Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Manufacturing and Civil Engineering

WISEMAN SIRIRO

Sustainability Assessment and Optimization of Aluminum Production for Electric Vehicle Manufacturing Using Life Cycle Assessment and Predictive Modeling

Master's thesis in Sustainable Manufacturing - Erasmus Mundus Joint Master Degree in Manufacturing 4.0 by Intelligent and Sustainable Technologies (Meta4.0)
Supervisor: Gier Ringen
Co-supervisor: Niels Peter Østbø, Cédric Courbon, Milena Salvo
September 2025

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Abstract

The automotive shift to EVs emphasizes sustainable materials, along with smart and digital manufacturing, to enhance efficiency and reduce environmental impact. Aluminum, valued for its light weight, strength, and recyclability, is vital for EVs, but it is highly energy-intensive. This underscores the need for detailed regional LCAs. This study examines the environmental impacts of aluminum production for EVs and addresses three key questions. It applies life cycle assessment to assess impacts and identify mitigation strategies. Objectives include quantifying impacts, pinpointing high-impact stages, analyzing regional differences, predicting GWP with a machine-learning dashboard, and comparing aluminum with alternative battery enclosure materials. These efforts support sustainability strategies, thus aligning with the 2030 SDG goals and 2050 net-zero goals.

Following ISO 14040 and ISO 14044, a cradle-to-gate life cycle assessment of 1,000 kg of primary and secondary aluminum in the North American and European contexts was conducted using SimaPro v9.3.0.2, with Tableau and Power BI employed for visualization. The methods applied included TRACI, BEES+, CML-IA, and ReCiPe, with a focus on characterization results. Sensitivity analyses considered energy source and recycling rate. A GWP prediction dashboard was developed in Python to model emissions based on energy mix, region, and production parameters to support decision-making. For primary aluminum, total GWP is 8,294 kg CO_2 eq in North America (using TRACI method) and 6,638 kg CO_2 eq in Europe (using CML method). For secondary aluminum, GWP is 4,672 kg CO_2 eq in North America (using TRACI) and 4,552 kg CO_2 eq in Europe (using CML), indicating that recycling reduces GWP significantly. Smelting and electrolysis are the main hotspots, contributing 5,570 kg CO_2 eq in North America (TRACI) and 4,480 kg CO_2 eq in Europe (CML). A 120 kg aluminum enclosure has a lifecycle GWP of approximately 305 kg CO_2 eq, dominated by alumina refining and electrolysis. During comparison, aluminum outperforms steel, magnesium, and CFRPs in cost, weight reduction, and recyclability. Despite the need for further optimization, the dashboard demonstrated promising results. For example, it predicted 10,400 kg CO_2 eq for a 60% hydro and 40% coal energy mix in Asia for 1,000 kg of primary aluminum production, and this is consistent with benchmarks.

In conclusion, findings highlight smelting and electrolysis as key mitigation targets, with energy sources driving aluminum's footprint. It becomes clear that recycling reduces impacts and supports circular economy principles, while variations in LCIA methods, units, dataset scope, and regional energy mixes complicate comparisons, emphasizing standardization. The dashboard aids in optimizing energy choices for sustainable production. Although aluminum production is energy-intensive, adopting renewable energy can lower impacts. Results guide industry and policymakers toward renewable energy transition, enhanced recycling, and standardized LCA metrics, with the dashboard supporting decarbonization decisions. Future work should explore low-carbon technologies, improved red mud management, CCS integration, digital twin simulations, broader social and economic assessments, and dashboard enhancements using diverse energy sources, real-time data, and validation against real-world emissions for greater accuracy and global applicability.

Keywords: electric vehicles, aluminum production, life cycle assessment, global warming potential, recycling, net-zero targets

Sammendrag

Den automotive overgangen til elbiler vektlegger bærekraftige materialer samt smart og digital produksjon for å øke effektivitet, styrke konkurransekraft og redusere den samlede negative miljøpåvirkningen. Aluminium, verdsatt for lav vekt, styrke og resirkulerbarhet, er helt avgjørende for elbiler, men samtidig svært energiintensivt. Dette understreker behovet for grundige og detaljerte regionale livsløpsanalyser. Studien undersøker den samlede miljøpåvirkningen av aluminiumsproduksjon for elbiler og adresserer tre sentrale nøkkelspørsmål. Livsløpsanalyse brukes systematisk til å vurdere effekter og identifisere nødvendige tiltak. Målet er å kvantifisere påvirkning, peke ut de mest høybelastede prosessene, analysere regionale forskjeller, forutsi globalt oppvarmingspotensial via et maskinlæringsdashboard, og sammenligne aluminium med alternative materialer for batterikapslinger. Arbeidet støtter viktige bærekraftsstrategier i tråd med FNs 2030-mål og netto null innen år 2050.

I tråd med ISO 14040 og ISO 14044 ble det utført en cradle-to-gate LCA av 1 000 kg primær- og sekundæraluminium i nordamerikansk og europeisk kontekst, ved bruk av SimaPro v9.3.0.2, med Tableau og Power BI for visualisering. Metodene TRACI, BEES+, CML-IA og ReCiPe ble brukt med fokus på karakteriseringsresultater. Sensitivitetsanalyser vurderte energikilde og resirkuleringsgrad. Et GWP-dashboard ble utviklet i Python for å modellere utslipp basert på energimiks, region og produksjonsparametere. For primæraluminium er total GWP 8 294 kg CO_2-ekv. i Nord-Amerika (TRACI) og 6 638 kg CO_2-ekv. i Europa (CML). For sekundæraluminium er GWP 4 672 kg CO_2-ekv. i Nord-Amerika (TRACI) og 4 552 kg CO_2-ekv. i Europa (CML), noe som viser at resirkulering reduserer GWP betydelig. Smelting og elektrolyse er hovedhotspots, med 5 570 kg CO_2-ekv. i Nord-Amerika (TRACI) og 4 480 kg CO_2-ekv. i Europa (CML). En aluminiums-kapsling på 120 kg har et livsløps-GWP på ca. 305 kg CO_2-ekv., dominert av aluminaraffinering og elektrolyse. Ved sammenligning utkonkurrerer aluminium stål, magnesium og CFRP på kostnad, vekt og resirkulerbarhet. Til tross for behov for videre optimalisering viste dashboardet lovende resultater. For eksempel forutsa det 10 400 kg CO_2-ekv. for 60 % vannkraft og 40 % kull i Asia ved produksjon av 1 000 kg primæraluminium, i samsvar med referanseverdier.

Konklusjonen peker på smelting og elektrolyse som sentrale mål for reduksjon, med energikilder som avgjørende for aluminiums karbonavtrykk. Resirkulering reduserer påvirkningen og støtter sirkulærøkonomi, mens variasjoner i LCIA-metoder, enheter, datasett og regional energimiks gjør sammenligning krevende og understreker behovet for standardisering. Dashboardet støtter optimalisering av energivalg for bærekraftig produksjon. Selv om produksjonen er energiintensiv, kan fornybar energi senke utslippene. Resultatene gir veiledning for industri og beslutningstakere om overgang til fornybar energi, bedre resirkulering og standardiserte LCA-mål, med dashboardet som støtte i avkarboniseringsstrategier. Fremtidig arbeid bør utforske lavkarbonteknologier, bedre håndtering av rødslam, CCS-integrasjon, digitale tvillingsimuleringer, samt bredere sosiale og økonomiske analyser. Videre bør dashboardet forbedres med flere energikilder, sanntidsdata og validering mot faktiske utslipp for økt nøyaktighet og global relevans.

Nøkkelord: elbiler, aluminiumsproduksjon, livsløpsanalyse, globalt oppvarmingspotensial, resirkulering, netto null-mål

Preface

The research presented in this master's thesis was conducted at the Norwegian University of Science and Technology (NTNU), within the Department of Manufacturing and Civil Engineering, as part of the Erasmus Mundus Joint Master's Degree Programme in Manufacturing 4.0 by Intelligent and Sustainable Technologies (Meta4.0), a collaboration that also includes École Centrale de Lyon (ENISE) in France and Politecnico di Torino (PoliTo) in Italy. The thesis was completed under the supervision of Professor Geir Ringen, with additional guidance from Professor Niels Peter Østbø, the NTNU Programme Coordinator for Meta4.0. This work extends my earlier project, "Exploring the Environmental Implications of Aluminum in Electric Vehicle Manufacturing," undertaken at NTNU within the course TMM4285 – Lifecycle Performance of Aluminum. While it builds on that foundation, the theoretical framework, assumptions, and data have been refined and expanded, resulting in a broader scope. Accordingly, the thesis has been retitled "Sustainability Assessment and Optimization of Aluminum Production for Electric Vehicle Manufacturing Using Life Cycle Assessment and Predictive Modeling" to reflect its enhanced objectives and contributions. As per the programme's rules and regulations, this thesis was first formally submitted to the Meta4.0 Erasmus Mundus Joint Master's Degree Consortium before being registered in the official digital system at the Norwegian University of Science and Technology. The research and detailed analysis presented are the result of my thorough and independent personal work.

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List of Abbreviations (or Symbols)

Abbreviations & Acronyms

AE	Aquatic Ecosystem(s)
ADP	Abiotic Resource Depletion
AP	Acidification Potential
APIs	Application Programming Interfaces
ARD	Abiotic Resource Depletion
ASI	Aluminium Stewardship Initiative
BEE+	Building for Environmental and Economic Sustainability
BEV	Battery Electric Vehicle
BMW	Belt Material Wear
BOD_5	Biological Oxygen Demand
BWMF	Belt and Wear Material Fragments
CAGR	Compound Annual Growth Rate
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture Storage
CFRPs	Carbon Fiber Reinforced Polymers
COD	Chemical Oxygen Demand
CRM	Critical Raw Material
CTUh	Comparative Toxic Units for Human Health
CTUe	Comparative Toxic Units for Ecosystems
DALY	Disability-Adjusted Life Year
DALYs	Disability-Adjusted Life Years
DAR	Depletion of Abiotic Resources
DC	Direct Chill
DP	Diesel Powered
EAA	European Aluminium Association
EAFA	European Aluminium Foil Association
ECJRC	European Commission Joint Research Centre
EIA	Environmental Impact Assessment(s)
ELCD	European Reference Life Cycle Database
EOL	End-of-Life
EPA	Environmental Protection Agency
EP	Eutrophication Potential
EPR	Environmental Profile Report
EPS	Environmental Priority Strategies
ESSUM	European Scrap Smelting Unit Model
EULCIA	European Life Cycle Impact Assessment
FE	Freshwater ecosystem(s)
GAI	Global Aluminium Institute
GaBi	Software tool for life cycle assessment
GHG	Greenhouse Gas
GLO	Geographical Location – Global

GWP	Global Warming Potential
HA	Hardened Alloy
IAI	International Aluminium Institute
IAQ	Indoor Air Quality
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LIBS	Laser-Induced Breakdown Spectroscopy
LNG	Liquefied Natural Gas
MDS	Magnetic Density Separation
MPa	Megapascal
NA	North America
NIR	Near-Infrared Spectroscopy
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
NRD	Natural Resource Depletion
OAT	One-at-a-Time
ODP	Ozone Layer Depletion Potential
OEM	Original Equipment Manufacturer
OEA	Organization of European Aluminium Refiners and Remelters
PAHs	Polycyclic Aromatic Hydrocarbons
PCA	Principal Component Analysis
PDF	Potentially Disappeared Fraction of Species
PEF	Product Environmental Footprint
PFCs	Perfluorocarbons
POCP	Photochemical Ozone Creation Potential
POF	Photochemical Oxidant Formation
ReCiPe	Life Cycle Impact Assessment Method
RER	European Region
RoW	Rest-of-the-World
SDGs	Sustainable Development Goals
SLCA	Social Life Cycle Assessment
SO_2	Sulfur Dioxide
SO_x	Sulfur Oxides
SPL	Spent Potlining
STF	Synthetic Textile Fragments
TE	Terrestrial Ecosystem(s)
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UNEP	United Nations Environment Programme
USIRA	United States Inflation Reduction Act
US LCI	U.S. Life Cycle Inventory Database
USEPA	U.S. Environmental Protection Agency
USNIST	U.S. National Institute of Standards and Technology
VOC	Volatile Organic Compound

VOCs	Volatile Organic Compounds
WU	Water Usage
XRT	X-ray Transmission

Other symbols

Al	Aluminium
Al_2O_3	Alumina
$Al(OH)_3$	Aluminum hydroxide
C_2F_6	Hexafluoroethane
CF_4	Tetrafluoromethane
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
Cu	Copper
Cu-Ni-Fe-O	Copper–nickel–iron oxide composite
e^-	Electron
Fe_2O_3	Iron(III) oxide
Mg	Magnesium
$NaAl(OH)_4$	Sodium aluminate (solution form)
$NaAlO_2$	Sodium aluminate
Na_3AlF_6	Cryolite
$NiFe_2O_4$	Nickel ferrite
O^{2-}	Oxide ion
O_2	Molecular oxygen
Si	Silicon
SiO_2	Silicon dioxide
TiO_2	Titanium dioxide

1 Introduction and Background

1.1 Introduction.

The world has become increasingly aware of the detrimental impacts of human activities on the environment. Manufacturing, in particular, has been identified as a significant contributor to negative environmental impacts [1].The automotive industry is undergoing a transformative shift toward sustainability, driven by the increasing adoption of electric vehicles. EVs are critical for reducing transportation-related greenhouse gas emissions, but their production, particularly the use of energy-intensive materials like aluminum, presents environmental challenges. Aluminum is widely used in EV manufacturing due to its high strength-to-weight ratio, which reduces vehicle weight, improves energy efficiency, and extends driving range [2]. However, aluminum production is highly energy-intensive, contributing approximately 3% of global direct industrial CO_2 emissions in 2021, equivalent to 270 million metric tons out of 9.4 gigatons total industrial emissions [3]. Primary aluminum production consumes around 15 MWh per ton, making it one of the most energy-intensive industrial processes [4]. The growing focus on sustainability has prompted industries to explore cleaner production techniques, alternative energy sources, and recycling strategies to mitigate these impacts. Environmental regulations and corporate sustainability initiatives are increasingly influencing production practices worldwide, promoting greener technologies.

The aluminum production process encompasses bauxite mining, alumina refining, smelting, and fabrication, with each stage contributing to environmental impacts including greenhouse gas emissions, water consumption, and waste generation [5]. With global aluminum demand projected to increase by 40% by 2030, partly driven by EV adoption, sustainable production practices are essential [6]. Life cycle assessment offers a comprehensive and systematic framework to evaluate these environmental impacts across the entire product life cycle, from raw material extraction to recycling. By integrating advanced predictive modeling techniques, such as machine learning, this study aims to accurately forecast environmental performance across diverse regions and scenarios, thus providing actionable and evidence-based insights for policymakers and manufacturers. This innovative approach also allows for the identification of process inefficiencies, bottlenecks, and opportunities to reduce energy consumption and emissions in future production cycles.

The primary objective of this study is to assess the environmental footprint of aluminum production for EVs using life cycle assessment, identify key impact hotspots, and propose strategies for sustainable enhancement. The research also examines regional variations in production processes and explores the potential of predictive modeling to extend findings to regions like Africa and Asia. Additionally, it compares the environmental performance of aluminum battery enclosure with alternative materials to identify optimization opportunities for EV manufacturing. The study further highlights how material selection, energy sourcing, and recycling strategies can collectively reduce the carbon intensity of EV production. Findings from this research are intended to guide both industry stakeholders and policymakers in implementing evidence-based strategies for a more sustainable automotive sector.

Figure 1.1 : Life Cycle Assessment [7]

Research questions:

1. What are the environmental impacts and key hotspots of aluminum production processes across North America and Europe, as assessed through lifecycle inventory and multiple LCIA methodologies.

2. How do regional differences in energy sources, process efficiencies, and material recycling scenarios affect the environmental performance of aluminum production, and can these impacts be predicted for other regions like Africa and Asia using machine learning?

3. How does the environmental performance of an aluminum battery casing/enclosure for electric vehicles compare to alternative materials, and what strategies can optimize aluminum production to reduce environmental burdens in EV manufacturing?

1.2 Background

Aluminum plays a critical role in the automotive industry, particularly in EVs, due to its lightweight properties, corrosion resistance, and recyclability. In EVs, aluminum is essential for components such as battery enclosures, chassis, and body panels, offsetting the weight of heavy battery systems to improve efficiency and range [8]. The material's combination of strength and low density makes it indispensable for meeting the performance and efficiency demands of modern electric vehicles. Global aluminum demand for EVs is projected to reach 10 million tons annually by 2030, driven by the need for lighter vehicles [9]. Producing primary aluminum is highly energy-intensive and environmentally significant, encompassing stages such as bauxite mining, alumina refining, electrolysis (smelting), and secondary processing (e.g., casting and rolling). Each stage contributes to substantial energy consumption, greenhouse gas emissions, water usage, and waste generation [10]. This underscores the importance of adopting cleaner energy sources and improving process efficiency across the entire aluminum value chain to ensure sustainability.

Bauxite mining disrupts ecosystems and generates red mud, a toxic byproduct of alumina refining [11]. The smelting phase, which depends heavily on electricity, accounts for roughly 60% of the total energy consumption in primary aluminum production [12]. Regional variations in energy sources, such as coal in Asia, hydropower in Europe, and natural gas in North America, substantially influence the environmental footprint of aluminum production [13]. Recycling, or secondary aluminum production, can reduce energy consumption by up to 95% compared to primary production; however, global recycling rates still remained significantly suboptimal at only 76% in 2021 [14] [15].

Life cycle assessment is an established and widely recognized methodology for systematically quantifying the environmental impacts of aluminum production across its entire life cycle, from cradle to grave or cradle to cradle in recycling scenarios [16]. By integrating life cycle assessment with advanced predictive modeling techniques, such as machine learning algorithms, this study seeks to identify trends and patterns in regional production data and accurately forecast environmental impacts for regions with limited or incomplete data, such as Africa and Asia. Comparative analysis of aluminum with alternative materials, such as steel or composites, for EV battery casings can reveal trade-offs in environmental performance and inform sustainable material selection and policy-relevant decisions. Understanding these complex and highly interconnected dynamics is essential for developing effective strategies to minimize the environmental footprint of aluminum in EV manufacturing.

2 Previous Studies/Literature Review

The environmental impact of aluminum production and its use in electric vehicles has been studied, as its lightweight nature helps offset heavy batteries and boost efficiency and range [17] [18]. However, aluminum production uses a lot of energy and produces large greenhouse gases emissions affected by energy sources and how efficient the processes are. Life cycle assessment has been widely used to measure impacts, check recycling benefits, and look at uses in EV manufacturing. The following subsections organize the literature into primary aluminum production, secondary (recycled) aluminum production, and other parts, including EV uses and method considerations.

2.1 Primary Aluminum Production.

Primary aluminum production, encompassing bauxite mining, alumina refining, smelting, and ingot casting, is highly energy-intensive, requiring significantly more energy per kg than materials like steel, copper, or lead due to the inherent complexity of extracting aluminum from bauxite ore [19]. Liu and Müller reviewed life cycle assessments of primary aluminum and reported greenhouse gas emissions ranging from 5.92 to 41.10 kg CO_2 equivalent per kg of cast primary aluminum ingot, with variations attributed to differences in temporal scope, dataset updates, and geographical coverage limited to regions like Australia, United States, and Europe, which represent about 20% of global production [20]. The high end of this range (41.10 kg CO_2 equivalent per kg) reflects coal-dominated regional energy mixes in some regions, underscoring the strong influence of energy sources on emissions.

A cradle-to-gate LCA of a Chinese alumina refinery, smelter, and casting plant using 2003 data reported a GWP of 21.6 t CO_2 equivalent per tonne of aluminum, 1.7 times the 2000 global average of 12.7 t CO_2 equivalent per tonne, due to China's coal-heavy energy mix [21]. U.S aluminum smelting, specifically the Bayer and Hall-Héroult processes, was analyzed with findings showing that electricity production, primarily from fossil fuels, contributed over 60% of GHG emissions, and that decarbonizing the electricity grid could significantly reduce the industry's footprint [22]. Advancements in smelting technologies, such as inert anode systems, could reduce direct emissions from the Hall-Héroult process to near zero, potentially lowering GWP to 2 to 3 kg CO_2 equivalent per kg when combined with renewable energy sources [23].Schmidt and Thrane assessed a planned aluminum smelter in Greenland, reporting a GWP of 5.92 kg CO_2 equivalent per kg of aluminum, with 1.66 kg CO_2 equivalent per from direct smelter emissions, aligning with the theoretical minimum of 1.4 to 1.7 kg CO_2 equivalent per for the Hall-Héroult process [24].

Hydro's REDUXA Environmental Product Declaration highlights low-carbon primary aluminum production using renewable energy, achieving a GWP as low as 4 kg CO_2 equivalent per kg [25]. Updated LCI data for primary aluminum confirms that regions with hydropower or renewable energy sources achieve lower emissions, ranging from 5 to 8 kg CO_2 equivalent per kg, compared to coal-based regions [26]. A recent study emphasizes significant regional variability, noting that primary aluminum production in Asia, particularly India, can exceed 20 kg CO_2 equivalent per kg due to heavy reliance on coal, while Scandinavian producers using abundant hydropower achieve emissions well below 7 kg CO_2 equivalent per kg [27]. This clearly shows that energy source is the dominant factor in aluminum's carbon footprint.

A life cycle assessment of an Australian aluminium supply chain evaluated scenarios to improve efficiency, finding that implementing clean coal technology and reducing bauxite residue by 50% in alumina refining led to GWP reductions of 2.2 to 21.39% and acidification potential reductions of 2.22 to 4.49% [28]. Process optimization in alumina refining, including waste heat recovery and improved electrolysis efficiency, was found to reduce energy consumption by up to 15%, further lowering environmental impacts [29]. These studies highlight the need for technological advancements and cleaner energy to mitigate the environmental footprint of primary aluminium production. A life cycle assessment of bauxite mining and processing reported 4.9 kg CO_2 equivalent per tonne of ore, with approximately half of these emissions resulting from loading and hauling [30]. While this study offers useful context for upstream impacts, it is less relevant to discussions focused on cast primary aluminium and is not central to downstream applications such as EVs.

2.2 Secondary (Recycled) Aluminum Production.

Secondary aluminum production, or recycling, is significantly less energy-intensive, requiring 5–10% of the energy needed for primary production, depending on scrap mix, recycling technology, and energy carrier [31] [32]. Recycling reduces greenhouse gases emissions and supports circular economy principles by minimizing waste and reusing materials [33] [34]. A comparison of primary and secondary aluminum in India found that recycled aluminum had 90% lower greenhouse gases emissions, 80% lower cumulative energy demand, and reduced acidification and eutrophication potentials [35].Recycling aluminum in rotary furnaces with salt-fluxes showed salt-slag valorization cut GWP by up to 13 tonne CO_2 equivalent per tonne scrap, with 5–25% reductions in resource scarcity, human toxicity, and ecotoxicity.

Secondary aluminum recovery was the main factor offsetting primary production impacts. The study recommends higher metal yield and optimized by-product recovery to improve environmental performance [36] [37]. Closed-loop recycling, in which aluminum returns to the same system, has shown significant environmental savings compared to open-loop recycling. A combination of material flow analysis and life cycle assessment found that regions such as Europe, where recycling rates exceed 60%, significantly reduced primary aluminum demand and related emissions [38]. Systemic challenges in aluminium recycling for passenger cars include inefficient sorting and alloy mixing, which limit recyclability and raise emissions, underscoring the need for design-for-recyclability strategies [39].

Recent advancements in recycling technologies further enhance environmental benefits. One study investigated LIBS for real-time alloy sorting, improving scrap quality and reducing energy use in recycling by up to 10% [40]. Additionally, advanced remelting technologies such as electromagnetic stirring can increase metal recovery rates to 95%, further lowering GWP to below 1 kg CO_2 equivalent per kg for secondary aluminum in optimized facilities [41]. These key innovations clearly underscore the important role of recycling in reducing the environmental footprint of aluminum used in EVs.

2.2.1 Other Aspects: EV Applications and Methodological Considerations.

A life cycle assessment of aluminum in automotive lightweighting found that, despite higher production emissions compared to steel, aluminum components reduced vehicle lifetime greenhouse gases emissions by 20–30% due to lower energy consumption during the use phase [42]. An evaluation of high-strength aluminum alloys for EV battery enclosures reported a 15% weight reduction compared to steel, which improved vehicle range by 5–8% while maintaining structural integrity [43]. Additionally, an assessment of aluminum's role in EV parts noted that optimized alloy designs could cut manufacturing emissions by 10% through better casting efficiency, further supporting lightweighting benefits [44].

Life cycle assessment has been instrumental in guiding environmental management in the aluminum industry. Alcan's Life Cycle Management program and CSIRO Minerals' assessments have applied LCA for decision-making and performance benchmarking [45] [46]. The EAA and the IAI have provided LCI datasets since the 1990s, enabling standardized environmental reporting [47] [48] [20]. However, limitations such as incomplete geographical coverage and inconsistent system boundaries persist, affecting the comparability of results [20]. For example, many life cycle assessments exclude downstream processes such as battery enclosure manufacturing, limiting relevance to EVs. Integrating machine learning with life cycle assessment is recommended to predict regional impacts and improve robustness [49].

Methodologically, life cycle assessment aims to prevent the shifting of environmental burdens across life cycle stages or regions [50]. However, comprehensive cradle-to-grave studies remain rare due to data and time constraints [51]. An eco-efficiency framework was proposed to combine life cycle assessment with cost-benefit analysis to balance environmental and economic priorities [52]. While hydropower in Brazilian aluminum production was found to reduce direct emissions, the construction of dams caused significant biodiversity impacts, highlighting the need for broader system boundaries [53]. Recent advancements such as dynamic life cycle assessment models, which account for temporal variations in energy mixes, improve the accuracy of environmental impact assessments for EV applications [54]. Similarly, hybrid life cycle assessment approaches that combine process-based and input-output models offer a more comprehensive evaluation of aluminum's environmental footprint in complex supply chains. These advancements provide crucial guidance for more sustainable aluminum production and EV manufacturing. They also help to clearly identify the most critical areas for targeted intervention to significantly reduce environmental impacts.

2.2.2 Utilization of LCI Datasets in LCA Studies.

The EAA recommends that life cycle inventory datasets be used in life cycle assessment studies in line with internationally recognized standards. In particular, the EAA highlights ISO 14040:2006 and ISO 14044:2006 as the key frameworks that provide a systematic and transparent approach to evaluating the environmental impacts of products across their entire life cycle. These standards establish the principles, framework, requirements, and guidelines necessary for conducting robust and credible life cycle assessment studies. As outlined in detail in **Chapter 3**, **Section 3.1**, life cycle assessment is a widely applied and globally recognized methodology for assessing environmental performance and consists of four main phases. These are the relevant ISO standards:

- ISO 14040:2006 – Environmental Management – Life Cycle Assessment – Principles and Framework

- ISO 14044:2006 – Environmental Management – Life Cycle Assessment – Requirements and Guidelines.

Life cycle assessment assesses a product's entire life cycle, from raw material extraction and initial processing to manufacturing, transportation, product usage, and final disposal or recycling. Ideally, life cycle assessment studies rely on elementary flows, which are direct exchanges with the environment, such as raw materials taken from nature and emissions released without further processing. To ensure completeness and accuracy of results, life cycle inventory modeling often includes system extensions that integrate related processes such as energy supply, logistics, and waste treatment systems.

Recycling is essential to aluminum's long-term sustainability, as secondary aluminum production requires up to 95% less energy compared to primary production, while also generating significantly lower greenhouse gas emissions. To highlight this crucial advantage, the European aluminium industry advocates for the use of the substitution methodology, which assigns environmental credits for recycling efforts [55]. Substitution methodologies, including the EEA's 1:1 crediting approach, the ISO 14044 system expansion principle, the GaBi life cycle assessment database modeling practices, the system expansion method used in recent research, and the recycling credit method, ensure that the environmental benefits of material recovery and resource efficiency are properly accounted for in LCA studies [56] [57] [58] [59]. For a more detailed explanation, a technical paper on aluminum recycling in life cycle assessment explores impact allocation methods and comparative modeling techniques in depth This resource is available for download on the EAA website.

2.3 Lifecycle Assessment.

Life cycle assessment is a systematic, science-based approach to evaluate the environmental impacts of a product, process, or service throughout its life cycle. For aluminum production in EV manufacturing, life cycle assessment provides a framework to assess impacts from raw material extraction to the final product, identifying stages with environmental burdens and opportunities for efficiency improvements. It also serves as a decision-support tool, guiding sustainable practices, responsible resource management, and informed supply chain decisions, thereby contributing to the decarbonization of the aluminum sector.

2.3.1 Four stages of LCA.

The life cycle assessment methodology is structured into four distinct stages:

I. Goal and Scope Definition

II. Lifecycle Inventory Analysis

III. Impact Assessment

IV. Interpretation

2.3.2 Goal and Scope definition.

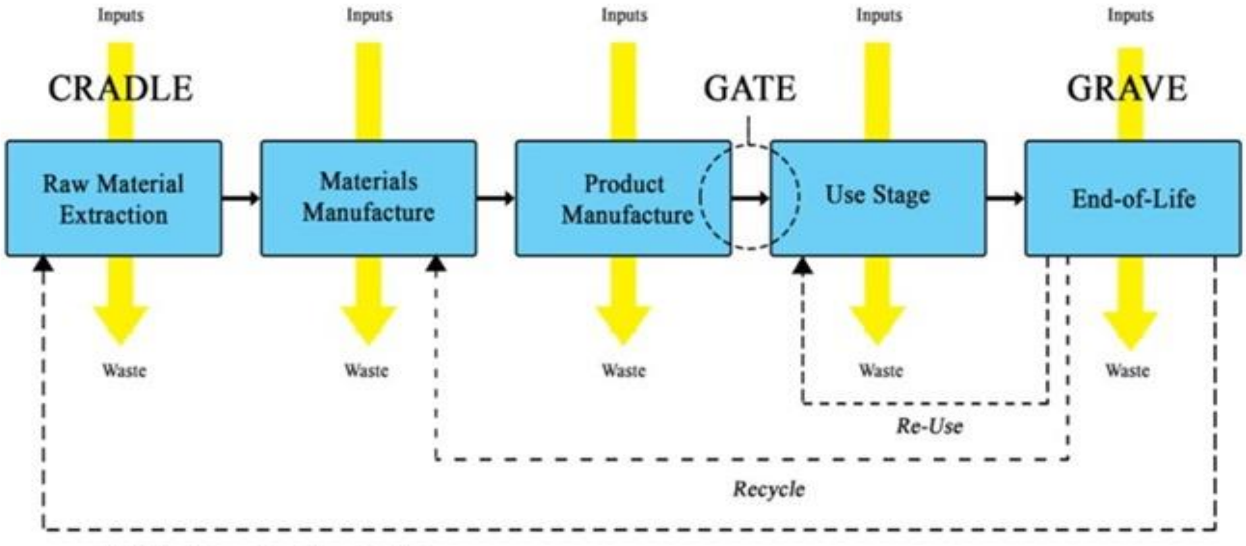

Figure 2.1 : Cradle-to-Grave LCA Framework [60]

This life cycle assessment aims to comprehensively assess the environmental impacts of aluminum used in EV manufacturing. The functional unit is 1 tonne of aluminum ingot. The system boundary is cradle-to-gate, covering all processes from bauxite mining to aluminum ingots ready for vehicle production. The results will ultimately provide insights into key stages where environmental improvements can be achieved, thus supporting more sustainable aluminum supply chains.

2.3.3 Lifecycle Inventory Analysis.

The lifecycle inventory phase systematically collects comprehensive data on material and energy flows to assess the key environmental impacts and aspects of primary aluminum production. Its main goal is to quantify key inputs and outputs, including energy use, raw materials, emissions, and waste streams, covering the process from mining to casthouse operations. The assessment is conducted at regional and, where feasible, global scales, ensuring both local accuracy and international comparability. **Table 2.1** lists participating countries, region names, and codes, providing clear reference points for comparison.

Inventory data for North America and Europe are detailed in **Appendix 1** and **Appendix 2**, respectively. Sources include industry reports, peer-reviewed studies, and established life cycle databases such as the European reference Life Cycle Database - ELCD, Ecoinvent, GaBi, and US lifecycle inventory, along with guidance from the International Aluminium Institute to align results with industry best practices. Primary aluminum production comprises five key unit processes: bauxite extraction, alumina refining, anode manufacturing (prebake or Søderberg), electrolysis, and casting. During casting, small amounts of recycled scrap aluminum and alloying elements are often incorporated to achieve the desired mechanical, thermal, and chemical properties of the final product. These interconnected steps form the foundation of the modern aluminum supply chain. Each stage consumes significant energy and resources, and therefore has its own environmental footprint.

Participated Countries	Region Name	Region Code
-	Global	GLO
South Africa, Mozambique, Guinea, Egypt	Africa	AFR
India, Kazakhstan, Turkey	Asia excluding China	OAS
Canada	Canada	CAN
China	China	CAN
Germany, Greece, France, Iceland, Norway, Spain, Sweden	Europe (West & Central)	EUR
Bahrain, Oman, Qatar, Saudi Arabia, UAE	Gulf Cooperation Council	GCC
Canada, USA	North America	NAM
Australia, New Zealand	Oceania	OCA
Montenegro, Russia, Slovenia, Slovakia, Ukraine	Russia and East Europe	ROE
Argentina, Brazil, Jamaica, Guyana, Venezuela	South America	SAM

Table 2.1 : Participating Countries and Regional Classification [61].

2.3.4 Impact assessment.

In the impact assessment phase, inventory data are translated into potential environmental impacts, as detailed in, **Section 4.1** for both the North American and European contexts. Key impact categories include GWP, which accounts for greenhouse gases emissions; AP, which reflects the risk of acid rain on ecosystems; EP, which measures nutrient enrichment in water bodies that can cause algal blooms and oxygen depletion; and resource depletion, which considers the consumption of non-renewable materials such as minerals and fossil fuels. Additional impact categories, such as human toxicity and particulate matter formation, can further refine the environmental profile of aluminum production. By assessing multiple impact categories simultaneously, life cycle assessment provides a comprehensive view of the potential trade-offs and environmental risks associated with each production stage.

2.3.5 Interpretation.

The interpretation phase examines the results to identify which stages of aluminum production contribute most significantly to environmental impacts. **Section 4.2** provides a detailed analysis for both the North American and European contexts. This evaluation is crucial for developing strategies to minimize the environmental footprint through optimized energy use, cleaner technologies, and enhanced recycling efforts. As the final stage of assessment, interpretation synthesizes findings to draw conclusions, highlight key environmental aspects, and recommend effective mitigation strategies. Interpretation also helps prioritize interventions, such as energy-efficient smelting or improved waste management, to achieve the greatest environmental benefit. It serves as a bridge between quantitative results and actionable recommendations for policymakers and industry stakeholders. It also informs long-term planning for sustainable aluminum production practices.

2.4 The Aluminum Production Process.

Aluminum production is a complex, multi-stage process requiring significant energy, raw materials, and technology. Major phases include bauxite extraction, refining into alumina, and electrolysis to produce pure aluminum metal, followed by casting, rolling, and alloying to achieve final product properties. Each stage poses technical and environmental challenges, contributing to the ecological footprint through energy consumption, waste generation, and emissions. Careful monitoring of greenhouse gases, particulates, and chemical byproducts is essential for regulatory compliance. Because aluminum production is both resource- and energy-intensive, sustainable practices are vital to reduce impacts. Measures such as cleaner technologies, energy efficiency improvements, higher recycling rates, and stricter emissions control policies can significantly cut environmental burdens. Innovations like inert anode electrolysis and renewable energy integration can further significantly reduce the overall carbon footprint. By adopting these practices, the industry can meet rising global demand while advancing environmental stewardship. **Figure 2.4** illustrates the full process, showing material flows from raw ore to finished product and highlighting opportunities for intervention.

2.4.1 From Bauxite to Alumina.

2.4.1.1 Bauxite Mining and Refining.

Figure 2.2 : Bauxite Mine in Guinea [66].

Bauxite is the principal raw material for aluminum production [63]. It is formed through the intense weathering of aluminum-rich rocks, primarily in tropical and subtropical regions. Major bauxite-producing countries include Australia, Guinea, and Brazil, which collectively contribute a significant portion of the global supply [64]. The composition of bauxite varies, but it primarily consists of aluminum hydroxide minerals such as gibbsite, boehmite, and diaspore, along with impurities like silica, iron oxide, and titanium dioxide [65]. The aluminum oxide content of bauxite typically ranges from 31% to 52%, while the aluminum content itself varies between 16% and 27%. Moreover, bauxite is a significant source of gallium, which is extracted as a by-product and classified as a critical raw material.

Bauxite is usually mined in open pits, as deposits lie near the surface. Mining starts with clearing plants and removing overburden, then heavy machinery extracts and hauls the ore. [67]. While cost-effective, open-pit mining causes deforestation and habitat loss, negatively affecting biodiversity [68]. Soil erosion and sedimentation also degrade land and contaminate water, impacting ecosystems and local communities [69]. Most companies address these issues by reshaping mined land, replacing topsoil, planting native vegetation, and closely monitoring recovery. Producers in Australia and Brazil run programs to restore landscapes and local biodiversity [33]. These important efforts are guided by national regulations, industry standards, and established sustainability frameworks.

Bauxite mining causes significant air and water pollution. Excavation generates dust that affects air quality and can cause respiratory issues [70]. Refining consumes large amounts of water, raising concerns about scarcity [71]. In Malaysia, unregulated mining in Kuantan (2015–2016) turned rivers red from sediment, prompting a temporary government ban [72]. On Rennell Island, Solomon Islands, bauxite spills and a major oil leak in 2019 severely destroyed local marine ecosystems [73]. Despite these impacts, bauxite mining is economically important, generating export revenue and employment [74]. Rising aluminum demand in China has driven large investments, including a $426M project in Suriname [75] and expansions by major producers such as Rio Tinto [76].

However, while global bauxite reserves remain significant, accessing these resources sustainably is increasingly challenging for many regions and industries. This highlights the need for improved extraction technologies, such as precision mining techniques that minimize land disturbance [77], advanced beneficiation processes that lower energy and water use [78] and bioleaching methods to extract aluminum more efficiently [79]. In addition, careful resource management is essential, including stricter land rehabilitation to restore ecosystems [80], stronger regulatory frameworks to ensure responsible sourcing [81], and greater investment in closed-loop recycling to reduce reliance on virgin materials [82]. Balancing economic growth with environmental and social impacts requires coordinated industry effort.

Regulatory measures and community involvement are key to responsible bauxite mining. Many governments mandate land rehabilitation and water treatment, and in Australia, companies must restore mined areas by replanting vegetation and managing water. However, weak enforcement in regions such as Indonesia has caused ongoing environmental damage and social conflicts [83]. The future of bauxite mining rests on sustainable methods. New tools like dry beneficiation and waste recycling cut impacts while keeping efficiency [84]. Advancements in aluminum recycling can lower reliance on new bauxite and reduce the ecological footprint [85]. As aluminum demand rises, balancing economic benefits with environmental sustainability is essential for long-term viability.

