphera process *Electricity and thermal energy from CHP*. Methane (CH4), Nitrous oxide (N2O) and dust (PM2.5) emission data is taken from the Sphera dataset. The efficiency and percentage share of total output is calculated for each turbine based on the unit's gas consumption and output. EGA sources a mix of natural gas from UAE (85%) and Quatar (15%). The energy mix for ATS and JAS are modelled as a weighted average based on the percentage shares from all sources. In the absence of primary and country-specific data, solar power was modelled using Sphera process *TR: Electricity from photovoltaics* for Turkey as a proxy. Figure 4 shows the GaBi model for the ATS factory electricity mix based on 100 MJ of electricity.

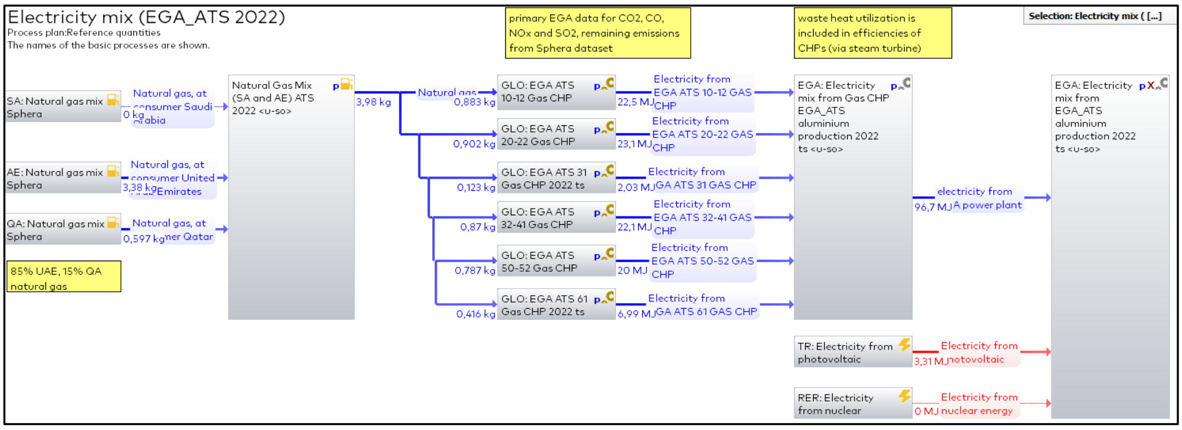

Figure 4: Electricity mix model for EGA ATS site

Thermal energy for EGA operations is modelled by Sphera process *SA: Thermal energy from natural gas* for Saudi Arabia, process steam is modelled by *RER: Process steam from natural gas 90%* for Europe, which are considered as approximations of geographic origin due to lack of data for UAE.

For non-ATA bauxite mining and alumina production, a global electricity mix was established by weighting regional power consumption shares from IAI surveys. Regional mixes, using proxy GaBi datasets (e.g., South Africa for Africa), were created based on energy carrier types (e.g., hydro, coal, natural gas, nuclear and other renewables), considering the specific consumption mix for the aluminium industry in each region, and the global mix is an average of these regional mixes. Such an electricity mix model was provided by IAI with data from the 2015 survey. For the purpose of this study, this model has been updated with data from the latest IAI 2019 survey. For detailed information (e.g. regional shares, energy source shares) on the power model, refer to the IAI report (IAI, 2022).

Similarly, for thermal energy production, industry-specific mixes are modelled for each energy source at the global level, utilizing data from the 2015 survey in absence of accessible data from the 2019 survey.

3.2.2 Production of auxiliary and intermediate materials

The various processes use a variety of auxiliary and intermediate materials, which are delivered by suppliers to the EGA sites. Wherever possible, primary data was collected from suppliers. Transportation was not considered for materials for which supplier and origin data, and thus a data base for estimating the weighted average transportation distances, were not available. Transportation has been considered for the most important raw materials by quantity, including Bauxite, Alumina, Calcined Petroleum Coke and the alloying additives silicon and magnesium. The following section describes the data basis for auxiliary materials, excluding alloying additives which are presented in section 313.2.7.2.

Aluminium fluoride:

Aluminium fluoride is required for the Hall-Héroult bath for the electrolysis and is modelled using the Sphera dataset: *EU-28: Aluminium fluoride* as proxy. Without supplier data, no transport was considered.

Argon:

Argon is used for inline degassing during the ingot casting and is modelled using Sphera dataset: *DE: Argon (gaseous) Sphera* as proxy. Without supplier data, no transport was considered.

Calcined lime:

Calcined lime is required for alumina refining and is modelled using the Sphera dataset: *RER: Lime (CaO; quicklime lumpy) (EN15804 A1-A3)* as proxy. Without supplier data, no transport was considered.

Calcined petroleum coke:

Calcined petrol coke is required to produce anodes and as cathode carbon for the electrolysis. The production is represented in the model using a combination of data sources, with 55% derived from secondary data, i.e. Sphera dataset: *EU-28: Calcined Petroleum Coke* and 45% primary data obtained from suppliers, including 21% PCIC 2019 (Kuwait), 10% Petrocoque 2019 (Brazil) and 14% OMV 2022 (Germany) data, which are integrated into the model by modifying the inputs and outputs of the Sphera dataset with primary data.

Transport distances were estimated based on the suppliers' production locations using the logistics platform routescanner.com (POR, 2023) and averaged on a weighted basis to 7937 km by sea and 314 km by rail.

Calcium carbonate:

Calcium carbonate is required for the dross recycling process and is modelled using the Sphera process *DE: Limestone flour (1mm).* Transport was not considered.

Carbon dioxide:

Carbon dioxide is used for inline degassing during the ingot casting ats JAS and is modelled using Sphera dataset: *DE: Carbon dioxide (CO_2) by-product ammonia (NH_3) (economic allocation)* as proxy. Without supplier data, no transport was considered.

Caustic Soda:

Caustic soda is required for alumina refining and is modelled using the Sphera dataset: *RER: Sodium hydroxide (caustic soda) mix (100%)* as proxy. Without supplier data, no transport was considered.

Hard coal pitch:

Pitch is required to produce anodes. Pitch production is represented in the model using a combination of data sources, with 65% derived from secondary data, i.e. Sphera process *DE: Pitch production* and 35% obtained from 2019 data for the supplier Sinocoalchem, which is integrated into the model by modifying the inputs and outputs of the Sphera dataset with primary data. Transport was not considered.

Nitrogen:

Nitrogen is used for inline degassing during the ingot casting ats JAS and is modelled using Sphera dataset: *RER: Nitrogen (gaseous)* as proxy. Without supplier data, no transport was considered.

Potassium chloride:

Potassium chloride is used as fluxing salt during dross recycling and is modelled using Sphera dataset: *RER: Potassium chloride (KCl/MOP, 60% K_2O) Fertilizers Europe.* Transport was not considered.

Refractory:

Refractory materials are used in alumina refining, anode production, electrolysis, and ingot casting processes to protect equipment at high temperatures for lining and thermal insulation. It is modelled using the commonly used alumina produced according to IAI GLO 2019 data. Without supplier data, no transport was considered.

Sodium chloride:

Sodium chloride is used as fluxing salt during dross recycling and is modelled using Sphera dataset: *RER: Sodium chloride (rock salt).* Transport was not considered.

Steel:

Steel is required for the anode production and for cathodes in the electrolysis and is modelled using the Sphera dataset*: DE: Steel sheet 1.5mm HDG (0.03mm Zn; 1side)* as proxy. Steel is produced using some steel scrap, which is taken into account by connecting this dataset with steel scrap recovered from used cathodes and anodes, supplemented by steel scrap data according to Sphera, i.e. *GLO: Value of scrap (worldsteel 2022)*. Without supplier data, no transport was considered.

3.2.3 Bauxite mining

Bauxite mining involves the extraction of bauxite ore containing 30% to 50% alumina by weight, typically from near-surface open pit mines using heavy machinery. Further steps may include beneficiation (washing), treatment of residues and waste, and transportation to processing facilities for refining into alumina (IAI, 2022).

In 2022, 48% of the bauxite demand for EGA production comes from GAC, which supplies the ATA refinery. This share is modelled using primary data from GAC, while the remaining 52% is modelled using IAI GLO 2019 data. Figure 5 exemplifies the model for bauxite mining for the IAI GLO 2019 data scaled to 1000 kg bauxite output, the GAC mining is modelled accordingly.

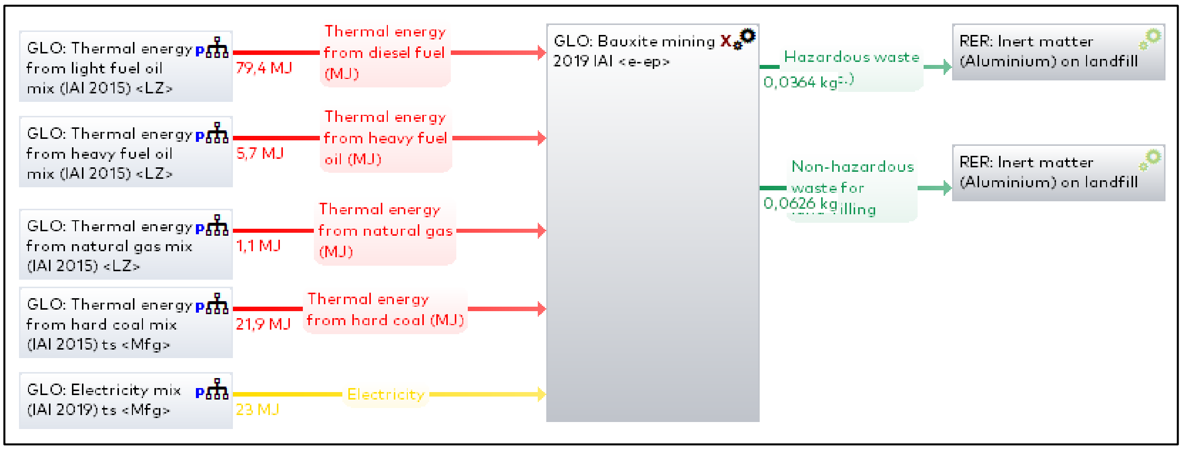

Figure 5: Bauxite mining model based on IAI GLO 2019 data

After mining, the bauxite is transported to an alumina refinery. GAC bauxite is transported 90 kilometres by rail from the mine to the port of Kamsar, Guinea. From there it is loaded onto bulk carriers and shipped 30,467 kilometres to Khalifa Port in the UAE. Upon arrival in the UAE, the bauxite is trucked 7 kilometres to the ATA bauxite shed. Transport distances of bauxite from other suppliers are based on IAI GLO 2019 data, which average 4305 km by sea, 566 km by rail and 22 km by road.

3.2.4 Alumina refining

In this process, the bauxite is converted into alumina using the Bayer Process with caustic soda and calcined lime. Bauxite is ground and mixed with a solution containing sodium carbonate and sodium hydroxide. After heating and pressure digestion, insoluble oxides (bauxite residue) are formed, while a concentrated sodium aluminate solution is filtered and seeded to create hydrate alumina crystals. These crystals are then heated in calciners to remove combined water, yielding pure alumina. The process requires energy in electricity, heat and process steam. Water is used for cooling, and air emissions (particulates, nitrous oxides, sulphur dioxide) mainly occur during calcination, while water emissions (hydrocarbons, suspended solids, mercury) relate to cooling and digestion. Most bauxite residue (red mud) is currently disposed of as solid waste and stored in large containment areas. Other inert materials from bauxite processing, such as sand, neutralized slurry or waste chemicals are usually landfilled (IAI, 2022).

In 2022, EGA's alumina supply consists of 48% from the ATA plant, 5% from South32, and the rest from unresponsive suppliers. The model of ATA alumina refining for the Standard Aluminium product scaled to 1000 kg alumina output is shown in Figure 6. The red mud generated is stored in a controlled storage area with a protective liner to prevent environmental contamination. This process as well as the landfilling of other inert materials is approximated with the Sphera process for Europe: *RER: Inert matter (Aluminium) on landfill.* South32's alumina production is modelled based on primary data from 2019 with IAI energy mixes as described in 3.2.1, while the remaining alumina supply is derived from 2019 IAI GLO data, accordingly. In contrast to the models just mentioned, the ATA refinery also uses fresh water from a desalination plant (product flow) in addition to seawater that does not require any further pretreatment (elementary flow). "Tap water from groundwater (RER)" is used as a proxy Sphera dataset, as no LCA dataset for fresh water from desalination was available.

