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SIMAPRO PROJECT

Exploring the Environmental Implications of Aluminum in Electric Vehicle Manufacturing

Table of Contents

Abstract.

This study examines the environmental impacts of aluminum production for electric vehicle (EV) applications, focusing on key processes such as bauxite mining, alumina refining, aluminum smelting, and ingot casting. SimaPro 9.3.0.2 was used to undertake a cradle-to-gate Life Cycle Assessment (LCA) with techniques such as CML-IA Baseline, TRACI 2.1, and ReCiPe 2016 Endpoint. The study measured implications in areas such as global warming potential (GWP), resource depletion, and toxicity. Aluminum ingot production is the most environmentally intensive stage, resulting in 13.5 kg CO_2 eq per kilogram of aluminum, primarily due to power usage (5.86 kg CO_2 eq). Smelting produced 3.96 kg CO_2 eq per kilogram using fossil fuel energy Bauxite mining had the lowest GWP (0.0672 kg CO_2 eq), but alumina processing produced large emissions (0.821 kg CO_2 eq) from natural gas and fuel oil usage. Greenhouse gas emissions, acidification, and energy usage were all significant factors to environmental damage. The findings underline the importance of adopting renewable energy, improving energy efficiency, and increasing recycling to reduce aluminum's environmental imprint. This study gives actionable insights into sustainable aluminum production in the electric vehicle (EV) industry, thereby contributing to global decarbonization goals.

Keywords: *aluminum, bauxite, alumina, smelting, electric vehicle, renewable energy, global warming, simapro*

1. Introduction.

Electric vehicles (EVs) are key to achieving a sustainable, low-emission future. EVs rely on electric motors, and their power is stored in large batteries built into each vehicle [12]. As demand for EVs rises, so does the importance of understanding the environmental impact of their production. EVs can be categorized into battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs), depending on their energy sources and powertrains [13]. Aluminum is an important material in the production of electric vehicles because of its lightweight and robust features, which improve vehicle efficiency, battery life, and performance. However, aluminum production requires ecologically intensive operations such as bauxite mining, alumina refining, smelting, and ingot casting. This report assesses the environmental footprint of aluminum in EV production, concentrating on the impacts from raw material extraction to the fabrication of aluminum ingots, thereby highlighting opportunities for more sustainable operation.

Figure 1- BYD Seal Electric Vehicle Model [8].

2. Goal & Scope.

2.1 Scope.

This study adopts a cradle-to-gate approach, assessing the environmental impact of each phase in aluminum production for EV manufacturing. The analysis examines four important processes: bauxite mining, alumina refining, aluminum smelting, and aluminum ingot casting. To provide consistent results, the functional unit for this life-cycle assessment (LCA) is 1 kilogram (kg) of aluminum ingot. This functional unit enables a consistent comparison of environmental inputs and outputs, such as energy consumption, raw material use, emissions, and waste generation, at all stages. The system boundary includes processes such as extraction, material transportation, and final ingot manufacture, including all activities from the "cradle" of raw material extraction to the "gate" of aluminum ingot production. Carbon dioxide, methane, nitrogen oxides, sulfur oxides, and solid waste are all evaluated to provide a comprehensive picture of aluminum's environmental impact.

2.2 Goal.

The main objective of this research is to assess and measure the environmental effects of aluminum production for electric vehicle applications, with a particular emphasis on a cradle-to-gate approach. By analyzing each stage of aluminum production, this research intends to provide a thorough assessment of crucial areas, such as greenhouse gas emissions, resource depletion, and harmful discharges to the air and water. This study also pinpoints important environmental stressors and indicates areas where emission reduction initiatives may have the most impact. The findings ultimately seek to assist in making well-informed choices on the usage of aluminum in the production of sustainable EVs (Electric Vehicles).