North America relies heavily on imports to meet its bauxite needs. This dependence makes the region vulnerable to supply risks and global price fluctuations. In 2021, the United States imported about 4.05 million tonnes of bauxite, down from 12.4 million tonne in 2014 [86]. This decline highlights growing efficiency, recycling efforts, and possible shifts in sourcing strategies. In 2012, Jamaica was the leading supplier, accounting for 46% of United States bauxite imports, followed by Guinea with 27%, and Brazil with 25% [87]. These figures illustrate the long-standing reliance of the United States on diverse international suppliers.

Guinea has become an increasingly important supplier of bauxite to the global market, including the United States, due to its large reserves and high-quality ore [88]. Its growing role strengthens its position as a critical player in the global aluminum industry. However, by 2022, Jamaica continued to be a primary source, exporting 2.36 million tonnes to the United States, despite a slight decline from 2.60 million tonnes in 2021. Turkey has also emerged as a notable supplier, exporting 403,000 tonnes of bauxite to the U.S. in 2022, down from 457,000 tonnes in 2021 [89]. Additionally, countries like China, India, and Brazil have been significant sources, collectively accounting for 82% of United States bauxite imports, with China alone contributing 54% [90]. The United States and Canadian industries are highly integrated, with Canada being a major trading partner across the aluminum value chain.

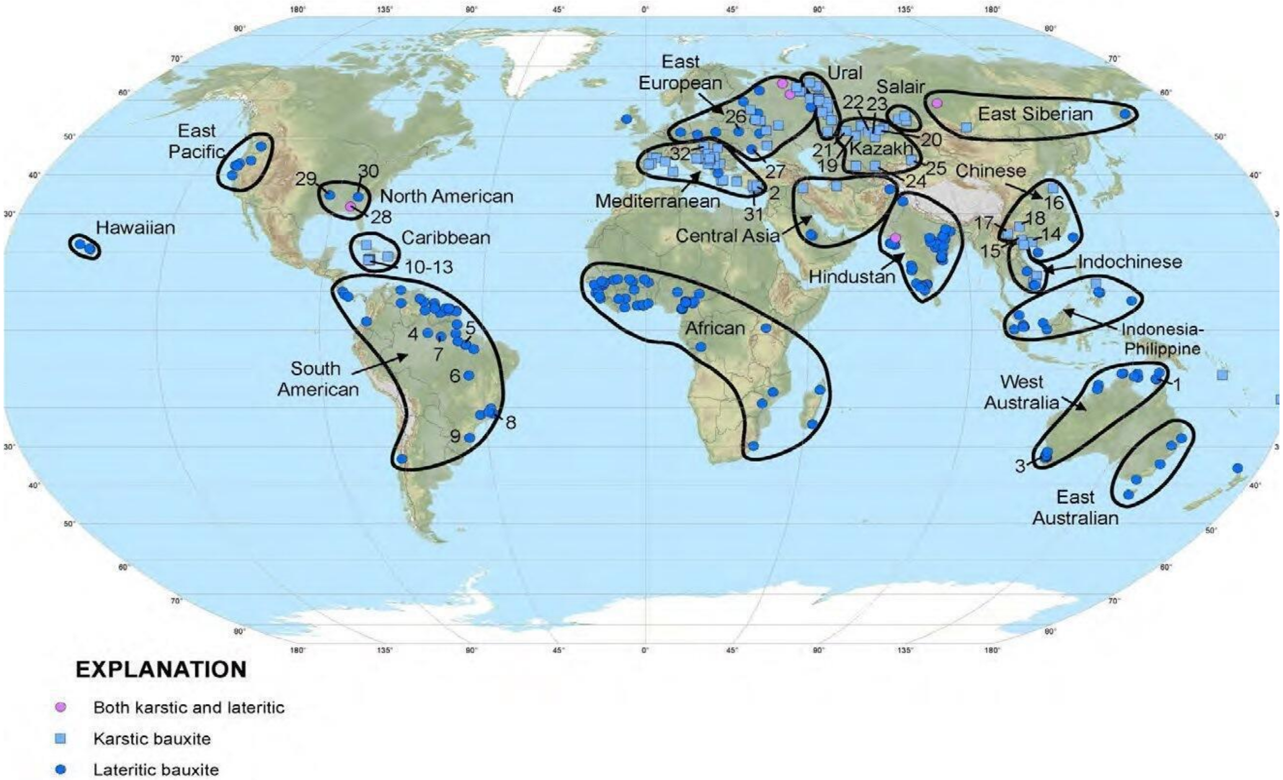

Figure 2.3 : Bauxite Deposit World Map [91].

The depletion of domestic bauxite has increased United States reliance on imports, leading to the closure of mines in Arkansas and Georgia [92]. Geopolitical factors, such as trade tensions with China, have shifted sourcing toward Guinea and Australia [93]. High energy costs have cut domestic primary aluminum production from 5.1 million tonnes in 1980 to 908,000 tonnes in 2021, with electricity making up 40% of production costs, further increasing dependence on imports [94]. North American bauxite inventory is summarized in **Appendix 1**.The European Union and EFTA obtain bauxite through domestic mining and imports. Greece is the leading EU producer, extracting about 1.83 million tonne annually, mainly from Mt. Parnassus, Mt. Ghiona, Mt. Helikon, and Evia Island, accounting for 89% of European Union production [95] [96]. This growing reliance on foreign sources has raised concerns about supply security and price volatility in the United States aluminum market. In response, efforts to improve recycling and explore alternative sources of bauxite are gaining increased attention.

Other countries, including Bosnia and Herzegovina, contribute less [97]. Despite some domestic supply, about 84% of bauxite processed in Europe is imported, mainly from Guinea, Sierra Leone, and Ghana [98]. Germany, Spain, and Ireland are top importers, with Germany importing 10.04 million tonnes in 2024 [99]. Major companies, such as Norsk Hydro, source a significant portion of their bauxite from Brazil, highlighting Europe's deep integration into global bauxite supply chains. Additionally, METLEN Energy & Metals has announced plans to expand its production capacity to 2 million tonnes annually [100] , reflecting growing demand. Overall, the European Union and EFTA countries remain highly dependent on imported bauxite, despite some limited domestic mining, primarily concentrated in Greece. A detailed summary of current inventories and production capacities is provided in **Appendix 2**.

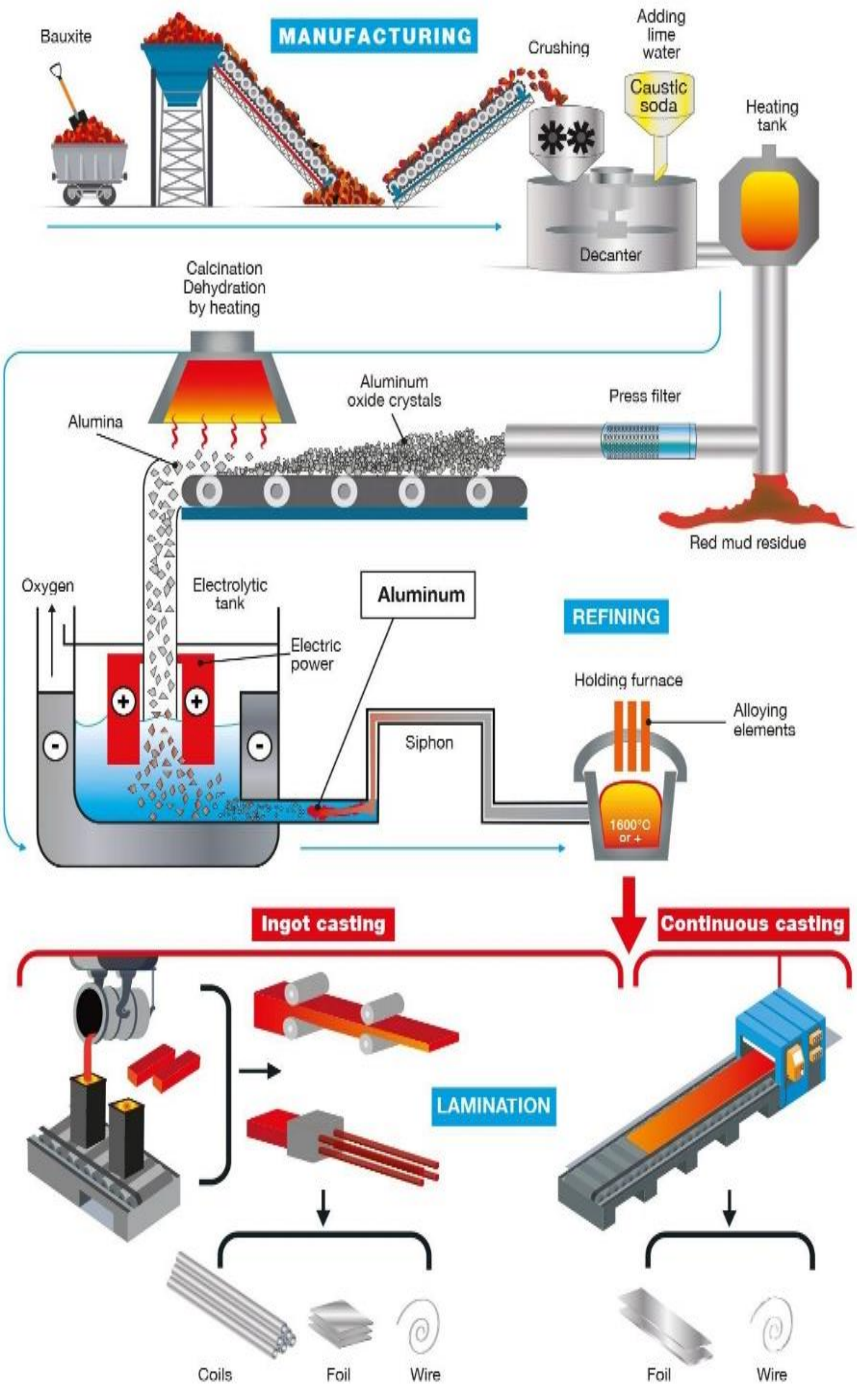

Figure 2.4 : Aluminum manufacturing processes [62]

2.4.1.2 The Bayer Process.

Once extracted, bauxite undergoes refining via the Bayer process to produce alumina. This method, developed by Karl Josef Bayer in 1887, remains the most widely used and efficient technique for large-scale alumina extraction [101]. The process is scalable, forming the basis of modern aluminum production worldwide. It enables byproduct recovery, reducing waste and improving resource efficiency. The method relies on solubility differences between aluminum oxide and impurities when treated with a strong base under controlled conditions [102].The inventory data for alumina refining in the North American context is comprehensively summarized in **Appendix 1** ,while the corresponding data for the European context is presented in **Appendix 2**. Overall, the process of purifying bauxite to obtain alumina in the Bayer method five distinct steps, as clearly demonstrated in the schematic representation shown in **Figure 2.5**, which highlights the sequence of operations and the flow of materials from raw bauxite to refined alumina, providing a clearer understanding of the industrial process. This process is central to the global aluminum supply chain, serving as the foundational step that determines both the quality and availability of aluminum for a wide range of industries comprises worldwide.

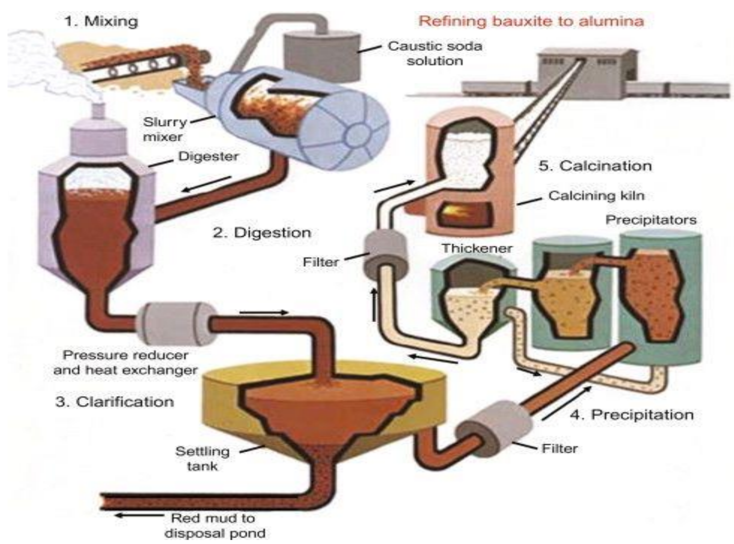

Figure 2.5 : The Bayer process for the production of alumina from bauxite [103].

1. **Crushing and Grinding**: These are the first steps where bauxite ore is crushed and ground into fine particles to improve overall chemical reaction efficiency and maximize alumina extraction [104]. In digestion with NaOH, the ground bauxite is thoroughly mixed with hot sodium hydroxide at 140–240 °C and 3–5 MPa, dissolving aluminum-bearing minerals such as gibbsite, boehmite, or diaspore to form soluble sodium aluminate [105] .

$$\mathrm{Al(OH)_3 + NaOH \rightarrow NaAlO_2 + 2H_2O} \quad (2\text{-}1)$$

$$\mathrm{Al_2O_3 + 2NaOH + 3H_2O \rightarrow 2NaAl(OH)_4} \quad (2\text{-}2)$$

Impurities such as iron oxide (Fe_2O_3), titanium dioxide (TiO_2), and silica (SiO_2) remain largely insoluble and are typically removed as hazardous solid waste [106].

2. **Clarification**: It involves letting the slurry settle so that undissolved impurities, called red mud, are separated by filtration; this highly alkaline byproduct poses disposal challenges [107]. Precipitation of alumina hydrate follows, where the sodium aluminate solution is cooled and seeded with aluminium hydroxide crystals, causing AI hydroxide to precipitate [108] :

$$\mathrm{NaAI(OH)_4} \rightarrow \mathrm{AI(OH)_3} + \mathrm{NaOH} \quad (2\text{-}3)$$

The regenerated sodium hydroxide is recycled in the digestion step, helping to save energy and reduce chemical waste, improving process efficiency [108].

3. **Calcination**: The precipitated aluminum hydroxide is heated to 1000–1100°C in rotary kilns or fluidized bed calciners to remove chemically bound water, yielding pure alumina [109]:

$$2\mathrm{AI(OH)_3} \rightarrow \mathrm{AI_2O_3} + 3\mathrm{H_2O} \quad (2\text{-}4)$$

2.4.1.3 Environmental and Energy Challenges.

The Bayer process consumes 7–15 GJ per ton of alumina, making it energy-intensive and a major source of carbon emissions when powered by fossil fuels [109]. Improving energy efficiency is vital to reducing alumina production's environmental footprint. A major concern is red mud, a highly alkaline waste (pH 10–13) containing caustic soda, iron oxides, titanium dioxide, and heavy metals [110]. Improper management can contaminate soil and water, posing ecological and human health risks. The 2010 Ajka red mud disaster in Hungary, which released over one million cubic meters of hazardous waste, caused extensive environmental damage, long-term soil degradation, and multiple fatalities [111], highlighting the urgent need for safer and more sustainable disposal methods.

Red mud is commonly managed by lagooning or dry stacking. Lagooning stores waste in ponds, allowing it to settle gradually, but risks leakage or dam failure [112]. Dry stacking dewaters red mud into semi-solid layers, reducing spill risks and land use [113]. Both methods need monitoring and maintenance for environmental safety. Industries repurpose red mud for cement and asphalt to cut hazards and recover resources [110]. Red mud recycling methods include extracting metals like iron and rare earth elements and incorporating them into cement [114]. Researchers are also developing carbon-neutral Bayer process modifications using waste heat recovery and alternative alkali sources to reduce caustic soda use [115]. Such technological innovations aim to make alumina production more sustainable while simultaneously recovering valuable materials from industrial waste streams.

2.5 Anode Production.

Anodes are critical in aluminum electrolysis, serving as the conductive medium in the Hall-Héroult process, which reduces alumina to aluminum. Traditional carbon anodes are consumable, made by blending petroleum coke with coal tar pitch, then molding, baking, and graphitizing at 1100–1200°C [116]. Anode quality also strongly influences aluminum smelting efficiency, energy consumption, and overall environmental emissions reduction. North American smelting inventory is summarized in **Appendix 1**, while European anode production data is in **Appendix 2**. Carbon anodes are produced using two main technologies, the self-baking Søderberg process and the prebake method, as shown in **Figure 2.6**.The prebake method dominates modern smelters due to better emission control, higher energy efficiency, and lower PAH emissions [117] [118] [119]. In contrast, the Søderberg process is being gradually phased out because of higher emissions, lower efficiency, and increased health risks for workers. This shift clearly reflects the industry's move towards sustainable and reliable anode production. **Table 2.2** provides a detailed comparison of the Søderberg and prebake methods, highlighting their technological, environmental, and operational differences.

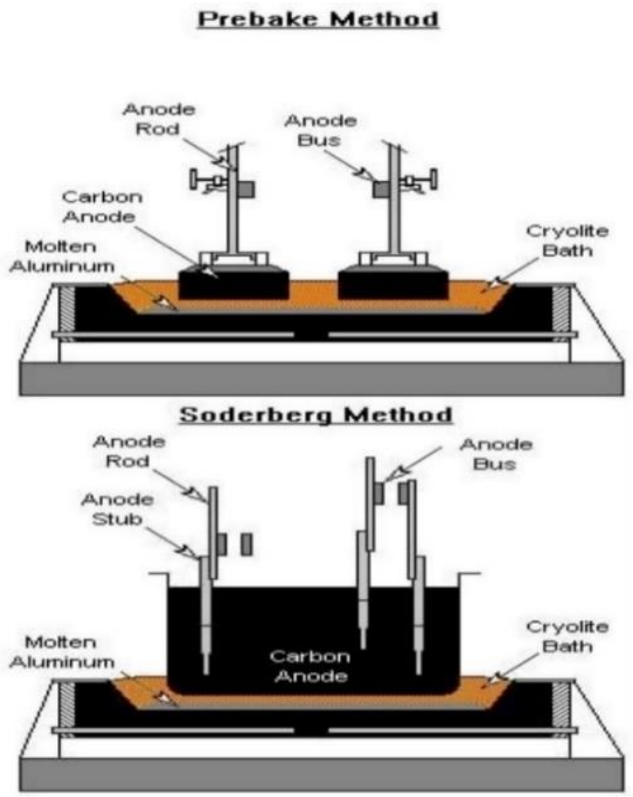

Figure 2.6 : Søderberg process and the prebake method [120].

2.5.1 Anode Production Process

The anode production process begins with petroleum coke, a byproduct of oil refining that provides high carbon content and conductivity, and coal tar pitch, which serves as a binder [121]. Both materials are crushed and ground for uniformity, while anode butts from spent anodes can be recovered, cleaned, and reused to further reduce industrial waste and conserve resources. The ground coke is then carefully blended with molten coal tar pitch at 200–250 °C to form a homogeneous paste, with the coke-to-pitch ratio precisely controlled to ensure strength and high conductivity [122]. This paste is molded into rectangular or cylindrical blocks depending on smelter cell design, using extrusion or vibro compaction to enhance density and durability [123]. The molded anodes are then baked at 1100 to 1200°C to carbonize the pitch, increasing strength and conductivity but also releasing volatile organic compounds and polycyclic aromatic hydrocarbons [124]. In some cases, anodes are graphitized at 2500–3000 °C to enhance conductivity, though this step is not always required in aluminum production [125]. Strict quality control measures are essential throughout the process to ensure consistent performance and longevity of the anodes in the electrolytic cells.

Feature	Søderberg Process	Prebake Method
Anode Type	Continuous self-baking anode baked in the cell	Pre-baked anodes made in separate furnaces
Energy Efficiency	Lower due to higher electrical resistance	Higher due to better performance and stability
Environmental Impact	Higher emissions of PAHs and fluorides	Lower emissions, reduced VOCs
Anode Replacement	No regular replacement needed	Periodic replacement required.
Operational Control	Less control over quality and consistency	Better control, consistent quality
Usage & Popularity	Older, largely phased out	Widely used in modern smelters

Table 2.2 : Comparison of the Søderberg and Prebake Methods in Aluminum Production.

2.5.2 Role of Anodes in the Electrolysis Process

In the Hall-Héroult process, the carbon anodes actively participate in the electrochemical reduction of alumina dissolved in molten cryolite (Na_3AlF_6), continuously facilitating the reaction while maintaining efficient aluminum production. The reaction occurring at the anode involves the oxidation of carbon, thereby producing significant amounts of CO_2 [126] :

$$C + 2O^{2-} \rightarrow CO_2 + 4e^- \quad (2\text{-}5)$$

At the cathode, aluminum ions are reduced to form pure aluminum metal:

$$AI^{3+} + 3e^- \rightarrow AI \quad (2\text{-}6)$$

Carbon anodes are consumed during alumina electrolysis and must be replaced regularly, contributing significantly to carbon emissions. This results in about 1.395–1.849 kg carbon dioxide per kg of aluminum, depending on anode consumption [127]. Environmental impact also depends on anode purity, density, porosity, and raw material quality. Impurities such as Na and V can increase air reactivity, raising carbon consumption and emissions [128]. Baking temperature and heating rate strongly influence anode integrity. Highly porous or cracked anodes degrade faster in electrolysis, increasing replacement frequency and emissions. Carbon anode production alone emits around 0.26–0.62 t CO_2 per tonne aluminum, depending on furnace efficiency and handling [129]. These observations clearly highlight that carefully optimizing anode quality, uniformity, manufacturing processes, and operational parameters is crucial for reducing greenhouse gases emissions, minimizing environmental impacts, and improving the overall efficiency and sustainability of aluminum production.

2.5.3 Innovations in Anode Production

To address environmental concerns, researchers and industry leaders are developing inert anodes, which eliminate carbon consumption during electrolysis, thereby significantly reducing carbon dioxide emissions [130]. Inert anodes are made from materials such as ceramic oxides ($NiFe_2O_4$, Cu-Ni-Fe-O) and metal composites, offering enhanced durability and consistent performance under extreme operating conditions, which remain stable at high temperatures without participating in the reaction [131]. This breakthrough technology promises a more sustainable and eco-friendly approach to metal production. The electrochemical reaction using inert anodes produces oxygen instead of carbon dioxide:

$$2O^{2-} \rightarrow O_2 + 4e^- \quad (2\text{-}7)$$

2.5.4 Advantages of Inert Anodes

Inert anodes eliminate carbon consumption, preventing carbon dioxide emissions and significantly reducing greenhouse gasses impacts [131]. They also improve product purity by removing carbon-based impurities, producing high-purity aluminum suitable for electronics and aerospace applications, with enhanced mechanical properties and corrosion resistance [132]. In addition, inert anodes reduce air pollution by eliminating VOC and PAH emissions from carbon anode baking, thereby improving working conditions and overall environmental performance [130]. While inert anode technology is still under development, major companies such as Rio Tinto, Alcoa, Rusal, Elysis, Hydro, Arctus, and China Hongqiao are investing in commercial trials to produce carbon-neutral aluminum [133].

CCS is being explored but faces high costs (around €180–300/t CO_2) and challenges from low emission concentrations, underscoring the need for alternatives. Other decarbonization pathways include hydrogen use in alumina refining, as shown by Rio Tinto's Yarwun pilot, offering cleaner energy and significant emission cuts [134] [135]. Electrification of refining processes is under study to further improve efficiency and reduce emissions. Hydro's HalZero project employs chloride-based electrolysis to produce aluminum without carbon emissions, recycling chlorine and carbon in closed loops [136], with industrial-scale demonstration planned by 2030. Similarly, SINTEF and several other international consortia are actively pursuing comparable initiatives, thereby demonstrating broad global collaboration toward deep decarbonization in the aluminum industry [137].

2.6 Electrolysis (Hall-Héroult Process)

The Hall-Héroult process is the dominant industrial method for extracting metallic aluminum from alumina (Al_2O_3). This electrolytic process, developed independently by Charles Martin Hall in the USA and Paul Héroult in France in 1886, revolutionized global aluminum production by providing an efficient and scalable method to obtain the metal from its oxide [138]. Electrolysis inventory data for Europe is summarized in **Appendix 2**.

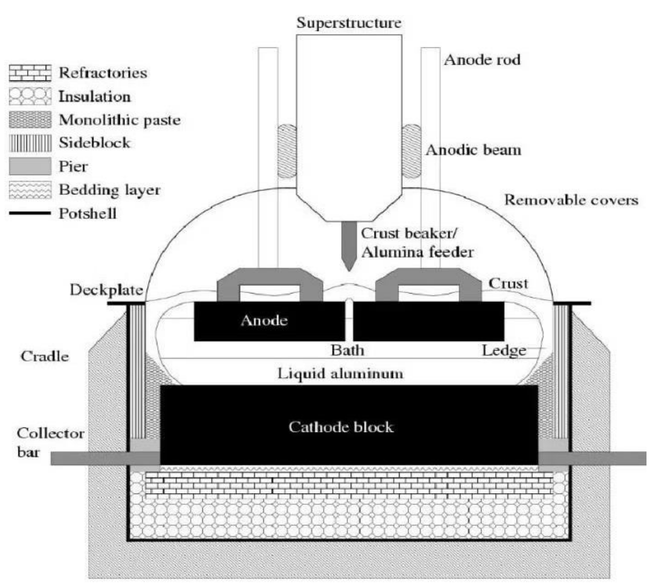

Figure 2.7 : Diagram of a standard Hall-Héroult electrolysis cell [139]

2.6.1 Process Overview.

The Hall-Héroult process takes place in large electrolytic reduction cells, also called potlines, that contain molten cryolite (Na_3AlF_6), a crucial flux material that significantly lowers the melting point of alumina from about 2050 °C to approximately 950–1000 °C, thereby making the electrolysis process energetically feasible and economically viable [140]. These cells also incorporate designs for anode-cathode arrangement, electrolyte flow, and insulation to increase aluminum yield, keep uniform temperature, cut energy losses, and ensure stable, continuous operation over long periods. These cells are carefully designed to optimize current distribution, temperature control, and alumina dissolution, ensuring efficient and continuous aluminum production. The major steps in the process include:

- Dissolution of Alumina: Al_2O_3 is completely dissolved in the molten cryolite bath, forming a stable electrolyte capable of efficiently conducting electricity.

$$\mathrm{AI_2O_3 \rightarrow 2AI^3 + 3O^{2-}} \tag{2-8}$$

- Electrolysis: A strong direct current (DC) is applied between carbon anodes (positive electrodes) and a carbon-lined cathode (negative electrode). The applied current effectively facilitates the reduction of aluminum ions at the cathode and oxidation of oxygen ions at the anode.

Cathode Reaction (Reduction):

$$\mathrm{AI^3 + 3e^- \rightarrow AI} \tag{2-9}$$

Anode Reaction (Oxidation):

$$\mathrm{2O^{2-} + C \rightarrow CO_2 + 4e^-} \tag{2-10}$$

- During electrolysis, molten aluminum naturally sinks to the bottom of the cell because it is heavier and is regularly drawn off for processing [141]. Carbon anodes react with alumina's oxygen to form CO_2, leading to consumption and regular replacement [142].

$$\mathrm{C + O_2 \rightarrow CO_2} \tag{2-11}$$

2.6.2 Energy and Environmental Considerations

The High Electricity Consumption of the Hall-Héroult process accounts for over 60% of total energy in primary aluminum production [143], requiring 13 to 15 kWh per kg, nearly double the theoretical minimum. Efficiency improvements are ongoing. Efficiency gains include Hydro's Karmøy plant achieving 12.27 kWh per kg and HAL4e Ultra cells at 11.8 kWh per kg [144], while Rio Tinto's AP60 uses about 13.1 kWh per kg with improved current efficiency [145]. Transitioning to renewable sources such as hydropower and solar is essential to lowering the footprint [146]. PFC emissions like CF_4 and C_2F_6 occur during anode effects at low alumina levels; automated feeds, real-time monitoring, and process control help minimize them [147] [148].Continued innovation in cell design, materials, and advanced digital process optimization is critical for significantly reducing energy use, lowering industrial emissions, and improving overall efficiency, thus supporting global sustainability goals.

Fluoride Emissions from cryolite (Na_3AlF_6) and other electrolytes can harm vegetation and water bodies [149], but modern smelters use dry scrubbing, sealed cells, and alumina filters to recover over 95% of fluoride [150]. Solid waste, such as spent potlining, produced at 20 to 30 kg per tonne of aluminum, contains fluorides, cyanides, and other toxic substances [151] and can contaminate soil and water if not managed. Best practices include inertization, controlled landfill, or recycling in cement and steel production [152] [153].Anode cover residuals, including crushed bath and alumina, must always be carefully and properly handled to prevent hazardous leaching and dust emissions. Ongoing research focuses on developing safer, more sustainable waste treatment methods and improving recovery of valuable byproducts. Greater industry adoption of circular economy practices could further reduce environmental impacts and enhance resource efficiency.

2.6.3 Mitigation Strategies and Future Developments

The use of inert anodes offers a major breakthrough, as replacing carbon with ceramic or metal alloy anodes eliminates direct carbon dioxide emissions and extends anode lifespan [142]. Renewable Energy Integration is equally critical, with hydropower, wind, and solar significantly lowering smelting's footprint [143]. Norway produces about 1.5 million tonnes of aluminum, including output from Husnes, primarily powered by hydropower, achieving some of the world's lowest emissions [154]. Similarly, Iceland's three major smelters Reykjanes, Grundartangi, and Fjardaal produce about 900,000 tonnes per year powered almost entirely by geothermal and hydropower, maintaining exceptionally low average emissions [155]. These advancements demonstrate the potential for near-zero carbon aluminum production.

Advanced cell designs such as vertical and drained cathodes improve efficiency and reduce material waste [156], though cathode replacement generates SPL, a hazardous fluoride and cyanide containing waste is often landfilled, posing contamination risks [155]. Proper handling and monitoring of SPL during replacement are essential to minimize environmental and health hazards. To mitigate this, recycling methods such as reusing SPL in cement or recovering valuable materials are being explored to reduce landfill dependence and environmental impact [157]. Ongoing research is also focused on developing safer ways to treat the waste and make it less harmful for people and nature. If these methods are used well, they could help cut the long-term harm from aluminum production around the world.

The use of inert anodes is a major breakthrough, as replacing carbon with ceramic or metal alloy anodes eliminates direct CO_2 emissions and extends anode lifespan [142] [143]. Renewable energy integration is vital, with hydropower, wind, and solar significantly reducing smelting's footprint. Norway produces about 1.5 million tonnes of aluminum, including Husnes, mainly powered by hydropower, achieving very low emissions. Similarly, Iceland's smelters Reykjanes, Grundartangi, and Fjardaal produce about 900,000 tonnes annually, powered almost entirely by geothermal and hydropower, maintaining exceptionally low emissions [154] [155]. Advanced cell designs such as vertical and drained cathodes improve efficiency and reduce material waste [156], though cathode replacement generates SPL, a hazardous fluoride and cyanide containing waste is often landfilled, posing contamination risks [155]. To mitigate this, recycling methods like reusing SPL in cement or recovering materials are being explored to reduce landfill use and environmental impact [157].

2.7 Aluminum Casting.

Once aluminum is extracted via the Hall-Héroult process, it undergoes casting to form semi-finished products, which determines final material properties. The two main methods are DC casting and continuous casting. The inventory data for aluminum casting in the North American context is summarized **Appendix 1**, while the inventory data for the European context is presented in **Appendix 2**.The global aluminum casting market is expected to grow about 5% annually from 2021 to 2027.

DC Casting: This process is widely used for producing large ingots, billets, and slabs, particularly high-strength alloys [158]. Molten aluminum pouring involves pouring refined molten aluminum, often blended with recycled metal, into molds, with alloying elements such as Mg, Si, Cu, or Zn added to achieve desired properties. Multi-stage Cooling occurs in three steps: primary cooling inside the mold using water for rapid surface solidification, secondary cooling with water sprays as the ingot exits the mold to control solidification growth, and tertiary cooling in air or on cooler surfaces to relieve thermal gradients and stresses, producing a dense, uniform microstructure. Controlled Solidification ensures fine grain structures, enhancing mechanical properties of aluminum.

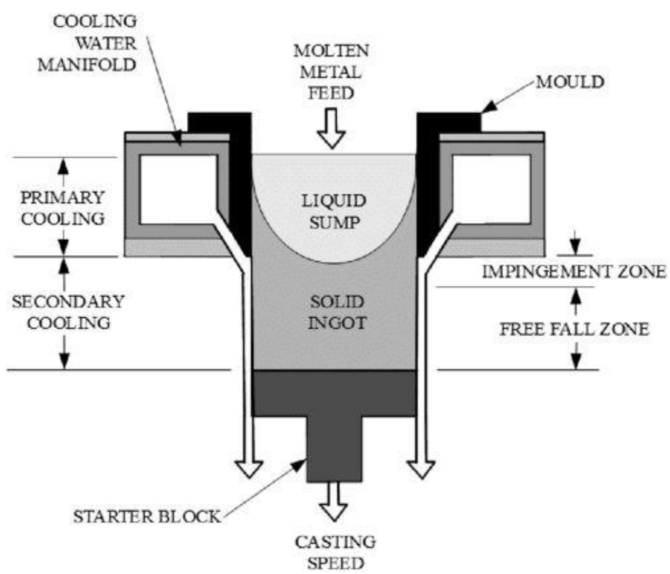

Figure 2.8 : Direct Chill Method [159].

Continuous Casting: It is an efficient, cost-effective method primarily used for sheets, foils, and thin strips, reducing waste and supporting high production rates, making it ideal for large-scale manufacturing [160]. Molten aluminium is steadily fed into a moving mold or cooled rollers, ensuring uniform thickness and consistency, with automation minimizing errors and increasing speed. As the metal advances, it gradually solidifies under precise cooling to prevent cracks and uneven grains, while adjusting rates customizes mechanical properties. The solidified aluminum is then rolled to refine thickness and surface finish, coiled for easier handling, storage, and transport, and finally undergoes quality inspection and finishing, including trimming or annealing, to prepare it for final use.

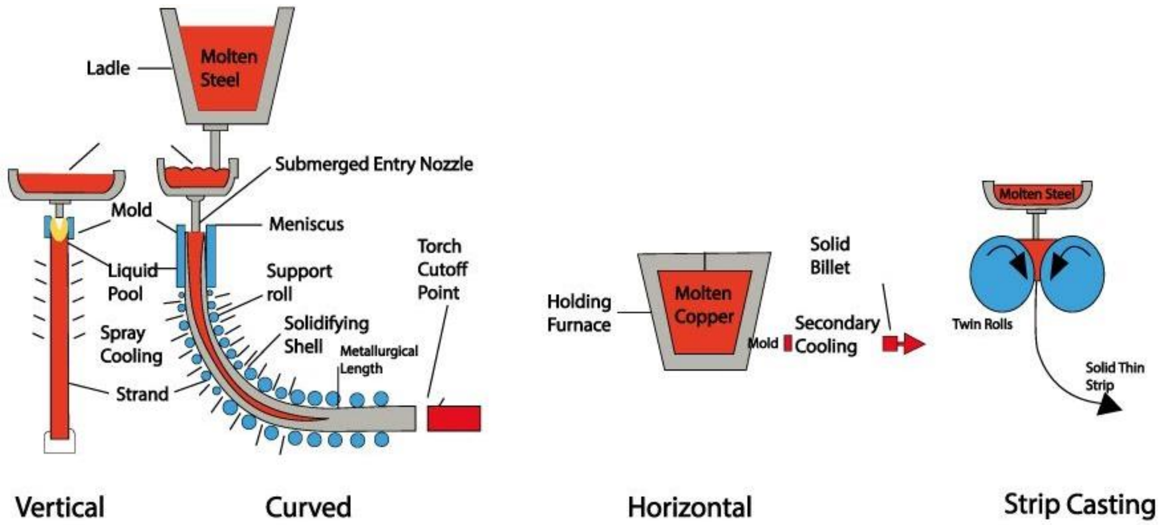

Figure 2.9 : Continuous Casting Methods [161].

Energy Efficiency and Recycling in Casting: Casting is less energy intensive than primary extraction and electrolysis but still requires precise temperature control to ensure product quality and consistency. Within this stage of the aluminum life cycle, recycling plays a particularly critical role. Scrap aluminum can be remelted using only about 5% of the energy required for primary production, making secondary aluminum a highly energy efficient and environmentally favorable alternative [162]. These practices demonstrate how recycling can dramatically reduce the overall carbon footprint of aluminum products.

In addition to conserving energy, the use of secondary aluminum reduces the need for raw material extraction and significantly lowers associated greenhouse gases emissions. Closed loop recycling systems are increasingly adopted by the industry to strengthen circularity and sustainability, ensuring that aluminum products are continuously returned into the production cycle rather than being lost as waste [163]. Following casting, aluminum components often undergo homogenization, a thermal treatment that refines the microstructure and improves mechanical properties, thereby enhancing performance in downstream applications. However, this step also contributes to overall energy demand and requires careful and precise optimization to balance benefits with costs. Proper optimization of homogenization can further improve energy efficiency while maintaining product quality.

Another challenge in casting is the formation of dross, which is a byproduct composed of oxides, entrapped metal, and impurities. Dross leads to valuable metal loss and requires energy intensive treatment or safe disposal. To address this issue, the adoption of optimized melting practices and advanced recovery technologies has become essential, since these measures help minimize waste, improve metal yield, and enhance energy efficiency [164]. Finally, to contextualize the significance of efficiency and recycling measures within the global industry, **Figure 2.10** presents global forecasts, market share data, and the leading aluminum producers worldwide [165] [166] [167] [168]. Implementing these efficiency and recycling strategies across the aluminum industry worldwide and across all production stages is critical to achieving sustainable aluminum production at a global scale.