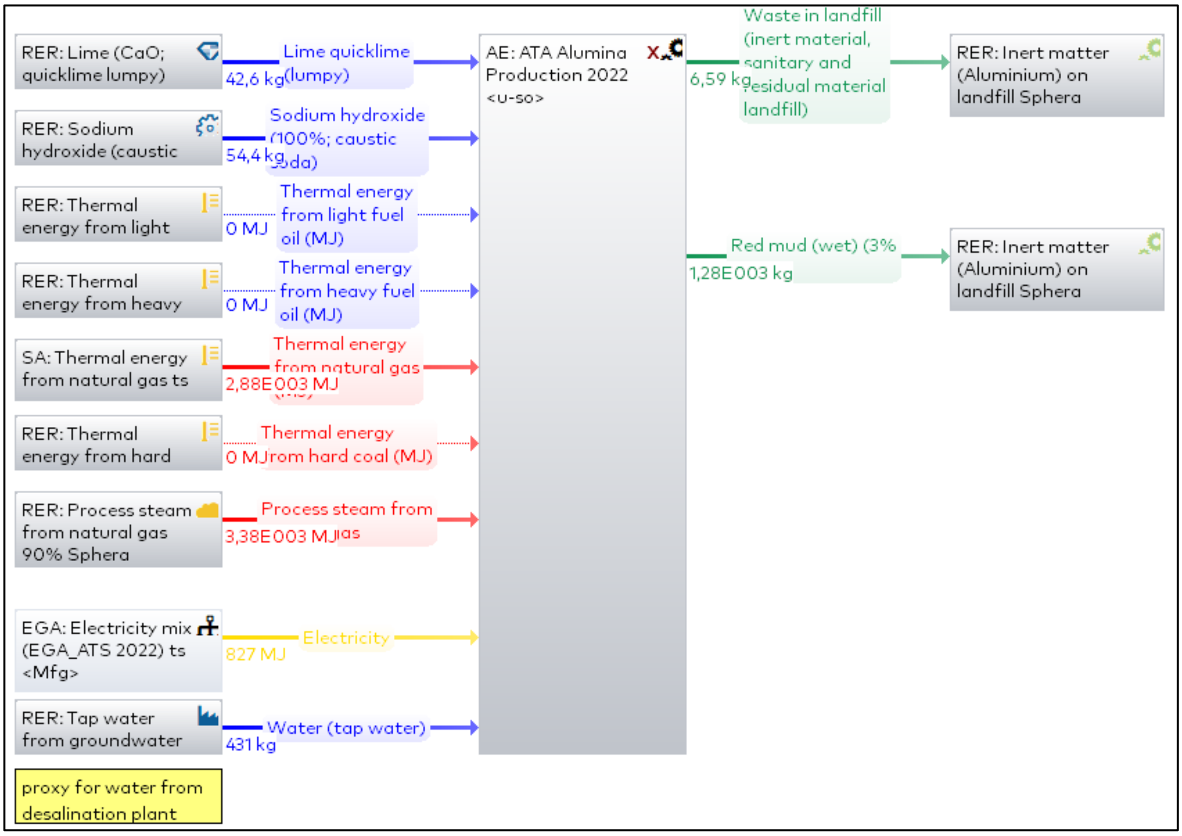

Figure 6: ATA alumina refining model for AT Standard Aluminium

3.2.5 Transport of alumina to EGA

Alumina from suppliers is shipped to EGA's dedicated berths at Jebel Ali and Khalifa Port with a weighted average sea distance of 1698 km for ATS, 7735 km for JAS and 4215 km for EGA Total, based on supply quantities and origins. ATA alumina is delivered to the adjacent ATS smelter, eliminating the need for transportation.

All transportation of bauxite, alumina, and selected alloying additives and auxiliary materials in this study is modeled on the basis of the IAI transport module shown in Figure 7, in which the respective transport distances of the individual means of transport are adjusted via parameters.

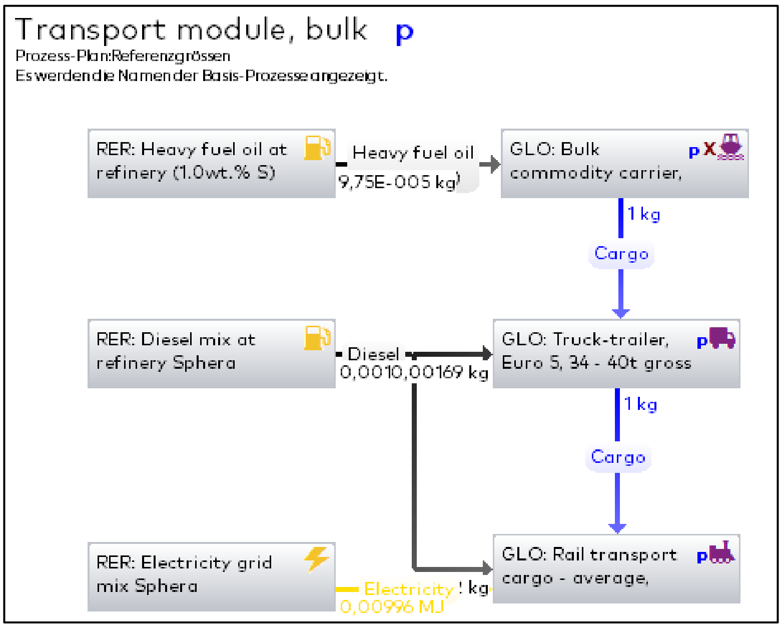

Figure 7: adjustable IAI transport module model for raw material transport

3.2.6 Aluminium smelting

Aluminium smelting refers to the production of anode and the electrolytic reduction process to produce molten aluminium from alumina.

3.2.6.1 Anode production

This process involves the manufacturing of carbon-based prebaked anodes used in the electrolytic reduction process. Petroleum coke is calcined, mixed with pitch, and formed into blocks which are further processed in baking furnaces. These furnaces are lined with refractory and cooled with fresh water or sea water. They are the primary consumers of energy. Furnace pollution control involves scrubbing, with the recovered material being returned to the process. The anodes are suspended from axial steel bars that serve both as supports for the anodes and as electrical conductors for the electrolysis. By-product steel recovered from the anode bars is sent for external recycling.

Air emissions of polycyclic aromatic hydrocarbons (PAHs), including benzo-a-pyrene (BaP), are generated during the process. The recycling of spent anode materials ("anode butts") recovered from electrolysis processes results in air emissions such as gaseous fluoride (as F) and particulate fluoride (as F) and water emissions such as fluoride (as F) and PAHs. Other emissions to water include suspended solids and oil. Solid waste includes carbon residues from dust filtration and anode butts cleaning, scrubber sludges, and refractory waste (IAI, 2022).

The GaBi model of the anode production for the AT Standard Aluminium scaled to 1000 kg anode output is shown in Figure 8 and JAS anode production is modelled accordingly. There is no difference between in the anode production between Standard, CelestiAL and CelestiAL-R aluminium.

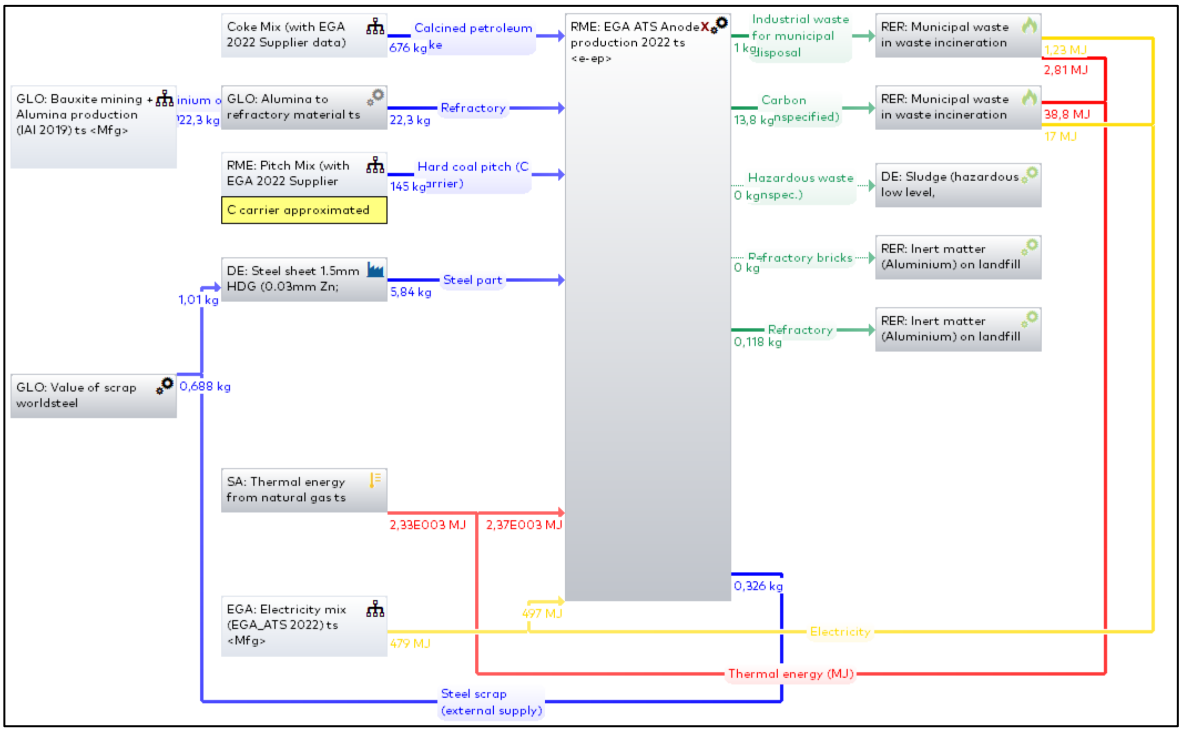

Figure 8: ATS anode production model for AT Standard Aluminium

Refractory waste is landfilled as inert matter (Sphera process: *RER: Inert matter (Aluminium) on landfill)*. Carbon and other industrial waste are subjected to thermal treatment (fire roasting) to burn off carbonaceous material, approximated using the Sphera process *RER: Municipal waste in waste incineration plant*. The process utilizes the generated heat for power generation and other thermal applications, with both forms of energy being recovered within a closed-loop modelling approach. The recycling of steel scrap by-products is also modelled with a closed-loop system, thus reducing the requirement for steel scrap from external sources (based on *GLO: Value of steel scrap*) and avoiding the need for allocation. The ATS facility does not produce any other hazardous landfill waste. As for the JAS facility, the management of this waste stream has been simulated using the Sphera process *DE: Sludge (hazardous low level, encapsulation and landfill)* without regional data, recognizing the limitations in terms of regional data representativeness.

3.2.6.2 Electrolysis

Molten aluminium (hot metal) is produced from alumina through the Hall-Héroult electrolytic process, with alumina dissolving in an aluminium flouride bath while an electric current is passed through the solution, decomposing alumina into aluminium and oxygen. The aluminium is collected from the reduction cell, while the oxygen combines with anode carbon to produce carbon dioxide. The process involves steel pots lined with refractory materials, including carbon cathodes filled with a cryolite bath, and anodes suspended in the bath.

Air pollution control systems like dry or wet scrubbers with adsorbents are commonly used to mitigate emissions, with dry scrubbers allowing for material recovery. Wet scrubbers recirculate an alkaline solution. Air emissions include gaseous fluoride (as F) and particulate fluoride (as F) from the bath, PAH from anode consumption, and perfluorocarbons (PFCs) like tetrafluoromethane and hexafluoroethane from uncontrolled voltage excursions (anode effect). Water emissions encompass fluoride (as F), suspended solids, oil and grease and PAH. Solid waste comprises SPL which consists of carbon and refractory residues contaminated with bath and molten metal, and waste carbon, such as from dust filtration, which are usually landfilled (IAI, 2022).

The GaBi model of the ATS electrolysis for the AT Standard Aluminium scaled to 1000 kg hot metal output is shown in Figure 9 and JAS electrolysis is modelled accordingly. The electrolysis for CelestiAL products is modelled differently in that the electricity consumption intensity has been adjusted to the most efficient technology at the site and the electricity mix has been replaced by solar power.

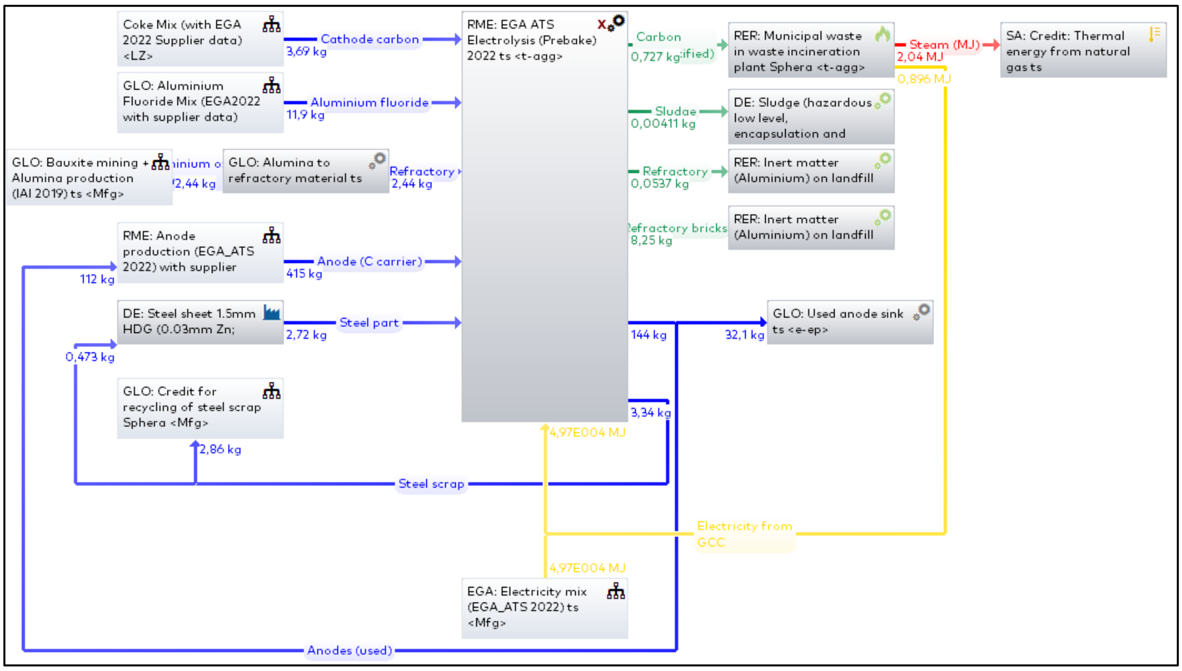

Figure 9: Electrolysis model for EGA ATS

Anode butts are recovered from the process with some losses and returned to anode production to make new anodes. Steel scrap from used cathodes is recycled (modelled as closed loop) and used as scrap input for primary steel production, while the excess fraction is credited through system expansion based on the inverted Sphera data set *GLO: Value of Scrap (worldsteel 2022)* to avoid allocation.