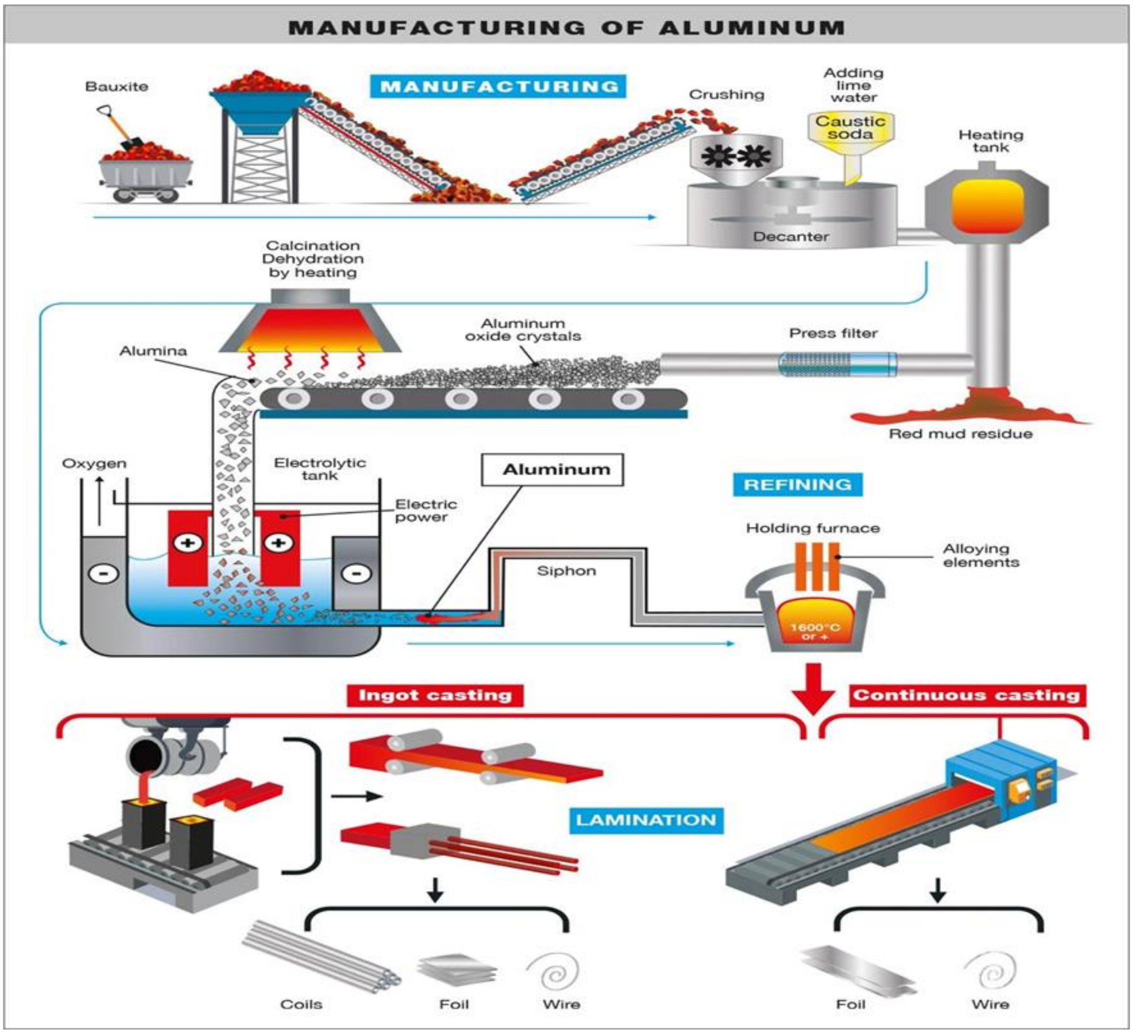


Figure 2 - Manufacturing Processes of Aluminum [7].

2.3 System Boundaries.

The system boundaries for this study span from the extraction of raw bauxite ore to the production of aluminum ingots, encompassing all related processes. Key stages include:

- *Bauxite Mining:* The extraction of raw bauxite ore, including its associated energy use and land disturbance.
- *Alumina Production*: The processing of bauxite to produce alumina (aluminum oxide) is energy-intensive and emits pollutants.
- *Aluminum Smelting*: Alumina is electrolytically reduced to make aluminum metal, a process that takes a lot of electricity, which is generally derived from fossil fuels.
- *Ingot Casting*: The conversion of raw aluminum into ingots suitable for use in EV manufacturing, including emissions from casting and transportation.

2.4 Impact Assessment.

This study uses SimaPro 9.3.0.2 software to assess the environmental impacts of aluminum production for electric vehicles (EVs). Three Life Cycle Assessment (LCA) methodologies are used: the CML-IA Baseline method, the TRACI 2.1 (Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts) method, and the ReCiPe 2016 Endpoint (H) Method.

- *TRACI 2.1 V1.06 / Canada 2005*: This methodology is appropriate for data originating in the United States and focuses on environmental implications such as global warming, acidification, and human health. It offers a locally relevant view on emissions.
- *CML-IA Baseline V3.07 / EU25*: This method is widely utilized in European LCAs and provides a broader global context for comparison across regions. It evaluates categories such as abiotic depletion, marine ecotoxicity, and acidification.
- *ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/A*: This globally applicable method offers a high-level view of sustainability by combining environmental consequences into endpoint categories such resource scarcity, ecosystem quality, and human health.