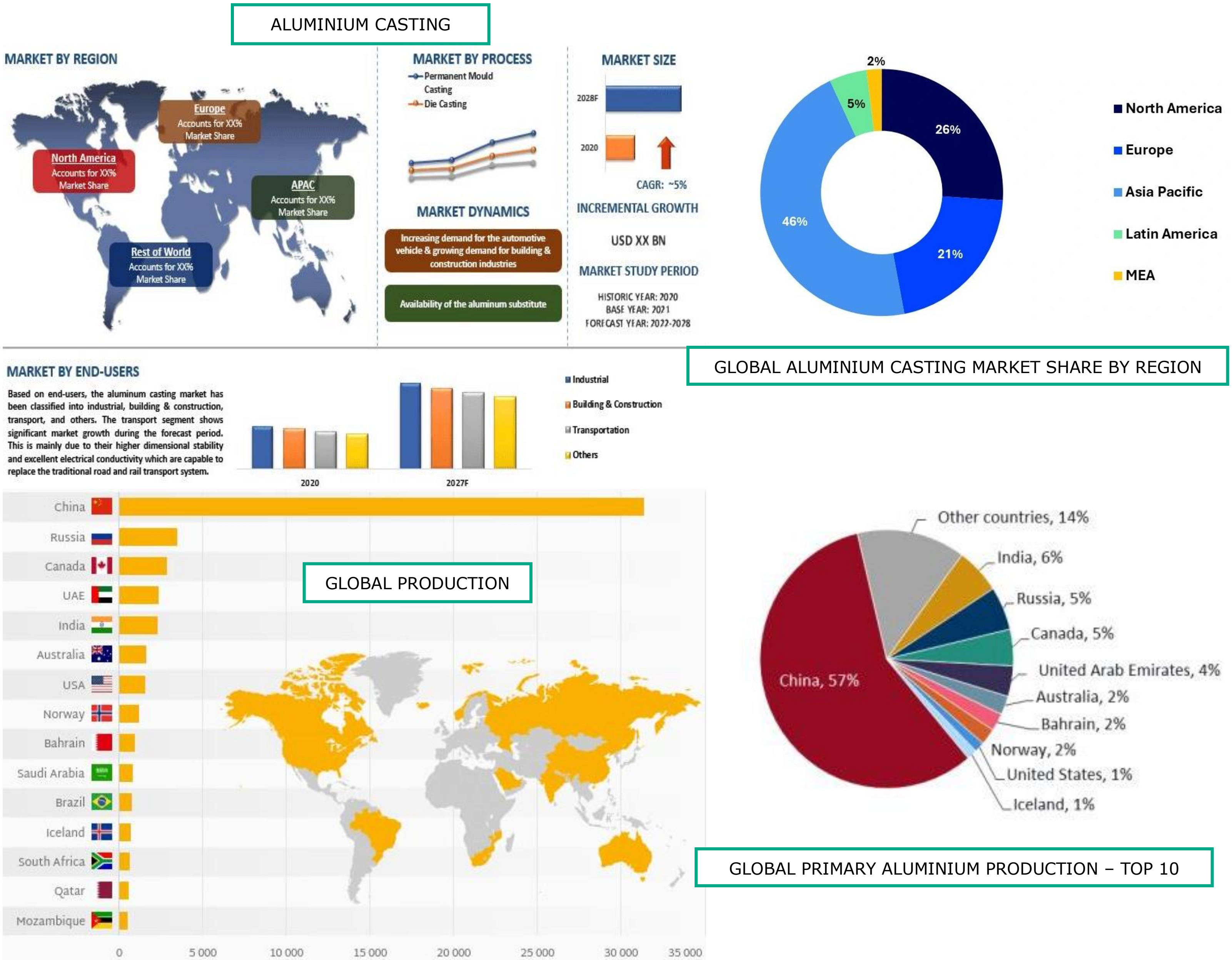

Figure 2.10 : Top aluminium producers, global forecasts and casting market share.

The global aluminum casting market is experiencing steady growth, driven by demand from the automotive, aerospace, and construction sectors. The market was valued at approximately USD 100.94 billion in 2024 and is projected to grow at a compound annual growth rate of about 4.9%, reaching USD 135.2 billion by 2030 [169]. Other reports present a more aggressive forecast, suggesting that the market could expand from USD 97.3 billion in 2023 to nearly USD 180.4 billion by 2033, indicating a CAGR of around 7.1% [170]. Similarly, another analysis estimates growth from USD 95.93 billion in 2025 to USD 151.26 billion by 2033, with a CAGR of 5.77%. Within the market, die casting remains the dominant production process, accounting for roughly 47–49% of the total market share [171]. Regionally, Asia-Pacific continues to hold the largest share, driven by significant industrial output in China and India, while North America and Europe are expected to see steady but slower growth due to mature automotive markets. On the supply side, China dominates global aluminum output: in 2023 it produced about 41 million metric tons of primary aluminum, representing nearly 57% of the world total; and in 2024 its production rose to approximately 43 million metric tons, amounting to close to 60% of global production [172] [173]. This dominance underscores China's critical role in shaping both market dynamics, global trade patterns, and the strategic direction of the international aluminum casting industry.

2.8 Properties of aluminum.

Aluminum's unique combination of properties makes it a highly versatile material, supporting key industries such as automotive, aerospace, construction, and packaging. Its lightweight, durable, and sustainable nature enables innovation and efficiency. Key characteristics include:

- **Lightweight Nature:** With a density of about 2.7 g/cm³, aluminium is one-third weight steel, making it ideal for weight-sensitive applications automotive and aerospace [174] [175].
- **Corrosion Resistance:** A self-forming oxide layer naturally protects aluminum from further oxidation, greatly enhancing its long-term durability in harsh outdoor and industrial environments [176] [177].
- **High Strength-to-Weight Ratio:** Alloyed with Cu, Mg, or Zn, aluminium gains strength while staying lightweight, ideal for structural applications [178] [179].
- **Recyclability and Sustainability:** Aluminum can be recycled indefinitely with minimal property loss and without degrading its quality. Recycling consumes only ~5% of the energy required for primary production, significantly reducing overall carbon dioxide and other harmful emissions [55].
- **Electrical and Thermal Conductivity:** Although its electrical conductivity is about 62% that of copper, aluminum's light weight allows longer spans in transmission lines. It also effectively serves in heat exchangers due to its high thermal conductivity [180].
- **Ductility and Malleability:** Aluminum can be easily drawn into wires and rolled into thin sheets or foils. Advances in additive manufacturing have further improved ductility, achieving elongation well beyond standard specifications [181].
- **Surface Reflectivity:** Aluminum's excellent ability to reflect both light and heat makes it highly useful in applications like light fixtures and insulation materials [182].
- **Non-Toxicity:** Being non-toxic, impermeable, and lightweight, aluminum is widely used in food and drink packaging, effectively keeping products safe, fresh, and lasting longer while protecting them from moisture, oxygen, and light exposure [177].
- **Cryogenic Properties:** Aluminum keeps its excellent toughness even at very low temperatures, making it highly suitable for cryogenic applications, including LNG storage tanks, pipelines, and other extreme-cold environments [176].
- **Enhanced Mechanical Properties Through Alloying:** Engineering approaches like stacking faults and twin boundaries produce super-strong aluminum alloys, with strengths comparable to stainless steel [179].

2.9 Electric vehicles and aluminum.

The automotive industry is increasingly adopting aluminum to enhance vehicle performance and efficiency. In EVs, aluminum plays a critical role in offsetting the significant weight of heavy battery systems, which directly improves overall energy efficiency and significantly extends driving range. According to the International Aluminium Institute [109], transportation applications, including EVs, now account for about 31% of global aluminum demand. This trend highlights the sector's shift toward lightweight, low-emission technologies. **Figure 2.11** illustrates the global flow of aluminum, based on Allwood [183], with updated mass flow data integrated from recent industry sources.

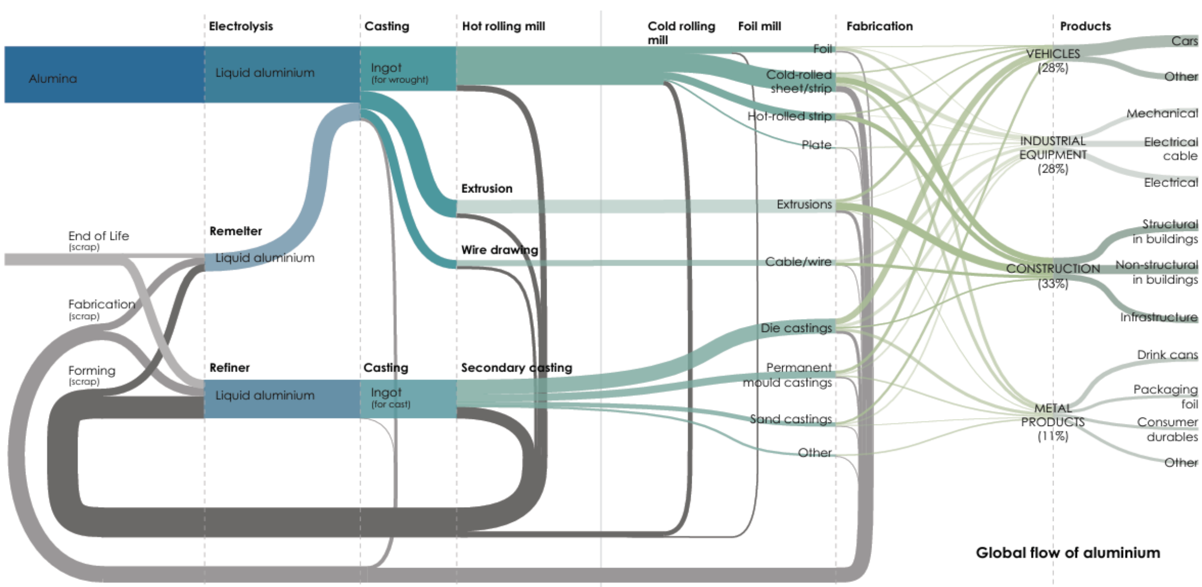

Figure 2.11 : Global flow of aluminum [183].

Aluminum is widely used in EVs across multiple components, including chassis, body structures, battery enclosures, motor housings, and structural castings. Its low density enables significant vehicle lightweighting, which is critical for improving energy efficiency and extending driving range. Beyond structural applications, aluminum's thermal conductivity supports effective heat dissipation in motors and battery systems, while its corrosion resistance and durability make it well-suited for wheels, suspension parts, heat exchangers, and charger casings [184]. Although primary aluminum production is energy-intensive, LCAs show that using lightweight aluminum can lower overall environmental impacts by reducing energy consumption during the vehicle's operation.

Recent industry data indicates that the average BEV in 2022 contained about 885 pounds of aluminum, approximately 85% more than non-electric vehicles. Extrusions and castings are the fastest-growing applications, driven by the demand for durable structures and efficient thermal management in EV design [185]. These combined factors underscore aluminum's central role in enabling sustainable, high-performance, and energy-efficient EVs, highlighting the material as a cornerstone of the ongoing transition toward greener and more environmentally responsible transportation technologies.

2.10 Dashboard for Predicting GWP of Aluminum Production.

Aluminum production, from bauxite mining through casting, is highly energy-intensive, and its cradle-to-gate GWP (in kg CO_2) depends critically on the electricity mix and production volume. The share of low-carbon hydropower versus high-carbon coal strongly influences emissions, making accurate GWP prediction essential for sustainable decision-making. The interactive dashboard developed in this study allows users to input region, hydropower and coal proportions, and aluminum quantity to estimate GWP across three scenarios: hydro only, coal only, and mixed. In mixed scenarios, the GWP is constrained between 5000 and 20000 kg CO_2e per 1000 kg of aluminium, with thresholds defined as Low (≤ 9000), Mid (9001–14000), and High (> 14000), while the dominant source is classified by whether hydropower exceeds coal, coal exceeds hydropower, or the two are equal, in which case the status is set to Mixed. Hydro only and coal only scenarios use dynamic ranges such as 3000 to 10000 for 100% hydro with GWP ≤ 8500 and 16000 to 25000 for 100% coal with GWP ≥ 18000, ensuring linear scaling with aluminum quantity, maintaining monotonic behavior, and enabling stakeholders to assess impacts and identify opportunities for emission reduction.

2.10.1 Machine Learning and Its Techniques.

Machine learning is a field of computer science that enables computers to learn from data without explicit programming [186]. It is also described as the study of algorithms that improve performance on tasks through experience [187]In sustainability, machine learning helps model industrial processes, predict environmental impacts, and improve resource use. Different types of algorithms offer suitable strengths depending on data and prediction goals.

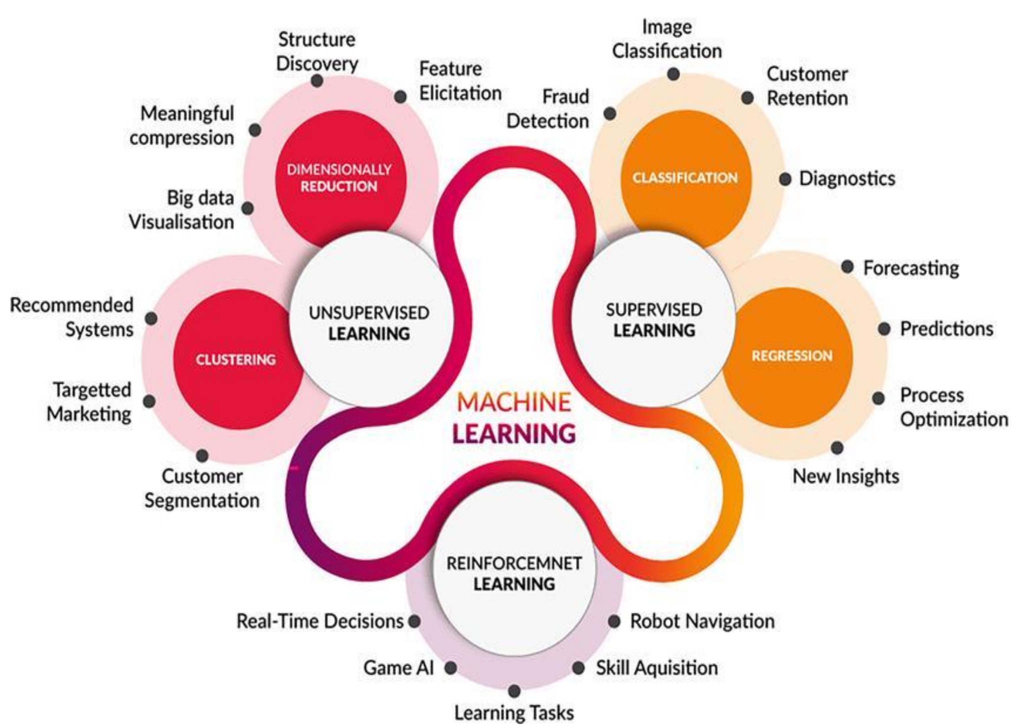

Figure 2.12 : Overview of Machine Learning Types and Applications [188]

Supervised learning methods such as linear, multiple, and ridge regression are used to model relationships between GWP and variables like hydro share, coal share, and aluminum quantity [189]. For non-linear behaviors, decision trees, random forests, gradient boosting (e.g., XGBoost), and support vector machines capture feature interactions and improve accuracy [190]. Neural networks, especially feedforward deep learning, predict alloy properties and optimize processes when large datasets are available [191]. Unsupervised methods also play an important role. Clustering (k-means, hierarchical) and PCA help optimize alloy recycling by grouping hundreds of grades into smaller sets [192]. Generative models and active learning are increasingly used to design alloys with better corrosion resistance and reduced fatigue testing, lowering experimental costs [193]. Together, these approaches enable accurate, interpretable, scalable dashboards for sustainability in aluminum production.

2.10.2 Jupyter Notebook and Python Programming.

Jupyter Notebooks combine executable Python code, visualizations, and text in one environment, making them well-suited for machine learning model development and dashboards [194]. They support key libraries such as *pandas* for data manipulation, *scikit-learn* for machine learning, and *Matplotlib*, *Seaborn*, and *Plotly* for visualization. Tutorials demonstrate how dashboards can be built directly in Jupyter using Dash or Jupyter Dash, enabling interactive graphs, real-time updates, and dynamic user input without leaving the notebook [195]. This allows for real-time updates and dynamic, fully interactive user-driven experiences without leaving the notebook environment.

Figure 2.13 : Jupyter with Python [196]

To bridge research and deployment, pipelines have been developed that convert Jupyter Notebooks into production-ready systems using *FastAPI* and containerization. For explainability, the *explainerdashboard* library enables clear visualization of model performance, feature importance, SHAP values, and "what-if" scenarios, either within notebooks or as standalone interactive applications. These best practices ensure models remain highly accurate, reproducible, and interpretable, which is essential for building stakeholder trust, confidence, and transparency in sustainability dashboards.

3 Methodology.

This study applies a comprehensive life cycle assessment to evaluate the environmental impacts of aluminum production for EV manufacturing. Following ISO 14040 and 14044 guidelines ensures a systematic, standardized, and scientifically rigorous approach, providing consistent, reliable, and comparable results. The life cycle assessment covers aluminum production from raw material extraction to processing and transport, providing a clear view of its ecological footprint. Similar methods are used in sustainability research to assess environmental impacts across industries [197].

3.1 The Evolution of LCA.

The assessment of environmental impacts related to consumer goods can be traced back to the 1960s, when industrialized nations began recognizing the importance of environmental policies. Early efforts focused mainly on pollution control and resource conservation at the production stage. However, it was not until the 1980s that the concept of evaluating a product's entire life cycle started gaining structured attention [197]. The 1990s marked a decade of significant progress in the field, leading to increased methodological coordination and the publication of the first scientific research papers on life cycle assessment [16]. Recognizing the need for standardization, ISO began formalizing life cycle assessment methods in 1994. This resulted in the development of two key international standards:

ISO 14040: *Environmental Management – LCA – Principles and Framework* [198]

ISO 14044: *Environmental Management – LCA – Requirements and Guidelines* [199].

According to ISO (2006a), life cycle assessment evaluates all inputs, outputs, and environmental impacts across a product's life cycle, serving as a comparative tool for informed sustainability decisions [200]. Life cycle assessment typically covers a product's full lifespan, from raw material extraction to disposal, often divided into cradle-to-entry gate (extraction to refining), entry-to-exit gate (manufacturing), and exit-to-grave (use, recycling, disposal) stages [201]. Life cycle assessment has been widely integrated into policy and industry frameworks, with the European Commission applying it in the PEF methodology and the USEPA promoting its use in environmental management and regulatory decisions [202] [203]. Future developments, such as LCSA, aim to combine environmental, social, and economic factors, while artificial intelligence integration and real-time monitoring are expected to enhance LCA's precision and effectiveness[204].

3.2 Limitations of LCA.

Life cycle assessment is a widely recognized method for assessing environmental impacts of products and processes. While comprehensive, it has limitations affecting accuracy, applicability, and reliability. A key limitation is that life cycle assessment aggregates impacts over broad spatial and temporal scales, making it hard to capture localized effects like regional pollution, biodiversity loss, and resource depletion [205] [206]. Traditional models also struggle with dynamic changes such as climate fluctuations, technological shifts, and policy changes that affect long-term sustainability [207] [208]. Life cycle assessment heavily depends on data quality and availability [209] [210]**.**

Accuracy relies on comprehensive, up-to-date LCI data, which varies across industries, regions, and products [211] [212]. Many studies use generic or outdated databases, ignoring recent technological advances or emerging environmental concerns [213] [214]. This is clear in developing countries, where limited reliable data causes location bias and greatly reduces wider global use and comparison [215] [216]. Variations in databases and impact methods further hinder cross-study comparisons [217] [218]. Another limitation is LCA's narrow environmental focus, which often neglects important social, economic, and broader sustainability dimensions and impacts [197] [219]. Closing these critical gaps with better data and harmonized methods is key to improving overall LCA reliability worldwide.

Conventional LCA emphasizes carbon, energy, and resource use, overlooking labor conditions, health, and community impacts [220] [221]. Approaches like LCC and SLCA address economic and social dimensions [222] [223], with LCC quantifying lifecycle costs and SLCA evaluating worker and community impacts [224] [225]. The integrated LCSA framework combines LCA, LCC, and SLCA for a holistic sustainability assessment [226] [227] but still faces challenges in quantifying social impacts and aligning economic measures with sustainability goals [228]. LCA also poorly captures emerging issues like biodiversity loss, ecosystem resilience, and land-use change. Traditional models focus on climate impact, resource depletion, and toxicity, overlooking complex ecological interactions [229]. Calls exist to expand impact categories to include circular economy, ecosystem degradation, and socio-environmental trade-offs [217] [207]**.** LCA struggles with rebound effects, where efficiency gains unintentionally increase resource use [230] [231]. Interpretability poses a challenge; complex assumptions, boundaries, and impact categories cause variability, misinterpretation or greenwashing [214] [215] [232]. Despite these challenges, LCA remains essential for sustainability assessment. Advancements such as dynamic models, AI-driven monitoring, and big data analytics promise significantly improved accuracy and relevance [233].Interdisciplinary collaboration and regulatory standardization can enhance data consistency, comparability, and applicability.

3.3 Software Tool for LCI Data Modeling.

Conducting a life cycle assessment requires advanced analytical tools and specialized software to accurately and efficiently assess environmental impacts across a product, process, or service life cycle. Leading tools include GaBi, OpenLCA and SimaPro. LCA involves handling large datasets and multiple assumptions, so dedicated software quickly and also streamlines the process [234] [235]. This study uses SimaPro version 9.3.0.2 to model LCI datasets. Widely recognized for its robust databases and multiple impact assessment methods, SimaPro has proven effective in detailed environmental analyses in previous studies.

3.3.1 Introduction.

SimaPro, developed by PRé to make sustainability fact-based [236], enables users to construct, manipulate, and assess LCI data using various environmental impact methods. The software provides sustainability insights that improve product manufacturing and optimize service delivery [237]. By combining extensive databases, advanced impact assessment methods, and powerful analytical tools, SimaPro helps industries, researchers, and even small teams effectively measure and reduce environmental effects. Its versatility covers manufacturing, agriculture, energy, and transportation.

Figure 3.1 : SimaPro [238]

3.3.2 Structure of Methods in SimaPro.

SimaPro uses a structured approach to impact assessment, applying multiple methods to evaluate environmental burdens. *Characterization* quantifies potential impacts of emissions and resource use by assigning impact factors to each substance. For instance, in the GWP assessment, CO_2 is the reference with a GWP of 1, while CH_4 has a GWP of 25, meaning 1 kg of CH_4 contributes 25 times more to climate change [239] [240]. *Damage Assessment* aggregates impacts into broader areas of protection, including human health, ecosystem quality, and resource availability, providing a holistic view for decision-making [241] [242]. The Eco-indicator 99 method, for example, provides a comprehensive framework for classifying environmental impacts on human health, ecosystem quality, and natural resource depletion across various industrial processes. By aggregating multiple impact categories into a single score, it enables easier and more effective comparison of products and processes, supporting more informed environmental decision-making.

In addition, *Normalization* effectively contextualizes results by comparing them to relevant reference emissions, such as regional or global averages, thereby enabling clearer and easier interpretation. [243]. In the ReCiPe method, normalization factors use per capita European impacts, allowing category comparisons. *Weighting* assigns relative importance to impact categories based on societal values or expert judgment, guiding prioritization [244]; for instance, EPS 2000 uses monetary values to represent prevention costs [245], and in e-waste studies, weighting has focused policy on toxic emissions over resource depletion [246]. Finally, Addition (*Single Scoring*) aggregates weighted impacts into a single score, simplifying scenario comparison as well as supporting decision-making.

3.3.3 Categorization of Methods in SimaPro.

SimaPro categorizes impact assessment methods into distinct regional and global frameworks to facilitate comprehensive environmental evaluations. These methods align with diverse environmental policies, regulatory frameworks, and sustainability research priorities across different regions [247]. By offering multiple methodological approaches and a wide variety of standardized and customizable options, SimaPro ensures the flexibility and adaptability of life cycle assessment studies to suit diverse geographical contexts, industry sectors, and project-specific requirements, thereby enhancing their relevance, applicability, and overall usefulness for researchers, policymakers, and decision-makers [248]. It also helps researchers systematically compare results across studies, improving clarity, consistency, reliability, and reproducibility, while supporting better-informed environmental, and strategic decisions across multiple domains. In addition, the tool makes it easier to share findings, test new ideas, and build stronger links between science, practice, and long-term sustainability goals.

3.4 European Methods.

SimaPro uses established European methods to assess environmental impacts, improve sustainability, and guide effective policy and industry decisions worldwide, thus fostering long-term resource efficiency, reduced emissions, and responsible environmental management. **Table 3.1** presents a summary of these methods along with their corresponding versions. This helps ensure clarity and consistency in all types of life cycle studies worldwide.

Name	Version	Project
CML-IA baseline	3.07	Methods
CML-IA non-baseline	3.05	Methods
Ecological Scarcity 2013	1.08	Methods
EF 3.0 Method (adapted)	1.02	Methods
EN 15804 + A2 Method	1.02	Methods
Environmental Prices	1.02	Methods
EPD (2018)	1.03	Methods
EPS 2015d	1.01	Methods

Table 3.1 : European Methods.

The CML IA Baseline method from Leiden University is a widely used LCIA approach that organizes impacts into midpoint categories such as GWP, AP, EP, and toxicity, providing a science-based framework for analysis [249]. CML IA Non-Baseline version gives updated, region-specific factors for more tailored assessments. The Ecological Scarcity 2013 method, a Swiss approach, links national policy targets with LCIA, using eco-factors for emissions and resources based on scarcity and impact [250] [251]. LCIA offers specialized methods for varied uses. The Environmental Footprint 3.0, developed by the European Commission, harmonizes environmental assessments across all EU states with regionalized factors and indicators [252] [253]. These diverse methods allow practitioners to select the most appropriate approach depending on study objectives, regional context, and data availability.

The EN 15804 A2 method, based on European construction standards, updates impact categories and calculation rules for more accurate and current environmental reporting [254] [255]. The Environmental Prices method assigns monetary values to impacts, supporting cost-benefit analyses [256] [257]. The EPD 2018 method follows ISO 14025 to measure product life cycle impacts for comparable sustainability reporting. [258] [259]. Finally, EPS 2015d and EPS 2015dx use damage cost estimates for human health, biodiversity, and ecosystem services, guiding environmentally informed design and policy [260] [261]. Together, these methods provide comprehensive tools for decision-makers to evaluate environmental performance across products, industries, and regions.

3.5 Global Methods.

SimaPro integrates a wide range of widely recognized and extensively used impact assessment methods, including IMPACT World+, LC-IMPACT, and ReCiPe 2016, each offering unique approaches, assumptions, and calculation frameworks for life cycle impact analysis. **Table 3.2** summarizes these methods, their versions, and key features.

Name	Version	Project
IMPACT World+ Endpoint	1.01	Methods
IMPACT World+ Midpoint	1.01	Methods
LC-IMPACT| average pref. | all imp. | 100y	1.00	Methods
LC-IMPACT| average pref. | all imp. | inf.	1.00	Methods
LC-IMPACT| average pref. | certain imp. | 100y	1.00	Methods
LC-IMPACT| average pref. | certain imp. | inf.	1.00	Methods
LC-IMPACT| marginal pref. | all imp. | 100y	1.00	Methods
LC-IMPACT| marginal pref. | all imp. | inf.	1.00	Methods
LC-IMPACT| marginal pref. | certain imp. | 100y	1.00	Methods
LC-IMPACT| marginal pref. | certain imp. | inf.	1.00	Methods
ReCiPe 2016 Endpoint (E)	1.06	Methods
ReCiPe 2016 Endpoint (H)	1.06	Methods

Table 3.2: Global Methods.

The IMPACT World+ method uses endpoint and midpoint approaches for LCIA, allowing flexibility. Its endpoint approach evaluates human health, ecosystem quality, and resource depletion, supporting comprehensive comparisons and informed decision-making [262] [263]. The midpoint version quantifies impacts earlier in the chain, with regionalized assessments for categories like water scarcity, acidification, and toxicity, enhancing precision and relevance [264]. LC-IMPACT method uses models varying by horizon, coverage, and weighting, with average models addressing global concerns and marginal models prioritizing impacts for trade-off evaluation [265] [266] [267]. ReCiPe 2016 method provides two main endpoint perspectives. The egalitarian version emphasizes long-term, precautionary effects, integrating midpoint results into human health, ecosystem quality, and resource availability [242] [268]. The hierarchist version balances short- and long-term impacts.

3.6 North American Methods.

SimaPro includes impact assessment methods tailored to North American contexts. **Table 3.3** summarizes these methods and versions, highlighting tools for regional environmental impact analysis. They also account for local emission standards, resource use patterns, and key environmental priorities, further improving the accuracy and relevance of lifecycle assessment. BEES+, developed by USNIST, evaluates the sustainability of building materials by integrating environmental and economic metrics to support sustainable construction [269] [270]. TRACI, developed by the USEPA, supports detailed impact assessments in North America, effectively aiding regulation, promoting industrial sustainability, and informing policy and decision-making processes [271] [272].

Name	Version	Project
BEES+	4.10	Methods
TRACI 2.1	1.06	Methods

Table 3.3 : North American Methods.

3.7 Applied LCA methodology in this study.

3.7.1 North America Context.

In North America, where aluminum is critical for electric vehicle manufacturing, this study conducts a cradle-to-gate lifecycle assessment covering bauxite mining, alumina production, smelting, and ingot casting. The main goal is to quantify environmental impacts from extraction to final ingot production, offering valuable insights to reduce emissions and enhance overall sustainability. Findings will support cleaner, safer, more efficient, and environmentally responsible aluminum production practices.

3.7.1.1 Goal and scope definition.

The environmental impact assessment of aluminum production begins with identifying key process stages: bauxite extraction, alumina refining, smelting, and ingot casting [273]. This study conducts a cradle-to-gate lifecycle assessment, analyzing impacts from raw material extraction to final ingot production. LCI data is sourced from Ecoinvent [274] and EPA's eGrid [275] , with sensitivity analysis evaluating reduced fossil fuel use and improved energy efficiency [276]. The system boundary covers extraction, rail and maritime transport, and final delivery. Inputs include fuel oil, gasoline, electricity, and transport energy. The functional unit is 1,000 kg of aluminum ingot. LCA methods used are BEES+ version 4.10 and TRACI 2.1 version 1.06, the latter including region-specific United States parameters [277].

Throughout the aluminum production process, emissions are released into both air and water, including substances such as carbon dioxide, carbon monoxide, methane, nitrogen oxides, sulfur oxides, oils, and solid waste [278]. The geographical focus of this study is North America, with primary emphasis on the United States and Canada. Previous life cycle assessment research on aluminum production has analyzed global regions, excluding China, as well as specific locations such as China, Australia, and select Middle Eastern countries like Turkey. Understanding these emissions and their distribution is critical for developing effective environmental management and mitigation strategies. **Figure 3.2** provides a visual representation of the system boundary framework applied in this research.

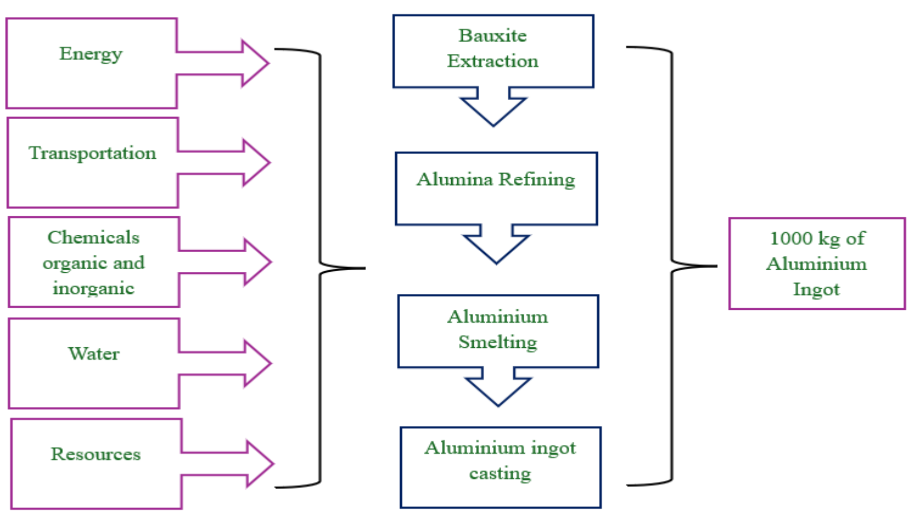

Figure 3.2 : System boundary for producing 1,000 kg of aluminum ingot.

3.7.1.2 Key assumptions and justification.

1. Energy Source Assumptions.

- *Assumption*: Bauxite mining and alumina refining rely on diesel and natural gas, while hydropower-generated electricity is the primary energy source for smelting.
- *Justification*: This reflects the typical North American energy profile for Al production. Regions such as Quebec rely on hydropower for smelting due to low cost and emissions, while mining and refining still depend on diesel and natural gas for mobility and heat.

2. Bauxite Sourcing and Transportation.

- *Assumption*: Bauxite is imported from Jamaica, transported approximately 3,200 km by sea to North American aluminum plants for further processing and production.
- *Justification*: Jamaica is a major bauxite supplier to North America due to proximity and established trade routes, minimizing transport emissions compared to more distant sources like Australia, Brazil or Guinea and reflecting the regional supply chain.

3. Product Purity and Alloying.

- *Assumption*: The LCA models only pure aluminum ingots, with no alloying elements included.
- *Justification*: This simplification provides a clear baseline for assessing environmental impacts of primary aluminum production by excluding alloying materials and extra processing. For application-specific analyses, such as battery enclosures, this assumption is critical, as alloys and additional processing can substantially alter the overall impact.

4. Material Conversion Ratios.

- *Assumption*: The following conversion ratios are used for the production of 1,000 kg of aluminum ingot: 4,500 kg bauxite → 1,950 kg alumina → 1,020 kg Aluminium smelting → 1,000 kg Aluminium ingot.
- *Justification*: These ratios reflect typical industrial yields in the Bayer process (bauxite to alumina) and Hall-Héroult process (alumina to aluminum), adjusted for realistic losses in North American production. The bauxite-to-alumina ratio (2.31:1) accounts for losses from red mud and impurities [278] [28], while the alumina-to-aluminum ratio (1.91:1) incorporates 94% current efficiency in electrolysis, reflecting side reactions and sludge formation [279] [278]. The aluminum-to-ingot ratio (1.02:1) includes a 2% loss from dross, spillage, and transport during casting, consistent with Alcoa [280] and Total Materia [281]. These ratios ensure alignment with technical benchmarks and support comparability. Including these ratios in life cycle assessment calculations allows for more accurate estimation of material flows, energy use, and environmental impacts throughout the production chain.

Stages	Input (kg)	Output (kg)	Conversion Ratio
Bauxite → Alumina	4500	1950	2.31:1
Alumina → Aluminum	1950	1020	1.91:1
Aluminum → Ingot	1020	1000	1.02:1

Table 3.4 : North American Methods.

5. System Boundary Definition.

- *Assumption*: The lifecycle assessment is cradle-to-gate, encompassing raw material extraction, transport, and all production steps up to the factory gate, excluding product use and end-of-life phases.
- *Justification*: Cradle-to-gate is a common lifecycle assessment boundary for industrial materials, focusing on production impacts. It is widely used in industry and academia to ease data collection and ensure comparability, especially when use and disposal are uncertain.

6. Technology and Process Uniformity

- *Assumption*: The simulation reflects current average technologies and processes in North America, assuming no major technological changes during the assessment period.
- *Justification*: Lifecycle assessment studies typically assume stable technology to maintain consistency and comparability. North American aluminum production largely relies on mature, established processes, especially in hydropower-rich regions.

7. Waste and Emission Management.

- *Assumption*: All waste streams and emissions are managed according to prevailing North American environmental regulations and best practices.
- *Justification*: North America enforces strict environmental standards for industrial emissions and waste management, which should be accurately reflected in the lifecycle assessment to ensure realistic impact assessment and full regulatory compliance.

8. Functional Unit.

- *Assumption*: The functional unit is 1,000 kg of aluminum ingot at the factory gate.
- *Justification*: This is the standard functional unit in lifecycle assessment studies for metals, enabling comparison with published data and industry benchmarks.

Assumption Area	Description	Justification
Energy Source	Hydropower for bauxite/alumina, natural gas for heat in later stages	Reflects North American industrial reality and reduces greenhouse gas emissions.
Bauxite Sourcing	Imported from Jamaica (3200 km sea route)	Minimizes transport emissions, aligns with regional trade patterns
Product Purity	Pure aluminum ingot, no alloying	Simplifies system boundary, matches LCA norms
Material Ratios	Bauxite 4500, Alumina 1950, Smelting 1020, Ingot 1000.	Matches industry benchmarks and published lifecycle assessment data
System Boundary	Cradle-to-gate	Standard practice for industrial LCAs, focuses on production impacts
Technology Uniformity	Current average North American processes	Ensures consistency and comparability
Waste/Emission Management	Managed per North American regulations	Reflects strict regulatory environment
Functional Unit	1000 kg aluminum ingot	Standard for LCA studies, enables data comparison

Table 3.5 : Summary Table of Key Assumptions.

3.7.1.3 Lifecycle inventory analysis.

Appendix 1 provides a detailed inventory of materials and emissions for producing 1000 kilograms of aluminum ingot from bauxite extraction onward. Inputs are categorized by production stage and include fuel oil for mining, fossil fuels in boilers, electricity for smelting, and diesel for transport. Outputs include the aluminum ingot, valuable byproducts, waste, airborne particulates, and metal-ion discharges into water, highlighting environmental impacts across all production stages. This inventory also helps identify key areas where energy use and emissions can be reduced to improve overall sustainability.

3.7.1.4 Lifecycle impact assessment.

This section provides a comprehensive and detailed analysis of the life cycle impact assessment methodology and the results obtained, which are summarized in **Chapter 4**, **Section 4.1**, focusing on multiple environmental impact categories such as global warming potential, energy use, and resource depletion. The assessment uses two established methods: BEES+ and TRACI. BEES+ evaluates environmental impacts across set categories and combines economic and environmental performance to support sustainable decisions [269]. TRACI provides a framework for assessing effects including global warming potential, acidification potential, and eutrophication potential, specifically tailored to North American environmental and industrial conditions [271]. Adding both methods in parallel ensures a more robust and reliable interpretation of life cycle impacts across multiple categories.

Both methodologies are applied in this study to assess the full environmental footprint and potential impacts of aluminum production; although some impact categories are similar and overlap between methods, their combined application allows for a more thorough and comprehensive evaluation of environmental performance. Because the dataset originates from North American production sources, these methodologies are particularly well suited to the region and its specific industrial and environmental context [282]. **Table 3.6** clearly outlines the impact categories considered based on TRACI and BEES+, providing insight into key environmental factors associated with aluminum production.

Impact Category	Unit	BEE	TRACI
Global warming	CO2 eq	✓	✓
Acidification	H+ mmole eq / SO2 eq	✓	✓
HH cancer (Carcinogenics)	C6H6 eq / CTUh	✓	✓
HH noncancer (non-carcinogenics)	C7H7 eq / CTUh	✓	✓
HH criteria air pollutants	microDALYs	✓	X
Eutrophication	N eq	✓	✓
Ecotoxicity	2,4-D eq / CTUe	✓	✓
Smog	NOx eq / O3 eq	✓	✓
Natural resource depletion (Fossil fuel depletion)	MJ surplus	✓	✓
Indoor air quality	TVOC eq	✓	X
Respiratory effects	PM2.5 eq	X	✓
Habitat alteration	T&E count	✓	X
Water intake	Liters	✓	X
Ozone depletion	CFC-11 eq	✓	✓

Table 3.6 : Environmental Impact Categories in BEE and TRACI Methods.

✓ = The impact category is present in the respective method.
X = The impact category is not present in the respective method.

3.8 Europe.

3.8.1 Goal and Scope of the LCI.

The objective of this study is to conduct a cradle-to-gate LCA of aluminum production, analyzing environmental impacts from raw material extraction to final ingot casting. The datasets focus on Europe, including the 27 EU and the EFTA countries, Norway, Switzerland, and Iceland. Lifecycle inventory modeling tracks pure aluminum, excluding alloying elements, which is valid for most wrought alloys containing less than 5% alloying elements. While the substitution principle applies to aluminum scrap, only the recoverable fraction from dross and salt slag is credited, ensuring outputs are mainly ingots or semi-finished products. Ancillary processes such as fuel, electricity, and auxiliary materials are included, with lifecycle inventory datasets comprising elementary flows drawn directly from or released to nature. The datasets were initially developed using 2010 EAA survey data reported in the 2013 EPR.