Carbon waste, scrubber sludges and refractory waste, including SPL, are treated as previously described in chapter 3.2.6.1. Thermal energy generated from carbon waste incineration is accounted for using system expansion by referencing the inverted Sphera process *SA: Thermal energy from natural gas,* which represents the thermal energy source for various processes at EGA. Since no direct thermal energy is utilized for electrolysis, a closed-loop approach is not applicable in this case.

Although SPL was assumed to be landfilled in the model due to data limitations, EGA actually recycles it and it is recommended to model this pathway in the future LCA updates. The SPL contains various materials, including carbon-based and refractory materials, as well as other impurities. It is either sold for external recycling or recycled internally. The former involves pre-treatment to remove impurities and volatiles, leaving carbonaceous material for recycling or co-processing in cement plants and other industrial applications. The latter involves internal crushing of stored SPL using EGA's SPL crusher and direct transfer to cement plants for recycling.

3.2.7 Ingot casting

The hot electrolysis metal is transferred to a casting complex. Further metal inputs are remelt ingot, internal run-around scrap and external pre- and post-consumer aluminium scrap. The composition is adjusted to customer requirements through the application of alloy additives in a holding furnace. After alloying, the metal is stirred, fluxed, and dross is skimmed off, with dross processing to recover aluminium content. The metal undergoes inline degassing with flushing gases, which consist of nitrogen or argon with the addition of chlorine, and filtration to remove impurities and is cast into various forms. To prepare the ingots for further processing, ingot sawing may be employed to cut the aluminium into specific shapes and sizes.

Recirculating water is used for cooling which is monitored for suspended solids and oil/grease (total PAH) before discharging. Filter dust from air filtration and refractory waste from furnace linings are either recycled or landfilled. Other landfill waste comprises municipal waste and waste from environmental abatement measures (e.g. filters) (IAI, 2022).

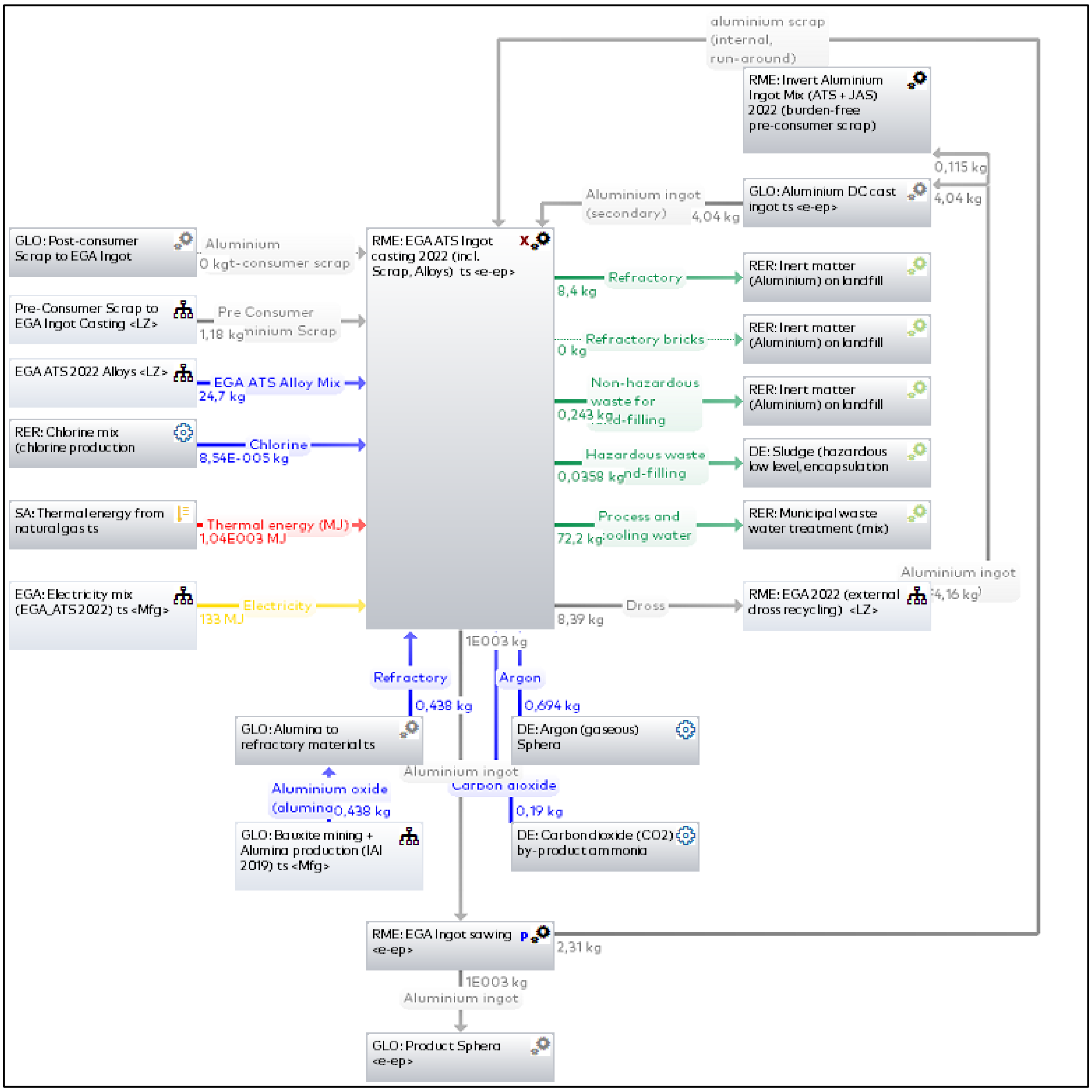

Figure 10: Ingot casting model for EGA ATS

The GaBi model for ATS standard ingot casting scaled to 1000 kg of sawn aluminium ingot output is shown in Figure 10 and the JAS casting is modelled accordingly. Site differences lie in the use of nitrogen instead of carbon dioxide and the application of a distinct alloying additives mix with a different composition. Post-consumer scrap is only purchased and used as a metal input at the JAS site at 1.3 kg per 1000 kg ingot. This fraction is considered as environmental burden-free as recommended by the IAI (Solinnen, 2022). CelestiAL products utilize solar electricity as power source instead of the average electricity mix. CelestiAL-R products additionally have a different metal composition with a higher recycled content, i.e. 16% of post-consumer scrap, 10% internal run-around scrap and 0% pre-consumer scrap. The burden of the internal run-around scrap is based on the Standard Aluminium ingot casting process, where the unit process impacts are allocated by mass to the scrap flow, rather than the CelestiAL-R casting process.

Blowdown sea water from cooling is discharged to a stormwater pond and then to an aeration basin for treatment, which is approximated using the Sphera process *RER: Municipal waste water treatment (mix)*. Landfilling of refractories, hazardous waste and other wastes is modelled as described in the previous processes. Internal scrap from ingot sawing is recovered and reused in the casting process along with remelt ingot recovered from dross recycling.

The alloying additives (mix), pre-consumer scrap according to different allocation scenarios and external dross recycling sub-plan models are described in the following chapters.

3.2.7.1 Dross recycling

Dross recycling in this study is based on information provided in the EA report (EA, 2021) and primary data obtained from EGA's external dross recycling partner, Kizad.

The process involves melting the collected dross in a rotary furnace to separate the aluminium from impurities and aluminium oxide. Fluxing salts, namely sodium chloride and potassium chloride, are utilized, serving several purposes, including facilitating degassing, preventing excessive oxidation of aluminium, and binding the impurities in the dross. As a result, a notable amount of 1358 kg of salt slag is generated for every 1000 kg of remelt ingot produced. This salt slag contains valuable components, including fluxing salts, aluminium oxide, and aluminium metal. The salt slag can be recycled to recover the fluxing salts and aluminium oxide, which can find applications in industries like refractory production (EA, 2021). Direct process emissions to air comprise carbon dioxide, carbon monoxide, nitrogen oxides and sulphur dioxide.

The GaBi model of the dross recycling is shown in Figure 11.

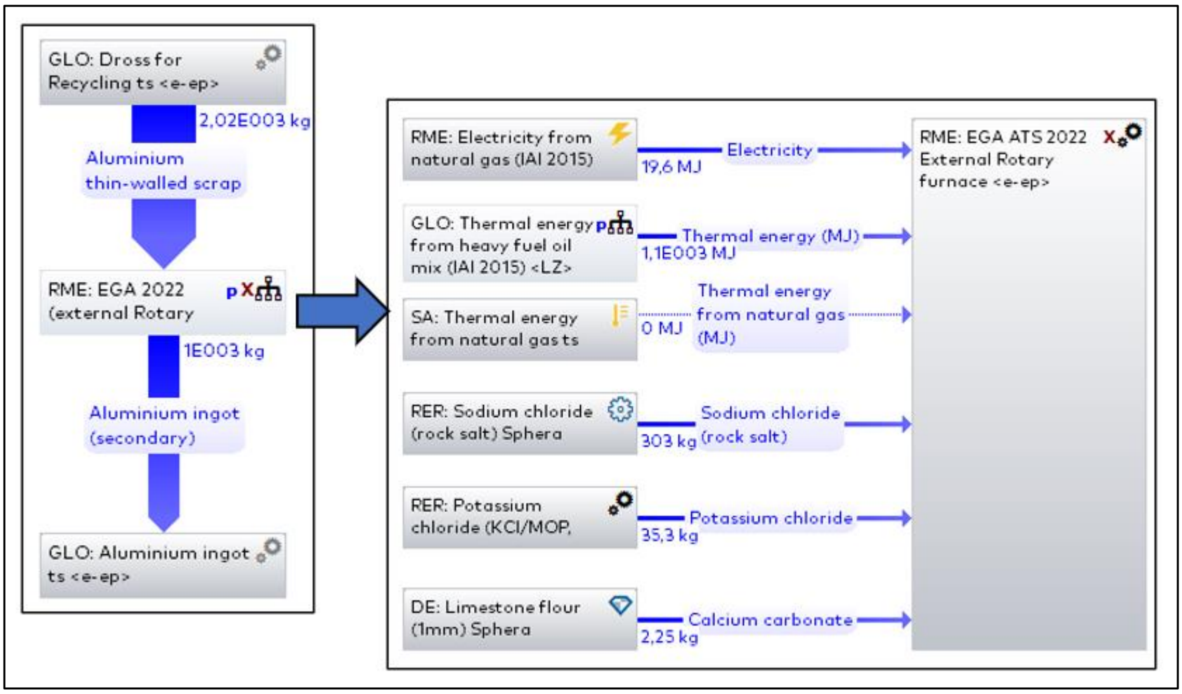

Figure 11 Dross recycling model

It's important to note that, due to limitations in available data, the recycling of salt slag and system expansion to incorporate the valorisation of recovered aluminium oxide have not been explicitly modelled within the scope of this study. Further, the environmental impacts of the recycling process are fully allocated to the remelt ingot. However, it is recommended considering these aspects in future endeavours to fully capture the value of the materials contained in this significant waste stream.

3.2.7.2 Alloying additives

The alloying additives mix which is used in the 2022 EGA ingot casting in 2022 encompasses various pure alloying elements, like magnesium or silicon, or master alloys, which consist of a base metal such as aluminium or copper combined with one or two other elements. Used alloying additives, their composition and regional origins have been identified in the LCI data collection for ATS and JAS, see attached inventory file. Master alloys are usually applied by adding their components to the molten metal without prior fusing of the components. For that reason, alloying additives are modelled by summing up the environmental impacts from the production of their components without any additional effort.

The unit process ingot casting is connected to a sub-system, which represents the addition of alloying additives during aluminium casting. The sub-system consists of different layers of sub-plans, which allow the selection and the alteration of quantity and composition of alloying additives. Figure 12 illustrates the alloying additives mix model exemplary for Tablet Copper. The first layer represents the composition of the 2022 alloy additive mix, merging all used alloy additives based on total usage quantity.

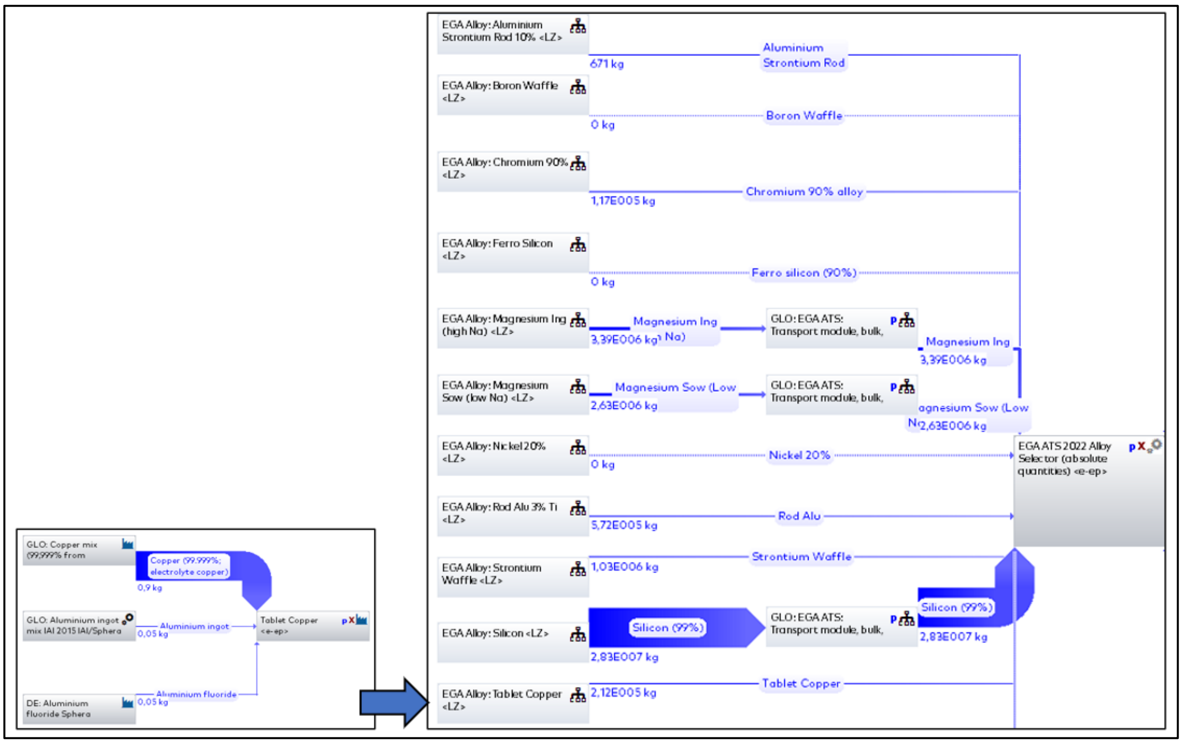

Figure 12: Layered alloying additives mix model as input for EGA ATS ingot casting, exemplary for tablet copper

The different alloy additives represent the next layer of the model. Each additive is characterized by its composition, and it is modelled by blending its constituents within a customizable unit process, e.g. Tablet Copper is made from 90% copper mixed with 5% each of aluminium and aluminium fluoride. Component data is derived from Sphera and Ecoinvent, with a preference for Sphera to maintain consistency. A complete list of utilized datasets is provided in Table 4. Whenever possible, datasets corresponding to the same reference region as the supply origin have been chosen; otherwise, global datasets are employed.