These methodologies enable a complete analysis of aluminum production's environmental and human health impacts, with a focus on carbon emissions, hazardous discharges, and resource depletion. Each method aids in identifying the steps with the greatest environmental impact, hence assisting efforts to reduce the carbon and pollutant footprint of aluminum in EV manufacturing.

SimaPro

Figure 3 - SimaPro: Life Cycle Assessment Software Logo [9].

2.5 Functions of Aluminum in Electric Vehicles.

Aluminum plays an important role in electric vehicles by reducing vehicle weight, which directly improves energy efficiency and driving range. This metal is widely utilized in electric vehicle components such as battery enclosures, chassis, body panels, and structural supports. Aluminum's lightweight nature allows for larger battery capacities and increased range without compromising performance or safety. Its durability and corrosion resistance improve EV performance, making it a viable material for both structural and safety considerations in electric vehicles.

In addition, aluminum's high recyclability makes it an environmentally favorable choice, as it can be repurposed at the end of its life cycle, thereby reducing the need for new raw materials and lowering the environmental impact of aluminum production over time. This circularity helps to reduce the EV industry's overall carbon footprint, making aluminum a key component of sustainable vehicle manufacture.

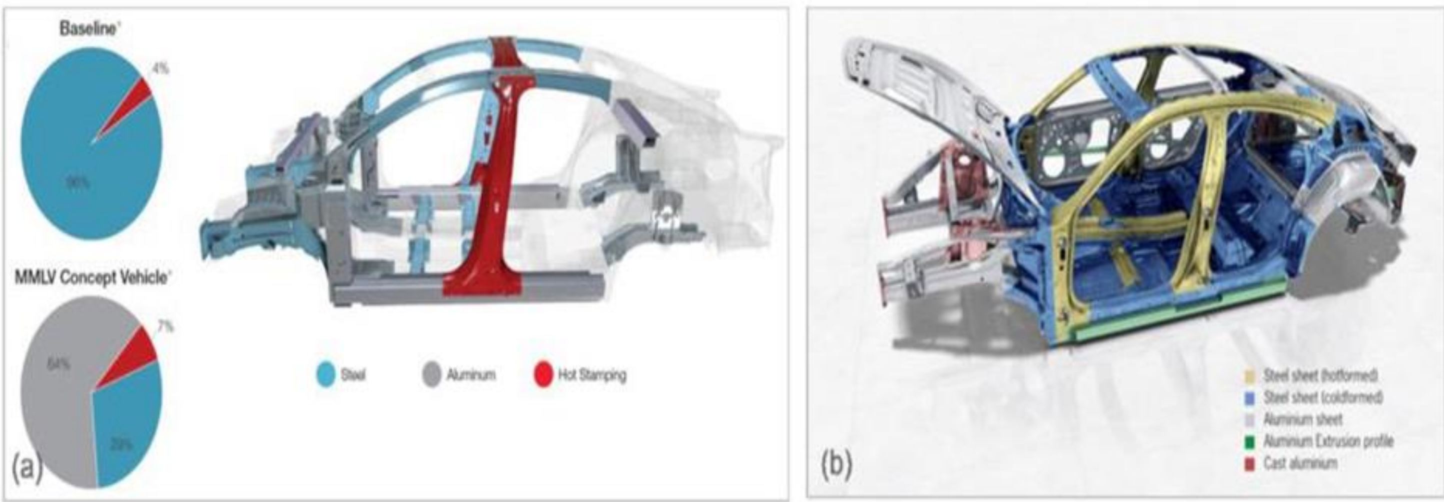


Figure 4 - Parts of a car where aluminum can be applied [5].

3. Literature Review.

Table 1. Comparative Literature Review on Environmental Impact Assessment in Aluminum Production.