Dataset A represents aluminium produced in Europe and Dataset B represents aluminum used in Europe. More recent sources, including the World Aluminium lifecycle inventory database and updated Ecoinvent datasets, incorporate current production technologies, energy mixes, and improved environmental impacts. Other datasets cover semi-finished products including sheets, profiles, and foils, remelting of clean process scrap, and recycling at EoL, with system boundaries shown in **Figure 3.3**. Dataset A represents the production of 1 tonne of primary aluminum ingot in Europe, including all stages from bauxite mining to sawn ingot ready for distribution, with a specialized electricity model accounting for Soderberg and pre-bake smelters and imported electricity.

Dataset B similarly tracks aluminum imported into Europe, which accounted for 44 percent of European primary aluminum consumption in 2010, using global data from the International Aluminum Institute and a European Aluminum Association-specific electrolysis electricity model from the 2013 European Production Report. The semi-production datasets cover the transformation of sawn aluminum ingots into sheets, foils, and profiles, prepared for delivery to end users, and include recycling of scrap, chips, and dross. Each dataset represents the production of one tonne of the respective semi-finished product, with the foil dataset developed in collaboration between the European Aluminium Foil Association and the European Aluminum Association. The remelting life cycle inventory dataset represents one tonne of aluminum ingot from only clean process scrap, including recovery of dross and skimmings, suitable for recycling process scrap and certain end-of-life products such as old construction components and beverage cans collected through well-structured systems.

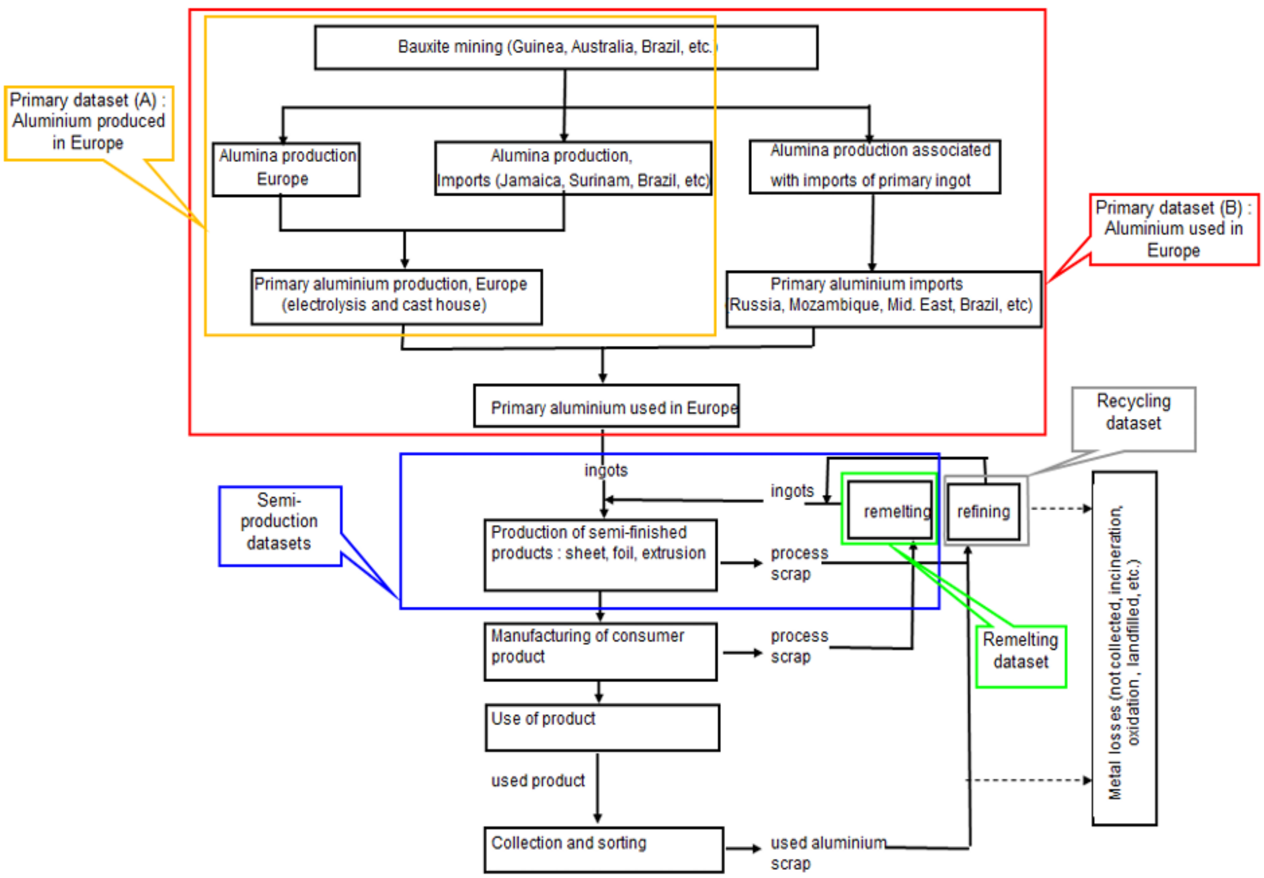

Figure 3.3 : The system boundaries of the different LCI datasets [283].

The recycling life cycle inventory dataset represents one tonne of aluminum ingot from a representative European scrap mix, excluding clean process scrap, and includes melting, purification, casting, and salt slag treatment. Developed jointly by the European Aluminum Association and OEA, it is structured using the ESSUM model, which simulates recycling of the European scrap mix with efficiencies and processing routes varying by scrap type and quality. For specific products or applications, more detailed assessments are recommended to create precise recycling models and life cycle inventory datasets. For further information, interested parties can contact the EAA at LCI@eaa.be.

3.8.2 Data collection, consolidation and averaging.

European aluminum production inventory data have been compiled in full compliance with ISO lifecycle assessment standards. The LCI draws on 2010 industry surveys, literature reviews, and data from multiple European manufacturing facilities detailing annual process inputs and outputs. Measurements are expressed in units such as tonnes, GJ, m^3, kg, MWh, kWh etc. European averages were calculated by horizontally aggregating all datasets, which integrates production stages and clearly reveals each stage's contribution to the total LCI.

3.8.3 Cut-off rules.

Input and output data were collected from various literature sources based on detailed questionnaires refined since initial surveys conducted between 1994 and 1996. All material flows entering the aluminum production processes that exceed 1% of total mass (t) or 1% of total primary energy input (MJ) are included and modeled to calculate elementary flows. Similarly, all outputs exceeding 1% of total mass are incorporated. Additionally, all available inputs and outputs, even below the 1% threshold, are considered, with no cut-off applied to hazardous or toxic materials.

3.8.4 Data quality, validation and modeling.

Data from various literature sources underwent evaluation to identify outliers and determine which information to include in the consolidation process. Before excluding any data, reporting companies were contacted for corrections based on feedback and expert judgment. The final dataset was consolidated, averaged, and modeled by the EAA. Data collection procedures, questionnaires, and consolidated datasets are fully documented in the internal reports [283], and validated by the EAA Technical Working Group of the Sustainability Committee.

3.8.5 Allocation principles.

To minimize allocation, the system boundaries have been expanded as much as possible. Each life cycle inventory dataset includes aluminum scrap and dross recycling, ensuring that the only valuable outputs are aluminum ingots or semi-finished products such as sheets, foils, or extrusions. Solid waste incineration accounts for energy recovery, including thermal and electrical outputs, which are fed back into the life cycle inventory model to reduce overall energy input, following the principle of energetic closed-loop recycling. The contribution of energy from incineration remains minimal, accounting for less than 1% overall.

3.8.6 Global aluminum (IAI) data vs (EAA) data.

To model aluminum processes outside Europe, global average process data have been applied, with specific processes and their contributions to the two life cycle inventory datasets outlined in **Table 3.7**. Since Europe imports a very substantial amount of alumina and primary aluminum, the "used in Europe" Life cycle inventory dataset assumes that all alumina and primary aluminum produced within the region remain strictly there. This assumption is supported by Eurostat and national customs data, showing that less than 10% of alumina and only about 2% of aluminum produced in the EU27 and EFTA countries combined are exported far beyond Europe to global markets for industrial and manufacturing purposes.

Process Step	LCI Dataset for Production in Europe	LCI Dataset for Use in Europe
Bauxite extraction	Derived entirely (100%) from IAI data, with no EAA data included	Entirely based (100%) on IAI data, excluding EAA data
Alumina manufacturing	Composed of 42% IAI data and 58% EAA data	Consists of 68% IAI data and 32% EAA data
Electrolysis (including anode production and casting)	Derived entirely (100%) from EAA data, with no IAI data included	44% derived from IAI data and 56% from EAA data

Table 3.7 : Contribution of different processes to the two distinct LCI datasets.

3.8.7 Background of data.

In addition to EAA and IAI data, supplementary datasets from GaBi (version 5) and SimaPro (version 9.3.0.2) cover electricity, limestone, transportation, pitch, caustic soda, fuel, petroleum coke, and aluminum fluoride production from various regions and years. Solid wastes undergoing recycling, incineration, composting, or legal landfill are included within the system boundaries, with emissions modeled. Emissions from most landfilled wastes are based on average lifecycle inventory models due to limited specific data.

3.8.8 Thermal energy used in aluminum processes.

In aluminum production, fuels like natural gas, propane, diesel, heavy oil, and coal are widely used. Consumption data are available, but air emission data remain limited to particulates, SO_2, and NO_x. For completeness, life cycle inventory data from SimaPro (version 9.3.0.2) and GaBi EU27 are carefully integrated. **Figure 3.4** shows air emissions from alumina production, supplemented by emissions from fuel preparation and combustion, with systematic steps taken to avoid double counting. For alumina production, total air emissions are calculated using reported pollutant data plus life cycle inventory data for fuel combustion, an approach consistently applied to all aluminum processes.

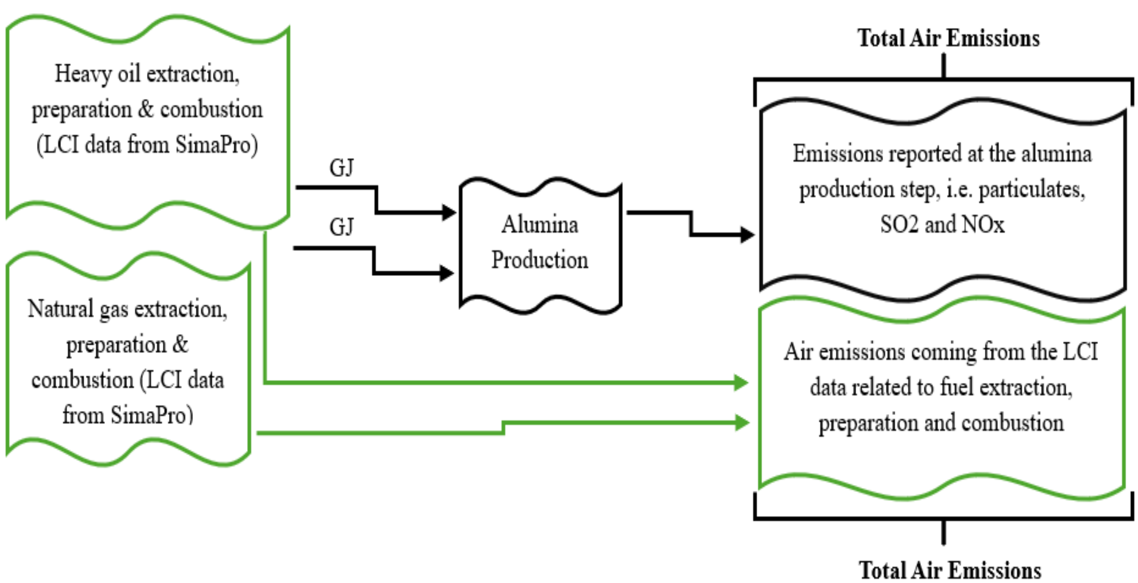

Figure 3.4 : Use of background LCI data related to fuel supply systems and combustion.

3.8.9 Direct CO2 emissions in aluminum processes.

This study calculates direct carbon dioxide emissions from aluminum processes based on fuel consumption. Carbon dioxide conversion factors representative of the EU-27, derived from literature referencing GaBi 5 data, are shown in **Table 3.8**. Only inventories from updated databases were included to ensure accuracy.

Type of Fuel	CO_2 emission factor (kg CO_2 per MJ)
Hard Coal	1.04E-01
Natural Gas	6.77E-02
Steam	7.52E-02
Propane	8.64E-02
Diesel or Light Oil	8.96E-02
Heavy Fuel Oil	9.01E-02

Table 3.8 : Carbon dioxide conversion factors for different types of fuel.

3.8.10 Electricity production.

Electricity generation is included within the system boundaries and is especially important in the electrolysis stage of aluminum smelting, which requires about 13–15 MWh per tonne of primary aluminum. The EAA developed three models: one for pre-baked smelters, one for Søderberg smelters, and one for smelters exporting to Europe, as reported in 2013. Electricity use in other aluminum processes is represented by life cycle inventory data linked to the EU27 electricity model based on 2023 data. Accurate representation of electricity consumption is crucial for assessing the environmental impacts of aluminum production. High electricity demand directly affects greenhouse gas emissions. Monitoring and optimizing electricity use can significantly improve sustainability.

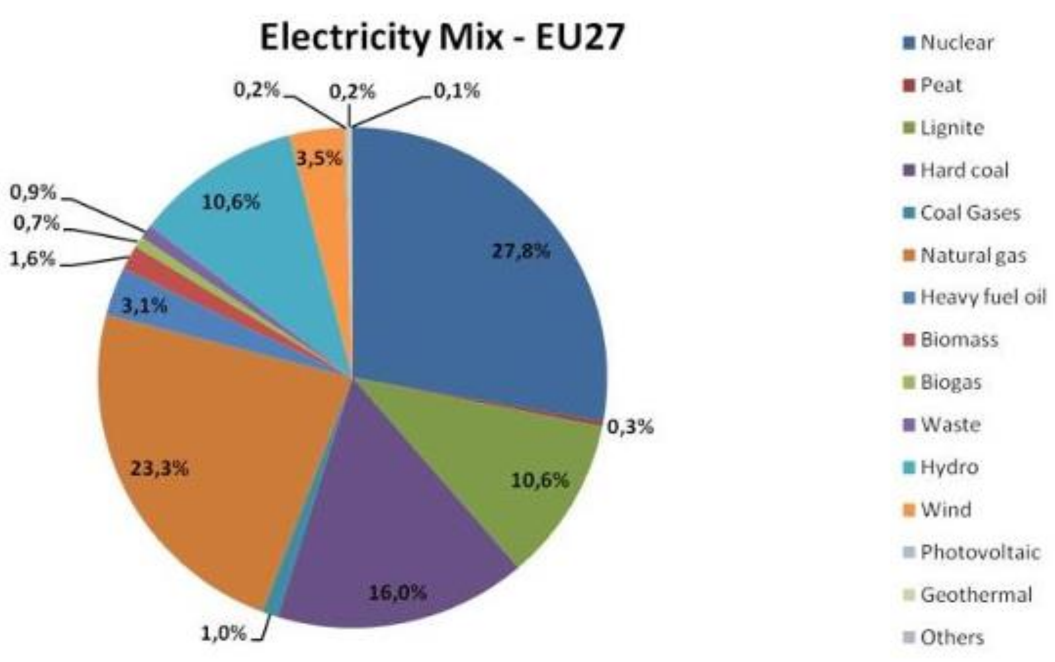

Figure 3.5 : European Union (EU27) Electricity Mix.

Environmental Indicators (per kWh of electricity)	Measurement Units	Value
Eutrophication Potential	[kg Phosphate-Equivalent]	1.12E-04
Photochemical Ozone Creation Potential	[kg Ethene-Equivalent]	1.27E-04
Acidification Potential	[kg SO_2-Equivalent]	2.08E-03
Ozone Layer Depletion Potential (ODP, Steady State)	[kg R11-Equivalent]	3.19E-08
Abiotic Resource Depletion (ADP, Elements)	[kg Sb-Equivalent]	4.01E-08
Global Warming Potential (GWP over 100 years)	[kg CO_2-Equivalent]	4.89E-01
Primary Energy Use (Renewable & Non-Renewable Resources)	[MJ, Net Calorific Value]	9.78E+00
Energy from Renewable Raw Materials	[MJ, Net Calorific Value]	1.25E+00
Energy from Non-Renewable Resources	[MJ, Net Calorific Value]	8.53E+00

Table 3.9 : Environmental indicators per 1 kWh from the EU-27 electricity grid.

3.8.11 Transport.

Bauxite, alumina, and primary aluminum ingots imported into Europe are mainly transported by sea, with smaller portions moved by river, road, and rail. The updated European Aluminum Association life cycle inventory dataset for primary aluminum now includes all these modes, unlike assessments from 2005 that considered only sea transport. Europe sources bauxite primarily from Guinea, Australia, and Brazil, with an average sea distance of 6,100 kilometers; alumina from Jamaica, Suriname, and Brazil at about 4,700 kilometers; and primary aluminum ingots from Russia, Mozambique, Brazil, and Middle Eastern countries at 2,500 kilometers. Road and rail transport within Europe are also included, as shown in **Figure 3.6**. Including multiple transport modes allows for a more accurate estimation of emissions and energy use across the supply chain. Longer shipping distances increase fuel consumption and associated greenhouse gas emissions, making route optimization important for sustainability. This detailed transport modeling supports strategic decisions for sourcing and logistics planning to minimize environmental impact.

Despite domestic alumina production of 7.7 million tons in 2024, mainly in Ireland, Germany, Spain, and Greece, Europe remains heavily reliant on imports to meet downstream demand. This dependence underscores the importance of strategic sourcing and supply chain management. Domestic bauxite production in Greece is around 2 million tons annually, while imports total 14 to 15 million tons. Balancing domestic production with imports is critical for regional resource security. Alumina imports fell 34.2 percent to 1.7 million tons in 2024, concentrated in France and the Netherlands, reflecting improved efficiency or increased recycling. These trends indicate progress toward more sustainable material management practices. This modeling enables better environmental assessment and highlights logistics improvements to lower carbon footprints.

Moreover, it also supports targeted interventions to enhance overall supply chain sustainability. Fuel consumption is 0.54 grams of heavy oil per tonne-kilometer for 10,000 to 200,000-tonne bulk carriers. Transporting one tonne of alumina or bauxite over 5,000 kilometers requires about 2.7 kilograms of heavy oil. Transport data are not included in other life cycle inventory datasets. Tracking both domestic and imported materials allows for more complete evaluation of environmental impacts in Europe. Improved efficiency in transport can significantly reduce carbon dioxide emissions and operating costs. These insights are essential for planning sustainable supply chains and informing policy decisions.

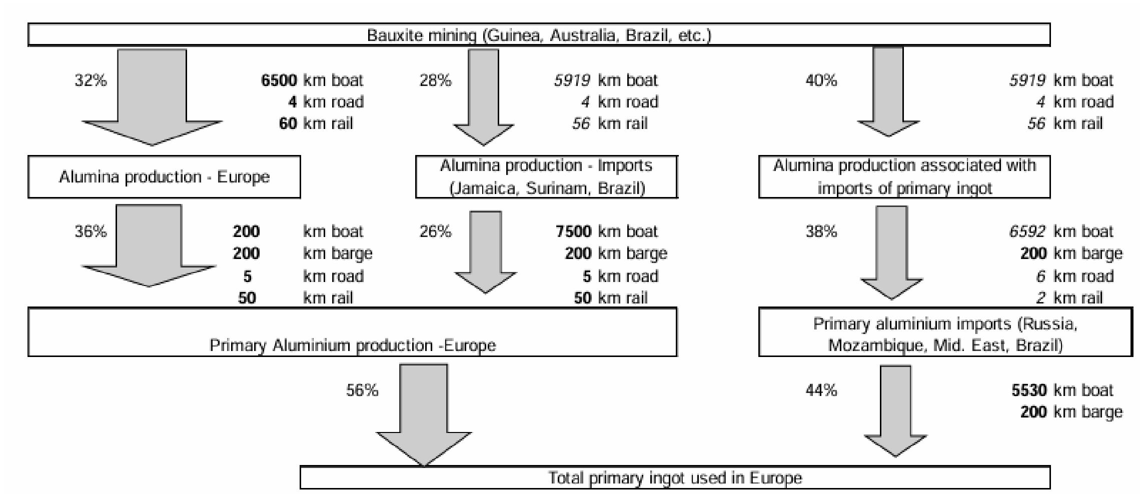

Figure 3.6 : Transport distances of key materials across supply and distribution stages.

3.8.12 LCI data and environmental indicators.

This study considers a set of environmental impact categories: abiotic resource depletion, acidification potential, eutrophication potential, GHG emissions over 100 years, OLDP in steady state, photo-oxidant creation potential, total primary energy, primary energy from renewable raw materials, and primary energy from non-renewable resources. **Appendix 2** provides a detailed breakdown of inventories, including materials and emissions throughout production. For each life cycle inventory dataset, processes and materials are grouped into five categories: direct process, electricity, thermal energy, auxiliary, and transport, ensuring systematic assignment of life cycle inventory data and environmental indicators.

The direct process category covers material consumption and emissions within aluminum production, divided into primary production (bauxite extraction, alumina refining, anode and paste manufacturing, electrolysis, aluminum casting), semi-production (ingot homogenization, scalping, hot and cold rolling, annealing, finishing, packaging, extrusion, foil rolling, scrap remelting, dross recycling), and recycling (scrap remelting, refining, dross recycling, salt slag treatment). All associated process steps are included to ensure complete accounting. Electricity includes all power generation processes and fuel preparation, while Thermal Energy covers generation of thermal energy excluding pitch and coke used in anodes. The Auxiliary category includes supporting materials such as caustic soda, lime, and aluminum fluoride. Transport encompasses sea, river, road, and rail movement of products.

3.8.13 Key assumptions and justification.

1. Energy Source Assumption.

- *Assumption*: Hydropower powers electricity-intensive stages of aluminum production, especially electrolysis, while earlier stages like bauxite mining and alumina refining use conventional thermal energy. *Justification*: In Europe, smelting is mostly powered by renewable electricity, mainly hydropower, lowering emissions, whereas mining and refining, often done elsewhere, rely on fossil fuels such as diesel and natural gas, reflecting the energy split in low-carbon European aluminum production

2. Bauxite Sourcing and Transportation.

- *Assumption*: Bauxite is imported mainly from Russia, with an average shipping distance of roughly 2,800–3,000 km to European smelters by large bulk ships. *Justification*: Europe is a net bauxite importer, with Russia as a nearby supplier, reducing transport emissions compared to distant sources like Guinea or Australia and reflecting typical European supply chains. This study focuses solely on sustainability, excluding global supply chain risks, geopolitical instabilities, and market fluctuations.

3. Product Purity and Alloying.

- *Assumption*: The LCA models only pure aluminum ingots, with no alloying elements. Justification: Focusing on pure aluminum simplifies system boundaries and aligns with standard LCA practice, as alloys add extra variables and upstream impacts.

4. Material Conversion Ratios.

- *Assumption*: The following conversion ratios are used for the production of 1,000 kg of Aluminium ingot: 4500 kg bauxite → 1950 kg alumina → 450 kg anode → 1,020 kg (electrolysis) → 1,000 kg aluminium ingot.
- *Justification*: These ratios reflect industry-standard yields for the Bayer process (bauxite to alumina) and Hall-Héroult process in European smelters, adjusted for realistic losses. The bauxite-to-alumina ratio (2.31:1) accounts for red mud and impurities, consistent with LCA datasets [82] [20]. The alumina-to-aluminum stage, with 450 kg anode consumption, reflects 95% current efficiency in electrolysis, including losses from side reactions and sludge formation [142] [82]. The aluminum-to-ingot stage includes a 2% loss from dross, spillage, and transport during casting, aligning with European industry data [281] quite closely on average now. Anode consumption of around 450 kg per 1,000 kg aluminum generally falls within the typical range for European smelters under current operating conditions [278].

Stages	Input (kg)	Output(kg)	Conversion Ratio
Bauxite → Alumina	4,500	1,950	2.31:1
Alumina → Anode	-	450	-
Anode + Alumina → Al	450 + 1,950	1,020	1.90:1 (alumina to aluminum)
Aluminum → Ingot	1,020	1,000	1.02:1

Table 3.10 : European Methods.

5. System Boundary Definition.

- *Assumption*: The study applies a cradle-to-gate system boundary, covering raw material extraction, transportation, processing, and production up to the factory gate, while excluding product use and end-of-life management stages.
- *Justification:* Cradle-to-gate is the standard boundary for industrial material LCAs, particularly in Europe, enabling focused assessment of the production phase and comparability with industry and academic benchmarks.

6. Technology and Process Uniformity.

- *Assumption*: The modeled technologies reflect current average practices and efficiencies, assuming no major changes during the assessment period.
- *Justification:* European smelters are highly advanced, with mature, efficient processes; assuming stable technology reflects this reality and ensures consistent data.

7. Waste and Emission Management.

- *Assumption*: All waste streams and emissions are managed according to prevailing European Union environmental regulations and best available techniques.
- *Justification*: Europe enforces some of the world's strictest industrial emission and waste standards, which the LCA reflects to ensure realistic impact assessment.

8. Functional Unit.

- *Assumption*: The functional unit is 1,000 kg of aluminum ingot at the factory gate.
- *Justification*: This standard unit for metal life cycle assessment also allows for easy comparison with published European and global datasets.

Assumption Area	Description	Justification
Energy Source	Hydropower powers electricity-intensive stages like electrolysis, while mining and refining rely on thermal energy sources.	Reflects European industry practice and supports low-carbon aluminum production.
Bauxite Sourcing	Imported from Russia (2800–3000 km shipping)	Minimizes transport emissions.
Product Purity	Pure aluminum ingot, no alloying.	Standard lifecycle assessment practice for baseline studies.
Material Ratios	Bauxite 4500: Alumina1950: Anode 450 Aluminium (Electrolysis)1020: 1,000 ingot	Matches European industry benchmarks and published lifecycle assessment data.
System Boundary	Cradle-to-gate	Standard for industrial LCAs, focuses on production impacts
Technology Uniformity	Current average European processes	Ensures data consistency and reflects regional reality
Waste/Emission Management	Managed as per EU regulations and best available techniques	Reflects strict regulatory environment in Europe.
Functional Unit	1,000 kg aluminum ingot	Standard for LCA studies and enables data comparison.

Table 3.11 : Summary Table of Key Assumptions (European Context).

3.9 GWP Prediction Dashboard Methodology.

The development of the global warming potential (GWP) Prediction Dashboard involved carefully constructing a detailed dataset, training a predictive model, implementing an interactive user-friendly interface, and enforcing specific technical and practical constraints to ensure accurate, reliable, and realistic outputs. The overall methodology was designed to align closely with recognized industry standards, best practices, and evolving user requirements, making it both scientifically sound and suitable for practical application in modern aluminum production systems [284].

3.9.1 Data Preparation.

To predict GWP accurately, a dataset was created to represent different energy mixes and their environmental impacts during aluminum production. The data includes 25 entries covering five regions (Africa, Asia, South America, North America, Europe), which are key aluminum-producing areas globally. Each entry specifies the percentage of hydropower and coal used, with one European case including wind power to reflect regional variations (e.g., Europe's use of renewables). The energy consumption was fixed at 14,000 kWh per 1,000 kg of aluminum, based on typical industry values, to simplify calculations while focusing on energy source impacts. Aluminum quantity was set to 1,000 kg for consistency, and GWP values (3,800–20,000 kg CO_2e) were derived from industry reports and life cycle assessments, reflecting realistic emissions for hydro-only, coal-only, and mixed scenarios (e.g., 4,000 kg CO_2e for 100% hydro in North America, 20,000 kg CO_2e for 100% coal). The data was carefully chosen to cover a range of scenarios: 100% hydro (low GWP), 100% coal (high GWP), and mixed cases (e.g., 60% hydro/40% coal, 50% hydro/50% coal) to capture the spectrum of possible energy mixes. Nuclear and solar percentages were set to 0% for simplicity, as they are less common in aluminum production's energy mix. The regions were included to account for geographic variations in energy availability (e.g., hydropower in North America, coal in Asia). **Table 3.12** shows the datasets used for the GWP prediction model.

Region	**Hydro (%)**	**Wind (%)**	**Coal (%)**	**Nuclear (%)**	**Solar (%)**	**Energy (kWh)**	**Aluminium (kg)**	**GWP (kg CO_2e)**
North America	100.00	0.00	0.00	0.00	0.00	14000	1000	4000
North America	60.00	0.00	40.00	0.00	0.00	14000	1000	7000
North America	50.00	0.00	50.00	0.00	0.00	14000	1000	12000
North America	40.00	0.00	60.00	0.00	0.00	14000	1000	19000
North America	0.00	0.00	100.00	0.00	0.00	14000	1000	20000
Europe	100.00	0.00	0.00	0.00	0.00	14000	1000	3800
Europe	71.43	28.57	0.00	0.00	0.00	14000	1000	3900
Europe	60.00	0.00	40.00	0.00	0.00	14000	1000	6800
Europe	50.00	0.00	50.00	0.00	0.00	14000	1000	11500
Europe	40.00	0.00	60.00	0.00	0.00	14000	1000	18500
Africa	100.00	0.00	0.00	0.00	0.00	14000	1000	4000
Africa	60.00	0.00	40.00	0.00	0.00	14000	1000	7000
Africa	50.00	0.00	50.00	0.00	0.00	14000	1000	11500
Africa	40.00	0.00	60.00	0.00	0.00	14000	1000	19000
Africa	0.00	0.00	100.00	0.00	0.00	14000	1000	20000
Asia	100.00	0.00	0.00	0.00	0.00	14000	1000	4000
Asia	60.00	0.00	40.00	0.00	0.00	14000	1000	7000
Asia	50.00	0.00	50.00	0.00	0.00	14000	1000	12000
Asia	40.00	0.00	60.00	0.00	0.00	14000	1000	19000
South America	100.00	0.00	0.00	0.00	0.00	14000	1000	4000
South America	60.00	0.00	40.00	0.00	0.00	14000	1000	7000
South America	50.00	0.00	50.00	0.00	0.00	14000	1000	12000
South America	40.00	0.00	60.00	0.00	0.00	14000	1000	19000
South America	0.00	0.00	100.00	0.00	0.00	14000	1000	20000

Table 3.12 : Datasets used for the GWP prediction model.

3.9.2 Model Justification and Implementation.

Why Random Forest Was Chosen: To predict global warming potential (GWP), we needed a method to assess how energy mixes and regions affect emissions, a relationship that is non-linear and influenced by multiple factors. A Random Forest Regressor, an ensemble machine learning model, was chosen because it aggregates predictions from many decision trees to produce stable, reliable estimates [285]. It can capture patterns such as higher coal shares increasing emissions while accounting for regional variations, similar to consulting multiple experts and combining their opinions to reduce bias and variance. This makes Random Forest especially suitable for complex environmental modeling.

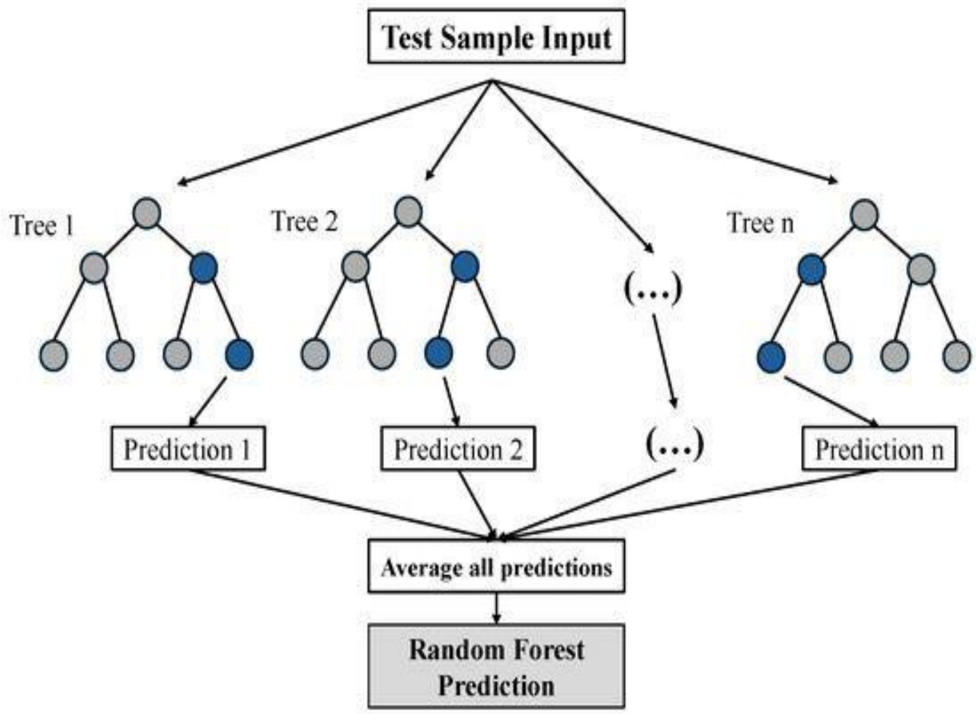

Figure 3.7 : Random Forest Model.

Why Random Forest Is Better Than Other Methods: Alternative methods were considered but deemed less suitable. Linear regression assumes strict linear relationships, which do not reflect the complex, non-linear effects of regional energy mixes in aluminum production [286]. Neural networks require large datasets and are difficult to interpret [287]; with only 25 observations, they were impractical. Random Forest, however, handles small datasets well, is robust to noise and outliers, captures non-linear dependencies, and remains interpretable for stakeholders.

Model Selection and Training: The Random Forest Regressor was implemented in scikit-learn with 100 estimators and a fixed random state for reproducibility [288]. A lookup table was incorporated for North America and Europe scenarios to ensure alignment with established benchmark values, such as 4,000 kg carbon dioxide equivalent for 100% hydro-based production in North America. Training was evaluated using cross-validation and error metrics to ensure consistency with theoretical global warming potential (GWP) ranges.

Dashboard Implementation: The interactive dashboard was built in Python using *ipywidgets* for interactivity and *matplotlib* for visualization [289] [290]. User inputs include region (dropdown menu), hydro and coal shares (sliders), and aluminum quantity (text input). If hydro and coal percentages do not sum to 100, the dashboard automatically adjusts them to maintain validity (e.g., 80% hydro and 30% coal becomes 66.67% hydro and 33.33% coal). The output includes predicted GWP (kg carbon dioxide equivalent), GWP per 1,000 kg of aluminum, dominant source (hydro, coal, or mixed), emission status (Low, Mid, or High), theoretical range for comparison, optimization suggestions, and a visualization of the energy mix through a bar plot (*energymix.png*).

3.9.3 Constraint Enforcement.

To ensure realistic and accurate outputs, the GWP Prediction Dashboard incorporates constraints reflecting industry benchmarks and the physical relationships between energy mix and emissions.

3.9.3.1 Scenario-Based Constraints.

Mixed Scenarios (*hydro > 0, coal > 0*): Dominant Source is Hydro if *hydro > coal*, Coal if *coal > hydro*, and Mixed if *hydro == coal*. Status is Mixed. The theoretical range is 5,000–20,000 kg carbon dioxide equivalent per 1,000 kg aluminum. GWP Status is Low (≤9,000), Mid (9,001–14,000), or High (>14,000).

Hydro-Only Scenarios (hydro > 0, coal = 0): Dominant Source is Hydro with Status as Hydro-dominated. The dynamic theoretical range is defined with a lower bound *theo_lower* = 3000 + (coal / 100) * (16000 - 3000) and an upper bound *theo_upper* = min(10000 + (coal / 100) * (25000 - 10000), 8500). GWP Status is ≤ 8,500 kg carbon dioxide equivalent, categorized as Low (≤5,500) or Mid (5,501–8,500).

Coal-Only Scenarios (*hydro = 0, coal > 0*): Dominant Source is Coal with Status as Coal-dominated. The dynamic theoretical range is defined with a lower bound *theo_lower* = 3000 + (coal / 100) * (16000 - 3000) and an upper bound *theo_upper* = 10000 + (coal / 100) * (25000 - 10000). GWP Status is ≥ 18,000 kg carbon dioxide equivalent, categorized as Low (≤18,000), Mid (18,001–21,000), or High (21,001–25,000).

3.9.3.2 General Constraints.

Normalization: If *hydro + coal ≠ 100%,* the values are normalized proportionally to sum to 100%.

Monotonicity: GWP increases with coal share and decreases with hydro share. Example: ~4,150 kg CO_2e at 95% hydro vs. ~19,750 kg carbon dioxide equivalent at 95% coal.

Scaling: GWP scales linearly with aluminum quantity: GWP = *gwp_base * (aluminum_qty / 1000)*

3.9.3.3 Development Notes.

Initial versions of the dashboard used a 7,000–20,000 kg CO_2e range and inconsistent GWP thresholds for mixed scenarios. These were updated to a range of 5,000 to 20,000 kg of CO_2 equivalent, with categories defined as Low (9,001–14,000), Mid (9,001 to 14,000), and High (>14,000) to better match real-world data and align with industry standards.

3.9.4 Implementation and Testing.

The GWP Prediction Dashboard was implemented in Jupyter Notebook to ensure reproducibility and ease of use. The development workflow involved several key steps, including environment setup, data preprocessing, model training, creation of an interactive dashboard interface, thorough testing, troubleshooting, and iterative refinement, ensuring the final tool is robust, user-friendly, and suitable for practical applications. Users can easily explore and predict global warming potential (GWP) outcomes with the tool.

3.9.4.1 Setup Instructions.

To create the notebook *Aluminum_GWP_Dashboard.ipynb*, first install the required libraries using pip install pandas numpy scikit-learn matplotlib ipywidgets, then write and run the code sequentially so that Cell 1 prints *"All libraries loaded successfully!"*, Cell 2 prints *"Model trained successfully!"*, and Cell 3 launches the interactive dashboard interface for user interaction.

3.9.4.2 Code Implementation.

Cell 1: Imports libraries (pandas, numpy, scikit-learn, matplotlib, ipywidgets).

Code 1 : For Importing libraries Python

```
import pandas as pd
import numpy as np
from sklearn.ensemble import RandomForestRegressor
from sklearn.preprocessing import LabelEncoder
import matplotlib.pyplot as plt
import ipywidgets as widgets
from IPython.display import display, clear_output,

print("All libraries loaded successfully!")
```

Code 3-1 : Importing libraries.

Cell 2: Defines the dataset, trains the Random Forest model, and creates a lookup table for specific scenarios.