Proxies are used if no data is available, which is the case for the following substances: Strontium, Chromium, Flux (Potassium Aluminium Flouride), Boron salt (KBF4), Titanium salt (K2TiF6). These substances are approximated using datasets for industrial precursors or substances with similar chemical compositions. It's important to note that these proxies may have limitations in representing these substances fully. Nevertheless, apart from chromium in “chromium 90%”, these elements are present only in small quantities within selected master alloys and do not constitute the primary components.

For both chromium and strontium, the calculation of their mass content in proxy substances is based on stoichiometry. The required quantity of the proxy substance is then adjusted using a conversion factor, which is the reciprocal of the mass content, to accurately reflect their presence. For example, in the case of ferro chrome, a conversion factor of 1.5 is applied to represent the 60% chromium content in ferrochrome.

Table 4: Used datasets to model alloying additives components

Component	Associated alloy additives	Used Dataset	Dataset Region	Source	Accordance note
Aluminium	Tablets, Waffles, Rods, Chromium 90%, Nickel 20%	Aluminium ingot mix IAI 2015	GLO	Sphera	Aluminium origin is unknown, therefore the IAI GLO average is used.
Boron salt (KBF4)	Boron Waffle, Rods	boron trifluoride production	GLO	Ecoinvent	BF3 may not be a representative proxy due to its different chemical composition, which does not reflect the extraction and processing of potassium-containing raw materials. However, KBF4 only constitutes a small percentage of associated alloy additives from 1-8%. Therefore, this choice is considered a practical solution given the limited available data.
Chromium	Chromium 90%	Ferro chrome (low carbon ~ 1%)	ZA	Sphera	Approximation with industrial precursor using a stoichiometric conversion factor
Copper	Tablet Copper	Copper mix (99,999% from electrolysis)	GLO	Sphera	High representativeness
Ferro Silicon (75% Si)	Ferro Silicon (75% Si)	Ferro silicon mix (90% Si)	GLO	Sphera	Deviant silicon content formulation
Iron	Tablet Iron	BF Steel billet / slab/ bloom	DN	Sphera	Steel is primarily made from iron, deeming it a suitable proxy.
Magnesium	Magnesium Ingot/ Sow	Magnesium ingot; pidgeon process	CN	Sphera	High representativeness
Manganese	Tablet Manganese	Manganese	GLO	Sphera	High representativeness
Nickel	Nickel 20%	Nickel mix	GLO	Sphera	High representativeness
Flux (Potassium Aluminium Fluoride)	Tablets, Chromium 90%	Aluminium Fluoride	DE	Sphera	AlF3 may not be a representative proxy for PAF due to its different chemical composition, which does not reflect the extraction and processing of potassium-containing raw materials. However, flux only constitutes a small percentage of alloy additives from 5-10%. Therefore, this choice is considered a practical solution given the limited available data.
Silicon	Silicon	Silicon mix (99%)	GLO	Sphera	High representativeness
Sodium impurities	Magnesium Ingot/ Sow	Sodium chloride (rock salt)	RER	Sphera	NaCl represents impurities in different Magnesium qualities.
Strontium	Alum. Strontium Rod, Strontium Waffle	Strontium carbonate production	GLO	Ecoinvent	Approximation with industrial precursor using a stoichiometric conversion factor
Titanium	Titanium Waffle, Tablet Titanium,	Titanium	GLO	Sphera	High representativeness
Titanium salt (K2TiF6)	Rods	Titanium dioxide pigment (chloride process)	RER	Sphera	Approximation with industrial precursor: K2SO4 + TiO2 + 4 HF → K2TiF6 + 2 H2SO4. TiO2 does not reflect the extraction and processing of potassium and fluoride containing raw materials. However, titanium salt only constitutes 3% of rods. Therefore, this choice is considered a practical solution given the limited available data.
Zinc	Zinc	Zinc mix	DE	Sphera	High representativeness

Transportation is considered for magnesium and silicon, which account for 88% of the mix by weight. Shipping distances are estimated by calculating a weighted average transport distance based on the supply quantity and origin. Sea routes are sourced from Routescanner (POR, 2023). Table 5 showcases the results of this estimation.

Table 5: Selected alloy additives transport distances based on (POR, 2023)

Silicon	**Distance seaborne transport (port to port) [km]**	**Quantity ATS [MT]**	**Quantity JAS [MT]**
Brazil (Santos)	17,274	700	550
Canada (Vancouver)	20,500	0	900
China (Shanghai)	10,500	32,016	29,211
Malaysia (Klang)	6,200	100	200
weighted distance (Si)		10,631 km	10,884 km
Magnesium	**Distance seaborne transport (port to port) [km]**	**Quantity ATS [MT]**	**Quantity JAS [MT]**
China (Shanghai)	10,500	8,392	5,755
Israel (Haifa)	6,000	0	194
weighted distance (Mg)		10,500 km	10,353 km

3.2.7.3 Pre-consumer scrap

The unit process "ingot casting" is connected to a sub-system, which represents the input of pre-consumer scrap. The sub-system consists of 10 plans, which represent 10 different allocation approaches, developed by the IAI. The rationale behind these approaches is to establish a method for allocating the environmental impacts arising from scrap generation between the product that initially generated the scrap and the product resulting from the scrap remelting process, which is in this case EGA aluminium ingot. For detailed information on the scenarios, see chapter 2.2.4 and the IAI report (Solinnen, 2022). The model of the pre-consumer scrap sub-system comprises three layers, as illustrated in Figure 13 for 1 kg of scrap. The first layer enables scenario selection, the second layer models the scrap generation during the production of semi-finished aluminium products, and the lowest layer allows for the selection of the aluminium source from which the scrap is generated.

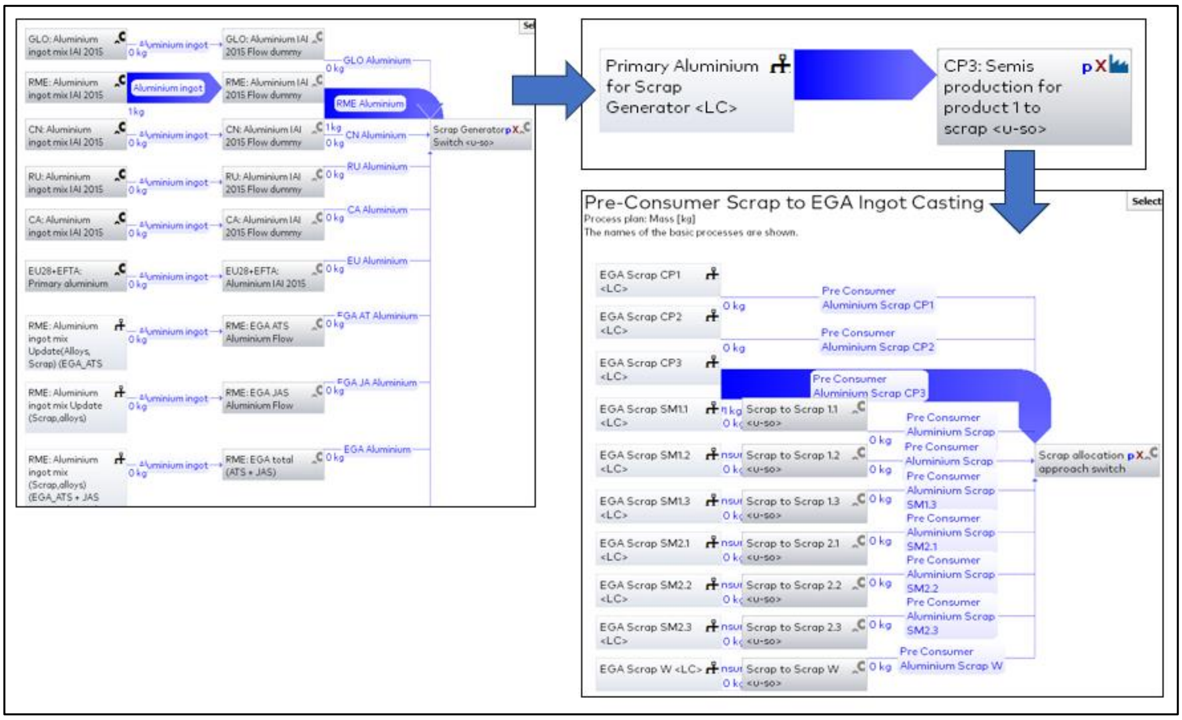

Figure 13 Layered pre-consumer scrap model as input for EGA ingot casting

All scenarios are incorporated into the model, with the baseline approach being per-flow allocation (CP3). In this approach, mass allocation is applied to material flows only, meaning that the gate-to-gate impacts of the scrap generating process are entirely allocated to the semi-finished product rather than to the scrap.

CP3 was chosen for several reasons. First, the purchased scrap is not recovered from a waste stream, making cut-off approaches inappropriate. Second, CP3 is preferred among co-product approaches by the IAI. Furthermore, there is no available data for the gate-to-gate impacts of semis production, and there is also no direct correlation between the amount of pre-consumer scrap generated and the energy usage of the process.

Additionally, a sensitivity analysis (see section 5.3) is conducted using the cut-off approach (W), allowing for a comparison of the results.

Pre-consumer scrap is procured from semi-finished product producers in the Region Middle-East (RME), and as a result, the aluminum source for the scrap generation process is configured as *RME: Aluminium ingot mix IAI 2015 IAI/Sphera.* Nevertheless, there are various sources available for selection, such as the IAI 2015 datasets for China, Russia, Canada, Global, EU28+EFTA, and EGA aluminum.

4 Life cycle impact assessment (LCIA)

In this section, the results of the LCIA (potential environmental impacts) of 1000 kg primary aluminium ingot from EGA are presented based on the six impact categories as defined in section 2.2.5. The results presented here are based on the pre-consumer scrap allocation approach CP3 and focus on EGA Total Aluminium products. Site-specific results for AT and JA are provided in the Annex. Detailed numeric results and contribution analyses are provided in Appendix C of this report.

4.1 LCIA profiles of EGA Total Aluminium products

The following sub-sections present the LCIA results for the three EGA Total Aluminium products. The impact of each life cycle phase is assessed across the LCIA categories considered. It should be noted that these life cycle stages aggregate several processes, e.g. bauxite mining and alumina production includes the transportation of bauxite to alumina refineries, electrolysis includes the production of anodes, and ingot casting includes the production of alloying additives and dross recycling.

4.1.1 LCIA profile of EGA Total Standard Aluminium

The indicator results per tonne of Total Standard Aluminium Ingot are reported in Table 6.

Table 6: Impact category indicator results per tonne EGA Total Standard Aluminium

Category	Unit	Bauxite mining and Alumina production	Transport (Alumina)	Electrolysis, Prebake	Ingot casting	Total
ADP (fossil)	[MJ]	24,498	338	128,304	5,388	158,528
EP	[kg Phosphate eq.]	1.21	0.08	1.13	0.14	2.55
POCP	[kg Ethene eq.]	0.76	0.04	1.08	0.15	2.03
ODP	[kg R11 eq.]	2.7E-09	2.2E-12	3.3E-08	1.4E-08	5.0E-08
AP	[kg SO2 eq.]	12.0	0.7	19.7	1.3	33.7
GWP100	[kg CO_2 eq.]	1,955	28	8,107	455	10,545

The contribution of the different phases to the overall indicator result is shown in Figure 14.