Reference	Software & Methods	Focus Area	Key Findings	Differences with Present Study
Abdollahi et al. (2021) [1]	ELECTRE, TOPSIS, SAW for multi-criteria analysis	Air pollution control in aluminum production	Identified alumina refining and electrolysis as major sources of SO_2, NO_x, and particulate matter. Recommended cyclones for particulate control, wet washing for SO_2, and adsorption for NO_x.	Abdollahi et al. (2021) [1] study focused on pollutant control strategies rather than a cradle-to-gate LCA. This study considers the full lifecycle environmental impact of aluminum production for EV manufacturing, including greenhouse gases and toxic discharges.
Bonollo et al. (2013) [3]	SimaPro 6.0, Eco-Indicator 99 method	Environmental comparison of cast iron vs. aluminum in vehicle cylinder blocks	Found that while aluminum has higher production-phase impacts, its lightweight properties contribute to lower emissions over the vehicle's life cycle.	This study specifically addresses the cradle-to-gate LCA of aluminum production for EV manufacturing, without comparing other materials. It also emphasizes the impact of emissions reduction across all production phases.
Nunez & Jones (2016) [10]	GaBi 6, CML (2001–2010) midpoint assessment	Global LCI of primary aluminum production	Alumina refining and smelting were identified as the main contributors to greenhouse gas (GHG) emissions, primarily due to energy demand.	While Nunez & Jones (2016) [10] focused on primary aluminum production impacts, this study applies U.S.-based analysis with regional emission factors for EV applications, using both TRACI and CML-IA impact assessments.
Adhikari et al. (2022) [2]	SimaPro 9.1, TRACI 2.1, LCI modeling	Ionic liquid electrorefining for aluminum recycling	Ionic liquid electrorefining for recycling reduces CO_2 emissions by 41.4% compared to traditional smelting, achieving profitability with lower lifecycle impacts in 6 out of 10 impact categories studied.	Adhikari et al. (2022) [2] study addressed aluminum recycling, and not primary production. Meanwhile, this study focuses on the cradle-to-gate lifecycle for primary aluminum ingot production specific to EV requirements.
Buxmann et al. (2013) [4]	GaBi software, regional water footprint methodology	Water scarcity in aluminum production processes	It was concluded that water use in alumina refining poses significant environmental concerns, especially in water-scarce regions.	This study primarily examines greenhouse gas emissions, pollutant discharges, and resource depletion without an in-depth focus on water scarcity impacts.
Farjana et al. (2019) [6]	SimaPro, ILCD, TRACI	Energy sensitivity in aluminum smelting	Determined that electricity use in smelting is the highest contributor to environmental impacts, with renewable energy integration seen as a key solution.	Farjana et al. (2019) [6] study focused on energy sensitivity and environmental burdens. However, this study investigates aluminum production for EV applications specifically, using multiple impact assessment methods for a comprehensive life cycle assessment (LCA).

4. Methodology.

4.1 Life Cycle Inventory (LCI).

The life cycle inventory (LCI) relies on both estimated data and data sourced from relevant literature studies, with the majority of the data coming from studies conducted by (Shahjadi et al. 2019) [6]. Table 2 presents the complete inventory data used in the life cycle assessment (LCA).

Table 2. Life Cycle Inventory (LCI) [6]

	UNIT	BAUXITE	ALUMINA	ALUMINUM SMELTING	ALUMINUM INGOT
PRODUCTS					
Bauxite	kg	1			
Alumina	kg		1		
Aluminum, smelt	kg			1	
Aluminum, primary, ingot	kg				1