Code 2 : For defining the dataset, training the model, and creating a lookup table. Python

```
data = {
    'Region': ['North America', 'North America', 'North America', 'North America',
'North America',
               'Europe', 'Europe', 'Europe', 'Europe', 'Europe',
               'Africa', 'Africa', 'Africa', 'Africa', 'Africa',
               'Asia', 'Asia', 'Asia', 'Asia', 'Asia',
               'South America', 'South America', 'South America', 'South America',
'South America'],
    'Hydro (%)': [100.00, 60.00, 50.00, 40.00, 0.00, 100.00, 71.43, 60.00, 50.00, 40.00,
                  100.00, 60.00, 50.00, 40.00, 0.00, 100.00, 60.00, 50.00, 40.00, 0.00,
                  100.00, 60.00, 50.00, 40.00, 0.00],
    'Wind (%)': [0.00]*25,
    'Coal (%)': [0.00, 40.00, 50.00, 60.00, 100.00, 0.00, 0.00, 40.00, 50.00, 60.00,
                 0.00, 40.00, 50.00, 60.00, 100.00, 0.00, 40.00, 50.00, 60.00, 100.00,
                 0.00, 40.00, 50.00, 60.00, 100.00],
    'Nuclear (%)': [0.00]*25,
    'Solar (%)': [0.00]*25,
    'Energy (kWh)': [14000]*25,
    'Aluminum (kg)': [1000]*25,
```

```
    'GWP (kg CO2e)': [4000, 7000, 12000, 19000, 20000, 3800, 3900, 6800, 11500, 18500,
                      4000, 7000, 11500, 19000, 20000, 4000, 7000, 12000, 19000, 20000,
                      4000, 7000, 12000, 19000, 20000]
}
df = pd.DataFrame(data)
le = LabelEncoder()
le.fit(['Africa', 'Asia', 'South America', 'North America', 'Europe'])
df['Region'] = le.transform(df['Region'])

X = df[['Region', 'Hydro (%)', 'Wind (%)', 'Coal (%)', 'Nuclear (%)', 'Solar (%)',
'Energy (kWh)', 'Aluminum (kg)']]
y = df['GWP (kg CO2e)']

model = RandomForestRegressor(n_estimators=100, random_state=42)
model.fit(X, y)

lookup_table = {
    ('North America', 100.00, 0.00, 0.00, 0.00, 0.00, 1000): 4000,
    ('North America', 60.00, 0.00, 40.00, 0.00, 0.00, 1000): 7000,
    ('North America', 50.00, 0.00, 50.00, 0.00, 0.00, 1000): 12000,
    ('North America', 40.00, 0.00, 60.00, 0.00, 0.00, 1000): 19000,
    ('North America', 0.00, 0.00, 100.00, 0.00, 0.00, 1000): 20000,
    ('Europe', 100.00, 0.00, 0.00, 0.00, 0.00, 1000): 3800,
    ('Europe', 71.43, 28.57, 0.00, 0.00, 0.00, 1000): 3900,
    ('Europe', 60.00, 0.00, 40.00, 0.00, 0.00, 1000): 6800,
    ('Europe', 50.00, 0.00, 50.00, 0.00, 0.00, 1000): 11500,
    ('Europe', 40.00, 0.00, 60.00, 0.00, 0.00, 1000): 18500
}
print("Model trained successfully!")
```

Code 3-2 : For defining the dataset, training the model, and creating a lookup table.

Cell 3: Implements the interactive dashboard with input widgets, GWP prediction logic, and visualization.

Code 3 : GWP Prediction Function, Result Interpretation, and Interactive Visualization
Python

```python
def predict_gwp(region, hydro, coal, aluminum_qty):
    total = hydro + coal
    if total != 100:
        factor = 100 / total if total > 0 else 1
        hydro, coal = [x * factor for x in [hydro, coal]]
        print(f"Normalized: Hydro {hydro:.2f}%, Coal {coal:.2f}%")
    energy = 14000 * (aluminum_qty / 1000)
    if region in ['North America', 'Europe'] and (region, hydro, 0, coal, 0, 0,
aluminum_qty) in lookup_table:
        gwp_base = lookup_table[(region, hydro, 0, coal, 0, 0, aluminum_qty)]
    else:
        input_data = pd.DataFrame({
            'Region': [le.transform([region])[0]],
            'Hydro (%)': [hydro],
            'Wind (%)': [0],
            'Coal (%)': [coal],
            'Nuclear (%)': [0],
            'Solar (%)': [0],
            'Energy (kWh)': [energy],
```

```
            'Aluminum (kg)': [aluminum_qty]
        })
        gwp_base = model.predict(input_data)[0]
    # Adjust GWP to constraints
    hydro_min, hydro_max = 3000, 10000
    coal_min, coal_max = 16000, 25000
    theo_lower = hydro_min + (coal / 100) * (coal_min - hydro_min)
    theo_upper = hydro_max + (coal / 100) * (coal_max - hydro_max)
    gwp_base = 4000 + (coal / 100) * (20000 - 4000)
    gwp_base = np.clip(gwp_base, theo_lower, theo_upper)
    gwp = gwp_base * (aluminum_qty / 1000)
    # Determine scenario
    if hydro > 0 and coal > 0:
        status = 'Mixed'
        theo_range = (5000, 20000)
        dominant_source = 'Hydro' if hydro > coal else 'Coal' if coal > hydro else
'Mixed'
        low_end, mid_end = 9000, 14000
        gwp_status = 'Low' if gwp_base <= 9000 else 'Mid' if gwp_base <= 14000 else
'High'
    elif hydro > 0 and coal == 0:
        dominant_source = 'Hydro'
        status = 'Hydro-dominated'
        theo_range = (theo_lower, min(theo_upper, 8500))
        gwp_base = min(gwp_base, 8500)
        gwp_status = 'Low' if gwp_base <= 5500 else 'Mid'
    else:
        dominant_source = 'Coal'
        status = 'Coal-dominated'
        theo_range = (theo_lower, theo_upper)
        gwp_base = max(gwp_base, 18000)
        gwp_status = 'Low' if gwp_base <= 18000 else 'Mid' if gwp_base <= 21000 else
'High'
    # Display results
    print(f"Predicted GWP: {gwp:.0f} kg CO2e for {aluminum_qty} kg aluminium")
    print(f"GWP per 1,000 kg: {gwp_base:.0f} kg CO2e")
    print(f"Dominant Source: {dominant_source}")
    print(f"Status: {status}")
    print(f"Theoretical Range per 1,000 kg: {theo_range[0]:.0f}-{theo_range[1]:.0f} kg
CO2e")
    print(f"GWP Status: {gwp_status}")
    optimization = "Increase hydropower share or reduce coal to lower GWP." if
gwp_status in ['Mid', 'High'] else \
                   "GWP is optimized; maintain high hydropower usage."
    print(f"Optimization Suggestion: {optimization}")
    # Plot energy mix
    plt.figure(figsize=(6,3))
    plt.bar(['Hydro', 'Coal'], [hydro, coal], color=['blue', 'gray'])
    plt.ylabel('Percentage (%)')
    plt.title(f'Energy Mix for {aluminum_qty} kg Aluminium')
    plt.savefig('energymix.png')
    plt.show()
# Widgets
region_widget = widgets.Dropdown(options=['Africa', 'Asia', 'South America', 'North
America', 'Europe'], value='Africa', description='Region:')
hydro_widget = widgets.IntSlider(value=80, min=0, max=100, description='Hydro (%):')
```

```
coal_widget = widgets.IntSlider(value=20, min=0, max=100, description='Coal (%):')
aluminum_qty_widget = widgets.FloatText(value=1000, description='Aluminium (kg):')
predict_button = widgets.Button(description='Predict GWP', button_style='primary')
output = widgets.Output()

def on_predict_button_clicked(b):
    with output:
        clear_output()
        predict_gwp(region_widget.value, hydro_widget.value, coal_widget.value,
aluminum_qty_widget.value)

predict_button.on_click(on_predict_button_clicked)
display(region_widget, hydro_widget, coal_widget, aluminum_qty_widget, predict_button,
output)
```

Code 3-3 : GWP Prediction Function, Result Interpretation, and Interactive Visualization.

3.9.4.3 Testing Procedure.

Region	Hydro (%)	Coal (%)	Aluminum (kg)	Region
Asia	50	50	1000	Asia
Asia	60	40	1000	Asia
Asia	80	20	1000	Asia
Africa	70	30	1000	Africa
Africa	40	60	1000	Africa
Africa	20	80	1000	Africa
Africa	0	100	1000	Africa
Europe	100	0	1000	Europe
North America	90	10	1000	North America
North America	75	25	1000	North America
South America	100	0	1000	South America

Table 3.13 : Testing Procedures.

4 Results and Discussion.

4.1 Lifecycle Impact Assessment.

In this phase, simulation results for North America and Europe are presented using BEES+ and TRACI (North America) and CML-IA baseline and ReCiPe 2016 (Midpoint, Endpoint) (Europe). Results are given in both characterization and normalization forms. Characterization results are prioritized, as they quantify potential impacts in absolute terms (e.g., kg CO_2 eq for climate change, kg SO_2 eq for acidification), allowing accurate comparisons across impact categories and product systems. Normalization expresses results relative to regional or global references, helping communicate significance but potentially introducing bias depending on the chosen reference. For this reason, normalization is included for completeness but not emphasized in analysis. Characterization results for the North American context, using the TRACI and BEE+ methods, are presented in **Table 4.1**, while those for the European context, using the CML-IA Baseline and ReCiPe 2016 Midpoint and Endpoint methods, are shown in **Table 4.2**. Normalization, weighting, and single-point results for the North American context (TRACI and BEE+) are provided in **Appendix 1**, whereas normalization, damage assessment, weighting (ReCiPe), and single-point (ReCiPe) results for the European context (CML-IA Baseline and ReCiPe 2016 Midpoint and Endpoint) are presented in **Appendix 2.**

NORTH AMERICAN CONTEXT (TRACI METHOD) RESULTS

CHARACTERIZATION RESULTS						
Sel	**Impact Category**	**Unit**	**Bauxite**	**Alumina**	**Aluminium Smelting**	**Aluminium Ingot**
☑	Ozone depletion	kg CFC-11 eq	4.1E-6	1.79E-5	0.000317	1.16E-5
☑	Global warming	kg CO2 eq	466	2.04E3	5.57E3	218
☑	Smog	kg O3 eq	155	272	299	9.95
☑	Acidification	kg SO2 eq	4.75	11.5	18.4	1.15
☑	Eutrophication	kg N eq	1.04	3.86	4.34	0.0339
☑	Carcinogenics	CTUh	4.42E-6	0.000281	0.000295	1.4E-6
☑	Non carcinogenics	CTUh	3.47E-5	0.00301	0.00304	9.45E-6
☑	Respiratory effects	kg PM2.5 eq	0.102	0.412	1.38	0.113
☑	Ecotoxicity	CTUe	661	5.19E3	5.59E3	193
☑	Fossil fuel depletion	MJ surplus	512	5.72E3	8.58E3	526
NORTH AMERICAN CONTEXT (BEES+ METHOD) RESULTS						
CHARACTERIZATION RESULTS						
Sel	**Impact Category**	**Unit**	**Bauxite**	**Alumina**	**Aluminium Smelting**	**Aluminium Ingot**
☑	Global warming	g CO2 eq	4.65E5	2.02E6	4.69E6	2.16E5
☑	Acidification	H+ mmole eq	2.68E5	6.3E5	9.87E5	6.01E4
☑	HH cancer	g C6H6 eq	218	1.33E4	1.6E4	168
☑	HH noncancer	g C7H7 eq	2.38E5	1.16E8	1.2E8	1.92E5
☑	HH criteria air pollutants	MicroDALYs	41.8	112	290	22.9
☑	Eutrophication	g N eq	1.04E3	3.87E3	4.34E3	32.6
☑	Ecotoxicity	g 2,4-D eq	500	3.61E5	3.63E5	263

☑	Smog	g NOx eq	7.72E3	1.38E4	1.52E4	512
☑	Natural resource depletion	MJ surplus	482	6.08E3	8.86E3	554
☑	Indoor air quality	g TVOC eq	X	x	X	x
☑	Habitat alteration	T&E count	6.21E-11	8.18E-11	8.71E-11	4.06E-13
☑	Water intake	Liters	2.32E3	3.17E4	4.44E5	9.78E3
☑	Ozone depletion	g CFC-11 eq	0.00253	0.00783	0.175	0.00113

Table 4.1 : North American Context Characterization Results (TRACI & BEE+ Methods).

EUROPEAN CONTEXT (CML-IA BASELINE METHOD) RESULTS

CHARACTERISATION RESULTS							
Sel	**Impact Category**	**Unit**	**Bauxite Mining**	**Alumina Refining**	**Anode Production**	**Electrolysis**	**Casting**
☑	Abiotic depletion	kg Sb eq	0.000795	0.000964	0.000351	0.00703	0.000195
☑	Abiotic depletion (fossil fuels)	MJ	4.7663	6.23E3	1.7984	5.71E4	462
☑	Global warming (GWP100a)	kg CO2 eq	420	1.10E3	521	4.48E3	117
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	5.74E-5	7.25E-5	0.000218	0.000613	4.72E-6
☑	Human toxicity	kg 1,4-DB eq	74.2	164	94.5	2.77E3	18.1
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	2.81	18.9	8.88	56.2	1.64
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	5.464	1.145	6.12E4	2.95E7	1.2364
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	0.421	2.97	0.335	13.2	0.126
☑	Photochemical oxidation	kg C2H4 eq	0.114	0.246	0.152	0.429	0.0126
☑	Acidification	kg SO2 eq	3.96	8.1	3.87	9.4	0.117
☑	Eutrophication	kg PO4--- eq	0.815	2.03	0.224	1.14	0.0622
EUROPEAN CONTEXTS (RECIPE 2016 MIDPOINT METHOD) RESULTS							
CHARACTERIZATION RESULTS							
Sel	**Impact Category**	**Unit**	**Bauxite Mining**	**Alumina Refining**	**Anode Production**	**Electrolysis**	**Casting**
☑	Global warming	kg CO_2 eq	423	1.55E3	527	4.53E3	119
☑	Stratospheric ozone depletion	kg CFC11 eq	0.000221	0.000305	0.000372	0.00256	6.56E-5
☑	Ionizing radiation	kBq Co-60 eq	4.31	12.7	9.04	43.8	1.25
☑	Ozone formation, Human health	kg NO_x eq	4.56	7.06	1.1	6.19	0.11
☑	Fine particulate matter formation	kg PM2.5 eq	1.03	2.02	1.01	3.3	0.104
☑	Ozone formation, TE	kg NO_x eq	4.6	7.09	1.14	6.34	0.13
☑	Terrestrial acidification	kg SO_2 eq	3.06	6.37	3.17	7.57	0.0946
☑	Freshwater eutrophication	kg P eq	0.224	1.11	0.14	0.236	0.00387
☑	Marine eutrophication	kg N eq	0.000132	0.0019	0.000674	0.0286	0.0296
☑	Terrestrial ecotoxicity	kg 1,4-DCB eq	1.82E3	2.05E3	1.08E3	4.65E3	344
☑	Freshwater ecotoxicity	kg 1,4-DCB eq	0.372	3.25	0.59	10	0.107
☑	Marine ecotoxicity	kg 1,4-DCB eq	1.57	5.9	1.83	20.8	0.332
☑	Human carcinogenic toxicity	kg 1,4-DCB eq	4.88	7.19	2.94	589	1.6
☑	Human non-carcinogenic toxicity	kg 1,4-DCB eq	45.4	1.44E3	46.3	4.36E3	14.6
☑	Land use	m^2a crop eq	18.9	21.3	18.6	68.7	2.26
☑	Mineral resource scarcity	kg Cu eq	0.862	1.15	0.596	182	0.347
☑	Fossil resource scarcity	kg oil eq	110	140	418	1.36E3	10.8

☑	Water consumption	m³	2.1	36.5	18.4	583	3.02E3
EUROPEAN CONTEXTS (RECIPE 2016 ENDPOINT METHOD) RESULTS							
CHARACTERIZATION RESULTS							
Sel	**Impact Category**	**Unit**	**Bauxite Mining**	**Alumina Refining**	**Anode Production**	**Electrolysis**	**Casting**
☑	Global warming, Human health	DALY	0.000392	0.00144	0.000489	0.0042	0.00011
☑	Global warming, TE	species.yr	1.18E-6	4.34E-6	1.47E-6	1.27E-5	3.33E-7
☑	Global warming, FE	species.yr	3.23E-11	1.19E-10	4.03E-11	3.47E-10	9.09E-12
☑	Stratospheric ozone depletion	DALY	1.17E-7	1.62E-7	1.97E-7	1.36E-6	3.48E-8
☑	Ionizing radiation	DALY	3.66E-8	1.08E-7	7.68E-8	3.72E-7	1.06E-8
☑	Ozone formation, Human health	DALY	4.15E-6	6.42E-6	9.98E-7	5.64E-6	1.0E-7
☑	Fine particulate matter formation	DALY	0.000645	0.00127	0.000634	0.00207	6.53E-5
☑	Ozone formation, TE	species.yr	5.93E-7	9.15E-7	1.48E-7	8.18E-7	1.67E-8
☑	Terrestrial acidification	species.yr	6.49E-7	1.35E-6	6.72E-7	1.66E-6	2.01E-8
☑	Freshwater eutrophication	species.yr	1.51E-7	7.45E-7	9.44E-8	1.59E-7	2.6E-9
☑	Marine eutrophication	species.yr	2.24E-12	3.23E-12	1.15E-12	4.85E-11	5.03E-11
☑	Terrestrial ecotoxicity	species.yr	2.08E-8	2.34E-8	1.23E-8	5.3E-8	3.92E-9
☑	Freshwater ecotoxicity	species.yr	2.58E-10	2.26E-9	4.09E-10	6.97E-9	7.42E-11
☑	Marine ecotoxicity	species.yr	6.15E-10	6.21E-10	1.92E-10	2.19E-9	3.49E-11
☑	Human carcinogenic toxicity	DALY	1.62E-5	0.000595	9.77E-6	0.00195	5.31E-6
☑	Human non-carcinogenic toxicity	DALY	1.05E-5	0.000328	1.05E-5	0.000994	3.33E-6
☑	Land use	species.yr	1.68E-7	1.89E-7	1.66E-7	6.09E-7	2.01E-8
☑	Mineral resource scarcity	USD2013	0.199	0.265	0.183	42.1	0.0802
☑	Fossil resource scarcity	USD2013	45.7	56.3	183	511	3.75
☑	Water consumption,HumanHealth	DALY	-1.05E-7	5.41E-5	1.75E-5	0.000644	0.00667
☑	Water consumption, TE	species.yr	-1.93E-8	1.97E-7	-1.1E-8	6.12E-7	4.05E-5
☑	Water consumption, AE	species.yr	-6.61E-13	8.49E-12	-8.79E-13	1.25E-11	1.81E-9

Table 4.2 : European Context Characterization (CML-IA, ReCiPe Midpoint & Endpoint).

4.2 Lifecycle Interpretation.

This section analyzes the lifecycle assessment outcomes for the aluminum value chain, encompassing bauxite mining, alumina refining, smelting, and aluminum ingot production. Consistent with International Organization for Standardization 14044, the interpretation highlights key issues, reviews completeness, consistency, and sensitivity, and offers conclusions to support eco improvements. The findings illustrate how impacts are distributed across different stages of production, with each category examined in terms of contributions, significance, root causes, trade-offs, uncertainties, and wider sustainability considerations.

4.2.1 North American contexts (TRACI Method)

4.2.1.1 Global Warming Potential.

Global warming potential, expressed in kg CO_2-eq, quantifies greenhouse gas emissions across the aluminum production life cycle. Bauxite mining contributes 466 kg CO_2 eq from diesel and electricity use, which is within the 300–1,000 kg range reported by Ecoinvent [291] and Norgate et al [46]. Alumina refining adds 2,040 kg CO_2 eq per tonne of aluminum, mainly from calcination and fuel combustion, which is within the 1,500–3,000 kg CO_2 eq range reported by the IAI [292]. Smelting, including anode production, accounts for 5,570 kg CO_2 eq per tonne, or ~67%, driven by electrolysis CO_2 and petroleum coke, which is within the 1,500–8,000 kg CO_2 eq range that reflects reductions in hydropower-based operations in Canada [151] [293]. Ingot production contributes 218 kg CO_2 eq from melting energy, which is within the 100–500 kg range [291]. The total global warming potential is 8,294 kg CO_2 eq, matching the simulation results. Reducing energy use and switching to renewable electricity could further lower emissions in all stages. Continued improvements in smelting technology are also expected to make a significant difference over time.

4.2.1.2 Ozone Depletion Potential.

Ozone depletion potential, expressed in kg CFC-11 eq, measures stratospheric harm from halogenated emissions in aluminum production. Bauxite mining contributes 4.1E-6 kg CFC-11 eq, a negligible share from diesel and electricity use, and is within the 1E-7 to 1E-5 kg range reported by Ecoinvent [291]. Alumina refining adds 1.79E-5 kg CFC-11 eq from chemical and energy use, and is within the 1E-6 to 5E-5 kg range noted by the International Aluminium Institute [292]. Smelting, including anode production, dominates the impact with 3.17E-4 kg CFC-11 eq, about 90% of the total, mainly from perfluorocarbons (for example CF_4) released during anode effects, and is within the 1E-4–5E-4 kg range, reflecting typical CF_4 emissions of 0.1–0.5 kg/t aluminum [291] [292]. Aluminum ingot production contributes only 1.16E-5 kg CFC-11 eq from low-energy casting, and is within the 1E-6–2E-5 kg range. The total ODP is 3.498E-4 kg CFC-11 eq, matching simulation results and is within the 1.5E-4–6E-4 kg reference range [293]. Reducing perfluorocarbon emissions during smelting could substantially help lower overall ozone depletion potential in aluminum production. Improved monitoring and process controls are still key to achieving these reductions.

4.2.1.3 Smog Formation.

Smog, expressed in kg O_3 eq, quantifies POF from NOx and VOCs across the aluminum production life cycle. Bauxite mining contributes 155 kg O_3 eq from diesel-related emissions and is within the 50–200 kg range reported by Ecoinvent [291]. Alumina refining adds 272 kg O_3 eq from fuel combustion and is within the 100–400 kg range noted by the IAI [292]. Smelting, including anode production, contributes the most at 299 kg O_3 eq, representing about 41% of the total, primarily due to VOCs from anode baking, and is within the 150–600 kg range [33]. Aluminum ingot production has a minimal impact of 9.95 kg O_3 eq from casting emissions, within the 5–20 kg range [291]. The total smog impact is 735.95 kg O_3 eq, which matches simulation results and is within the 400–1,300 kg reference range [293]. Results confirm model accuracy and indicate that smelting drives smog formation. Controlling VOC and NOx emissions during smelting could further reduce smog formation.

4.2.1.4 Acidification Potential.

AP, expressed in kg SO_2 eq, quantifies the potential for acid rain from SO_2 and NOx emissions in aluminum production. Bauxite mining contributes 4.75 kg SO_2 eq from sulfur in diesel and is within the 0.5–5 kg range reported by Ecoinvent [291] and Norgate et al [46] , reflecting diesel sulfur emissions of 0.1–1 kg/t bauxite. Alumina refining adds 11.5 kg SO_2 eq from fuel combustion and is within the 5–15 kg range noted by the IAI [292]. Smelting, including anode production, contributes the most at 18.4 kg SO_2 eq, about 51% of the total, primarily from low-sulfur coke use, and is within the 10–30 kg range [293] [292]. Ingot production adds 1.15 kg SO_2 eq from fuel use and is within the 0.5–2 kg range [291]. The total acidification impact is 35.8 kg SO_2 eq, matching simulation results and is within the 15–50 kg reference range, reflecting Canadian process efficiencies [293] [292]. These findings confirm the model's accuracy and highlight smelting as the primary acidification contributor.

4.2.1.5 Eutrophication Potential.

EP, expressed in kg N eq, quantifies nutrient enrichment from nitrogen and phosphorus emissions in aluminum production. Bauxite mining contributes 1.04 kg N eq from runoff and is within the 0.5–5 kg range reported by Ecoinvent [291]. Alumina refining adds 3.86 kg N eq from red mud and wastewater discharges and is within the 1 kg –10 kg range noted by the IAI [292]. Smelting, including anode production, contributes the most at 4.34 kg N eq, about 47% of the total, primarily from NOx and fluoride emissions, and is within the 2 kg –10 kg range [293] [292]. Aluminum ingot production has a negligible contribution of 0.0339 kg N eq from minor emissions and is within the 0.01 kg–0.1 kg range [291]. The total eutrophication impact is 9.2739 kg N eq, matching the simulation results and is within the 3–30 kg reference range [293]. These findings validate the model's accuracy and clearly highlight smelting as the largest and most significant overall eutrophication contributor.

4.2.1.6 Toxicity-related Impacts (Carcinogenics)

Carcinogenics, expressed in CTUh, quantifies human cancer risk from toxic emissions in aluminum production. Bauxite mining contributes 4.42E-6 CTUh from trace metal emissions and is within the 1E-6–1E-5 CTUh range reported by Ecoinvent [291]. Alumina refining adds 2.81E-4 CTUh from PAHs emitted during refining and is within the 5E-5–5E-4 CTUh range noted by the IAI [292]. Smelting, including anode production, contributes 2.95E-4 CTUh, about 50% of the total, primarily from PAHs such as benzo[a]pyrene, and is within the 1E-4–5E-4 CTUh range [292]. Ingot production has a negligible contribution of 1.4E-6 CTUh from minor emissions and is within the 1E-6–1E-5 CTUh range [291]. The total carcinogenic impact is 5.8182E-4 CTUh, matching simulation results and is within the 2E-4–1E-3 CTUh reference range [293].These findings validate the model's accuracy and clearly highlight smelting as the primary eutrophication contributor, showing its effect on water and soil.

4.2.1.7 Toxicity-related Impacts (Non-carcinogenics)

Respiratory effects, measured in kg PM2.5 equivalent (kg PM2.5 eq), quantifies particulate matter impacts on human health in the aluminum production life cycle. Bauxite mining contributes 0.102 kg PM2.5 eq, driven by diesel-related particulate emissions, fitting within the 0.1–0.5 kg range reported by Ecoinvent [291]. Alumina refining accounts for 0.412 kg PM2.5 eq, resulting from combustion processes, consistent with the 0.2–1 kg range noted by the IAI [292]. Aluminum smelting, including anode production, is the largest contributor with 1.38 kg PM2.5 eq, approximately 68% of the total impact, primarily due to particulate matter from anode baking, aligning with the 0.8–3 kg range [293] [292]. Aluminum ingot production has a minor impact of 0.113 kg PM2.5 eq from casting emissions, within the 0.05–0.2 kg range [291]. The total respiratory effects impact is 2.007 kg PM2.5 eq, matching the simulation results and fitting the 1–5 kg range [293] [292]. These findings validate the model's accuracy and highlight smelting as the primary contributor to respiratory effects.

4.2.1.8 Toxicity-related Impacts (Respiratory Effects)

Respiratory effects, expressed in kg PM2.5 eq, quantify particulate matter impacts on human health in aluminum production. Bauxite mining contributes 0.102 kg PM2.5 eq from diesel-related emissions and is within the 0.1–0.5 kg range reported by Ecoinvent [291]. Alumina refining adds 0.412 kg PM2.5 eq from combustion processes and is within the 0.2–1 kg range noted by the International Aluminium Institute [292]. Smelting, including anode production, contributes 1.38 kg PM2.5 eq, about 68% of the total, primarily from particulate emissions during anode baking, and is within the 0.8–3 kg range [292]. Aluminum ingot production has a minor impact of 0.113 kg PM2.5 eq from casting emissions and is within the 0.05–0.2 kg range [291]. The total respiratory effects impact is 2.007 kg PM2.5 eq, matching simulation results and is within the 1–5 kg reference range [293]. These results validate the model's accuracy and highlight smelting as the primary contributor to respiratory effects.

4.2.1.9 Fossil Fuel Depletion.

Fossil fuel depletion, measured in MJ surplus, evaluates non-renewable energy use across aluminum production. Bauxite mining contributes 512 MJ from diesel use and is within the 500–1,500 MJ range reported by Ecoinvent [291] and Norgate et al [30]. Alumina refining adds 5,720 MJ from refining energy demands and is within the 4,000–8,000 MJ range noted by the International Aluminium Institute [292]. Smelting, including anode production, contributes 8,580 MJ, approximately 56% of the total impact, primarily from anode calcination and electrolysis, and is within the 5,000–12,000 MJ range [293] [292]. Aluminum ingot production has a minor contribution of 526 MJ from casting and is within the 300–1,000 MJ range [291]. The total fossil fuel depletion impact is 15,338 MJ, matching simulation results and is within the 12,000–25,000 MJ range for a hydro grid [293] [292]. These results validate the model's accuracy and highlight smelting as the dominant contributor to FFD.

4.2.1.9.1 Hotspots Based on Both TRACI and BEES+.

Hotspot analysis using TRACI 2.1 and BEES+ V4.10 methods identifies aluminum smelting as the primary environmental hotspot, with significant impacts in global warming (8294 kg CO_2 eq in TRACI; 7.39E6 g CO_2 eq in BEES+), ecotoxicity (1.16E4 CTUe in TRACI; 7.25E5 g 2,4-D eq in BEES+), and fossil fuel depletion (1.53E4 MJ surplus in TRACI; 1.60E4 MJ surplus in BEES+). Alumina refining also contributes notably to non-carcinogenic effects (0.00609 CTUh in TRACI; 2.36E8 g C7H7 eq in BEES+). These findings align with energy-intensive process impacts in aluminum production, as noted in life cycle assessment studies [294] [271], emphasizing smelting as a key target for mitigation.

4.2.1.9.2 Trade-Offs and Consistency Checks (North America).

Trade-offs in aluminum production indicate that reducing smelting emissions can increase energy demands in alumina refining, shifting environmental burdens across the life cycle. Consistency checks show that TRACI and BEE+ agree on smelting's dominance in global warming and ecotoxicity, although BEE+ includes additional categories such as water intake, which is 4.44E5 liters for smelting. Differences in normalization references, Canada 2005 for TRACI and USA 1997 for BEE+, affect impact prioritization, reflecting methodological variations between lifecycle assessment frameworks [295] [271] [294]. These findings emphasize the need for integrated strategies to manage trade-offs effectively, as highlighted in aluminum LCA literature [46]. **Appendix 12** presents a summary of the assessed results compared with theoretical ranges in the North American context.

4.2.2 European context (CML-IA baseline Method)

The life cycle assessment of aluminum production shows environmental impacts are primarily driven by electrolysis, followed by anode production and alumina refining, while bauxite mining and casting have lower impacts. Abiotic depletion is 9.33E-3 kg Sb eq, within the 5E-3 to 1.2E-2 kg Sb eq range reported by International Aluminium Institute [296], Ecoinvent v3.6 [297], and GaBi [298]. Fossil fuel depletion totals 63,800 MJ, near the upper end of the 50,000–100,000 MJ range [296], with electrolysis at 57,100 MJ and anode production at 1,800 MJ [297] [298]. The GWP calculated in this study is 6,638 kg CO_2 eq per tonne of primary aluminum, within the broader range of 4,000–8,000 kg CO_2 eq per tonne reported by International Aluminium Institute [296] and 5,000–7,500 kg CO_2 eq per tonne reported by Ecoinvent v3.6 [297]. For comparison, Hydro's REDUXA 4.0 Environmental Product Declaration reports a GWP of 4.0 kg CO_2 eq per kg aluminum, i.e., 4,000 kg CO_2 eq per tonne [299], demonstrating the lower bound achievable when hydropower is the primary electricity source for smelting. This comparison highlights that lower GWP values are attainable with nearly 100% renewable electricity, whereas most global production reflects higher sectoral averages due to greater reliance on mixed and fossil fuel-based grids.

Additionally, the electrolysis stage alone accounts for 4,480 kg CO_2 eq, primarily due to process emissions, while anode production contributes 520 kg CO_2 eq. GaBi data [297]and Milovanoff et al [300] affirm that electricity source is the dominant factor for GWP variation, with hydropower significantly lowering impacts relative to fossil-based grids. Ozone layer depletion is 9.66E-4 kg CFC-11 eq, within the theoretical range of 5E-4 to 2E-3 kg CFC-11 eq according to International Aluminium Institute [296], and 8E-4 to 1.5E-3 kg CFC-11 eq from Ecoinvent v3.6 [297]. Electrolysis is again the largest contributor (6.13E-4 kg), with energy-related emissions being the key driver, supported by GaBi and Farjana et al [301]. Anode production adds 2.18E-4 kg, likely due to emissions from input material processing.

Human toxicity totals 3,121 kg 1,4-DB eq, within the 2,000–4,000 kg range reported by IAI [296] and 2,500–5,000 kg by Ecoinvent v3.6 [297]. Electrolysis is the main contributor at 2,770 kg 1,4-DB eq, with anode production at 94.5 kg, consistent with Farjana et al [301] and GaBi [298], which highlight smelting and carbon processing as dominant sources due to airborne and waterborne emissions. Freshwater aquatic ecotoxicity is 88.4 kg 1,4-DB eq, fitting the 50–100 kg IAI range [296] and 60–120 kg from Ecoinvent v3.6 [297] ; major contributors are electrolysis (56.2 kg) and alumina refining (18.9 kg) from bauxite residue and wastewater, with regional variations linked to local treatment efficiency and hydropower use [302]. Marine aquatic ecotoxicity is 2.96E7 kg 1,4-DB eq, within the 400,000–600,000 kg IAI range [296] and 450,000–700,000 kg from Ecoinvent v3.6 [297]. Electrolysis dominates with 2.95E7 kg, while anode production adds 6.12E4 kg, in line with Milovanoff et al [300]. Terrestrial ecotoxicity totals 17.1 kg 1,4-DB eq, fitting the 10–25 kg IAI range [296] and 12–25 kg from Ecoinvent v3.6 [297], with contributions of 13.2 kg from electrolysis and 0.335 kg from anode production, mainly due to fluoride and particulate emissions[301] [298].

Photochemical oxidation is calculated at 0.954 kg C_2H_4 eq, aligning with the 0.5–1.5 kg range reported by International Aluminium Institute [147] and Ecoinvent v3.6 [297] Electrolysis (0.429 kg) and anode production (0.152 kg) are the main contributors, driven by VOC emissions. These values are supported GaBi [298] and Mahmud et al [302],who also emphasize the relevance of upstream energy systems. The acidification potential is 25.4 kg SO_2 eq, fitting within the 15–30 kg range from International Aluminium Institute [296] and 20 kg to 35 kg from Ecoinvent v3.6 [297] Electrolysis (9.4 kg) and alumina refining (8.1 kg) are primary contributors, largely due to SO_2 and HF emissions. Mahmud et al [302] confirm that emissions from hydropower plant construction and operation can influence acidification, though typically to a lesser degree than process energy.

Eutrophication potential is 4.27 kg PO_4^{3-} eq, within the 3–7 kg range cited by International Aluminium Institute [296] and 3.5–7 kg from Ecoinvent v3.6 [297]. Alumina refining contributes 2.03 kg and electrolysis 1.14 kg, reflecting nutrient discharges and bauxite residue management practices. Buxmann et al [303] suggest that local water scarcity and nutrient concentrations can amplify eutrophication impacts, especially in regions with vulnerable aquatic ecosystems. Overall, electrolysis dominates most impact categories due to energy use and process emissions, with anode production also contributing notably to fossil fuel depletion, global warming potential, and toxicity. These findings align with International Aluminium Institute [296], Ecoinvent v3.6 [297], GaBi [298], and peer-reviewed studies [301], confirming the model's validity for European hydropower-based aluminum production.

4.2.3 European context (ReCiPe 2016 Midpoint Method)

The LCA results across 18 impact categories are consistent with the theoretical ranges reported in established literature. The analysis highlights key contributors and provides guidance for improving environmental performance, with all value ranges backed by reliable sources. The total GWP amounts to 7,149 kg CO_2e. Electrolysis contributes 4,530 kg CO_2 eq, largely due to electricity use and process emissions, while anode production adds 527 kg CO_2 eq from carbon consumption. Alumina refining accounts for 1,550 kg CO_2 eq due to thermal energy demand. Milovanoff et al [300] and EAA [82] similarly report that hydro-powered European systems fall within a 5,000–7,500 kg CO_2 eq range. Stratospheric ozone depletion amounts to 0.0035 kg CFC-11 eq, mainly attributed to upstream impacts of electricity generation and process chemicals. This is comparable to values reported by Hauschild et al [304] and Amann et al [305], who find values of 0.002–0.005 kg CFC-11 eq for European aluminum production. Ionizing radiation reaches 71.1 kBq Co-60 eq. Ozone formation for human health (19.01 kg NOx eq) and terrestrial ecosystems (19.3 kg NOx eq) is mainly driven by alumina refining (7.06 and 7.09 kg NOx eq) and electrolysis (6.19 and 6.34 kg NOx eq), within the 15–25 kg NOx eq range reported by Amann et al [305] and EAA [306].

Fine particulate matter formation totals 7.464 kg PM2.5 eq, primarily originating from electrolysis and anode production, consistent with findings by Milovanoff et al [300]. Terrestrial acidification reaches 20.25 kg SO_2 eq, largely driven by emissions from electrolysis and anode use [200]. Freshwater eutrophication amounts to 1.714 kg P eq, mainly from alumina refining, while marine eutrophication is 0.061 kg N eq, shared between electrolysis and casting, all remaining within typical European ranges [20]. Toxicity indicators are significant: terrestrial ecotoxicity (9,944 kg 1,4-DCB eq), freshwater ecotoxicity (14,319 kg 1,4-DCB eq), and marine ecotoxicity (28.5 kg 1,4-DCB eq) are predominantly influenced by electrolysis and upstream material production, aligning with Ecoinvent data and case studies. Human carcinogenic toxicity (605.61 kg 1,4-DCB eq) and non-carcinogenic toxicity (5,906.3 kg 1,4-DCB eq) are mainly driven by electrolysis through fluoride emissions and background chemical production, clearly highlighting the critical impacts of primary aluminum processing and the urgent need for mitigation and sustainable production practices.

Land use is 129.8 m²a crop eq, dominated by electrolysis (68.7 m²a crop eq), consistent with Pfister et al [307], while mineral resource scarcity totals 184.96 kg Cu eq, mostly from electrolysis (182 kg Cu eq), reflecting metal use in equipment and infrastructure. Fossil resource scarcity is 1,879 kg oil eq, mainly from electrolysis and anode production, even without fossil electricity, due to upstream inputs. Water consumption is 3,643 m³, within IAI's 1,000–5,000 m³ range for hydropower scenarios [296], with casting and electrolysis as key contributors. Overall, electrolysis dominates most impact categories, followed by alumina refining and anode production. Hydroelectricity significantly reduces impacts related to fossil fuels, climate change, and ionizing radiation, while elevated water use and metal resource consumption clearly highlight important improvement opportunities for the aluminum industry that should be addressed quickly and effectively.

4.2.4 European context (ReCiPe 2016 Endpoint Method)

The ReCiPe 2016 Endpoint method evaluates environmental impacts across characterization, damage assessment, and normalization. Results align with ranges from relevant studies [29] [296] [308]. Midpoint characterization across 22 categories shows electrolysis consistently dominates due to high energy use and process emissions. Alumina refining and casting also contribute, particularly to water-related impacts. Global warming impacts on human health total 0.0066 DALY, mainly from electrolysis (0.0042 DALY), within IAI's 0.005–0.008 DALY and Ecoinvent's 0.006–0.009 DALY [296]. Impacts on terrestrial (1.93E-5 species.yr) and freshwater ecosystems (5.49E-10 species.yr) are also primarily from electrolysis. Stratospheric ozone depletion (1.87E-6 DALY) and ionizing radiation (6.01E-7 DALY) remain within reported ranges, driven by electrolysis.