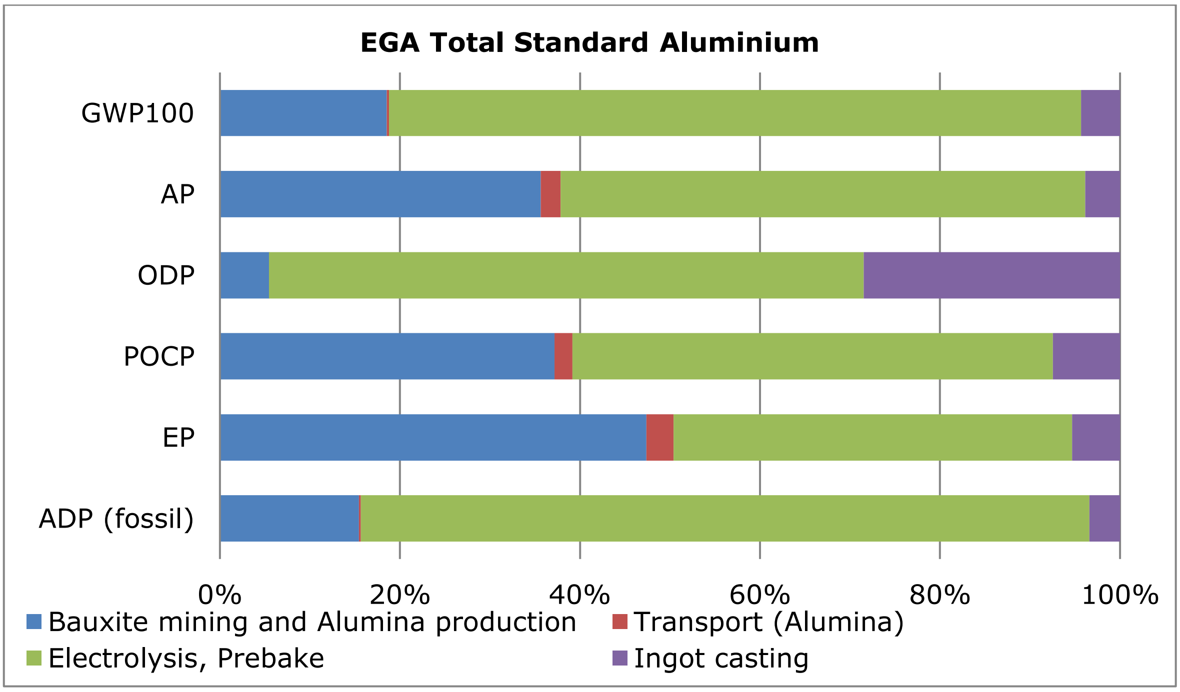

Figure 14: Overall LCIA profile of EGA Total Standard Aluminium

The results indicate that the life cycle stages Bauxite mining and Alumina production (5-47%) and Electrolysis, including prebake anode production, (44-81%) are the major contributors to most impact categories. For the ODP, ingot casting is also relevant with a contribution of 28%. The contributions of the alumina transport (0-3%) and ingot casting excluding the ODP (3-7%) are less significant.

Each impact category is analysed separately in the following sections, presenting disaggregated results and processes contributions. Anode production and bauxite mining are presented separately from electrolysis and alumina production, respectively. However, the transportation of raw materials is aggregated into the production phase, with bauxite mining encompassing bauxite transport and alumina production encompassing alumina transport. This evaluation is a one-off example for the EGA Total Standard Aluminium product and is not carried out for other products in order not to go beyond the scope.

4.1.1.1 Abiotic Depletion Potential (fossil)

Figure 15 shows the life cycle stage and process contributions for the ADP (fossil). Electrolysis accounts for 71% of the ADP, mainly due to the electricity production in EGA's power plants from natural gas. Other significant contributors are alumina production (14%), primarily due to the generation of required thermal energy, and anode production (10%), primarily related to the production of calcined petroleum coke and pitch.

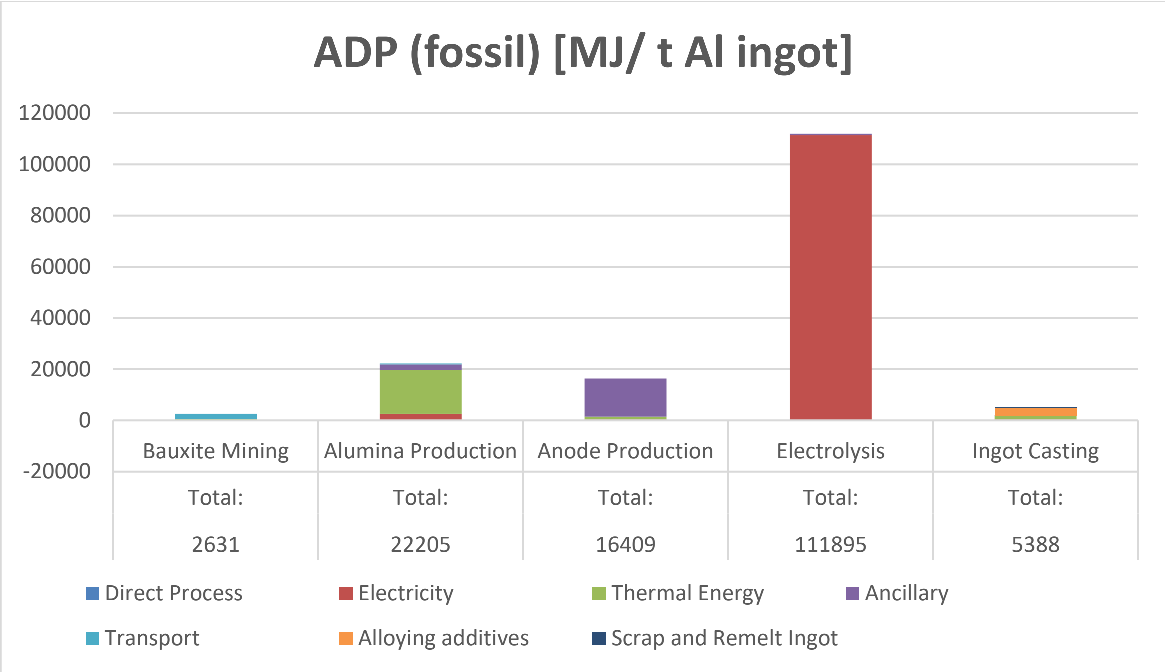

Figure 15: EGA Total Standard Aluminium process contributions in ADP

4.1.1.2 Acidification Potential

Figure 16 shows the life cycle stage and process contributions for the AP. The electrolysis accounts for 46% of the AP, which is mainly related due to direct process emissions of sulphur dioxides during the electrolysis. Other significant contributors are alumina production (24%), mainly due to the combustion of fuels in the production of thermal energy, bauxite mining (13%), mainly due to shipping of bauxite to alumina refineries and the associated emissions of sulphur dioxide and nitrogen oxides from the combustion of heavy fuel oil, and anode production (13%), through the production of ancillary materials.

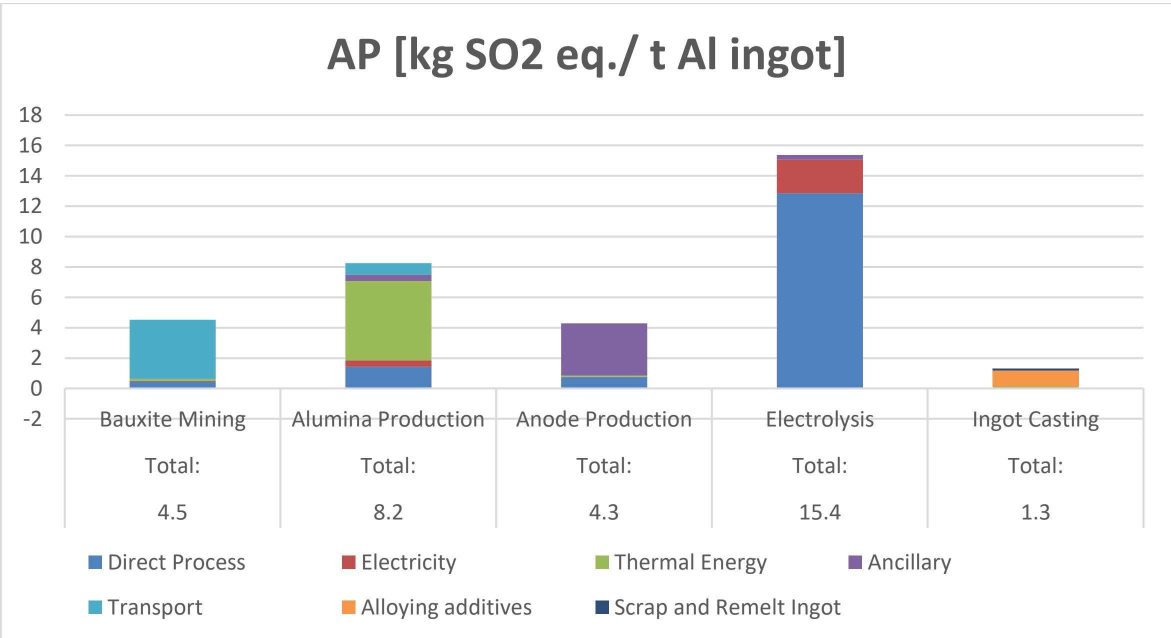

Figure 16: EGA Total Standard Aluminium process contributions in AP

4.1.1.3 Eutrophication Potential

Figure 17 shows the life cycle stage and process contributions for the EP. No single hotspot can be identified, as several processes contribute significantly to the total. Bauxite mining accounts for 21% of the EP, mainly due to shipping of bauxite to alumina refineries and the associated discharge of ship-borne nutrients, nitrogen and phosphorus, into the sea. Alumina production (29%), anode production (24%), and electrolysis (20%) follow, with the EP mainly associated with the production of thermal energy, auxiliary materials (mainly petcoke), and electricity, respectively.

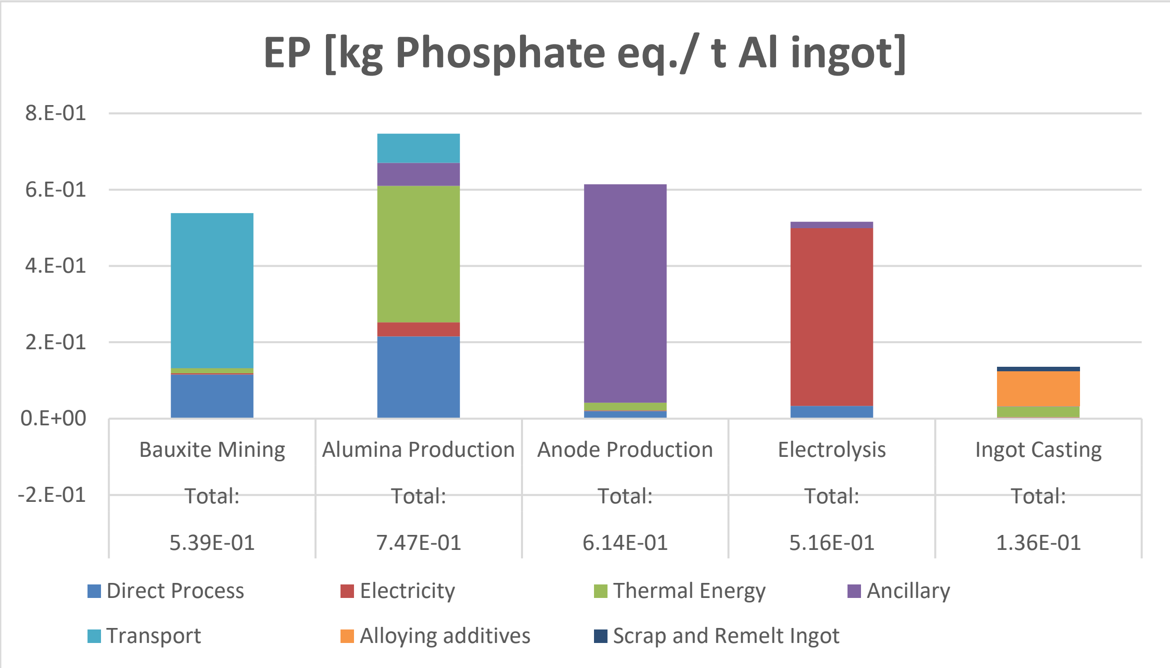

Figure 17: EGA Total Standard Aluminium process contributions in EP

4.1.1.4 Global Warming Potential, 100 years

Figure 18 shows the life cycle stage and process contributions for the GWP. The electrolysis accounts for 71% of the GWP. The significant electricity demand of the electrolysis process is a major driver of the GWP results by 56% as EGA uses natural gas, a fossil fuel source, as its primary energy source. Additionally, notable contributors to GWP include the thermal energy production (12% of total GWP) associated with alumina refining and the direct emissions (14% of total GWP) of PFCs and carbon dioxide during electrolysis.

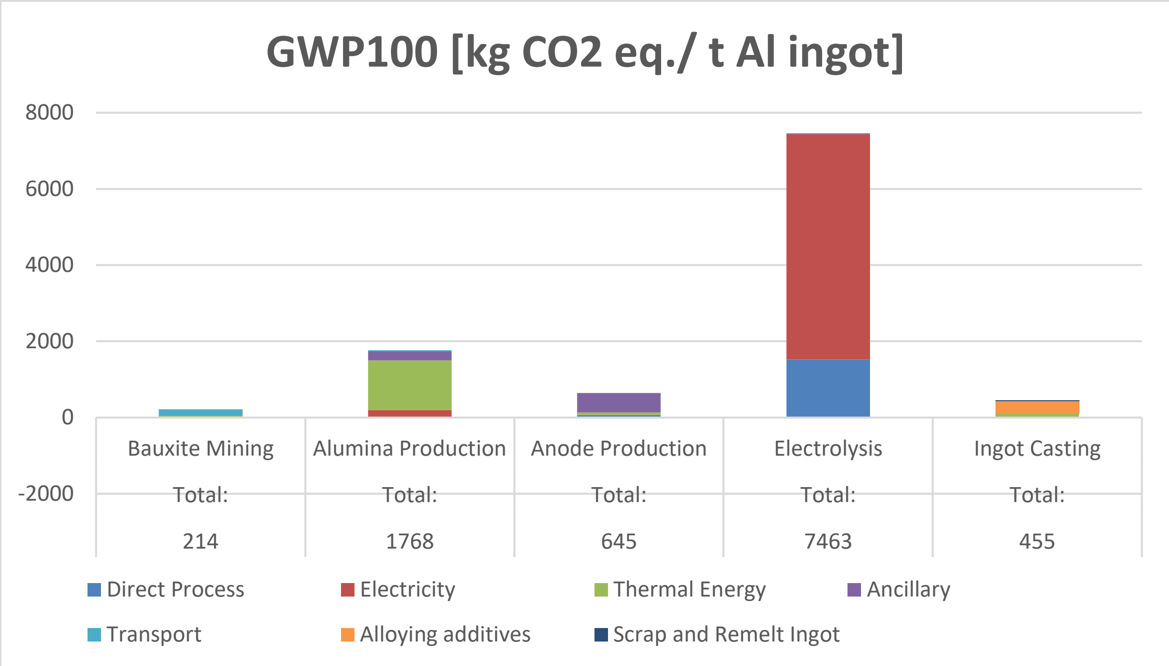

Figure 18: EGA Total Standard Aluminium process contributions in GWP

4.1.1.5 Ozone Layer Depletion Potential

Figure 19 shows the life cycle stage and process contributions for the ODP. Electrolysis, and more specifically the electricity from photovoltaics, contributes to 65% of the total ODP, which may appear counterintuitive, given that solar electricity only accounts for 3.3% at EGA ATS and 0.3% at JAS, with the majority of power sourced from their natural gas power plants. This anomaly is linked to emissions in the upstream production of photovoltaic modules, included in the Sphera dataset *RER: Electricity from photovoltaics*. Ingot casting represents 28% of the ODP, primarily associated with a specific alloy additive, strontium waffle, more specifically its strontium component, which is based on an Ecoinvent dataset *GLO: strontium carbonate production*. In general, Ecoinvent datasets for metals and metalloids have significantly higher ODP values that differ significantly from comparable Sphera datasets, highlighting a potential consistency issue. However, in this case there was no suitable Sphera proxy available.