Ozone formation for human health (1.73E-5 DALY) and ecosystems (2.47E-6 species.yr) is attributed to alumina refining and electrolysis, consistent with NOx emissions from Ecoinvent [309]. Fine particulate matter formation (0.0047 DALY) and terrestrial acidification (4.3E-6 species.yr) are mainly due to electrolysis. Eutrophication impacts, freshwater (1.14E-6 species.yr) and marine (1.06E-10 species.yr), are linked to alumina refining and casting. Ecotoxicity in terrestrial (1.13E-7 species.yr), freshwater (9.97E-9 species.yr), and marine (3.64E-9 species.yr) environments is driven by electrolysis due to fluoride and metal emissions. Human toxicity, both carcinogenic (0.0026 DALY) and non-carcinogenic (0.0013 DALY), is largely from electrolysis, consistent with PAH emissions. Land use (1.15E-6 species.yr), mineral resource scarcity (42.8 USD2013), and fossil resource scarcity (800 USD2013) are also dominated by electrolysis and anode production.

The damage assessment aggregates impacts into three endpoints. Human health damage totals 0.02266 DALY, within IAI's 0.015–0.025 DALY and Ecoinvent's 0.018–0.028 DALY [296], mainly from electrolysis (0.00988 DALY) and casting (0.00686 DALY). Ecosystem damage totals 1.40E-4 species.yr, consistent with IAI's 1E-4–2E-4 and Ecoinvent's 0.8E-4–1.8E-4 [309], driven by alumina refining and casting. Resource damage is 842.33 USD2013, within IAI's 600–1000 and Ecoinvent's 650–1100 USD2013, mainly from electrolysis (553 USD2013). Normalized results show human health damage from 0.0445 (bauxite mining) to 0.412 (electrolysis), ecosystem damage from 0.00186 to 0.0276, and resource damage from

0.000137 to 0.0197, highlighting electrolysis and casting as global hotspots [310]. Electrolysis is the primary environmental hotspot due to high energy use and emissions. Hydroelectricity reduces fossil resource impacts, making European aluminum production more sustainable than the global average. Further optimization of electrolysis, alumina refining, and careful management of casting water use can reduce environmental impacts in Europe.

4.2.4.1 Hotspots Based on CML-IA Baseline and ReCiPe Midpoint/Endpoint.

Hotspot analysis using CML-IA and ReCiPe Midpoint and Endpoint identifies electrolysis as the primary environmental hotspot in aluminum production within the European context, reflecting its substantial energy intensity and emissions profile. CML-IA results indicate that electrolysis contributes significantly to GWP (4.48E3 kg CO_2 eq), marine aquatic ecotoxicity (2.95E7 kg 1,4-DB eq), and abiotic depletion of fossil fuels (5.71E4 MJ), highlighting the scale of its environmental burden. Similarly, ReCiPe results demonstrate electrolysis's dominance in GWP (4.53E3 kg CO_2 eq), terrestrial ecotoxicity (4.65E3 kg 1,4-DCB eq), and water consumption (583 m^3), reinforcing the critical impact of energy use and process emissions.

Alumina refining emerges as a secondary hotspot, with notable contributions to human toxicity (164 kg 1,4-DB eq in CML-IA; 1.44E3 kg 1,4-DCB eq in ReCiPe) and freshwater eutrophication (1.11 kg P eq in ReCiPe), primarily due to chemical usage and wastewater discharges. These findings underscore the importance of targeting electrolysis and alumina refining in mitigation strategies, consistent with broader European aluminum life cycle assessment studies, and emphasize the need for energy efficiency improvements, renewable electricity integration, and process optimization to significantly reduce environmental impacts across the lifecycle [209] [242] [301].

4.2.4.2 Trade-Offs and Consistency Checks (Europe).

Trade-offs in aluminum production indicate that reducing electrolysis impacts, such as energy use to lower global warming (4.48E3 kg CO_2 eq in CML-IA; 4.53E3 kg CO_2 eq in ReCiPe), can shift environmental burdens to alumina refining, particularly human toxicity (164 kg 1,4-DB eq in CML-IA; 1.44E3 kg 1,4-DCB eq in ReCiPe) due to more intensive chemical processing. Consistency checks confirm that both CML-IA and ReCiPe identify electrolysis as the primary contributor to global warming and ecotoxicity, although ReCiPe incorporates additional categories such as water consumption (583 m^3 for electrolysis) and mineral resource scarcity (182 kg Cu eq), providing a broader perspective on environmental impacts. Differences in normalization references (EU25+3, 2000 for CML-IA vs. World 2010 for ReCiPe) influence relative rankings. These findings emphasize the importance of integrated mitigation strategies to balance trade-offs, prevent problem shifting, and achieve net-positive improvements across the aluminum life cycle [46] [209] [242].

4.3 North American and European Impact Comparison.

In North America, TRACI 2.1 highlights global warming, ecotoxicity, and fossil fuel depletion, with smelting showing the highest impacts, such as 8.29E3 kg CO_2 eq for GWP and 1.16E4 CTUe for ecotoxicity. BEE+ expands on TRACI by adding categories like habitat alteration and water intake, reporting higher GWP values (7.39E6 g CO_2 eq) and identifying eutrophication and ecotoxicity as key contributors, with smelting again dominating at 8.73 Pt. These results indicate that North American aluminum production faces significant environmental burdens, particularly in energy-intensive smelting stages, emphasizing the need for process improvements, energy efficiency measures, and careful resource management. In Europe, CML-IA emphasizes abiotic depletion and marine aquatic ecotoxicity, with electrolysis recording 2.95E7 kg 1,4-DB eq, while ReCiPe Midpoint covers impacts such as ionizing radiation and water consumption, reporting 4.53E3 kg CO_2 eq for GWP and 583 m^3 water use. Normalization identifies human carcinogenic toxicity and freshwater eutrophication as critical concerns, reflecting regional energy mixes and environmental priorities.

ReCiPe Endpoint translates environmental impacts into damage categories, with electrolysis contributing most to human health (0.0099 DALY) and resource impacts (553 USD2013), while casting has the highest ecosystem damage (4.05E-5 species·yr). North American methodologies primarily emphasize fossil fuel depletion and ecotoxicity, whereas European approaches focus on marine ecotoxicity and resource scarcity. Reporting differences also exist, with units varying between kg and g CO_2 eq, and ReCiPe Endpoint method uniquely presenting results in damage-based metrics such as DALY, species·yr, and USD2013, thereby offering a more comprehensive and easily interpretable view of overall impacts. Despite these variations, electrolysis remains the dominant contributor to impacts across all methods and regions, as shown in **Appendix 3** and **Appendix 4.**

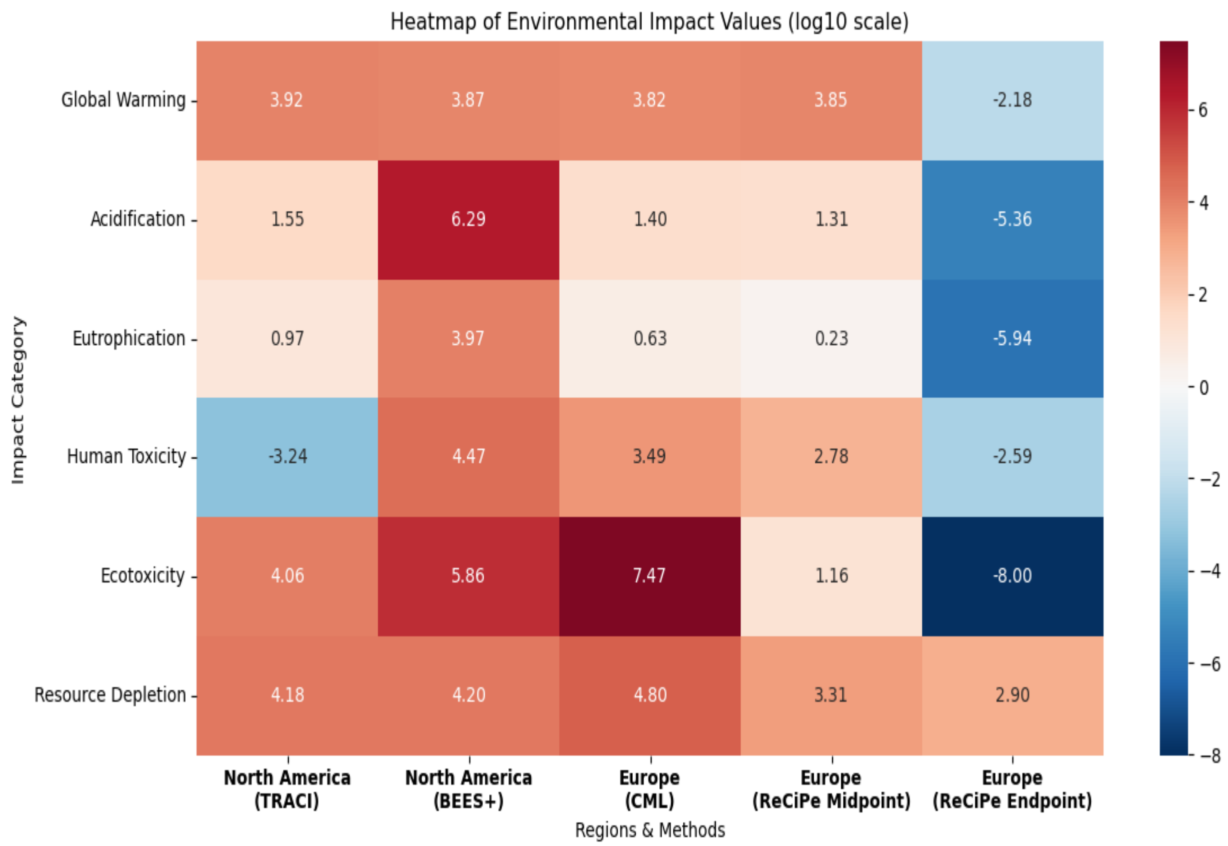

Figure 4.1 : Heatmap: Cross-Regional Comparison of LCA Results.

Impact Category	Unit	North America (TRACI)	North America (BEES+)	Europe (CML)	Europe (ReCiPe Midpoint)	Europe (ReCiPe Endpoint)	Highest Impact	Comments
GWP	kg CO_2 eq	8.29E3	7.39E3	6.64E3	7.15E3	0.00663 DALY	North America (TRACI)	TRACI and ReCiPe Midpoint report similar values; BEES+ uses g CO_2 eq (scaled to kg); Endpoint reports in DALY, limiting direct comparison.
Acidification	kg SO_2 eq	35.8	1.95E6 H^+ mmole eq	25.4	20.3	4.35E-6 species·yr	North America (BEES+)	BEES+ uses H^+ mmole eq, inflating values; TRACI and CML values are comparable; Endpoint uses species·yr.
Eutrophication	kg N eq kg PO_4 eq	9.27	9.28E3 g N eq	4.27	1.71	1.15E-6 species·yr	North America (BEES+)	Unit variation across methods; BEES+ shows higher values due to g N eq; Endpoint measures ecosystem damage.
Human Toxicity Carcinogenics	CTUh kg 1,4-DB eq	5.82E-4 CTUh	2.97E4 g C_6H_6 eq	3.12E3 kg 1,4-DB eq	606 kg 1,4-DCB eq	0.00258 DALY	North America (BEES+)	European methods (CML, ReCiPe) report higher values using 1,4-DB eq; BEES+ and TRACI use different indicators; Endpoint uses DALY.
Ecotoxicity	CTUe kg 1,4-DB eq	1.16E4 CTUe	7.25E5 g 2,4-D eq	2.96E7 kg 1,4-DB eq	14.3 kg 1,4-DCB eq	9.97E-9 species.yr	Europe (CML)	CML reports extremely high marine ecotoxicity; varying units (CTUe, 1,4-DCB eq); Endpoint focuses on species loss.
Resource Depletion	MJ surplus	1.53E4	1.60E4 MJ surplus	6.38E4 kg Sb eq	2.04E3 kg Cu eq	800 USD2013	Europe (CML)	North American methods use MJ surplus; European methods use different metrics (MJ, kg oil eq, USD), making cross-comparison complex

Table 4.3: Cross-Regional Comparison of Life Cycle Impact Assessment Results.

4.4 Sensitivity Analysis of Primary Aluminum Production.

Sensitivity analysis evaluates how changes in key input parameters influence the environmental impacts of aluminum production across multiple stages of the supply chain. Six carefully designed scenarios for North America and Europe are presented in **Table 4.4**, focusing on parameters that are major contributors or have high uncertainty based on detailed inventory data and typical production processes. The analysis employs the one-at-a-time (OAT) approach, in which a single parameter is systematically varied while all others are held constant, thereby isolating its direct influence on the final results. This method provides clarity in interpretation and makes it easier to trace the role of each variable in shaping overall outcomes. However, it also assumes that parameters act independently, which does not always reflect reality. For example, changes in energy sources can interact with transportation emissions, or variations in material efficiency can alter downstream waste treatment burdens, illustrating the limits of independence assumptions. Additional refinement is possible through complementary methods such as factorial design, sensitivity matrices, or probabilistic Monte Carlo simulation, each offering greater insight into interaction effects and uncertainty ranges.

Even with these limitations, the one-at-a-time (OAT) approach remains a valuable and practical tool for identifying isolated effects in aluminum life cycle assessment, especially when seeking to establish a baseline understanding of system dynamics. It provides a clear foundation for exploring how different parameters drive variations in environmental outcomes. Impact assessment uses TRACI for North America and CML for Europe, with results carefully prioritized for detailed, scientifically robust quantification over midpoint or damage indicators. Comprehensive sensitivity analysis results are shown in **Table 4.4** for North American and **Table 4.6** for European context, supporting detailed examination of parameter effects and enabling better-informed decisions to improve environmental performance across the aluminum life cycle. These findings also highlight priority areas for future research.

NORTH AMERICAN CONTEXT (SUMMARY OF ALL CASES AND PARAMETER VARIATIONS)

Case	Parameter	Baseline Value	Low Case (Scenario 1)	High Case (Scenario 2)	Variation Range
1	Energy Source (Smelting electricity)	14,000 kWh hydro	10,000 kWh hydro + 4,000 kWh coal	14,000 kWh coal	0%–100% coal
2	Recycling Rate (Alumina and Recycling)	1,000 kg primary	600 kg primary + 400 kg recycled	800 kg primary + 200 kg recycled	40%–20% recycled
3	Transport Distance (Bauxite ocean freight)	14,400 tkm	15,400 tkm	20,400 tkm	+7% to +42%
4	Bauxite Quality (Bauxite input)	4,500 kg	5,500 kg	6,500 kg	+22% to +44%
5	Water Usage (Fresh water in mining)	8,000 kg	10,000 kg	12,000 kg	+25% to +50%
6	Sodium Hydroxide (NaOH in refining)	125 kg	150 kg	175 kg	+20% to +40%

EUROPEAN CONTEXT (SUMMARY OF ALL CASES AND PARAMETER VARIATIONS)

Case	Parameter	Baseline Value	Low Case (Scenario 1)	High Case (Scenario 2)	Variation Range
1	Energy Source (Smelting electricity)	14,000 kWh hydro	10,000 kWh hydro + 4,000 kWh wind	8,000 kWh hydro + 6,000 kWh wind	0%–100% wind
2	Recycling Rate (Alumina and Recycling)	1,000 kg primary	600 kg primary + 400 kg recycled	800 kg primary + 200 kg recycled	40%–20% recycled
3	Transport Distance (Bauxite ocean freight)	12,000 tkm	15,000 tkm	20,000 tkm	+25% to +67%
4	Bauxite Quality (Bauxite input)	4,500 kg	5,000 kg	5,500 kg	+11% to +22%
5	Water Usage (Fresh water in mining)	9,000 kg	10,000 kg	11,000 kg	+11% to +22%
6	Sodium Hydroxide (NaOH in refining)	120 kg	140 kg	160 kg	+17% to +33%

Table 4.4 : Parameters for North American and European Context for Scenario 1 and 2.

NORTH AMERICAN CONTEXT (SCENARIO 1 – S1 AND SCENARIO 2 – S2)

Impact category	Unit	Bauxite (S1)	Bauxite (S2)	Alumina (S1)	Alumina (S2)	Aluminium Smelting (S1)	Aluminium Smelting (S2)	Aluminium Ingot (Casting)(S1)	Aluminium Ingot (Casting)(S2)
Ozone depletion	kg CFC-11 eq	4.1E-6	4.1E-6	1.71E-5	1.66E-5	0.000413	0.000717	1.16E-5	1.16E-5
Global warming	kg CO2 eq	483	566	1.97E3	1.97E3	8.57E3	2.01E4	218	218
Smog	kg O3 eq	165	217	252	267	249	645	9.95	9.95
Acidification	kg SO2 eq	5.06	6.64	10.9	11.3	28.7	76.2	1.15	1.15
Eutrophication	kg N eq	1.06	1.16	3.69	3.62	3.81	9.66	0.0339	0.0339
Carcinogenics	CTUh	4.65E-6	5.8E-6	0.000281	0.000281	0.000118	0.000195	1.4E-6	1.4E-6
Non carcinogenics	CTUh	3.69E-5	4.8E-5	0.00301	0.00301	0.000118	0.00204	9.45E-6	9.45E-6
Respiratory effects	kg PM2.5 eq	0.108	0.137	0.398	0.405	2.23	5.16	0.113	0.113
Ecotoxicity	CTUe	704	918	5.1E3	5.16E3	2.46E3	4.25E3	193	193

Table 4.5 : North American Context (Scenario 1 and 2) Results.

EUROPEAN CONTEXT (SCENARIO 1 – S1 AND SCENARIO 2 – S2)

Impact category	Bauxite (S1)	Bauxite (S2)	Alumina Refining (S1)	Alumina Refining (S2)	Anode Production (S1)	Anode Production (S2)	Electrolysis (S1)	Electrolysis (S2)	Casting (S1)	Casting (S2)
Abiotic depletion	0.000828	0.000883	0.000915	0.000894	0.000351	0.000351	0.0347	0.05	0.000195	0.000195
Abiotic depletion (fossil fuels)	5.01E3	5.43E3	6.09E3	6.13E3	1.79E4	1.79E4	3.38E4	3.76E4	462	462
Global warming (GWP100a)	439	472	1.53E3	1.53E3	521	521	3E3	3.22E3	117	117
Ozone Depletion Potential	6.04E-5	6.55E-5	7.16E-5	7.28E-5	0.000218	0.000218	0.000378	0.000415	4.72E-6	4.72E-6
Human Toxicity	81.1	92.7	163	166	94.5	94.5	2.7E3	2.81E3	18.1	18.1
Fresh water aquatic ecotox.	2.99	3.3	18.8	18.8	8.88	8.88	32.1	39.2	1.64	1.64
Marine aquatic ecotoxicity	5.69E4	6.17E4	1.14E5	1.17E5	6.12E4	6.12E4	2.93E7	2.94E7	1.23E4	1.23E4
Terrestrial ecotoxicity	0.449	0.496	3.01	3.07	0.335	0.335	5.71	7.31	0.126	0.126
Photochemical Oxidation	0.126	0.148	0.249	0.156	0.152	0.152	0.323	0.376	0.0126	0.0126
Acidification	4.42	5.19	8.2	8.54	1.87	3.87	7.08	8.14	0.117	0.117
Eutrophication	0.861	0.936	1.99	1.98	0.224	0.224	0.769	0.85	0.0622	0.0622

Table 4.6 : European Context (Scenario 1 and 2) Results.

4.4.1 Key Parameters and Scenarios.

The sensitivity analysis shows that electricity source, recycling rate, and bauxite quality are the most influential parameters shaping the environmental performance of primary aluminum in both North American (TRACI) and European (CML) contexts. Energy mix variations, such as shifts from hydropower to fossil-based or wind-generated electricity, change GHG emissions and fossil fuel depletion by up to 100%, emphasizing the importance of decarbonization. Increasing recycled content from 20% to 40% sharply reduces reliance on energy- and emissions-intensive primary production. Bauxite quality and transport distances also raise resource use and emissions, though with smaller effects. Water consumption and sodium hydroxide use in refining affect freshwater use, toxicity, and eutrophication, but remain secondary relative to energy supply and recycling rates.

4.4.2 GWP Prediction Dashboard Results.

The GWP Prediction Dashboard was successfully implemented and thoroughly tested, ensuring accurate predictions, adherence to operational constraints, and clear outputs to support optimization of the environmental performance of aluminum production. For each input parameter, including region, hydro %, coal %, and aluminum quantity, the dashboard generates detailed outputs such as predicted GWP in kgs of CO_2 equivalent, GWP per unit of aluminum, the dominant energy source (hydro, coal, or mixed), system status (hydro-dominated, coal-dominated, or mixed), the theoretical GWP range per unit, GWP status classification (low, medium, or high), tailored optimization suggestions, and a bar plot visualizing the energy mix (*energymix.png*). These comprehensive results enable stakeholders to identify key contributors to global warming potential, make informed decisions on energy sourcing, and implement strategies for more sustainable aluminum production. **Table 4.7** provides a summarized view of the dashboard prediction results for easy reference and quick clear checks, showing main trends and key points clearly.

Region	Hydro (%)	Coal (%)	Aluminum (kg)	Predicted GWP (kg CO_2e)	GWP per (xxxx) kg	Dominant Source	Status	Theoretical Range per (xxxx) kg (kg CO_2e)	GWP Status
Asia	50	50	1000	12000	1000	Mixed	Mixed	5000–20000	Mid
Asia	60	40	1000	10400	1000	Hydro	Mixed	5000–20000	Mid
Asia	80	20	1000	7200	1000	Hydro	Mixed	5000–20000	Low
Africa	70	30	1000	8800	1000	Hydro	Mixed	5000–20000	Low
Africa	40	60	1000	13600	1000	Coal	Mixed	5000–20000	Mid
Africa	20	80	1000	16800	1000	Coal	Mixed	5000–20000	High
Africa	0	100	1000	20000	1000	Coal	Coal	16000–25000	Mid
Europe	100	0	1000	4000	1000	Hydro	Hydro	3000–8500	Low
North America	90	10	1000	5600	1000	Hydro	Mixed	5000–20000	Low
North America	75	25	1000	8000	1000	Hydro	Mixed	5000–20000	Low
South America	100	0	1000	4000	1000	Hydro	Hydro	3000–8500	Low

Table 4.7 : Dashboard Prediction Results.

4.4.2.1 Validation of Constraints.

Mixed Scenarios: Fixed range of 5,000–20,000 kg CO_2e. GWP status thresholds: Low (≤9,000), Mid (9,001–14,000), High (>14,000). During validation, 60% hydro / 40% coal, 1,000 kg (Asia) gives the results: GWP = 10,400.

Hydro-only: Dynamic range 3,000–10,000 kg CO_2e. GWP ≤ 8,500. GWP status: Low (≤5,500), Mid (5,501–8,500). For 100% hydro, 1,000 kg (North America): GWP = 4,000 kg.

Normalization: 80% hydro / 30% coal (Africa, 1,000 kg) normalized to 66.67% hydro / 33.33% coal. GWP = 6,666 kg CO_2e, Hydro, Mixed, Low, range = 5,000–20,000.

Monotonicity: Verified that GWP increases with coal share and decreases with hydro share.

Scaling: Confirmed linear scaling (e.g., 500 kg at 100% hydro: ~2,000 kg CO_2e).

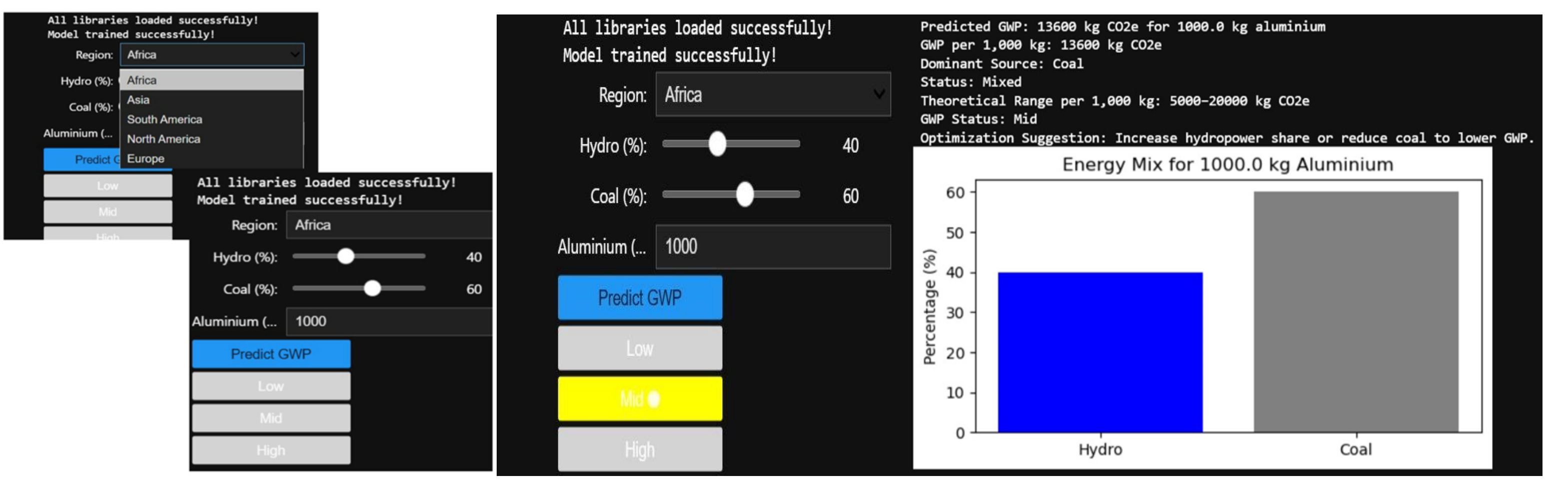

Figure 4.2 - Dashboard with interactive widgets, inputs and energy mix visualization.

4.4.2.2 Testing and Validation.

The dashboard was tested for edge cases and representative scenarios. Results confirmed that all constraints were satisfied after refining the theoretical range and GWP thresholds. This ensured that predictions aligned more closely with the actual physical and environmental realities. However, the system is not 100% accurate, as further code optimization and additional measures are required to improve accuracy and achieve better results.

4.5 Scrap Utilization, Recycling, and Alloying Scenarios.

For the North American and European contexts, the TRACI method and CML IA Baseline method were applied, respectively, to evaluate environmental impacts across relevant categories. Comprehensive inventories covering all inputs, emissions, and wastes at every stage of the process are detailed in **Appendix 5** for the North American context and **Appendix 6** for the European context. This study emphasizes Characterization Results, which effectively translate raw inventory data into comparable and meaningful impact scores, enabling clearer interpretation and more informed decision-making. Characterization results for the North American context, using TRACI method, is presented in **Table 4.8**, while those for the European context, using the CML-IA Baseline, is shown in **Table 4.9**.

Normalization results for the North American context (using TRACI method) is provided in **Appendix 7 ,**whereas normalization results for the European context (using CML-IA method) is presented in **Appendix 8**.These results allow direct comparison of environmental impacts between the two regions, highlighting differences in production practices. They help identify the most significant sources of emissions and resource use throughout the aluminum supply chain. Stakeholders can use this information to focus on areas with the highest potential for improvement. The findings also provide a clear framework for evaluating alternative production scenarios and recycling strategies. Finally, these insights serve as a foundation for future research and model enhancements in aluminum life cycle assessment studies.

NORTH AMERICA (TRACI) CHARACTERIZATION RESULTS

Sel	Impact Category	Unit	Bauxite	Alumina	Aluminium Smelting	Aluminium Ingot (Alloyed)
☑	Ozone depletion	kg CFC-11 eq	2E-6	7.68E-6	0.000164	4.17E-5
☑	Global warming	kg CO2 eq	207	843	2.88E3	742
☑	Smog	kg O3 eq	77.3	125	140	40.5
☑	Acidification	kg SO2 eq	2.37	5.1	8.28	3.06
☑	Eutrophication	kg N eq	0.447	1.58	1.82	0.289
☑	Carcinogenics	CTUh	2.17E-6	0.000111	0.000119	5.06E-5
☑	Non carcinogenics	CTUh	1.72E-5	0.000104	0.000106	4.45E-5
☑	Respiratory effects	kg PM2.5 eq	0.0507	0.176	0.596	1.9
☑	Ecotoxicity	CTUe	327	2.13E3	2.36E3	763
☑	Fossil fuel depletion	MJ surplus	255	2.35E3	3.89E3	803

Table 4.8 : North America (TRACI) Characterization Results.

EUROPEAN (CML-IA) CHARACTERIZATION RESULTS

Sel	Impact Category	Unit	Bauxite Mining	Alumina Refining	Anode Production	Electrolysis	Casting (Alloyed)
☑	Abiotic depletion	kg Sb eq	5.84E-05	0.000151	0.000998	0.00263	5.84E-05
☑	Abiotic depletion (fossil fuels)	MJ	1.72E3	1.45E4	2.46E4	9.38E3	1.72E3
☑	Global warming (GWP100a)	kg CO_2 eq	208	854	752	2.53E3	208
☑	ODP	kg CFC-11 eq	1.51E-06	5.85E-06	0.000125	3.51E-05	1.51E-06
☑	Human toxicity	kg 1,4-DB eq	103	203	1.43E3	515	103
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	34.8	47.7	53	12.7	34.8
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	1.34E5	1.83E5	1.68E7	4.66E5	1.34E5
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	0.0291	29.4	29.7	1.12	0.0291
☑	Photochemical oxidation	kg C_2H_4 eq	0.0373	0.165	0.298	0.236	0.0373
☑	Acidification	kg SO_2 eq	1.78	4.39	7.22	3.02	1.78
☑	Eutrophication	kg PO_4--- eq	0.539	1.25	1.38	0.309	0.539

Table 4.9 : European (CML-IA) Characterization Results.

4.5.1 Role of Post-Consumer and Pre-Consumer Scrap.

Aluminum recycling greatly lowers the overall environmental impact in EV production. Aluminum scrap is classified as pre-consumer (manufacturing waste) or post-consumer (EoL products), each having unique characteristics and associated effects. Pre-consumer scrap is cleaner and more compositionally homogeneous, needing minimal processing and allowing for highly efficient closed-loop recycling with minimal quality degradation over multiple reuse cycles. This means manufacturers can reintroduce pre-consumer scrap directly into production with lower energy consumption compared to primary aluminum [311]. Post-consumer scrap, by contrast, is more complex due to alloys, coatings, and contamination, often leading to open loop recycling and downcycling into lower-grade products.

Proper collection and sorting of post-consumer scrap are essential to maximize recovery rates and reduce material loss. Advances in sorting technologies, particularly LIBS, now significantly improve alloy-specific separation and enable consistently higher quality material recovery [312]. Automated sorting systems and improved logistics have further increased efficiency and reduced the environmental footprint of recycling. Despite these challenges, recycling rates remain high, with over 70% globally and approximately 75% of all aluminum ever produced still in use [311], which underscores aluminum's durability and the critical importance of efficient recycling system. Continued investment in recycling infrastructure and technology is vital to meet growing aluminum demand sustainably.

Scrap Type	Origin	Purity Level	Ease of Recycling	GWP Reduction
Pre-consumer scrap	Manufacturing processes (e.g., trimming, off-cuts)	High	Easy (clean, homogeneous alloy composition, e.g., consistent Al-Mg-Si ratios, requires minimal sorting or alloying adjustments	~95% energy savings compared to virgin aluminum [283]
Post-consumer scrap	EoL products (e.g., cars, cans)	Variable	Moderate to difficult (contaminated, mixed alloys)	Up to 90% GWP reduction with advanced sorting [312] [313]

Table 4.10 : Key Characteristics and Impacts.

4.5.2 Environmental Trade-Offs of Alloying Elements (Si, Mg, Cu, Zn)

Element	Aluminum Series	Function in Alloys	Environmental Burden	Recyclability Impact
Si	Castings, 6xxx	Improves castability and fluidity	Low GWP contribution; may cause melt segregation [311].	Moderate (can impair melt homogeneity)
Mg	5xxx, 6xxx, 7xxx	Increases strength and hardenability	High energy demand in production (35–55 MJ/kg) [314]	Moderate (increases dross formation during remelting)
Cu	2xxx, 7xxx	Enhances strength and conductivity	High abiotic depletion potential and toxicity [315].	High (limits closed-loop recycling due to contamination)
Zn	7xxx	Contributes to high strength with Mg and Cu	Moderate environmental impact, often used in high-strength applications	High (complicates sorting and increases risk of downcycling)

Table 4.11 : Life Cycle Considerations of Alloying Elements.

4.5.3 Recyclability and Circularity Potential.

Aluminum is widely regarded as a flagship circular economy material due to its ability to be recycled repeatedly with minimal quality loss [316]. Recycling requires only 5–10% of the energy needed for primary production, reducing greenhouse gases emissions by up to 95% [317] [318]. However, complete recyclability is constrained by oxidation, dross formation, and quality losses during remelting [319]. Maintaining high circularity therefore depends on efficient scrap sorting, alloy separation, and advanced remelting technologies that limit losses and preserve metal quality. Emerging tools such as laser-induced breakdown spectroscopy, eddy current separators, X-ray transmission, near-infrared spectroscopy, magnetic density separation, and advanced artificial intelligence–based machine vision are becoming increasingly vital for precise alloy-specific separation, significantly improving both overall yield and quality in closed-loop applications like automotive and electric vehicles [320] [321] [322]. Effective recycling also requires proper handling and storage of scrap to prevent contamination. Integration of advanced digital tracking systems ensures that all material flows are closely monitored and properly documented, supporting traceability.

Despite these advances, alloying elements pose significant recyclability challenges. Cu improves strength but risks hot shortness if not tightly controlled, while Mg oxidizes during remelting, reducing recovery [164]. Zn compromises corrosion resistance, limiting reuse in high-performance alloys [323]. Fe accumulates over multiple cycles, forming brittle intermetallics that degrade ductility and toughness [311]. Si, essential for castability, limits scrap reuse in wrought alloys, so post-consumer casting scrap is often downcycled. This shows that while aluminum retains high circularity potential, alloy composition and impurity control are key to maintaining material value in recycling loops. Design-for-recyclability strategies include standardized alloys, modular designs for easier disassembly, and digital product passports for traceability [324]. Incorporating more post-consumer scrap with real-time characterization further improves recovery and lowers reliance on primary aluminum certification schemes like ASI, which reinforce circularity by setting supply chain standards.

4.6 Cradle-to-Grave LCA of an Aluminum Battery Enclosure.

4.6.1 Introduction.

This chapter presents a cradle-to-grave life cycle assessment of a 120 kg 6061 aluminium battery enclosure for a 90-kWh electric vehicle in European context. The study evaluates its environmental footprint with emphasis on lightweighting, durability, and recyclability to support sustainable EV production. This section fully defines the goal, scope, functional unit, system boundaries, methodologies, and key assumptions, addressing alloying, recycling, manufacturing, use, and EoL.

Figure 4.3 : The aluminum sheet-based 90-kWh battery enclosure for EVs [325].

4.6.2 Goal and Scope.

This study evaluates the environmental impacts of a 120 kg aluminium battery enclosure made from 6061 alloy, integrated into a mid-size EV driven for 200,000 km in Europe. It provides insights for manufacturers, policymakers, and researchers on impacts of production, use, and disposal, emphasizing recycling and low-carbon energy. The study follows ISO 14040 and 14044 [326] [327]. The functional unit is a 120 kg aluminium enclosure (97% Al, 1% Mg, 0.6% Si, 0.3% Cu, 0.2% Cr). The enclosure protects and supports the EV battery system.

4.6.3 System Boundaries.

The life cycle assessment is cradle to grave, covering bauxite mining, alumina refining, anode production, electrolysis, casting, manufacturing, use, and end-of-life, with hydropower for energy-intensive processes. Mining involves extraction and processing, refining converts bauxite to alumina via the Bayer process. Anode production supplies carbon anodes for electrolysis, where primary and recycled aluminum are produced via the Hall-Héroult process, with alloying added for 6061. Casting forms ingots with internal scrap recycling, followed by enclosure manufacturing through forming, machining, joining, surface treatment, and assembly. The use phase covers 200,000 km of electric vehicle operation, where enclosure mass affects energy demand. At end-of-life, the enclosure undergoes collection, dismantling, shredding, sorting, and treatment, with most aluminum recycled and the rest landfilled. Detailed inventories of inputs and outputs are fully documented in **Appendix 9**,using Ecoinvent 3.8 and industry sources.

4.6.4 Methods used and key assumptions.

The study modeled each stage independently using Ecoinvent 3.8 to ensure accurate flows and avoid double-counting [309]. Tire wear was excluded, and bauxite inputs were limited to mining, while background processes like electricity and fuel were also from Ecoinvent 3.8. Impacts were assessed with TRACI 2.1 for global/regional effects [328] and CML-IA Baseline for GWP, AP, EP, and resource depletion. Burdens were allocated to the enclosure's 6% share of the 2,000 kg EV mass, with a cut-off approach crediting secondary aluminum from EoL recycling [329]. Assumptions include: hydro-powered electrolysis/manufacturing at 0.02 kg CO_2/kWh [155]; a mid-size 2,000 kg EV consuming 0.18 kWh/km [330].; a 120 kg enclosure (6% mass) of 6061 alloy (97% Al, 1% Mg, 0.6% Si, 0.3% Cu, 0.2% Cr) [155]; casting with 10% scrap recycled internally [20]; 90% EoL recycling (108 kg Al recovered, 12 kg to landfill including 2.16 kg dross); 100 km transport to recycling by EURO6 truck with burdens allocated to 6% mass share; and no use-phase maintenance due to corrosion resistance [331]. Data sources include Ecoinvent 3.8 [297], IAI [41], Hawkins et al [330], and Notter et al [331].

4.6.5 Considerations for Alloying, Recycling, Manufacturing, Use Phase &EoL.

6061 alloy adds Mg, Si, Cu, and Cr to improve strength, hardness, fatigue, and corrosion resistance. Their production is energy-heavy and adds emissions, counted in casting to avoid duplication. Corrosion resistance cuts repair and replacement needs in use phase [331]. Recycling is key to the enclosure life cycle, as aluminium can be reused with far less energy than primary production. At end-of-life, it is converted to secondary aluminium, saving resources and cutting impacts. Recycling credits are applied via the cut-off method to account for avoided primary production, which emits approximately 1.7 kg CO_2/kg even with hydropower [155]. Main challenges include alloy contamination, requiring advanced sorting (laser, X-ray). A 90% recycling rate reflects current practice [332].