It is essential to note that the significance of the ODP category has diminished over time, thanks to international agreements like the Montreal Protocol, which has drastically reduced ODS by 98% compared to 1990 levels (UNEP, 2023). As a result, ODP values now have an exceptionally low baseline due to the substantial success in minimizing these substances. Even a minor presence of an ODS in an LCA dataset model can lead to significant relative ODP increases, given that these substances are now present at extremely low levels.

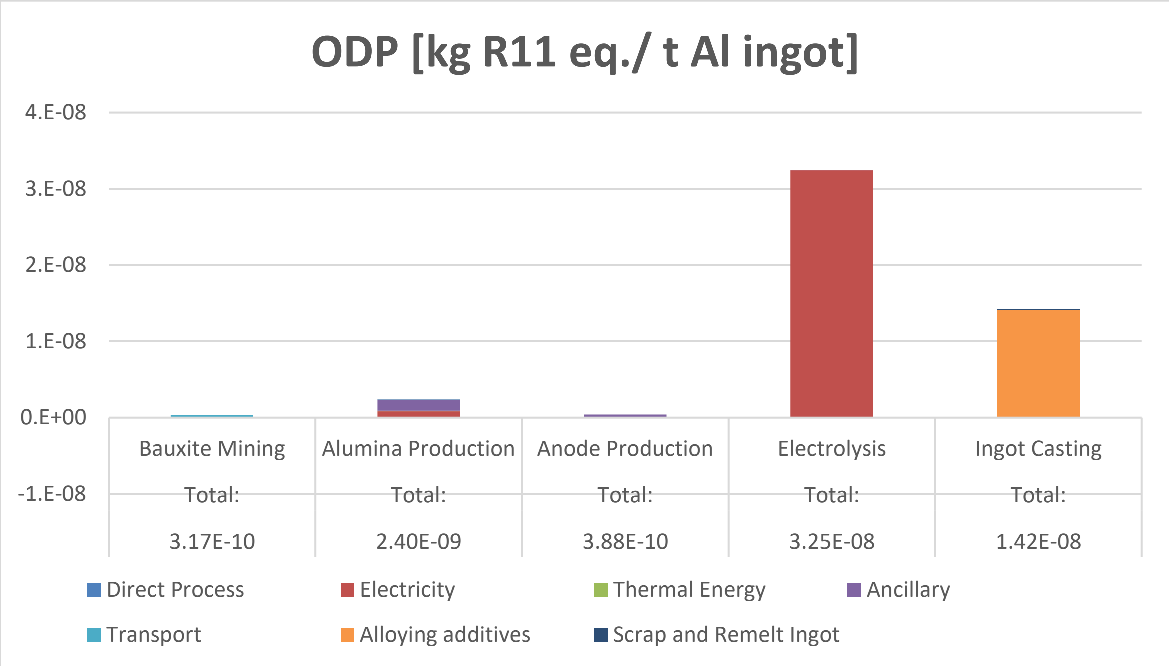

Figure 19: EGA Total Standard Aluminium process contributions in ODP

4.1.1.6 Photochemical Ozone Creation Potential

Figure 20 illustrates the life cycle stages and their respective contributions to the POCP. It is evident that POCP emissions do not have a single predominant source, as several processes release ozone precursor gases, such as volatile organic compounds and nitrogen oxides. These gases originate from various combustion processes, including ship engines, the combustion of fuels for thermal energy or electricity, and emissions in the aluminium smelting process from both electrolytic cells and anode effects. Electrolysis contributes 39% of the POCP, of which about two-thirds is related to direct process emissions and one-third to electricity generation. Alumina production (27%) is the second largest contributor, mainly related to thermal energy. Bauxite mining contributes 12% to the POCP, mainly due to bauxite shipping (fuel combustion in engines). The POCP of anode production (14%) is primarily related to upstream petcoke production and the POCP of ingot casting (7%) is mainly associated with the production of alloying additives.

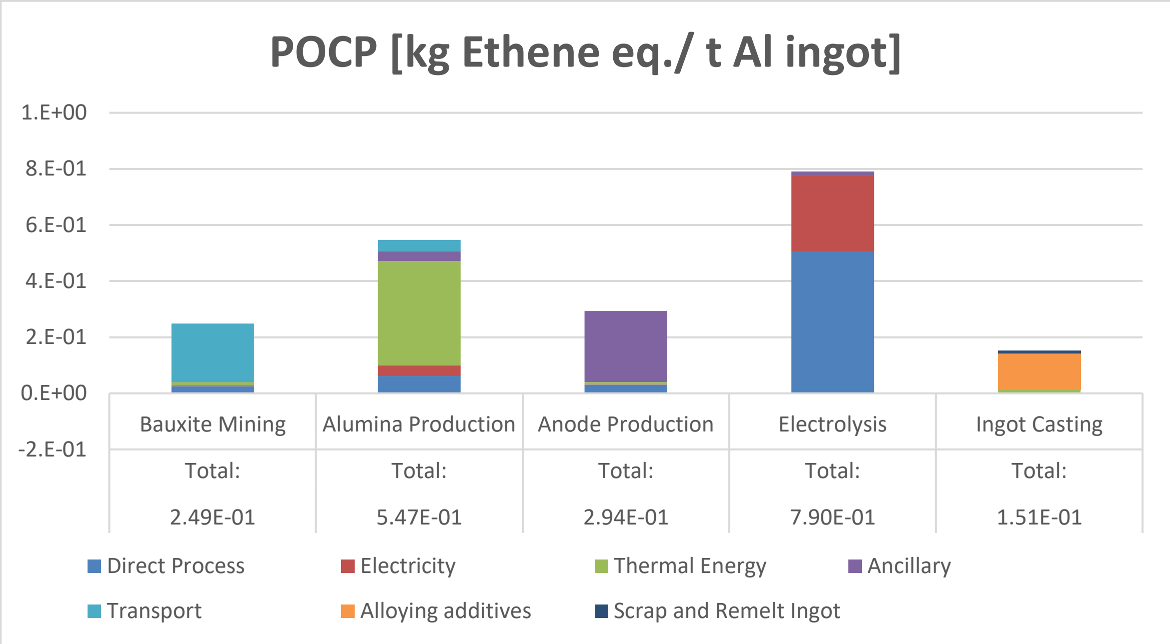

Figure 20: EGA Total Standard Aluminium process contributions in ODP

4.1.2 LCIA Profile of EGA Total CelestiAL Aluminium

The indicator results per tonne of Total CelestiAL Aluminium Ingot are reported in Table 7.

Table 7: Impact category indicator results per tonne EGA Total CelestiAL Aluminium

Category	Unit	Bauxite mining and Alumina production	Transport (Alumina)	Electrolysis, Prebake	Ingot casting	Total
ADP (fossil)	[MJ]	18,612	44	20,915	5,008	44,578
EP	[kg Phosphate eq.]	1.2E+00	1.7E-03	8.0E-01	1.3E-01	2.1E+00
POCP	[kg Ethene eq.]	4.9E-01	-2.3E-03	9.5E-01	1.5E-01	1.6E+00
ODP	[kg R11 eq.]	5.1E-08	3.3E-13	1.6E-06	2.0E-08	1.6E-06
AP	[kg SO2 eq.]	8.0	0.0	18.8	1.3	28.1
GWP100	[kg CO_2 eq.]	1,270	3	2,565	435	4,273

The contribution of the different phases to the overall indicator result is shown in Figure 21.

LCIA results are dominated by Electrolysis, including prebake anode production, (38-96%) and Bauxite Mining and Alumina Production (28-55%, excluding ODP [3%]). Contributions of Ingot casting (1-11%) and Alumina Transport (0%) are less significant.

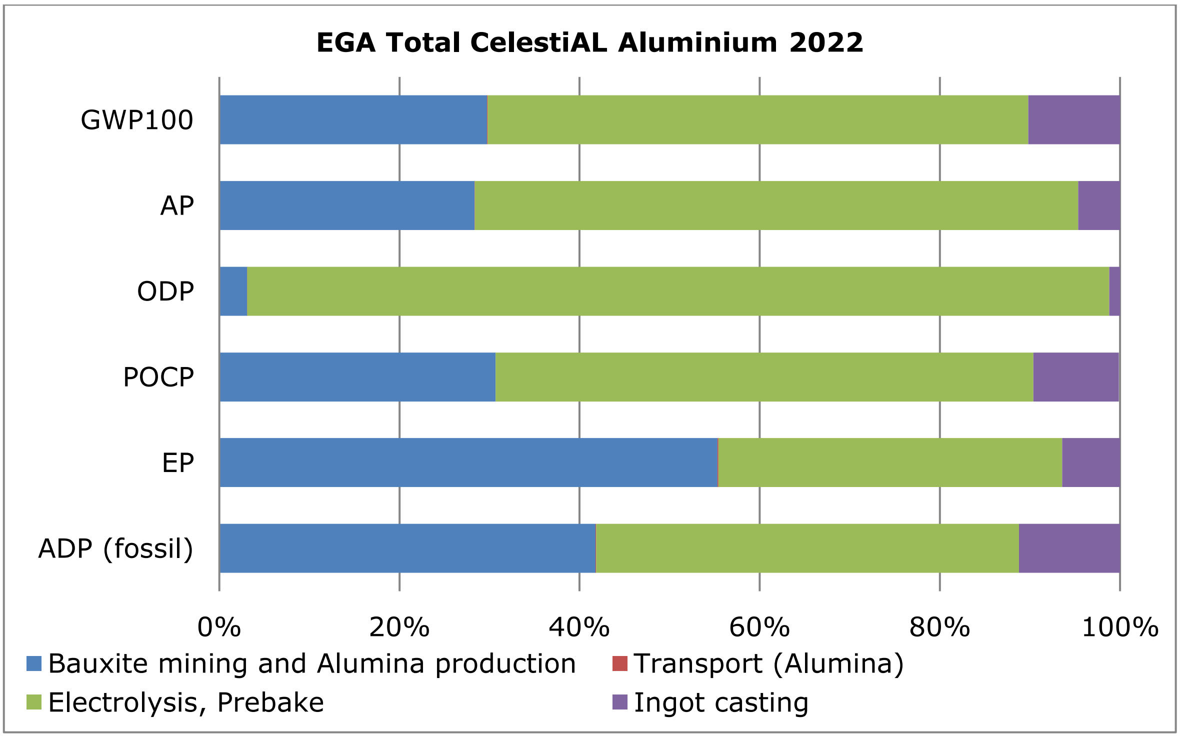

Figure 21: Overall LCIA profile of EGA Total CelestiAL Aluminium

4.1.3 LCIA Profile of EGA Total CelestiAL-R Aluminium

The indicator results per tonne of Total CelestiAL-R Aluminium Ingot are reported in Table 8.

Table 8: Impact category indicator results per tonne EGA Total CelestiAL-R Aluminium

Category	Unit	Bauxite mining and Alumina production	Transport (Alumina)	Electrolysis, Prebake	Ingot casting	Total
ADP (fossil)	[MJ]	13,706	32	15,401	5,202	34,341
EP	[kg Phosphate eq.]	8.5E-01	1.3E-03	5.9E-01	1.4E-01	1.6E+00
POCP	[kg Ethene eq.]	3.6E-01	-1.7E-03	7.0E-01	1.6E-01	1.2E+00
ODP	[kg R11 eq.]	3.8E-08	2.4E-13	1.2E-06	2.1E-08	1.2E-06
AP	[kg SO2 eq.]	5.9	0.0	13.8	1.3	21.0
GWP100	[kg CO_2 eq.]	935	2	1,889	454	3,280

The contribution of the different phases to the overall indicator result is shown in Figure 22.

LCIA results are dominated by Electrolysis, including prebake anode production, (37-95%) and Bauxite Mining and Alumina Production (28-54%, excluding ODP [3%]). Contributions of Ingot casting (2-15%) and Alumina Transport (0%) are less significant.

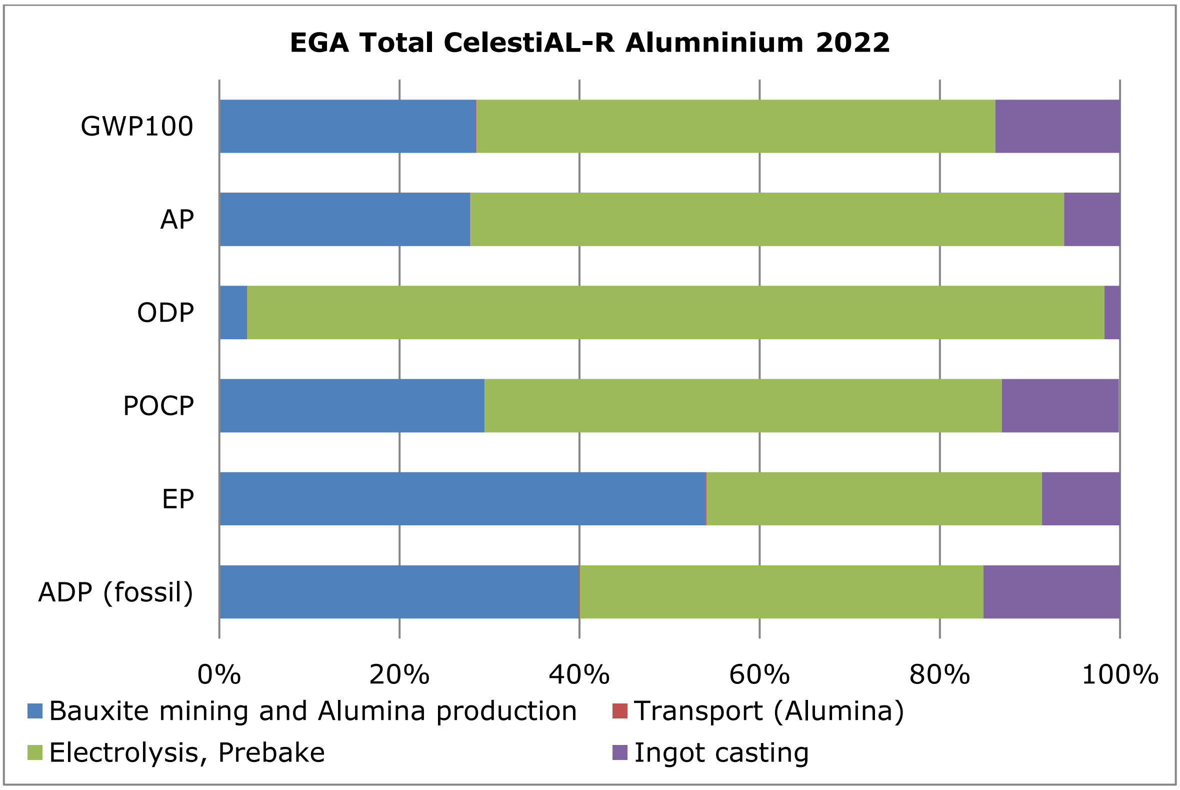

Figure 22: Overall LCIA profile of EGA Total CelestiAL-R Aluminium

5 Interpretation

In the following subsections, the results of the LCA are interpreted, including the identification of significant issues (hotspots) at the process level (5.1), sensitivity analysis to examine the identified hotspots and the impact of assumptions (5.3), a completeness and consistency (5.4) and a summary of the main findings of the LCA study (5.5).

5.1 Identification of significant parameters

The extent to which individual processes contribute to the results is assessed as part of a significance analysis for the EGA Total Standard Aluminium first. Table 9 summaries the main contributing phases and process for all impact categories. The disaggregated results show that electrolysis, including prebake anode production, is the largest contributor to environmental impacts for all impact categories except EP. Electricity generation for this energy-intensive process remains the emission hotspot for GWP, ADP (fossil) and ODP.

Table 9: Main contributing phases and processes to EGA Total Standard Aluminium

Impact category	Main phase contributing to overall results	Main process contributing to overall results
GWP	Electrolysis (Prebake): 77%	Electricity: 56%
AP	Electrolysis (Prebake): 46%	Direct Process: 38%
ODP	Electrolysis (Prebake): 65%	Electricity: 65%
POCP	Electrolysis (Prebake): 39%	Direct Process: 25%
EP	Bauxite Mining: 29%	Petcoke for Anode production: 22%
ADP (fossil)	Electrolysis (Prebake): 71%	Electricity: 70%

In terms of GWP, emissions from electricity for electrolysis account for 56%, followed by direct emissions from the electrolysis process (14%) and emissions associated with the provision of thermal energy for alumina refining (12%). This order of contribution aligns with the findings in the IAI report for global aluminium production (IAI, 2022), which has been critically reviewed by external experts.

The prior results have shown that alumina, including bauxite mining, transport and alumina refining, is the second highest contributor in all categories, except ODP. The choice of aluminium supplier is therefore very relevant to the overall result. With 772 kg CO2eq per ton, ATA alumina, including GAC bauxite and bauxite transport, performs significantly better in terms of GWP100 than Souh32 alumina (1379 kg CO2eq) and IAI GLO average alumina (1289 kg CO2eq). The resulting EGA alumina supply mix therefore has a GWP100 of 1051 kg CO2eq per ton of alumina. However, it is important to note that GWP is not the only category that should be considered when selecting suppliers in order to avoid trade-offs.

5.2 Comparative Analysis of EGA products

The prior analysis has shown that electricity production for the electrolysis is an environmental hotspot for the EGA Total Standard Aluminium. Electricity emissions are strongly related to energy sources.

CelestiAL Aluminium represents a product produced from solar electricity compared to the Standard product which primarily relies on electricity from natural gas. The following comparison is intended to show the effect on the results if EGA's most efficient electrolysis technology and solar power are used instead of the average electrolysis technology and electricity mix. Table 10 shows how the results change in absolute and relative terms per life cycle stage.

Table 10: EGA Total CelestiAL results in comparison to EGA Total Standard Aluminium

Category	Bauxite mining and Alumina production		Transport Alumina		Electrolysis, Prebake		Ingot casting		Total	
	absolute	relative	absolute	relative	absolute	relative	absolute	relative	absolute	relative
ADP (fossil)	-5886	-24%	-294	-87%	-107389	-84%	-380	-7%	-113949	-72%
EP	-5.1E-02	-4%	-7.5E-02	-98%	-3.3E-01	-29%	-1.2E-03	-1%	-4.6E-01	-18%
POCP	-2.7E-01	-35%	-4.3E-02	-106%	-1.3E-01	-12%	-4.9E-04	0%	-4.4E-01	-22%
ODP	4.9E-08	1792%	-1.9E-12	-85%	1.5E-06	4698%	5.6E-09	39%	1.6E-06	3213%
AP	-4.1E+00	-34%	-7.4E-01	-99%	-8.5E-01	-4%	-3.1E-03	0%	-5.7E+00	-17%
GWP100	-685	-35%	-24	-89%	-5542	-68%	-20	-4%	-6272	-59%

Significant reductions in emissions of the EGA Total CelestiAL Aluminium compared to the Standard variant are observed for ADP Fossil (-72%) and GWP100 (-59%). Smaller reductions are observed for EP (-18%), POCP (-22%), and AP (-17%). Notably, there is a substantial increase in ODP by 3212%, primarily due to the small baseline values of ODS, resulting in significant relative increases by the emission of ODS from upstream processes of the photovoltaics production.

The highest absolute levels of induced changes are found in the electrolysis and alumina production processes. The former is primarily influenced by the substitution of electricity from natural gas by solar power and, to a lesser extent, by a slight reduction in electricity consumption compared to the average technology. The latter is influenced by the replacement of alumina from other sources with ATA alumina and the use of solar power in the refining process. Changes in ingot casting are less pronounced due to its lower power demand compared to the electrolysis. A substantial relative decrease for Alumina Transport impacts can be observed across all categories, due to the significantly reduced transportation distance of ATA alumina compared to the average alumina supply mix from various sources.

Another indirect way to address the identified environmental hotspot of aluminium (electrolysis) is to increase the amount of cold metal in the product, replacing the hot metal from electrolysis in the ingot casting process. It has to be noted that the impact of such a measure depends on the environmental impacts allocated to the used scrap.

CelestiAL-R Aluminium represents an EGA product with increased recycled content, i.e. 16% post-consumer, 10% internal and 0% pre-consumer scrap compared to approximately 0.05%, 0.21% and 0.27% respectively for the EGA Total Standard and CelestiAL products. Table 11 compares the EGA Total CelestiAL-R results to CelestiAL Aluminium.

Table 11: EGA Total CelestiAL-R results in comparison to CelestiAL Aluminium

Category	Upstream		Ingot casting		Total	
	absolute	relative	absolute	relative	absolute	relative
ADP (fossil)	-10431	-26%	194	4%	-10,237	-23%
EP	-5.2E-01	-26%	2.1E-03	2%	-5.1E-01	-25%
POCP	-3.8E-01	-26%	7.2E-03	5%	-3.7E-01	-23%
ODP	-4.3E-07	-26%	1.4E-09	7%	-4.3E-07	-26%
AP	-7.1	-26%	0.00	0%	-7.05	-25%
GWP100	-1012	-26%	19	4%	-993	-23%

For this specific product, the reduction in the impact of electrolysis and all other upstream processes amounts to 26% compared to CelestiAL Aluminium due to a decreased requirement for hot metal. The impacts of ingot casting slightly increase due to a shift from hot metal to cold metal (scrap), associated with the increased internal scrap which affects the Standard product casting process turnover, as post-consumer scrap is considered burden-free.

For illustrative purposes, the GWP results of the EGA Total Aluminium products are compared in Figure 23. It shows that the GWP changes between the products on an absolute GWP level are mainly related to the electrolysis and the substitution of the electricity source, which is the main electricity consumer in the process chain.

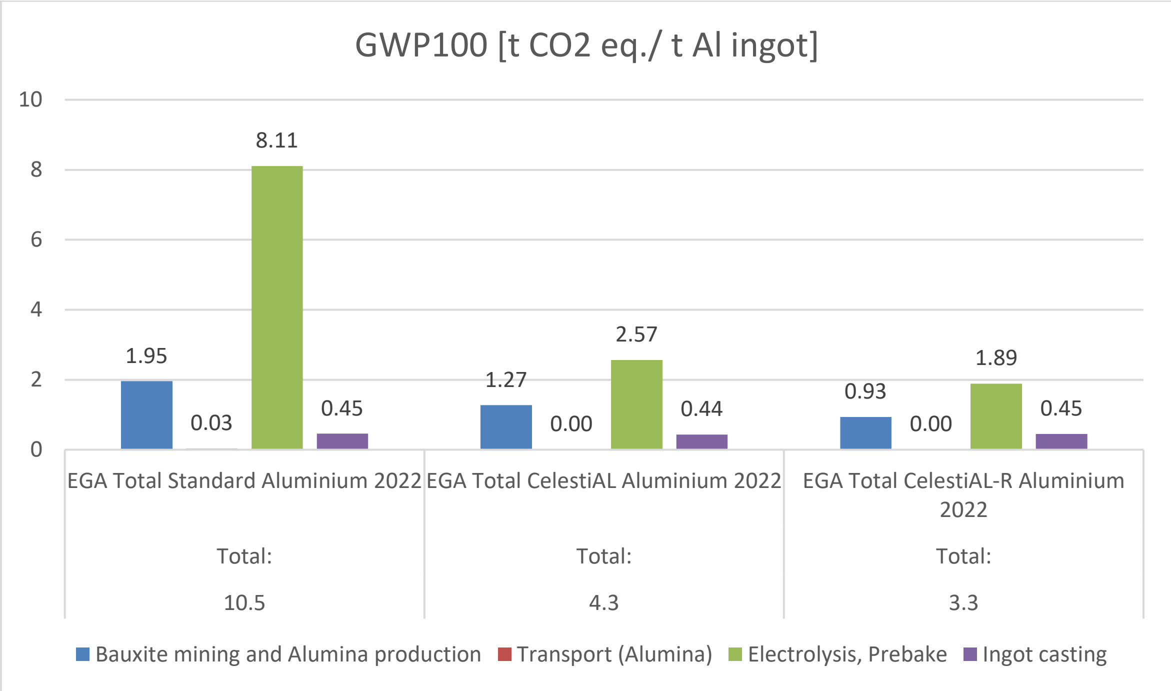

Figure 23: GWP results of EGA Total Aluminium products in comparison

5.3 Sensitivity analysis

In the following section, the sensitivity of the results is discussed based on selected influencing parameters relevant to the results.

A significant parameter identified has been shown to be the electrolysis and the associated electricity. In this sense, the previous comparative analysis of the different products can be understood as a sensitivity analysis, which examines the influence of the substitution of the average electricity mix with solar electricity from renewable sources and the influence of increasing the recycled content of the product.

The sensitivity test also serves to assess the uncertainties of a LCA study. Since the quality of the data is considered to be high, as the study is based on primary data, verified secondary data from the IAI, and established data sets from LCA databases, the uncertainties of this study are mainly related to methodological choices, such as the approach to pre-consumer scrap allocation.

5.3.1 Pre-consumer scrap scenario

As discussed in section 3.2.7.3, the IAI defines 10 scenarios for the allocation of environmental impacts of pre-consumer scrap between the scrap generator and remelter. The choice of the scenario is at the discretion of the LCA practitioner. In the following sections, we will assess the impact of these scenarios by comparing the previous results obtained using the CP3 approach with the cut-off approach (W) as an extreme case study, assuming EGA receives this scrap without any burden.

The results of this analysis are presented in Table 12, which shows that the sensitivity of the scrap allocation approach to the overall results is minimal, with a maximum sensitivity for the EP, POCP and AP categories (relative reduction of 0.4%).

Table 12: Scenario results for pre-consumer scrap allocation approach cut-off (W) in comparison to CP3 for EGA Total Standard Aluminium

Category	Unit	Ingot casting		Total	
		Total	change	Total	change
ADP (fossil)	[MJ]	-330	-6%	-330	-0.2%
EP	[kg Phosphate eq.]	-1.1E-02	-8%	-1.1E-02	-0.4%
POCP	[kg Ethene eq.]	-7.6E-03	-5%	-7.6E-03	-0.4%
ODP	[kg R11 eq.]	-7.2E-15	0%	-7.2E-15	0.0%
AP	[kg SO2 eq.]	-0.12	-9%	-0.12	-0.4%
GWP100	[kg CO_2 eq.]	-25	-6%	-25	-0.2%

To date, EGA uses 3.4 kg and 1.2 kg of pre-consumer scrap per ton of Standard Aluminium ingot, for AT and JA products respectively. If this percentage is increased in the future, the scrap allocation method may become more important. As the scrap basically replaces hot metal from the electrolysis, the impact on the results depends on the scrap allocation method and the aluminium source from which this scrap is derived, which determines whether its use is increase or decreases the overall results (i.e. whether the scrap has a higher or lower burden than the hot metal).