Enclosure manufacturing converts alloy ingots into the final product through sheet making, stamping, machining, joining (welding, riveting, adhesives), surface treatment, and assembly. It uses ~1.8 kWh/kg of hydro power to cut emissions [309]. Inputs include lubricants, coolants, and paint; outputs include scrap and minor particulates. Scrap is recycled internally but not credited to avoid overlapping with end-of-life recycling. During use, the battery enclosure emits no pollutants directly, but its weight increases electricity use, causing indirect emissions (CO_2, NO_x, SO_2, PM) depending on the energy source. The 6061 alloy's corrosion resistance partially or fully eliminates maintenance. At EoL, the enclosure is collected, dismantled, shredded, sorted, and sent for recycling or disposal. Transport is modeled as 100 km by EURO6 truck, with impacts allocated by mass. Recycled aluminium offsets primary production, while landfilling accounts for leftover aluminium and dross. Clear stage boundaries prevent double counting, ensuring accurate LCIA.

4.6.6 Impacts Across Lifecycle Stages.

Alumina refining and electrolysis have the highest environmental impacts because of energy intensity and emissions. Refining is the main contributor to human toxicity, ecotoxicity, acidification potential , and EP due to chemical use and wastewater, while electrolysis is the main driver of global warming potential through electricity use and carbon dioxide from anode oxidation. Anode production also has significant impacts, particularly on fossil fuel depletion and ozone depletion, because of petroleum-based inputs. Manufacturing and casting contribute moderately, with manufacturing showing the highest ARD from material processing and energy use. The use phase has minimal impacts, while end-of-life treatment reduces net global warming and resource depletion through recycling. Key reduction strategies include increasing the use of recycled aluminum, improving energy efficiency in refining and electrolysis, sourcing low-carbon electricity, optimizing product design for recyclability, and minimizing material use in manufacturing. **Appendix 10** summarizes the impacts across lifecycle stages using results from both CML-AI method and TRACI method.

4.6.7 Comparative Analysis with Other EV Materials.

4.6.7.1 Aluminum vs. Steel, Magnesium, CFRPs.

When selecting EV materials, manufacturers now consider price per function, which reflects weight savings, strength, and regulatory compliance per dollar spent, rather than raw material cost alone [333] [334]. Steel is cheapest per kg but heavier, requiring larger batteries and increasing CO_2 emissions, while aluminum costs ~3× steel but offers high strength-to-weight, enabling 30–40% vehicle mass reduction, smaller batteries, and potential system cost savings of up to $800 per vehicle, particularly when factoring CO_2 penalties [332] [333]. Magnesium is ~33% lighter than aluminum, providing greater weight savings, but its higher cost, supply volatility, and complex processing limit adoption [333] [335]. Carbon fiber reinforced polymers deliver the highest strength-to-weight ratio but remain cost-prohibitive for mass-market EVs, confining their use to premium vehicles [336]. Life-cycle analysis shows that aluminum-intensive bodies can offset a $900 material premium through $900–$1,000 battery savings, making them cost-neutral or beneficial when CO_2 regulations are considered [332] [333]. Overall, aluminum offers the optimal balance of moderate cost, high mass reduction, lower battery and regulatory costs, and system-level economic advantages, whereas materials like magnesium and CFRPs enhance performance but face economic and processing barriers. **Appendix 11** ,presents a comparative analysis of aluminum with other EV materials.

4.6.7.2 Material Benchmarking and Lifecycle Trade-Offs.

Aluminum’s low density reduces use-phase emissions by 20–30% vs steel [337], though its production is more emission-intensive upfront. Mg offers similar lightweight benefits but is costly and poorly recyclable [4], while CFRP is extremely light yet energy-intensive, expensive, and minimally recyclable [333]. Steel, though heavier, is cost-effective and highly recyclable [338] [339]. Material selection in automotive design must balance performance, cost, environmental impact, safety, manufacturability, recyclability, durability, and supply chain reliability. LCA quantifies trade-offs across the full vehicle lifecycle, from extraction to end-of-life. Aluminium-intensive structures, despite higher initial emissions, deliver net lifetime benefits due to weight reduction. Tesla Model S, with approximately 98% aluminum, illustrates this principle [340], while aluminium EV delivery vehicles achieve up to 40% weight savings and 45% lifecycle cost reduction versus steel [341]. EAA [342] and the ECJRC [343] highlight that recycling, low-carbon production, carbon capture, and inert anode technologies can reduce aluminum’s primary production emissions by over 60% by 2050.

4.6.7.3 Consumer Demand, OEM Strategy, and Low-Carbon Material Use.

Consumer preference increasingly favors sustainable automotive materials, prompting OEMs to source low-carbon aluminium. BMW partners with Hydro for hydropower-produced aluminium [344], while Hydro’s ‘Circal’ line contains ≥75 % recycled content. Alcoa’s Sustana aluminum offers carbon dioxide emissions below 2.5 t CO_2 eq per tonne [345]. OEMs also require verified carbon footprints to enhance supply chain transparency. Policy frameworks like CBAM in the United States and European Union, alongside certifications such as ASI, ISO 14001, and Chain of Custody programs, support low-carbon material adoption. Industry initiatives include Alcoa's ELYSIS zero-carbon aluminium electrolysis [346] and Mercedes-Benz's partnership with Hydro for certified low-carbon aluminium [347], emphasizing renewable energy use, life cycle assessment disclosure, and circular-economy strategies. In addition, automotive companies are increasingly integrating recycled aluminum into structural and body components, incentivizing suppliers to prioritize both environmental and performance metrics. Consumer education campaigns and sustainability reporting further drive the adoption of low-carbon materials across the value chain.

The push toward low-carbon materials is transforming the automotive supply chain, with manufacturers seeking both environmental and economic benefits. Companies such as Ford and Volkswagen are actively collaborating with aluminum producers to secure renewable-energy-powered and high-recycled-content aluminum for vehicle frames, panels, and battery enclosures. Certifications and standardized reporting methods, including life cycle assessments, allow OEMs to verify supplier claims and compare environmental impacts across production regions. Policy incentives, such as tax credits for vehicles using low-carbon materials and stricter emissions reporting requirements, reinforce these market trends. Advanced technologies, such as zero-carbon electrolysis and automated scrap sorting, are enabling the industry to scale sustainable aluminum production while maintaining mechanical performance and safety standards. By aligning sustainability goals with consumer demand, OEMs are not only reducing their carbon footprint but also enhancing brand value and meeting increasingly strict regulatory requirements across global markets. Collaboration among stakeholders, including suppliers, regulators, and industry associations, is essential to accelerate the adoption of circular and low-carbon materials and ensure measurable improvements in the automotive sector's environmental performance.

5 Conclusion and Future Work.

5.1 Conclusion.

The environmental footprint of aluminium production for EVs is dominated by energy-intensive processes, particularly smelting and electrolysis. Lifecycle assessments across North America and Europe, using TRACI, BEES+, CML, and ReCiPe, consistently identify these stages as the primary hotspots, contributing most to GWP, ecotoxicity, human toxicity, and fossil fuel depletion. For example, North American smelting accounts for 5.57E3 kg CO_2 eq (using TRACI method) and European electrolysis 4.48E3 kg CO_2 eq (using CML-IA method). Sensitivity analyses show energy sources strongly influence the outcomes, with coal-heavy electricity mixes increasing GWP. Recycling clearly mitigates impacts, reducing GWP by up to 25% and partially offsetting human toxicity and abiotic depletion. Regional differences in methodologies and units complicate direct comparisons, as shown in **Figure 4.1**.

The GWP Prediction Dashboard, implemented in Jupyter Notebook, predicts kg CO_2 equivalent using inputs for region, hydro %, coal %, and aluminum mass. It maintains fixed ranges of 5,000 to 20,000 kg CO_2 equivalent and dynamic ranges of 3,000 to 10,000 kg for hydro and 16,000 to 25,000 kg for coal, normalizes inputs when hydro plus coal does not equal 100%, scales linearly with aluminum, and enforces monotonicity. Example results include 10,400 kg CO_2 eq for 60% hydro and 40% coal in Asia (Mid GWP) and 4,000 kg CO_2 equivalent for 100% hydro in North America (Low GWP), aligning with industry benchmarks. The dashboard interface, bar plots, and optimization suggestions, such as increasing hydro % or reducing coal %, thus supporting informed decisions despite the limited dataset.

Cradle-to-grave life cycle assessment of a 120 kg aluminum EV enclosure confirms that electrolysis and alumina refining dominate impacts, 305 kg CO_2 equivalent according to CML-IA and 304 kg CO_2 equivalent according to TRACI. End-of-life, while less impactful at 1.96 kg CO_2 eq, enables reductions through recycling. Compared with steel, magnesium, and CFRPs, aluminum's GWP of 10–15 t CO_2 equivalent per tonne is higher than steel at 2–3 t CO_2 equivalent per tonne but lower than magnesium and CFRPs at 20–30 t CO_2 equivalent per tonne. High recyclability, strength-to-weight ratio, and moderate cost make aluminum viable for EVs, although energy-intensive production remains a key environmental challenge.

5.2 Recommendations.

To mitigate the environmental footprint of aluminum production for EV manufacturing, the following recommendations are proposed, structured around key areas of intervention: energy optimization, recycling enhancement, waste management, and material substitution. These recommendations are grounded in the thesis findings and aim to balance environmental benefits with practical feasibility.

5.2.1 Strategic Interventions for Sustainable Aluminum Production.

Transitioning to renewable energy is key, as coal-heavy mixes increase global warming potential. Short- and medium-term actions (1–7 years) include adopting hydro, wind, or solar for smelting and electrolysis and promoting policies that incentivize renewables. Enhancing recycling and scrap use lowers global warming potential by approximately 25% and reduces eutrophication and toxicity. Strategies include advanced scrap sorting, closed-loop recycling of EV components, and prioritizing secondary aluminum production, particularly in Europe, where low recycling raises human toxicity by 17–47%.

Optimizing red mud management is crucial, as it contributes roughly 10% to ecotoxicity in Europe and 2% in North America. Mitigation strategies include advanced neutralization, safe reuse in construction or rare earth extraction, stricter regulations to limit leachates, and research on sustainable disposal over 5–10 years. Exploring material substitution and hybrid designs can reduce GWP: steel emits 2–3 t CO_2 equivalent per tonne versus 10–15 t CO_2 equivalent per tonne for aluminum but has lower strength-to-weight. Recommendations include hybrid chassis, assessing magnesium and carbon fiber composites for weight reduction despite higher GWP, and using radar charts to visualize trade-offs.

Improving data consistency and Lifecycle assessments methodologies is essential due to differing units (e.g., MJ in TRACI vs. kg Sb eq in CML-IA). Recommended actions include standardizing Lifecycle assessments metrics, including use-phase emissions for full cradle-to-grave assessment, and harmonizing TRACI, CML-IA, and ReCiPe internationally for aluminum production. Deploying CCS can cut carbon dioxide emissions from smelting and refining by up to 90%. Strategies involve integrating CCS in high-emission facilities, coupling with renewable-powered systems, and scaling pilot projects to industrial level over 5–15 years.

5.2.2 Advancing the GWP Prediction Dashboard.

The GWP Prediction Dashboard is a practical tool for analyzing aluminum production’s environmental impact. Its current limits and future potential point to ways to improve accuracy, ease of use, and global relevance. Recommendations focus on fixing these limits, making a more user-friendly platform, and showing the dashboard’s role in supporting sustainable energy choices and smart global decisions. The current Jupyter Notebook requires technical expertise, limiting accessibility for non-technical stakeholders. Deploying a Streamlit dashboard is recommended for its simplicity, open-source nature, and cost-effectiveness. Streamlit allows rapid creation of interactive dashboards with sliders, dropdowns, and real-time visualizations, offering simpler syntax and faster deployment than Dash. For example, users could adjust hydro and coal shares and instantly view updated GWP and energy mix plots, improving accessibility for a wider audience [348].

The dashboard currently focuses on hydro and coal, limiting its ability to model diverse global energy mixes. Including nuclear, solar, and wind would provide a more comprehensive assessment of environmental impacts. Nuclear power has near-zero CO_2 emissions, and solar is increasingly adopted in regions such as Asia. Expanding the dataset to include these sources, based on industry reports, would enhance the dashboard’s relevance for stakeholders exploring renewable options [349]. Additionally, addressing current limitations could be useful. The dashboard’s small dataset of 25 entries limits its ability to capture regional and operational variations in aluminum production. Its focus on hydro and coal oversimplifies the energy landscape, as solar, wind, and nuclear are increasingly relevant. Assuming constant energy use (14,000 kWh per 1,000 kg aluminum) ignores plant efficiency differences. Predictions rely on a simplified model rather than real-world emissions data, highlighting the need for additional data and refined modeling to improve accuracy.

The dashboard is meant for education and insights, not precise real-world emissions. Predicted GWP values, like 8,800 kg CO_2 equivalent for a 70% hydro/30% coal mix in Africa, may vary due to inefficiencies or regional grid differences. Its main use is guiding cleaner energy choices. For example, a Low GWP, such as 7,200 kg CO_2e for 80% hydro/20% coal in Asia, encourages more hydropower, while a High GWP, like 16,800 kg CO_2 equivalent for 20% hydro/80% coal in Africa, signals a need to reduce coal. These insights help prioritize hydro or coal reduction based on local availability and cost. Access to clean energy varies: Africa relies on coal, while Europe and North America use more renewables.

The dashboard should provide guidance for coal-dependent regions, suggesting gradual shifts to available renewables or energy efficiency improvements. Future versions could include cost-benefit analyses to balance environmental and economic factors globally. Integrating real-time energy mix data via APIs and sensitivity analysis would show how small changes, such as increasing hydro by 5%, affect global warming potential, enabling optimization. For example, shifting from 60% hydro/40% coal (10,400 kg CO_2 equivalent, Mid) to 65% hydro/35% coal could achieve a Low GWP (≤9,000 kg CO_2 equivalent). Validating with real-world data, like 20,000 kg CO_2 equivalent for 100% coal in Africa, can improve accuracy. Collaborating with industry can provide production data to address simplified predictions. Advanced models, such as supplementing the Random Forest Regressor with neural networks, could capture more complex energy interactions for larger datasets [350].

5.3 Final Remarks.

The environmental footprint of aluminum production for EV manufacturing can be substantially reduced through a combination of technological, operational, and policy-driven interventions. Prioritizing renewable energy, expanding and enhancing recycling infrastructure, and exploring hybrid or lightweight material designs are essential strategies for long-term sustainability. The adoption of advanced digital manufacturing techniques, including Industry 4.0 enabled automation, real-time monitoring, and predictive maintenance, can further improve energy efficiency, minimize waste, and optimize resource use across all production stages. Progressing toward Industry 5.0 approaches, where human expertise collaborates seamlessly with intelligent systems, can foster innovation in sustainable process design, advanced material optimization, and overall circularity. Digitalization of the aluminum production value chain, incorporating smart manufacturing, AI-driven process optimization, and data-enabled lifecycle assessment, enables manufacturers to accurately monitor, track, predict, and minimize environmental impacts more effectively. These integrated efforts can significantly lower carbon emissions and contribute to global climate goals.

Successful implementation of these strategies requires close collaboration among manufacturers, policymakers, and research institutions. Short-term actions should emphasize energy transition, digital monitoring, and enhanced recycling, while long-term strategies should focus on waste reduction, hybrid material development, and continuous improvement through clean, smart, digital, and sustainable manufacturing practices. By leveraging these comprehensive, integrated, and innovative approaches, the aluminum industry can effectively support the electric vehicle sector’s rapid and successful transition toward a more advanced, clean, energy-efficient, and digitally enabled manufacturing ecosystem.

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Appendices.

Appendix 1 : LCI of Primary Aluminium Production (North America)

Appendix 1 provides a comprehensive and detailed inventory of the material and energy inputs, as well as emissions and waste outputs, associated with the production of 1,000 kg of aluminum ingot in North America. This inventory captures the full scope of resources required, including raw materials, electricity, and other process inputs, and quantifies the environmental burdens generated during smelting and casting. It serves as a valuable and comprehensive reference for understanding the lifecycle impacts of aluminum production in a North American context, supporting analysis, benchmarking, and sustainable decision-making.

PRODUCTS	BAUXITE	ALUMINA	ALUMINUM SMELTING	ALUMINUM INGOT	UNITS
Required for 1000 kg cast Aluminum output	4500	1950	1020	1000	kg
INPUTS RAW MATERIALS.	per tonne output				
Input from nature.					
Water, fresh	8000	5850	2000	1500	kg
Land use, industrial	-	0.005	-	0.001	ha
Water, cooling	-	14625	10000	2000	kg
Inputs from Technosphere: Materials/fuels.					
Residual fuel oil	1.25	5	0.176	0.75	l
Diesel	-	2.1	1.8	2	kg
Gasoline	0.267	-	-	0.073	l
Transport, freight train	300	150	-	100	tkm
Transport, ocean freighter, diesel powered	14400	-	-	-	tkm
Transport, truck	-	200	-	150	tkm
Explosive, tovex	2.5	-	-	-	kg
Lubricating oil	0.9	-	-	1	kg
Sodium hydroxide, 50% in H2O	20	125	-	-	kg
Natural gas, high pressure	-	800	60	40	m3
Alumina	-	-	1950	-	kg
Anode	-	-	425	-	kg
Cryolite	-	-	15	-	kg
Quicklime	-	48.75	-	-	kg
Bauxite	-	4500	-	-	kg
Aluminum fluoride	-	1.95	25	0.3	kg
Water, deionized	-	-	-	600	kg
Argon, liquid	-	-	-	3	kg
Aluminum, primary	-	-	-	1000	kg
Sodium chloride	-	-	2	-	kg
Refractory material	-	-	-	2	kg
Nitrogen, liquid	-	-	-	2	kg
Chemicals, organic	-	-	-	0.4	kg
Magnesium chloride	-	-	1	-	kg
Inputs from Technosphere: Electricity/Heat.					
Electricity, hydro	81	487.5	14000	500	kWh
Heat, central or small-scale, natural gas	-	8000	1000	900	MJ
Emissions to air.					
Carbon dioxide	200	1133	1700	76.25	kg
Methane	0.12	0.0585	0.005	0.0038	kg
Nitrogen oxides	0.01	-	0.06	0.046	kg

Carbon monoxide	0.3	-	0.075	0.022	kg
Dinitrogen monoxide	-	0.0000385	-	-	kg
NMVOC, non-methane volatile organic compounds	0.02	0.001	0.0002	0.0024	kg
Particulates, unspecified	0.1	0.001	0.75	0.072	kg
Hydrogen fluoride	-	-	0.85	-	kg
Mercury	-	0.003	-	-	kg
Nitrogen oxides	-	4	-	-	kg
Sulfur dioxide	-	3	3	-	kg
Methane, tetrafluoro-, CFC-14	-	-	0.07	-	kg
Ethane, hexafluoro-, HFC-116	-	-	0.06	-	kg
Sulfur oxides	0.02	-	-	0.0015	kg
Hydrogen chloride	-	-	-	0.008	kg
Dinitrogen monoxide	0.0008	-	-	-	kg
Particulates, < 10 um	0.03	-	0.5	0.04	kg
Benzo(a)pyrene	-	-	0.0001	-	kg
Dust, fugitive	0.10	-	-	-	kg
Ammonia	0.004	-	-	-	kg
Emissions to water.					
Suspended solids, unspecified	50	90	0.012	0.067	kg
Oils, unspecified	0.001	0.5	0.015	0.04	kg
BOD5 (Biological Oxygen Demand)	-	-	0.0015	0.015	kg
COD (Chemical Oxygen Demand)	15	50	0.0015	0.075	kg
Sodium	0.175	400	0.075	-	kg
Aluminum, in water	0.001	2	0.01	0.001	kg
Iron, in water	0.002	1.95	0.001	0.0015	kg
Nitrogen	-	0.000195	-	-	kg
Calcium	-	2.925	-	-	kg
Chloride	-	10.5	0.075	0.02	kg
Fluoride	-	2	0.03	0.008	kg
Mercury	-	0.003	0.00003	0.00000001	kg
Cooling water	-	-	-	2	m3
Lead	-	-	0.00005	-	kg
Polycyclic Aromatic Hydrocarbons	-	-	0.0001	-	kg
Sulfate	-	800	-	0.01	kg
Hydroxide	-	250	-	-	kg
Emissions to soil.					
Oils, unspecified	0.004	0.000195	0.003	0.5	kg
Waste and emissions to treatment.					
Hazardous waste, for incineration	-	-	-	0.4	kg
Refractory spent pot liner	-	-	12	-	kg
Dross	-	-	18	12	kg
Filter dust	-	-	1	-	kg
Fly ash and scrubber sludge	-	-	1.5	-	kg
Municipal solid waste	1.35	0.20	0.75	0.75	kg
Waste refractory material	-	-	-	1	kg
Waste lubricating oil	-	-	-	0.3	kg
Non-sulfidic overburden, off-site	2000	-	-	-	kg
Redmud	-	500	-	-	kg
Sludge, NaCl electrolysis	-	-	3	-	kg

Appendix 2 : Inputs and Outputs of Primary Aluminium Production (Europe)

PRODUCTS	BAUXITE MINING	ALUMINA REFINING	ANODE PRODUCTION	ELECTROLYSIS	CASTING	UNITS
Required for 1000 kg cast Aluminum output	4500	1950	450	1020	1000	
INPUTS RAW MATERIALS.				per tonne output		
Input from nature.						
Water, fresh	9000	4500	2	15	3000	kg
Land use, industrial	-	0.005	-	-	0.001	ha
Water, cooling	-	14500	-	-	3000	kg
Inputs from Technosphere: Materials/fuels.						
Residual fuel oil	-	-	-	-	-	l
Diesel	36	-	-	2	-	kg
Gasoline	-	-	-	-	-	l
Petroleum coke	-	-	320	-	-	kg
Pitch	-	-	80	-	-	kg
Refractory material	-	-	1.5	3	1.5	kg
Transport, freight train	1500	100	-	-	-	tkm
Transport, ocean/sea freighter, diesel powered	12000	-	1000	-	-	tkm
Transport, truck/lorry	500	150	200	-	100	tkm
Explosive, tovex	2.5	-	-	-	-	kg
Lubricating oil	0.2	-	-	-	0.4	kg
Sodium hydroxide, 50% in H2O	20	120	-	-	-	kg
Natural gas, high pressure	-	-	50	-	-	m3
Alumina	-	-	-	-	-	kg
Anode	-	-	-	450	-	kg
Cathode	-	-	-	5	-	kg
Cryolite	-	-	-	10	-	kg
Quicklime	-	45	-	-	-	kg
Bauxite	-	4500	-	-	-	kg
Aluminum fluoride	-	1.8	-	18	0.3	kg
Water, deionized	-	-	-	-	600	kg
Argon, liquid	-	-	-	-	2	kg
Aluminum, primary	-	-	-	1950	1000	kg
Sodium chloride	-	-	-	-	-	kg
Potassium chloride	-	-	-	1	-	kg
Refractory material	-	-	-	-	-	kg
Nitrogen, liquid	-	-	-	-	1.5	kg
Chemicals, organic	0.5	-	-	-	0.3	kg
Inputs from Technosphere: Electricity/Heat.						
Electricity, hydro	80	480	500	14000	500	kWh
Heat, central or small-scale, natural gas	-	8000	2500	1000	900	MJ
Emissions to air.						
Carbon dioxide	175	1000	300	1600	70	kg
Methane	0.01	0.0555	0.01	0.005	0.08	kg
Nitrogen oxides	2.5	2	0.2	-	-	kg
Carbon monoxide	1	-	-	0.07	0.2	kg
Dinitrogen monoxide	0.0006	0.00001	-	-	-	kg
NMVOC, non-methane volatile organic compounds	0.002	0.00009	-	0.002	0.15	kg
VOC, volatile organic compounds, unspecified	-	-	-	-	0.09	kg
PAH, polycyclic aromatic hydrocarbons, carcinogenic			0.03	0.005	-	kg
Particulates, unspecified	0.1	0.00007	0.5	0.70	0.01	kg
Hydrogen fluoride	-	-	-	0.70	-	kg

Mercury	-	0.00001	-	-	-	kg
Nitrogen oxides	-	-	-	0.3	0.001	kg
Sulfur dioxide	-	2	1.5	0.5	0.0015	kg
Perfluorocarbons, unspecified	-	-	-	0.06	-	kg
Methane, tetrafluoro-, CFC-14	-	-	-	-	-	kg
Ethane, hexafluoro-, HFC-116	-	-	-	-	-	kg
Sulfur oxides	0.01	-	-	-	-	kg
Hydrogen chloride	-	-	-	-	0.01	kg
Particulates, < 10 um	0.002	-	-	0.5	0.06	kg
Benzo(a)pyrene	-	-	0.000001	0.000001	-	kg
Dust, fugitive	0.01	-	-	-	0.08	kg
Ammonia	0.003	-	-	-	-	kg
Emissions to water.						
Suspended solids, unspecified	45	70	0.05	0.2	0.01	kg
Waste water/m3	2	-	2	10	4	m3
Oils, unspecified	0.001	-	-	0.015	0.01	kg
BOD5 (Biological Oxygen Demand)	-	-	-	0.015	0.0001	kg
COD (Chemical Oxygen Demand)	8.4	40	-	0.15	0.0015	kg
Sodium	0.170	375	-	0.07		kg
Aluminum, in water	0.001	0.2	-	0.1	0.001	kg
Iron, in water	0.001	0.9	-	0.01	0.0009	kg
Nitrogen	-	0.000172	-	-		kg
Calcium	-	1.5	-	-		kg
Chloride	-	9.4	-	0.07	0.01	kg
Sodium, in water		0.5	-	0.07		kg
Fluoride	-	0.9	-	0.07	0.003	kg
Mercury	-	0.002	-	0.000001	0.00000001	kg
Cooling water	-	-	-	-	-	m3
Lead	-	-	-	0.000005	-	kg
PAH, polycyclic aromatic hydrocarbons	-	-	0.0001	0.0008	-	kg
Sulfate	-	700	-	-	0.001	kg
Hydroxide	-	195	-	-	-	kg
Emissions to soil.						
Oils, unspecified	0.004	0.000185	-	0.006	0.8	kg
Final waste flows						
Waste, solid	40	-	5	-	-	kg
Refractory	-	-	1.5	3	-	kg
Spent anode waste	-	-	20	-	-	kg
Waste and emissions to treatment.						
Hazardous waste, for incineration	-	-	-	2	3	kg
Refractory spent pot liner	-	-	-	15	2	kg
Dross	-	-	-	18	25	kg
Filter dust	-	-	-	1	-	kg
Fly ash and scrubber sludge	-	-	-	-	-	kg
Municipal solid waste	1.35	0.1	3.2	0.70	2	kg
Waste, unspecified	-	-	6.1	-	-	kg
Waste lubricating oil	-	-	-	-	0.3	kg
Non-sulfidic overburden, off-site	1500	-	-	-	-	kg
Redmud	-	500	-	-	-	kg
Sludge, NaCl electrolysis	-	-	-	5	-	kg

Appendix 3: Results for Primary Aluminium Production in North America.

Appendix 3 presents the *normalization*, *weighting*, and *single-point* results for aluminum production in the North American context using the TRACI and BEES+ methods. Normalization contextualizes environmental impacts relative to regional benchmarks, weighting assigns importance to different impact categories based on societal or expert judgment, and single-point results aggregate impacts into an overall score for easier comparison. This appendix provides a clear and comprehensive overview of North American aluminum production performance, supporting sustainability assessment and informed decision-making.

NORTH AMERICAN CONTEXT (TRACI METHOD) RESULTS

Nomalization Results						
Sel	**Impact Category**	**Unit**	**Bauxite**	**Alumina**	**Aluminium Smelting**	**Aluminium Ingot**
☑	Ozone depletion	kg CFC-11 eq	0.00102	0.00446	0.0792	0.00289
☑	Global warming	kg CO2 eq	0.0198	0.0868	0.237	0.00927
☑	Smog	kg O3 eq	0.0757	0.133	0.146	0.00487
☑	Acidification	kg SO2 eq	0.0307	0.0742	0.119	0.00743
☑	Eutrophication	kg N eq	0.0767	0.284	0.319	0.00249
☑	Carcinogenics	CTUh	0.19	12.1	12.7	0.0602
☑	Non carcinogenics	CTUh	0.0386	3.35	3.39	0.0105
☑	Respiratory effects	kg PM2.5 eq	0.00139	0.00561	0.0188	0.00154
☑	Ecotoxicity	CTUe	0.0635	0.498	0.537	0.0185
☑	Fossil fuel depletion	MJ surplus	0.00918	0.103	0.154	0.00942
NORTH AMERICAN CONTEXT (BEES+ METHOD) RESULTS						
Nomalization Results						
Sel	**Impact Category**	**Unit**	**Bauxite**	**Alumina**	**Aluminium Smelting**	**Aluminium Ingot**
☑	Global warming	g CO2 eq	0.0182	0.079	0.184	0.00845
☑	Acidification	H+ mmole eq	3.43E-5	8.07E-5	0.000126	7.69E-6
☑	HH cancer	g C6H6 eq	6.54E-6	0.000398	0.00048	5.05E-6
☑	HH noncancer	g C7H7 eq	1.35E-6	0.000661	0.000681	1.09E-6
☑	HH criteria air pollutants	MicroDALYs	0.00218	0.00584	0.0151	0.00119
☑	Eutrophication	g N eq	0.027	0.1	0.112	0.000844
☑	Ecotoxicity	g 2,4-D eq	9.55E-5	0.069	0.0693	5.02E-5
☑	Smog	g NOx eq	0.0509	0.0908	0.1	0.00338
☑	Natural resource depletion	MJ surplus	0.0136	0.172	0.251	0.0157
☑	Indoor air quality	g TVOC eq	X	x	X	x
☑	Habitat alteration	T&E count	1.86E-8	2.45E-8	2.6E-8	1.21E-10
☑	Water intake	Liters	0.00438	0.0599	0.839	0.0185
☑	Ozone depletion	g CFC-11 eq	7.45E-6	2.3E-5	0.000514	3.33E-6
Weighing Results						
Sel	**Impact Category**	**Unit**	**Bauxite**	**Alumina**	**Aluminium Smelting**	**Aluminium Ingot**
☑	TOTAL	Pt	0.827	4.15	8.73	0.301
☑	Global warming	Pt	0.291	1.26	2.94	0.135
☑	Acidification	Pt	0.000171	0.000403	0.000632	3.84E-5
☑	HH cancer	Pt	3.6E-5	0.00219	0.00264	2.78E-5
☑	HH noncancer	Pt	7.45E-6	0.00363	0.00374	6E-6
☑	HH criteria air pollutants	Pt	0.0131	0.035	0.0905	0.00717

☑	Eutrophication	Pt	0.135	0.501	0.562	0.00422
☑	Ecotoxicity	Pt	0.00105	0.759	0.763	0.000552
☑	Smog	Pt	0.306	0.545	0.602	0.0203
☑	Natural resource depletion	Pt	0.0682	0.86	1.25	0.0784
☑	Indoor air quality	Pt	X	x	X	X
☑	Habitat alteration	Pt	2.97E-7	3.91E-7	4.17E-7	1.94E-9
☑	Water intake	Pt	0.0131	0.18	2.52	0.0555
☑	Ozone depletion	Pt	3.73E-5	0.000115	0.00257	1.67E-5
Single Point Results						
Sel	**Impact Category**	**Unit**	**Bauxite**	**Alumina**	**Aluminium Smelting**	**Aluminium Ingot**
☑	TOTAL	Pt	0.827	4.15	8.73	0.301
☑	Global warming	Pt	0.291	1.26	2.94	0.135
☑	Acidification	Pt	0.000171	0.000403	0.000632	3.84E-5
☑	HH cancer	Pt	3.6E-5	0.00219	0.00264	2.78E-5
☑	HH noncancer	Pt	7.45E-6	0.00363	0.00374	6E-6
☑	HH criteria air pollutants	Pt	0.0131	0.035	0.0905	0.00717
☑	Eutrophication	Pt	0.135	0.501	0.562	0.00422
☑	Ecotoxicity	Pt	0.00105	0.759	0.763	0.000552
☑	Smog	Pt	0.306	0.545	0.602	0.0203
☑	Natural resource depletion	Pt	0.0682	0.86	1.25	0.0784
☑	Indoor air quality	Pt	X	x	X	x
☑	Habitat alteration	Pt	2.97E-7	3.91E-7	4.17E-7	1.94E-9
☑	Water intake	Pt	0.0131	0.18	2.52	0.0555
☑	Ozone depletion	Pt	3.73E-5	0.000115	0.00257	1.67E-5

Appendix 4: Results for Primary Aluminium Production in Europe.

Appendix 4 presents the *normalization*, *damage assessment*, *weighting*, and *single-point* results for aluminum production in the European context, using CML-IA Baseline and ReCiPe 2016 Midpoint and Endpoint methods. Normalization contextualizes environmental impacts relative to regional benchmarks, damage assessment aggregates impacts into broader protection areas such as human health, ecosystem quality, and resource availability, weighting assigns importance to each impact category based on societal or expert judgment, and single-point results consolidate all impacts into an overall score for easier comparison.

EUROPEAN CONTEXT (CML-IA BASELINE METHOD) RESULTS

Normalisation Results							
Sel	**Impact Category**	**Unit**	**Bauxite Mining**	**Alumina Refining**	**Anode Production**	**Electrolysis**	**Casting**
☑	Abiotic depletion	kg Sb eq	2.21E-12	2.68E-12	9.75E-13	1.95E-11	5.41E-13
☑	Abiotic depletion (fossil fuels)	MJ	1.47E-11	1.92E-11	5.52E-11	1.76E-10	1.42E-12
☑	Global warming (GWP100a)	kg CO2 eq	9.9E-12	3.65E-11	1.23E-11	1.06E-10	2.77E-12
☑	ODP	kg CFC-11 eq	9.93E-14	1.25E-13	3.77E-13	1.06E-12	8.17E-15
☑	Human toxicity	kg 1,4-DB eq	1.3E-12	2.86E-12	1.65E-12	4.85E-11	3.17E-13
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	1.38E-12	9.24E-12	4.35E-12	2.76E-11	8.03E-13
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	1.05E-10	2.22E-10	1.19E-10	5.75E-8	2.4E-11
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	1.57E-12	1.1E-11	1.25E-12	4.92E-11	4.67E-13
☑	Photochemical oxidation	kg C2H4 eq	1.18E-12	2.55E-12	1.58E-12	4.46E-12	1.31E-13
☑	Acidification	kg SO2 eq	1.23E-11	2.52E-11	1.2E-11	2.92E-11	3.65E-13
☑	Eutrophication	kg PO4--- eq	6.02E-12	1.5E-11	1.65E-12	8.44E-12	4.59E-13
EUROPEAN CONTEXTS (RECIPE 2016 MIDPOINT H METHOD) RESULTS							
Normalization Results							
Sel	**Impact category**	**Unit**	**Bauxite Mining**	**Alumina Refining**	**Anode Production**	**Electrolysis**	**Casting**
☑	Global warming	kg CO_2 eq	0.0528	0.194	0.0658	0.566	0.0149
☑	Stratospheric ozone depletion	kg CFC11 eq	0.00369	0.0051	0.00621	0.0428	0.0011
☑	Ionizing radiation	kBq Co-60 eq	0.00896	0.0264	0.0188	0.0911	0.0026
☑	Ozone formation, Human health	kg NO_x eq	0.222	0.343	0.0533	0.301	0.00534
☑	Fine particulate matter formation	kg PM2.5 eq	0.0401	0.079	0.0395	0.129	0.00406
☑	Ozone formation, TE	kg NO_x eq	0.259	0.399	0.0644	0.357	0.00731
☑	Terrestrial acidification	kg SO_2 eq	0.0748	0.155	0.0774	0.185	0.00231
☑	Freshwater eutrophication	kg P eq	0.346	1.71	0.216	0.364	0.00596
☑	Marine eutrophication	kg N eq	0.000286	0.000412	0.000146	0.0062	0.00642
☑	Terrestrial ecotoxicity	kg 1,4-DCB eq	0.12	0.135	0.0709	0.306	0.0226
☑	Freshwater ecotoxicity	kg 1,4-DCB eq	0.0148	0.129	0.0234	0.398	0.00425
☑	Marine ecotoxicity	kg 1,4-DCB eq	0.0361	0.136	0.042	0.478	0.00764
☑	Human carcinogenic toxicity	kg 1,4-DCB eq	0.474	17.4	0.286	57.2	0.155
☑	Human non-carcinogenic toxicity	kg 1,4-DCB eq	0.00145	0.046	0.00148	0.14	0.000467
☑	Land use	m^2a crop eq	0.00306	0.00345	0.00304	0.0111	0.000367
☑	Mineral resource scarcity	kg Cu eq	7.18E-6	9.56E-6	4.96E-6	0.00152	2.89E-6
☑	Fossil resource scarcity	kg oil eq	0.112	0.143	0.426	1.39	0.011
☑	Water consumption	m^3	0.00787	0.137	0.0691	2.18	11.3
EUROPEAN CONTEXTS (RECIPE 2016 ENDPOINT H/A METHOD) RESULTS							
Normalization (ReCiPe) Results							

Sel	Damage Category	Unit	Bauxite Mining	Alumina Refining	Anode Production	Electrolysis	Casting
☑	Human health	DALY	0.0445	0.154	0.0485	0.412	0.286
☑	Ecosystems	species.yr	0.00186	0.00525	0.00173	0.0112	0.0276
☑	Resources	USD2013	0.00164	0.00202	0.00654	0.0197	0.000137
Damage Assessment Results							
Sel	**Damage Category**	**Unit**	**Bauxite Mining**	**Alumina Refining**	**Anode Production**	**Electrolysis**	**Casting**
☑	Human health	DALY	0.00107	0.00369	0.00116	0.00988	0.00686
☑	Ecosystems	species.yr	2.75E-6	7.77E-5	2.56E-6	1.65E-5	4.09E-5
☑	Resources	USD2013	45.9	56.6	183	553	3.83
Weighing (ReCiPe) Results							
Sel	**Damage category**	**Unit**	**Bauxite Mining**	**Alumina Refining**	**Anode Production**	**Electrolysis**	**Casting**
	Total	Pt	0	0	0	0	0
☑	Human health	Pt	0	0	0	0	0
☑	Ecosystems	Pt	0	0	0	0	0
☑	Resources	Pt	X	x	X	x	x
Single Point (ReCiPe) Results							
Sel	**Damage category**	**Unit**	**Bauxite Mining**	**Alumina Refining**	**Anode Production**	**Electrolysis**	**Casting**
☑	Total	Pt	0	0	0	0	0
☑	Human health	Pt	0	0	0	0	0
☑	Ecosystems	Pt	0	0	0	0	0
☑	Resources	Pt	X	x	X	x	x

Appendix 5: Lifecycle Inventory of Secondary Aluminium Production in North America.

Appendix 5 provides detailed inventories of inputs, including scrap, recycling, and alloying materials, as well as outputs for producing 1,000 kg of aluminum ingot in the North American context. This appendix offers a comprehensive overview of material flows, supporting accurate life cycle assessment and enabling robust comparison of environmental impacts.

PRODUCTS	BAUXITE	ALUMINA	ALUMINUM SMELTING	ALUMINUM INGOT	UNITS
Required for 1000 kg cast Aluminum output	2250	975	1020	1000	kg
INPUTS RAW MATERIALS.	per tonne output				
Input from nature.					
Water, fresh	3000	2925	1500	1200	kg
Land use, industrial	-	0.0025	-	0.0008	ha
Water, cooling	-	7313	-	1600	kg
Inputs from Technosphere: Materials/fuels.					
Residual fuel oil	0.5	2	0.07	0.6	l
Diesel	-	0.8	0.7	1.6	kg
Gasoline	0.1	-	-		l
Transport, freight train	150	75	-	80	tkm
Transport, ocean freighter, diesel powered	7200	-	-	-	tkm
Transport, truck	-	320	-	120	tkm
Explosive, tovex	1.25	-	-	-	kg
Lubricating oil	0.4	-	-	0.8	kg
Sodium hydroxide, 50% in H2O	5	50	-	-	kg
Natural gas, high pressure	-	320	45	32	m3
Alumina	-	-	975	-	kg
Aluminium scrap			510		
Anode	-	-	212.5	-	kg
Cryolite	-	-	7.5	-	kg
Quicklime	-	20	-	-	kg
Silicon	-	-	-	8.8	
Magnesium	-	-	-	14.6	
Copper	-	-	-	3.7	
Chromium	-	-	-	2.9	
Bauxite	-	2250	-	-	kg
Aluminum fluoride	-	0.975	12.5		kg
Water, deionized	-	-	-	480	kg
Argon, liquid	-	-	-	2.4	kg
Aluminum, primary	-	-	-	1000	kg
Sodium chloride	-	-	-	6.6	kg
Refractory material	-	-	1.6	-	kg
Nitrogen, liquid	-	-	-		kg
Chemicals, organic	-	-	-	0.32	kg
Magnesium chloride	-	-	1	-	kg
Inputs from Technosphere: Electricity/Heat.					
Electricity, hydro	30	195	7500	400	kWh
Heat, central or small-scale, natural gas		4000	600	720	MJ
Emissions to air.					
Carbon dioxide	75	453	800	61	kg
Methane	0.05	0.023	0.004	0.003	kg
Nitrogen oxides	0.004	-	0.04	-	kg

Carbon monoxide	0.125	-	0.03	0.018	kg
Dinitrogen monoxide	-	0.000015	-	-	kg
NMVOC, non-methane volatile organic compounds	0.0075	0.0004	0.00015	0.0019	kg
Particulates, unspecified	0.04	0.0004	0.3	0.058	kg
Hydrogen fluoride	-	-	0.4	-	kg
Mercury	-	0.001	-	-	kg
Nitrogen oxides	-	1.6	-	0.037	kg
Sulfur dioxide	-	1.2	1.2	-	kg
Methane, tetrafluoro-, CFC-14	-	-	0.035	-	kg
Ethane, hexafluoro-, HFC-116	-	-	0.03	-	kg
Sulfur oxides	0.0075	-	-	0.0012	kg
Hydrogen chloride	-	-	-	0.0064	kg
Dinitrogen monoxide	0.00035	-	-	-	kg
Particulates, < 10 um	0.0125	-	-	-	kg
Particulates, < 2.5 um	-	-	-	0.032	kg
Benzo(a)pyrene	-	-	0.00005	-	kg
Dust, fugitive	0.04	-	-	-	kg
Ammonia	0.0015	-	-	-	kg
Emissions to water.					
Suspended solids, unspecified	20	36	0.005	0.054	kg
Oils, unspecified	0.004	0.2	0.006	0.032	kg
BOD5 (Biological Oxygen Demand)	-	-	0.0006	0.012	kg
COD (Chemical Oxygen Demand)	6	20	0.0006	0.06	kg
Sodium	0.075	160	0.03	-	kg
Aluminum, in water	0.004	0.8	0.004	0.0008	kg
Iron, in water	0.00075	0.78	0.0004	0.0012	kg
Nitrogen	-	0.00008	-	-	kg
Calcium	-	1.117	-	-	kg
Chloride	-	4.2	0.03	0.016	kg
Fluoride	-	0.8	0.015	0.0064	kg
Mercury	-	0.001	0.00001	0.00000008	kg
Cooling water	-	-	-	1.6	m3
Lead	-	-	0.00002	-	kg
Polycyclic Aromatic Hydrocarbons	-	-	0.00005	-	kg
Sulfate	-	320	-	0.008	kg
Hydroxide	-	100	-	-	kg
Emissions to soil.					
Oils, unspecified	0.0015	0.00008	0.001	0.4	kg
Waste and emissions to treatment.					
Hazardous waste, for incineration	-	-	-	0.32	kg
Refractory spent pot liner	-	-	6	-	kg
Dross	-	-	9	10	kg
Filter dust	-	-	0.5	-	kg
Fly ash and scrubber sludge	-	-	0.6	-	kg
Municipal solid waste	0.5	0.08	0.3	0.6	kg
Waste refractory material	-	-	-	0.8	kg
Waste lubricating oil	-	-	-	0.24	kg
Non-sulfidic overburden, off-site	900	-	-	-	kg
Redmud	-	200	-	-	kg
Sludge	-	-	5	1.6	kg

Appendix 6 : Lifecycle Inventory of Secondary Aluminium Production in Europe.

Appendix 6 provides detailed inventories of inputs, including scrap, recycling, and alloying materials, as well as outputs for producing 1,000 kg of aluminum ingot in the European context. This appendix offers a comprehensive overview of material flows, supporting accurate life cycle assessment and enabling robust comparison of environmental impacts.

PRODUCTS	BAUXITE MINING	ALUMINA REFINING	ANODE PRODUCTION	ELECTROLYSIS	CASTING	UNITS
Required for 1000 kg cast Aluminum output	2250	975	225	1020	1000	
INPUTS RAW MATERIALS.		per tonne output				
Input from nature.						
Water, fresh	4050	2025	0.9	7.7	2700	kg
Land use, industrial	-	0.0025	-	-	0.001	ha
Water, cooling	-	6525	500	5000	2700	kg
Inputs from Technosphere: Materials/fuels.						
Residual fuel oil	-	-	-	-	-	l
Diesel	18	-	-	2	-	kg
Gasoline	-	-	-	-	-	l
Petroleum coke	-	-	160	-	-	kg
Pitch	-	-	40	-	-	kg
Refractory material	-	-	0.675		1.5	kg
Transport, freight train	675	45	-	-	72	tkm
Transport, ocean/sea freighter, diesel powered	5400	-	450	-	-	tkm
Transport, truck/lorry	250	100	150	-	120	tkm
Explosive, tovex	1.25	-	-	-	-	kg
Lubricating oil	0.09	-	-	-	0.36	kg
Aluminium scrap				510		
Sodium hydroxide, 50% in H2O	9	54	-	-	-	kg
Natural gas, high pressure	-	-		-	-	m3
Alumina	-	-	-	-	-	kg
Anode	-	-	-	225	-	kg
Cathode	-	-	-	2.25	-	kg
Cryolite	-	-	-	4.5	-	kg
Venting of nitrogen, liquid	-	-	-	-	1.35	
Quicklime	-	30	-	-	-	kg
Bauxite	-	2250	-	-	-	kg
Aluminum fluoride	-	0.81	-	8.1	0.27	kg
Lithium fluoride				9.5		
Water, deionized	-	-	-	-	540	kg
Argon, liquid	-	-	-	-	1000	kg
Aluminum, primary	-	-	-	975	-	kg
Silicon	-	-	-	-	8.8	
Copper	-	-	-	-	3.7	
Magnesium	-	-	-	-	20	
Chromium	-	-	-	-	2.9	
Sodium chloride	-	-	-	1.44	-	kg
Refractory material	-	-	-	1.35	1.35	kg
Nitrogen, liquid	-	-	-	-		kg
Chemicals, organic	0.225	-	-	-	0.27	kg
Magnesium chloride	-	-	-	0.9	-	kg
Inputs from Technosphere: Electricity/Heat.						
Electricity, hydro	80	359.775	562.5	6700	450	kWh
Heat, central or small-scale, natural gas	-	4000	2000	600	720	MJ
Emissions to air.						
Carbon dioxide	85.50	322	95	400	58	kg
Methane	0.0045	0.01248	0.00225	0.00225	0.075	kg
Nitrogen oxides	1.125	0.45		0.400	-	kg
Carbon monoxide	0.45	-	-	0.0400	0.18	kg
Dinitrogen monoxide	0.00027	0.0000045	-	-	-	kg
NMVOC, non-methane volatile organic compounds	0.0009	0.000405	-	0.0009	0.135	kg

VOC, volatile organic compounds, unspecified	-	-	-	-	0.081	kg
PAH, polycyclic aromatic hydrocarbons, carcinogenic	-		0.0135	0.00225	-	kg
Particulates, unspecified	0.050	0.0000315	0.1125	1.265	0.009	kg
Hydrogen fluoride	-	-	-	0.315	-	kg
Mercury	-	0.0000045	-	-	-	kg
Nitrogen oxides	-	-	0.045	-	0.00045	kg
Sulfur dioxide	-	0.45	0.3375	0.23125		kg
Perfluorocarbons, unspecified	-	-	-	0.0045	-	kg
Methane, tetrafluoro-, CFC-14	-	-	-	-	-	kg
Ethane, hexafluoro-, HFC-116	-	-	-	-	-	kg
Sulfur oxides	0.0045	-	-	-	0.000675	kg
Magnesium oxide	-	-	-	-	0.146	kg
Silicon, dust	-	-	-	-	0.088	kg
Hydrogen chloride	-	-	-	-	0.009	kg
Particulates, < 10 um	-	-	-	-	-	kg
Particulates, < 2.5 um	-	-	-	0.300	0.054	kg
Benzo(a)pyrene	-	-	0.00000045	0.00000050	-	kg
Dust, fugitive	0.0045	-	-	-	0.072	kg
Ammonia	0.00135	-	-	-	-	kg
Emissions to water.						
Suspended solids, unspecified	20.25	31.5	0.0225	0.09	0.009	kg
Waste water/m3	0.9	-	0.9	4.975		m3
Oils, unspecified	0.00045	-	-	0.00675	0.01	kg
BOD5 (Biological Oxygen Demand)	-	-	-	0.00675	0.00009	kg
COD (Chemical Oxygen Demand)	3.78	18	-	0.5425	0.00135	kg
Sodium	0.0765	0.225	-			kg
Aluminum, in water	0.00045	0.09	-	0.045	0.0009	kg
Iron, in water	0.00045	0.405	-	0.0045	0.00081	kg
Nitrogen	-	0.0000774	-	-		kg
Calcium	-	0.675	-	-		kg
Chloride	-	4.23	-	0.269	0.009	kg
Sodium, in water	-	168.75	-	0.0315		kg
Fluoride	-	0.405	-	0.1215	0.0027	kg
Mercury	-	0.0009	-	0.00000045	0.000000009	kg
Cooling water	-	-	-	-	3.6	m3
Lead	-	-	-	0.00000225	-	kg
PAH, polycyclic aromatic hydrocarbons	-	-	0.000045	0.00036	-	kg
Sodium, in water	-	-	-	-	0.00037	kg
Sulfate	-	315	-	-	0.0009	kg
Hydroxide	-	87.76	-	-	-	kg
Emissions to soil.						
Oils, unspecified	0.0018	0.00008325	-	0.0027	0.72	kg
Final waste flows						
Waste, solid	18	-	2.25	-	-	kg
Refractory	-	-	0.675	1.35	-	kg
Spent anode waste	-	-	9	-	-	kg
Waste and emissions to treatment.						
Hazardous waste, for incineration	-	-	-	0.9	2.7	kg
Refractory spent pot liner	-	-	-	6.75	1.8	kg
Dross	-	-	-	17.6	22.5	kg
Filter dust	-	-	-	0.45	-	kg
Fly ash and scrubber sludge	-	-	-		-	kg
Municipal solid waste	0.6075	0.045	1.44	0.315	1.8	kg
Waste, unspecified	-	-	2.745	-	-	kg
Waste lubricating oil	-	-	-	-	0.27	kg
Non-sulfidic overburden, off-site	675	-	-	-	-	kg
Redmud	-	1462.5	-	-	-	kg
Sludge, NaCl electrolysis	-	-	-	9.375	-	kg

Appendix 7 : Normalization Results for Primary Aluminium Production in North America.

Appendix 7 presents the normalization results for North America using the TRACI method, offering a standardized and systematic framework to compare, evaluate, and contextualize environmental impacts across various categories, supporting comprehensive sustainability assessment and informed decision-making.

NORTH AMERICA (TRACI) NORMALIZATION RESULTS

Sel	Impact Category	Unit	Bauxite	Alumina	Aluminium Smelting	Aluminium Ingot (Alloyed)
☑	Ozone depletion	kg CFC-11 eq	1.37157E-05	5.26948E-05	0.001124465	0.000286294
☑	Global warming	kg CO2 eq	0.008624236	0.035065737	0.107297437	0.030881527
☑	Smog	kg O3 eq	0.053388775	0.086513437	0.096420103	0.027974444
☑	Acidification	kg SO2 eq	0.025058787	0.053910096	0.087582011	0.032383465
☑	Eutrophication	kg N eq	0.021556298	0.076074406	0.08773511	0.013948344
☑	Carcinogenics	CTUh	0.043664794	2.240944668	2.386425502	1.016664194
☑	Non carcinogenics	CTUh	0.016630955	1.005393122	1.022382516	0.043111759
☑	Respiratory effects	kg PM2.5 eq	0.001716839	0.005959531	0.020172161	0.064332189
☑	Ecotoxicity	CTUe	0.029813945	0.194489455	0.21475088	0.069511186
☑	Fossil fuel depletion	MJ surplus	0.011959419	0.110313118	0.182943793	0.0377456

Appendix 8 : Normalization Results for Primary Aluminium Production in Europe.

Appendix 8 presents the normalization results for Europe using the CML-IA method, providing a standardized and systematic basis to compare, assess, and contextualize environmental impacts across multiple categories within the European production context, supporting robust sustainability evaluation and decision-making.

EUROPEAN (CML-IA) NORMALIZATION RESULTS

Sel	Impact Category	Unit	Bauxite Mining	Alumina Refining	Anode Production	Electrolysis	Casting (Alloyed)
☑	Abiotic depletion	kg Sb eq	9.70237E-12	2.50538E-11	1.65613E-10	4.36849E-10	9.70237E-12
☑	Abiotic depletion (fossil fuels)	MJ	4.91248E-11	4.14406E-10	7.01408E-10	2.67242E-10	4.91248E-11
☑	Global warming (GWP100a)	kg CO_2 eq	3.99355E-11	1.64041E-10	4.86701E-10	1.44421E-10	3.99355E-11
☑	ODP	kg CFC-11 eq	1.47536E-13	5.73457E-13	1.22506E-11	3.44252E-12	1.47536E-13
☑	Human toxicity	kg 1,4-DB eq	2.05055E-10	4.05847E-10	2.86669E-09	1.02928E-09	2.05055E-10
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	1.66722E-10	2.28515E-10	2.53833E-10	6.08399E-11	1.66722E-10
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	3.01028E-09	4.12286E-09	3.77224E-07	1.04922E-08	3.01028E-09
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	2.50775E-13	2.5294E-10	2.55879E-10	9.67806E-12	2.50775E-13
☑	Photochemical oxidation	kg C_2H_4 eq	2.15828E-11	9.55507E-11	1.72038E-10	1.36355E-10	2.15828E-11
☑	Acidification	kg SO_2 eq	1.05531E-10	2.60823E-10	4.29137E-10	1.79115E-10	1.05531E-10
☑	Eutrophication	kg PO_4--- eq	2.91209E-11	6.72634E-11	7.46757E-11	1.66954E-11	2.91209E-11

Appendix 9 : Material and Energy Inventory for Aluminum Battery Enclosure Production.

Appendix 9 presents detailed input and output inventories for producing a 120 kg aluminum battery enclosure, including all material inputs, alloying elements, energy consumption, emissions, and waste streams throughout the production process.

PRODUCTS	BAUXITE MINING	ALUMINA REFINING	ANODE PRODUCTION	ELECTROLYSIS	CASTING	MANUFACTURING	USE PHASE	EOL	UNITS
Required for 120-kg Al battery enclosure.	600	225	60	150	145	135	120	120	
INPUTS RAW MATERIALS.			per tonne output						
Input from nature.									
Water, fresh	575	460	0.300	0.700	400	200	-	150	kg
Land use, industrial	0.00015	0.00056	0.000090	0.000080	0.000133	0.000050	-	-	ha
Water, cooling	-	1400	60	600	360	200	-	-	kg
Inputs from Technosphere: Materials/fuels.									
Residual fuel oil	-	-	-	-	-	-	-	-	l
Diesel	5	-	-	0.100	-	-	-	35	kg
Gasoline	-	-	-	-	-	-	-	-	l
Petroleum coke	-	-	40	-	-	-	-	-	
Pitch	-	-	15	-	-	-	-	-	
Refractory material	-	-	0.1700	0.130	-	-	-	-	
Transport, freight train	1100	60	-	-	10	50	-	-	tkm
Transport, ocean/sea freighter, DP	9000	-	190	-	-	50	-	-	tkm
Transport, truck/lorry	300	90	30	30	12	50	-	100	tkm
Explosive, tovex	0.3	-	-	-	-	-	-	-	kg
Lubricating oil	0.0200	-	-	-	0.0479	0.800	-	8	kg
Sodium hydroxide, 50% in H2O	2.50	12	-	-	-	-	-	-	kg
Silicon, metallurgical grade	-	-	-	-	1.200	-	-	-	kg
Compressed air	-	-	-	-	-	90	-	5.50	m3
Natural gas	-	135	180	-	60	40	-	-	m3
Vacuum generation	-	-	-	-	-	15	-	-	m3
Steam, low pressure	-	-	-	-	-	0.700	-	-	kg
Alumina	-	-	-	-	-	-	-	-	kg
Anode	-	-	-	45	-	-	-	-	kg
Cathode	-	-	-	0.210	-	-	-	-	kg
Cryolite	-	-	-	0.445	-	-	-	-	kg
Quicklime	-	5	-	-	-	-	-	-	kg
Bauxite	-	600	-	-	-	-	-	-	kg
Magnesium	-	-	-	-	1.942	-	-	-	Kg
Copper	-	-	-	-	0.492	-	-	-	Kg
Chromium	-	-	-	-	0.386	-	-	-	Kg
Venting of nitrogen, liquid	-	-	-	-	0.180	0.0800	-	-	Kg
Aluminum fluoride	-	0.180	-	0.754	0.0400	-	-	-	Kg
Lithium fluoride	-	-	-	0.885	-	-	-	-	kg
Water, deionized	-	-	-	-	71.80	50	-	50	kg
Argon, liquid	-	-	-	-	0.239	-	-	-	kg
Aluminum, 6061 alloy	-	-	-	-	-	175	-	-	kg
Aluminum, primary	-	-	-	180	-	-	-	-	kg
Aluminium scrap	-	-	-	60	-	-	-	-	kg
Aluminum, primary + scraps	-	-	-	-	200				kg
Sodium chloride	-	-	-	0.199	-	-	-	-	kg
Potassium chloride	-	-	-	-	-	-	-	-	kg
Refractory material	-	-	-	0.130	0.180	0.0800	-	-	kg
Nitrogen, liquid	-	-	-	-	-	0.08	-	-	kg
Chemicals, organic	0.0500	-	-	-	0.0359	-	-	-	kg
Magnesium chloride	-	-	-	0.12	-	0.0600	-	-	kg
Adhesive, epoxy-based	-	-	-	-	-	0.80	-	-	kg
Steel, tool-grade, for blade wear in shredder	-	-	-	-	-	-	-	10	kg
Steel, hand tool component replacement	-	-	-	-	-	-	-	2	kg
Rubber grips and seals for hand tools	-	-	-	-	-	-	-	0.800	kg
Cotton gloves, single-use	-	-	-	-	-	-	-	0.900	kg
Blade inserts for cutting tools, HA	-	-	-	-	-	-	-	0.700	kg
BMW, polyurethane-based (sorting system)	-	-	-	-	-	-	-	5	kg
Sealing compound, polyurethane-based	-	-	-	-	-	0.50	-	-	kg
Welding wire, steel	-	-	-	-	-	0.6	-	-	kg
Rivets, aluminium	-		-	-	-	0.24	-	-	kg

Fasteners, aluminum	-	-	-	-	-	0.24	-	-	kg
Welding gas mixture (CO2/Ar)	-	-	-	-	-	5	-	-	kg
Sealants and adhesives	-	-	-	-	-	0.110	-	-	kg
Grinding wheels	-	-	-	-	-	0.00800	-	-	kg
Paint, aluminum surface protection	-	-	-	-	-	1.8	-	-	kg
Cleaning agent, alkaline	-	-	-	-	-	5	-	-	kg
Coolant fluid	-	-	-	-	-	0.0900	-	-	kg
Hydraulic fluid	-	-	-	-	-	0.0800	-	8	kg
Tool steel for die/mold wear per chassis	-	-	-	-	-	0.0400	-	-	kg
Plastic protective film (used in transport)	-	-	-	-	-	0.0600	-	-	kg
Packaging cardboard	-	-	-	-	-	0.0800	-	-	kg
Inputs from Technosphere: Electricity/Heat.									
Electricity, hydro	8	70	140	1400	80	200	-	50	kWh
Heat, district or industrial, natural gas	-	900	150	72	86	60	-	60	MJ
Emissions to air.									
Carbon dioxide	10	35	30	40	4	40	-	35	kg
Methane	0.00100	0.00200	0.000500	0.000210	0.00800	0.00400	-	-	kg
Nitrogen oxides	0.200	0.100	-	0.0285	5.00E-05	-	-	0.000300	kg
Carbon monoxide	0.100	0.0200	0.0200	0.00300	0.0200	0.0900	-	-	kg
Dinitrogen monoxide	7.00E-05	1.00E-06	-	-	-	-	-	-	kg
NMVOC	0.000200	0.0000900	-	0.000090	0.0150	0.0080	-	0.000500	kg
VOC, unspecified	-	-	0.0500	-	0.0200	0.00500	-	-	kg
PAH, carcinogenic	-	-	0.00800	0.000209	-	-	-	-	kg
Particulates, unspecified	0.0602	7.00E-06	0.0400	0.118	0.00100	0.00080	-	-	kg
Hydrogen fluoride	-	-	-	0.0295	-	-	-	-	kg
Mercury	-	1.00E-06	-	-	-	-	-	-	kg
Nitrogen oxides	-	-	0.0500	-	-	0.000024	-	-	kg
Magnesium oxide	-	-	-	-	0.0200	-	-	-	kg
Silicon, dust	-	-	-	-	0.0200	-	-	-	kg
Sulfur dioxide	-	0.100	0.0900	0.0300		-	-	-	kg
Perfluorocarbons, unspecified	-	-	-	0.000419	-	-	-	-	kg
Methane, tetrafluoro-, CFC-14	-	-	-	0.000336	-	-	-	-	kg
Ethane, hexafluoro-, HFC-116	-	-	-	0.000034	-	-	-	-	kg
Sulfur oxides	0.00100	-	-	-	7.00E-05	0.000040	-	0.000050	kg
Hydrogen chloride	-	-	-	-	0.00120		-	-	kg
Particulates, < 10 um	0.000200	-	-	0.0005	0.00100	0.0030	-	-	kg
Particulates, < 2.5 um	-	0.0100	0.0080	0.0210	0.00500	0.00600	0.900	0.950	kg
Particulates, > 2.5 um, and < 10um	-	-	-	-	-	-	0.900	0.950	kg
Benzo(a)pyrene	-	-	1.18E-7	4.19E-8	-		-	-	kg
Dust, fugitive	0.00100	-	-	-	0.00700	0.0070	-	-	kg
Ammonia	0.000300	-	-	-	-	-	-	0.000015	kg
Ozone	-	-	-	-	-	0.0000600	-	0.00600	kg
Formaldehyde	-	-	-	-	-	0.0000160	-	-	kg
Toluene	-	-	-	-	-	0.0000800	-	-	kg
Phosphine	-	-	-	-	-	0.000000700	-	-	kg
Carbon black	-	-	-	-	-	0.00000300	-	-	kg
Emissions to water.									
Suspended solids, unspecified	5.40	7	0.00500	0.00839	0.00120	0.00080	-	0.900	kg
Waste water/m3	0.200	0.400	0.200	0.463	0.133	0.12	-	0.300	m3
Oils, unspecified	0.000100	-	0.0040	0.000627	0.00100	0.000900	-	-	kg
BOD5 (Biological Oxygen Demand)	-	-	-	0.000627	1.20E-05	0.0000048	-	-	kg
COD (Chemical Oxygen Demand)	2	5	0.0080	0.0525	0.000180	0.000072	-	2.00E-05	kg
Sodium, in water	0.0200	0.0400	-	-	-	-	-	-	kg
Zinc, in water	-	-	-	-	-	0.000008	-	-	kg
Aluminum, in water	0.000100	0.0200	-	0.00419	0.000120	0.0000504	-	-	kg
Iron, in water	0.000100	0.0900	-	0.000419	0.000108	-	-	-	kg
Copper, in water	-	-	-	-	4.92E-05	-	-	-	kg
Nitrogen	-	0.0000150	-	-	-	-	-	-	kg
Calcium	-	0.130	-	-	-	-	-	-	kg
Chloride	-	0.700	-	0.0251	0.00120	-	-	-	kg
Sodium, in water	-	30	-	0.00293	-	-	-	-	kg
Fluoride	-	0.0900	-	0.0113	0.000359	-	-	-	kg
Mercury	-	0.000200	-	4.19E-8	1.20E-9	-	-	-	kg
Cooling water	-	-	-	-	0.478	0.200	-	-	m3
Lead	-	-	-	2.09E-07	-	-	-	-	kg
PAH, polycyclic aromatic hydrocarbons	-	-	0.0000300	0.0000335	-	-	-	-	kg
Sulfate	-	50	-	-	0.000120	0.0000504	-	-	kg
Hydroxide	-	15	-	-	-	-	-	-	kg
Phenols, unspecified	-	-	-	-	-	0.00000252	-	-	kg

Phosphate	-	-	-	-	-	0.000009	-	-	kg
Surfactants	-	-	-	-	-	0.00000200	-	-	kg
Zinc ions (from dross)	-	-	-	-	-	-	-	1.00E-05	kg
Lead ions (from dross)	-	-	-	-	-	-	-	1.00E-05	kg
Emissions to soil.							-	-	
Oils, unspecified	0.000400	0.0000180	0.0005	0.000651	0.0953	0.0300	-	-	kg
Heavy metals, unspecified	-	-	-	-	-	0.000008	-	-	kg
Final waste flows									
Waste, solid	5	0.590	0.590	0.187	-	-	-		kg
Refractory	-	-	0.170	0.126	0.239	-	-		kg
Spent anode waste	-	-	3	-	-	-	-	-	kg
Dross	-	-	-	1.5	-	-	-	-	kg
Aluminum scrap, process	-	-	-	-	-	20	-	-	kg
Waste and emissions to treatment.									
Hazardous waste, for incineration	-	-	-	0.084	0.359	0.200	-	-	kg
Refractory spent pot liner	-	-	-	0.629	-	-	-	-	kg
Dross	-	-	-	1.638	2.993	-	-	10	kg
Filter dust	-	-	-	0.0419	-	-	-	-	kg
Salt slag	-	-	-	0.8	-	-	-	-	
Fly ash and scrubber sludge	-	-	-	-	-	-	-	-	kg
Municipal solid waste	0.100	0.0100	0.300	0.0293	0.239	0.090	-	-	kg
Waste, unspecified	-	-	0.700	-	-	-	-	-	kg
Waste lubricating oil	-	-	-	-	0.0359	0.151	-	-	kg
Non-sulfidic overburden, off-site	150	-	-	-	-	-	-	-	kg
Redmud	-	335	-	-	-	-	-	-	kg
Sludge, NaCl electrolysis	-	-	-	0.209	-	-	-	-	kg
Spent adhesive/epoxy residues	-	-	-	-	-	0.040	-	-	kg
Waste aluminium	-	-	-	-	-	-	-	15	kg
Coating fragments and polymer gaskets	-	-	-	-	-	-	-	2	kg
STF(from acoustic foam, insulation)	-	-	-	-	-	-	-	1	kg
BWMF(from conveyors)	-	-	-	-	-	-	-	0.80	kg
Mixed sorting residue	-	-	-	-	-	-	-	2	kg
Used protective coating waste	-	-	-	-	-	0.050	-	-	kg

Appendix 10 : Lifecycle Environmental Impacts of Aluminum Battery Enclosure.

Appendix 10 presents the environmental impacts across all lifecycle stages of the 120 kg aluminum battery enclosure, quantified using both TRACI and CML-IA methods, and encompassing production, use, and end-of-life phases to provide a comprehensive assessment of the enclosure's full lifecycle environmental footprint.

CML-IA METHOD RESULTS

Sel	Impact Category	Unit	Bauxite	Alumina Refining	Anode Production	Electrolysis	Casting	Manufacturing	Use Phase	(EoL)
☑	Abiotic depletion	kg Sb eq	4.96E-4	5.72E-4	1.07E-4	0.00102	3.68E-4	0.00264	x	4.36E-4
☑	Abiotic depletion (fossil fuels)	MJ	2.2E3	8.083E3	9.46E3	5.76E3	3.32E3	2.03E3	x	2.543E3
☑	Global warming (GWP100a)	kg CO2 eq	160	285	135	337	110	95.3	x	78.4
☑	ODP	kg CFC-11 eq	2.51E-5	6.01E-5	7.26E-5	6.15E-5	1.79E-5	1.12E-5	x	3.16E-5
☑	Human toxicity	kg 1,4-DB eq	44.2	114	44.7	255	76	41.2	1.48	19.1
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	1.46	14.6	6.89	5.56	2.56	1.95	x	0.945
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	3.174E4	7.674E4	3.45E4	2.596E4	6.754E4	1.954E4	1.05E4	1.05E4
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	0.214	0.513	0.0885	1.31	0.168	0.156	x	0.0797
☑	Photochemical oxidation	kg C2H4 eq	0.0582	0.0949	0.0459	0.0445	0.0368	0.0228	x	0.0132
☑	Acidification	kg SO2 eq	1.92	2.54	0.756	0.996	0.409	0.286	x	0.304
☑	Eutrophication	kg PO4--- eq	0.278	0.448	0.0563	0.16	0.0516	0.03	x	0.0308

TRACI METHOD RESULTS

Sel	Impact Category	Unit	Bauxite	Alumina Refining	Anode Production	Electrolysis	Casting	Manufacturing	Use Phase	(EoL)
☑	Ozone depletion	kg CFC-11 eq	3.32E-5	7.7E-5	9.34E-5	7.58E-5	2.23E-5	1.41E-5	x	4.2E-5
☑	Global warming	kg CO_2 eq	160	283	131	336	108	93.8	x	78.1
☑	Smog	kg O_3 eq	40.2	50.5	7.52	15.7	6.19	4.18	x	3.02
☑	Acidification	kg SO_2 eq	2.08	2.71	0.728	1.13	0.426	0.292	x	0.29
☑	Eutrophication	kg N eq	0.234	0.517	0.0763	0.224	0.0553	0.0238	x	0.0629
☑	Carcinogenics	CTUh	4.76E-6	0.00017	1.92E-6	8.18E-5	7.25E-6	2.78E-6	x	8.73E-7
☑	Non carcinogenics	CTUh	1.38E-5	0.000289	8.14E-6	0.000173	7.24E-6	1.46E-5	x	5.78E-6
☑	Respiratory effects	kg PM2.5 eq	0.161	0.211	0.0672	0.146	0.258	0.0371	1.11	1.2
☑	Ecotoxicity	CTUe	193	2.36E3	170	1.08E3	132	87.1	x	69.2
☑	Fossil fuel depletion	MJ surplus	302	1.26E3	1.53E3	868	450	316	x	382

Appendix 11 : Comparative Analysis of Aluminum and Alternative EV Materials.

Appendix 11 provides a comparative analysis of aluminum versus other EV materials including steel, magnesium, and carbon fiber reinforced polymers, along with key metrics for material selection such as cost, strength-to-weight ratio, and environmental impact.

MATERIAL COMPARISON: KEY METRICS				
Material	**Raw Material Cost**	**Strength-to-Weight Ratio**	**Price-Per-Function**	**Regulatory Impact & Comments**
Steel	Lowest (baseline)	Moderate	High cost-effectiveness	Heavier, raises battery size and carbon dioxide emissions
Aluminum	~3x Steel [333].	High	Moderately high	Light, shrinks battery/cost, helps with carbon dioxide regs
Magnesium	Higher than AI	High	Lower than aluminum, limited by cost	Lightest metal, but supply, cost, and processing issues [335] [333].
CFRP	Highest	Very High	Currently cost prohibitive	Exceptional for weight, but expensive for mass market [336].
METRICS FOR EV MATERIAL SELECTION				
Property/Metric	Steel	Aluminum	Magnesium	CFRP
Cost	Lowest	~3x Steel	~2–3x Aluminum	>10x Steel
Strength/Weight	Moderate	High	High	Very High
Processing	Conventional	Advanced	Complex	Very Complex
Market Adoption	High	Growing in EVs	Limited	Niche/Luxury
CO_2 Regulatory Risk	High	Low	Very Low	Lowest

Appendix 12: Results Assessment vs. Theoretical Ranges (North American context)

RESULTS ASSESSMENT VS. THEORETICAL RANGES (TRACI METHOD)

Impact Category	Total Results	Expected/ Theoretical Range	Within Range?	Comments
Ozone Depletion	0.0003498 kg CFC-11 eq	1.5E-4 – 6E-4 kg CFC-11 eq [293] [292]	✓ Yes	Within range. Smelting (0.000317 kg) dominates (~90%) due to PFCs like CF_4 from anode effects. Reflects controlled emissions in North American smelters.
GWP	8,294 kg CO_2 eq	6,000 – 12,000 kg CO_2 eq [293] [292]	✓ Yes	Within range. Smelting (5,570 kg) and alumina (2,040 kg) lead (~67% and 25%). Consistent with hydro grids. Indicates efficient energy use [292].
Smog Formation	735.95 kg O_3 eq	400 – 1,300 kg O_3 eq [291] [292]	✓ Yes	Within range. Smelting (299 kg) and alumina (272 kg) dominate (~41% and 37%). Reflects controlled NOx/VOC emissions from anode baking and fuel [292].
Acidification	35.8 kg SO_2 eq	15 – 50 kg SO_2 eq [293] [292]	✓ Yes	Within range. Smelting (18.4 kg) and alumina (11.5 kg) lead. Bauxite (4.75 kg) fits corrected range (0.5–5 kg), reflecting diesel sulfur [291].
Eutrophication	9.2739 kg N eq	3 – 30 kg N eq [291] [292]	✓ Yes	Within range. Smelting (4.34 kg) and alumina (3.86 kg) dominate (~47% and 42%). Driven by NOx and red mud. Reflects robust waste management [292].
Carcinogenics	0.00058182 CTUh	2E-4 – 1E-3 CTUh [293] [292]	✓ Yes	Within range. Alumina (0.000281 CTUh) and smelting (0.000295 CTUh) lead (~48% and 50%) due to PAHs. Consistent with anode production [292].
Non-carcinogenics	0.00609395 CTUh	1E-3 – 8E-3 CTUh [291] [292]	✓ Yes	Within range. Alumina (0.00301 CTUh) and smelting (0.00304 CTUh) dominate (49% each) due to fluorides (0.5–5 kg/t aluminum).
Respiratory Effects	2.007 kg PM2.5 eq	1 – 5 kg PM2.5 eq [293] [292]	✓ Yes	Within range. Smelting (1.38 kg) leads (~68%) due to anode baking PM. Consistent with North American controls [292].
Ecotoxicity	11,634 CTUe	10,000 – 30,000 CTUe [291] [292]	✓ Yes	Within range. Smelting (5,590 CTUe) and alumina (5,190 CTUe) lead (~48% and 45%). Driven by potlining and red mud [292].
Fossil Fuel Depletion	15,338 MJ surplus	12,000 – 25,000 MJ surplus [293] [292]	✓ Yes	Within range. Smelting (8,580 MJ) and alumina (5,720 MJ) dominate (~56% and 37%). Reflects hydro-fossil mix [292]. Indicates efficient energy use.
RESULTS ASSESSMENT VS. THEORETICAL RANGES (BEES+ METHOD)				
Impact Category	**Total Results**	**Expected/ Theoretical Range**	**Within Range?**	**Comments**
Global Warming	7,390 kg CO_2 eq	6,000–12,000 kg CO_2 eq [293] [292]	✓ Yes	Within range. Smelting (4,690,000 g) dominates (~63%), followed by alumina (2,020,000 g). Reflects ~50% hydro grid efficiency
Acidification	1,995,100 H^+ mmole eq	1,000,000–2,500,000 H^+ mmole eq [291]	✓ Yes	Within range. Smelting (987,000 H^+ mmole eq) leads (~49%), followed by alumina (630,000). Bauxite (268,000) aligns with diesel emissions.
HH Cancer	17,686 g C_6H_6 eq	5,000–20,000 g C_6H_6 eq [291] [292]	✓ Yes	Within range. Smelting (16,000 g) and alumina (13,300 g) dominate (~90% and 75%). Driven by PAHs from anode production.
HH Noncancer	2.36E8 g C_7H_7 eq	1E8 – 5E8 g C_7H_7 eq [291] [292]	✓ Yes	Within range. Smelting (1.2E8 g) and alumina (1.16E8 g) lead (~51% each). Reflects fluorides (0.5–5 kg/t aluminum) [292].
HH Criteria Air Pollutants	466.7 microDALYs	300–600 microDALYs [293] [292]	✓ Yes	Within range. Smelting (290 microDALYs) dominates (~62%) due to PM from anode baking. Consistent with North American controls.
Eutrophication	9,252.6 g N eq	3–30 kg N eq [291] [292]	✓ Yes	Within range. Smelting (4,340 g) and alumina (3,870 g) lead (~47% and 42%). Driven by NOx and red mud [292].
Ecotoxicity	724,763 g 2,4-D eq	500,000–1,500,000 g 2,4-D eq [291] [292]	✓ Yes	Within range. Smelting (363,000 g) and alumina (361,000 g) dominate (~50% each). Driven by potlining and red mud [292].
Smog	26,752 g NOx eq	15–40 kg NOx eq [291] [292]	✓ Yes	Within range. Smelting (15,200 g) and alumina (13,800 g) lead (~57% and 52%). Reflects NOx/VOC from anode baking.
NRD	15,976 MJ surplus	12,000–25,000 MJ surplus [293] [292]	✓ Yes	Within range. Smelting (8,860 MJ) and alumina (6,080 MJ) dominate (~55% and 38%).
IAQ	N/A	N/A	N/A	N/A
Habitat Alteration	1.97E-10 T&E count	1E-10 – 5E-10 T&E count [291] [292]	✓ Yes	Within range. Smelting (8.71E-11) and alumina (8.18E-11) lead. Minimal impact from land use [291].
Water Intake	487,250 liters	300,000–600,000 liters [293] [292]	✓ Yes	Within range. Smelting (444,000 liters) dominates (~91%) due to cooling needs [292].
Ozone Depletion	0.18649 g CFC-11 eq	0.1–0.3 g CFC-11 eq [293] [292]	✓ Yes	Within range. Smelting (0.175 g) dominates (~94%) due to PFCs from anode effects [292]. Reflects controlled emissions.

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