5.4 Completeness and consistency check

Completeness has been checked at cradle-to-gate level for all process steps and inputs and has been verified with EGA and IAI data. The data quality for the processes can be considered very good, as it is primarily based on primary data. Data gaps have been filled with state-of-the-art secondary data from the IAI and the LCA databases of Sphera and Ecoinvent. No significant data gaps exist according to this evaluation and all flows relevant for representing the life cycle phases under consideration of the goal and scope definition (see section 2.1) are included.

The principles of ISO 14040/44 and the IAI guidelines were followed, and strict adherence was made to the pre-defined objective and scope to ensure methodological and data consistency in this LCA. Throughout this process, rigorous cross-referencing of data sources was performed to ensure data consistency. Primary data from suppliers that did not meet the set data requirements were neglected and replaced by secondary data. In addition, the detailed results analysis and comparison with IAI data and results from previous EGA LCA projects ensures that there are no errors in main processes relevant to the results. Data plausibility and results were also compared between the two production sites JAS and ATS.

By way of example, the GWP results of the previous LCA project for the reference year 2019 are presented in Figure 24 as a plausibility check. Overall, there is a reduction of

9.8% in the GWP100 of the EGA Total Standard Aluminium ingot. This change is mainly driven by alumina, which has become significantly less carbon intensive by around 29%. This is related to an increased share of alumina supply from EGA´s ATA plant and a significant improvement in GWP of the IAI GLO average alumina between 2015 and 2019. The GWP reduction is more pronounced for the AT Standard Aluminium, which profits from an increased supply of alumina from nearby ATA plant. Similarly, the GWP of the EGA Total Standard Aluminium Electrolysis and Ingot Casting process decreased by 3% and 6%, respectively.

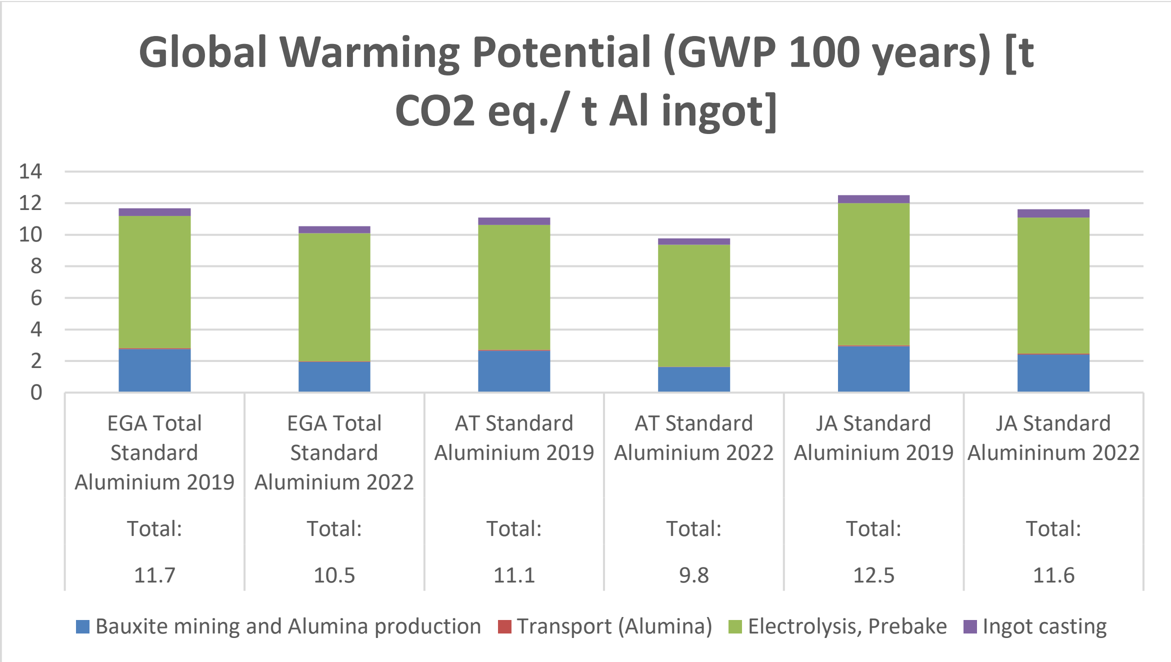

Figure 24: Site-specific GWP results compared to 2019

The comparison of the results with IAI averages of all companies which participated in the LCI survey 2019, showed a similar range of the overall environmental results in terms of approximate order of magnitude and individual process contributions shares.

5.5 Conclusions and Recommendations

The cradle-to-gate LCA study evaluates the environmental performance of EGA primary aluminium ingots. Potential environmental impacts related to the considered life cycle including bauxite mining, transport of bauxite, alumina production, transport of alumina, prebaked anode production, electrolysis and ingot casting, are analysed. Total results per 1,000 kg of primary EGA Total Aluminium ingot yield:

Table 13: EGA Total product results

Category	Unit	EGA Total Standard	EGA Total CelestiAL	EGA Total CelestiAL-R
ADP (fossil)	[MJ]	158,528	44,578	34,341
EP	[kg Phosphate eq.]	2.6	2.1	1.6
POCP	[kg Ethene eq.]	2.0	1.6	1.2
ODP	[kg R11 eq.]	5.0E-08	1.6E-06	1.2E-06
AP	[kg SO2 eq.]	33.7	28.1	21.0
GWP100	[kg CO_2 eq.]	10,545	4,273	3,280

The outcomes show that the major contributors to the overall potential environmental impacts are Electrolysis and Alumina production, aligning with findings from previous EGA LCA projects and from the IAI (IAI, 2022). Overall, the Electrolysis, including prebake anode production, can be considered as the most relevant process in this specific study. It has the highest contribution within all impact categories (53-81%) except EP (44%) for the EGA Total Standard Aluminium. The study also shows that electricity generation from natural gas for the electrolysis is the dominant process in most environmental impact categories. The results of the EGA Total CelestiAL Aluminium have underscored, that replacing natural gas as the main power source for EGA with solar power, alongside using the most efficient electrolysis technology and relying entirely of alumina from EGA's own ATA refinery, presents a significant reduction potential for all impact categories (from -17% for AP to -59% for GWP 100 and up to -72% for ADP (Fossil)) except ODP, which experiences an increase due to upstream emissions of photovoltaic production. The increase of the recycled content with the EGA total CelestiAL-R Aluminium decreases the impacts further by 23% to 26%.

Bauxite mining and alumina production has the second highest burden in most categories (15-47%) except ODP (5%) for EGA Total Standard Aluminium. This is highly relevant for EGA's current upstream expansion and existing/potential supply chain partners. For example, compared to other EGA suppliers, ATA Alumina performs significantly better in terms of GWP. For CelestiAL and CelestiAL-R, the relative contribution of alumina refining to GWP, EP and ADP (fossil) results increases as electrolysis impacts decrease, underscoring the increasing relevance of clean alumina supply.

CelestiAL and CelestiAL-R are aluminium products characterized by a low carbon footprint achieved through exclusive use of solar energy, ATA alumina, and highly efficient electrolysis technology. These products are already integrated to a small extent within EGA Standard aluminium. Double counting these products with rather low carbon footprint might lead to underestimation of impacts, which should be disclosed when communicating impact results to customers. Therefore, when a specific quantity of CelestiAL or CelestiAL-R aluminium is already claimed by a customer, the Standard Aluminium should be adjusted to the "residual" Standard Aluminium mix by excluding the low carbon products already accounted for, to avoid the double counting of clean energy, alumina or efficient electrolysis technology.

So far, the impact of the use of pre-consumer scrap as a cold metal input to the ingot casting process is small as shown by sensitivity analyses, due to the small amounts of scrap added. Increased use of scrap could increase the importance of allocation approaches.

The impact of alloying additives on GWP is relatively minor, with the GWP of the alloying additives mix, at 12 t CO2 eq./t, falling within the range of the final product. Nonetheless, this may not remain the case when considering an increased use of high-GWP outliers, like Magnesium from China, which carries a GWP of 33 t CO2/t due to the energy-intensive Pidgeon process and China's current fossil-fuel-heavy energy mix. The ODP impact of certain additives such as strontium waffle is significant, likely due to differences in dataset models between Ecoinvent and Sphera datasets as the Ecoinvent-based strontium carbonate dataset exhibits an unusually high ODP in this context.

Furthermore, data quality has been evaluated as high. However, sustaining and improving the currently developed internal data collection routes is highly recommended, in order to increase the primary data share and decrease the uncertainty of information for future projects. The methods and data used are complete and consistent with the ISO standards and IAI guidelines.

This report has been subjected to an ongoing independent third-party review. A summary report is attached as appendix B to this report.

It is recommended to include further impact categories, such as water scarcity footprints, toxicity and land-use in future LCAs. Overall, the results of this study can be used as a solid basis for further projects, for responding to customer inquiries and for strengthening sales and marketing forces.

6 References

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7 Annex

Table 14: LCIA profile of AT Standard Aluminium

Category	Unit	Bauxite mining and Alumina production	Transport (Alumina)	Electrolysis, Prebake	Ingot casting	Total
ADP (fossil)	[MJ]	22,928	137	122,481	4,515	150,061
EP	[kg Phosphate eq.]	1.19	0.03	1.04	0.12	2.38
POCP	[kg Ethene eq.]	0.59	0.02	0.85	0.13	1.59
ODP	[kg R11 eq.]	2.90E-09	9.03E-13	5.28E-08	1.32E-08	6.89E-08
AP	[kg SO2 eq.]	9.42	0.30	14.48	1.12	25.33
GWP100	[kg CO_2 eq.]	1,623	11	7,735	393	9,762

Table 15: LCIA profile of JA Standard Aluminium

Category	Unit	Bauxite mining and Alumina production	Transport (Alumina)	Electrolysis, Prebake	Ingot casting	Total
ADP (fossil)	[MJ]	26,664	615	136,337	6,595	170,210
EP	[kg Phosphate eq.]	1.24	0.14	1.25	0.16	2.79
POCP	[kg Ethene eq.]	0.98	0.07	1.40	0.18	2.64
ODP	[kg R11 eq.]	2.45E-09	4.06E-12	5.32E-09	1.55E-08	2.33E-08
AP	[kg SO2 eq.]	15.6	1.4	26.8	1.6	45.3
GWP100	[kg CO_2 eq.]	2,413	50	8,621	539	11,624

Table 16: LCIA profile of AT CelestiAL Aluminium

Category	Unit	Bauxite mining and Alumina production	Transport (Alumina)	Electrolysis, Prebake	Ingot casting	Total
ADP (fossil)	[MJ]	18,718	0	20,753	4,238	43,708
EP	[kg Phosphate eq.]	1.16	0.00	0.77	0.11	2.05
POCP	[kg Ethene eq.]	0.49	0.00	0.75	0.13	1.38
ODP	[kg R11 eq.]	5.16E-08	0.00E+00	1.57E-06	1.74E-08	1.64E-06
AP	[kg SO2 eq.]	8.0	0.0	13.9	1.1	23.0
GWP100	[kg CO_2 eq.]	1,277	0	2,490	379	4,146

Table 17: LCIA profile of JA CelestiAL Aluminium

Category	Unit	Bauxite mining and Alumina production	Transport (Alumina)	Electrolysis, Prebake	Ingot casting	Total
ADP (fossil)	[MJ]	18,466	103	21,138	6,073	45,780
EP	[kg Phosphate eq.]	1.15	0.00	0.83	0.16	2.15
POCP	[kg Ethene eq.]	0.48	-0.01	1.22	0.18	1.87
ODP	[kg R11 eq.]	5.09E-08	7.81E-13	1.59E-06	2.30E-08	1.6614E-06
AP	[kg SO2 eq.]	7.89	0.02	25.62	1.55	35.08
GWP100	[kg CO_2 eq.]	1,260	7	2,668	512	4,448

Table 18: LCIA profile of AT CelestiAL-R Aluminium

Category	Unit	Bauxite mining and Alumina production	Transport (Alumina)	Electrolysis, Prebake	Ingot casting	Total
ADP (fossil)	[MJ]	13,771	0	15,269	4,494	33,534
EP	[kg Phosphate eq.]	0.86	0.00	0.57	0.12	1.55
POCP	[kg Ethene eq.]	0.36	0.00	0.56	0.14	1.06
ODP	[kg R11 eq.]	3.79E-08	0.00E+00	1.15E-06	1.87E-08	1.21E-06
AP	[kg SO2 eq.]	5.89	0.00	10.20	1.16	17.25
GWP100	[kg CO_2 eq.]	939	0	1,832	403	3,175

Table 19: LCIA profile of JA CelestiAL-R Aluminium

Category	Unit	Bauxite mining and Alumina production	Transport (Alumina)	Electrolysis, Prebake	Ingot casting	Total
ADP (fossil)	[MJ]	13,615	76	15,585	6,181	35,457
EP	[kg Phosphate eq.]	0.85	0.00	0.62	0.16	1.63
POCP	[kg Ethene eq.]	0.36	0.00	0.90	0.18	1.43
ODP	[kg R11 eq.]	3.75E-08	5.76E-13	1.17E-06	2.45E-08	1.23E-06
AP	[kg SO2 eq.]	5.82	0.01	18.89	1.51	26.23
GWP100	[kg CO_2 eq.]	929	5	1,967	524	3,426