MATERIALS/FUELS					
Residual fuel oil	l	1.25E-03	0.099	4.59E-04	1.86E-02
Gasoline	l	2.67E-04	2.3E-05	2.8E-04	7.3E-05
Diesel	l	4.3E-03	1.6E-03	1.8E-03	1.18E-04
Electricity	kWh	3.9E-04	0.109	1.54	0.21
Transport, train, diesel powered	tkm	0.349	0.486	-	-
Transport, ocean freighter, residual fuel oil powered	km	2.527	2.5	-	-
Transport, ocean freighter, diesel powered	tkm	0.28	0.28	-	-
Natural gas		-	0.225	-	
Bituminous coal		-	8.59E-03	-	
Sodium hydroxide		-	0.0739	-	
Quicklime		-	0.0457	-	
Bauxite		-	2.64	-	
Liquefied petroleum gas		-	-	0.005	1.5E-03
Alumina		-	-	1.9	-
Anode		-	-	0.455	-
Aluminum, primary, smelt		-	-	-	1
EMISSIONS TO AIR					
Carbon dioxide, fossil	kg	7.9E-04	-	1.52	9.3E-04
Carbon monoxide	kg	3.2E-06	-	0.06	6E-06
Methane	kg	6.6E-06	1.7E-05	3.5E-04	-
Nitrogen oxides	kg	4E-05	-	1.1E-04	2.6E-05
Dinitrogen monoxide	kg	3.4E-07	2.2E-07	-	-
NMVOC, non-methane volatile organic compounds	kg	4.5E-07	4.7E-05	9.1E-04	3.8E-06
Particulates, unspecified	kg	0.0023	4.5E-04	4.75E-04	5.8E-05
Sulfur oxides	kg	1.1E-06	-	-	1.1E-05
Hydrocarbons chlorinated	kg	-	6.7E-10	1.2E-04	0.017
Mercury	kg	-	2.1E-08	-	-
Carbonyl sulfide	kg	-	-	1.12E-03	-
Hydrogen cyanide	kg	-	-	3.7E-05	5.3E-05
Hydrogen fluoride	kg	-	-	6.2E-04	2.3E-06
Ethane, hexafluoro-, HFC-116	kg	-	-	2.28E-05	-
PAH, polycyclic aromatic hydrocarbons	kg	-	-	1.15E-04	-
Chlorine	kg	-	-	-	1.8E-05
Fluorine	kg	-	-	-	1.9E-05
Lead	kg	-	-	-	9.4E-09
Metals, unspecified	kg	-	-	-	1.6E-07
Organic substances, unspecified	kg	-	-	-	1.1E-05
EMISSIONS TO WATER					
Detergents, unspecified	kg	2.5E-09	-	5.9E-07	1.5E-08
Suspended solids, unspecified	kg	2.1E-07	1E-05	7.6E-05	1.8E-04
Nitrogen	kg	6.5E-10	-	4.9E-07	-
Oils, unspecified	kg	1.9E-09	3.9E-07	9.9E-06	2.3E-05
Phosphate	kg	2.5E-09	-	-	-
Suspended solids, unspecified	kg	1.5E-08	1.3E-04	6E-05	6.7E-05
Acids, unspecified	kg	-	6.1E-05	-	-
BOD5, Biological Oxygen Demand	kg	-	6.1E-15	9.1E-06	4.1E-05
Calcium	kg	-	5.8E-06	-	-
Chloride	kg	-	7.6E-06	8.4E-06	7.888E-06
COD, Chemical Oxygen Demand	kg	-	4.6E-05	7.9E-05	
Fluoride	kg	-	7.9E-07	5.1E-05	2.1E-04
Iron	kg	-	1.6E-08	2.2E-06	2.7E-06
Mercury	kg	-	6.1E-10	4.0E-10	8.6E-07
Metallic ions, unspecified	kg	-	6.9E-05	8.2E-06	1.4E-11
Phenol	kg	-	3.9E-10	1.8E-07	2.6E-06
Sodium	kg	-	1.96E-03	6.2E-06	1.2E-09
Sulfate	kg	-	1.75E-03	-	-
Ammonium, ion	kg	-	-	5.7E-07	3.6E-07
Organic compounds (dissolved)	kg	-	-	1.3E-05	1.3E-05
Hydrocarbons, unspecified	kg	-	-	4.8E-09	-
Lead	kg	-	-	4.6E-09	3.2E-09

Cyanide	kg	-	-	-	1.7E-09
Sulfur	kg	-	-	-	5.7E-07
WASTE TO TREATMENT					
Dummy disposal, solid waste	kg	0.136	1.125	0.059	0.021

5. Life Cycle Impact Assessment (LCIA).

5.1 Methods.

This study employs a variety of impact assessment methods to thoroughly evaluate environmental impacts, ensuring both regional relevance and detailed analysis of intermediate and end-point categories.

- CML-IA Baseline Method.
- TRACI 2.1 Method.
- ReCiPe 2016 Endpoint (H).

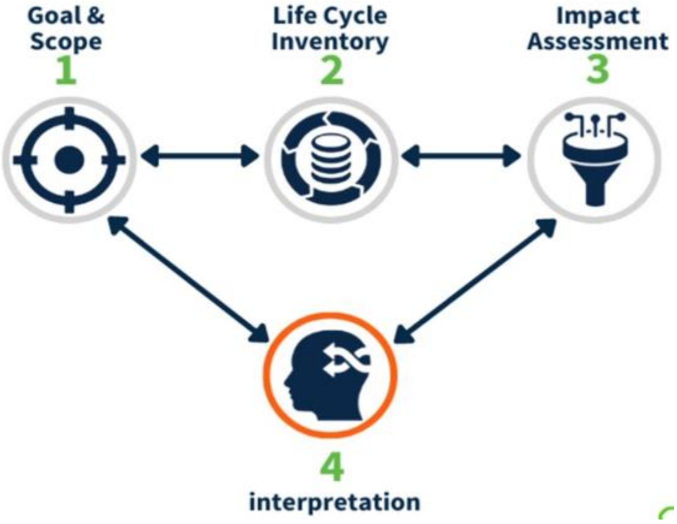


Figure 5 - Life Cycle Assessment (LCA) Framework [15]

6. Results.

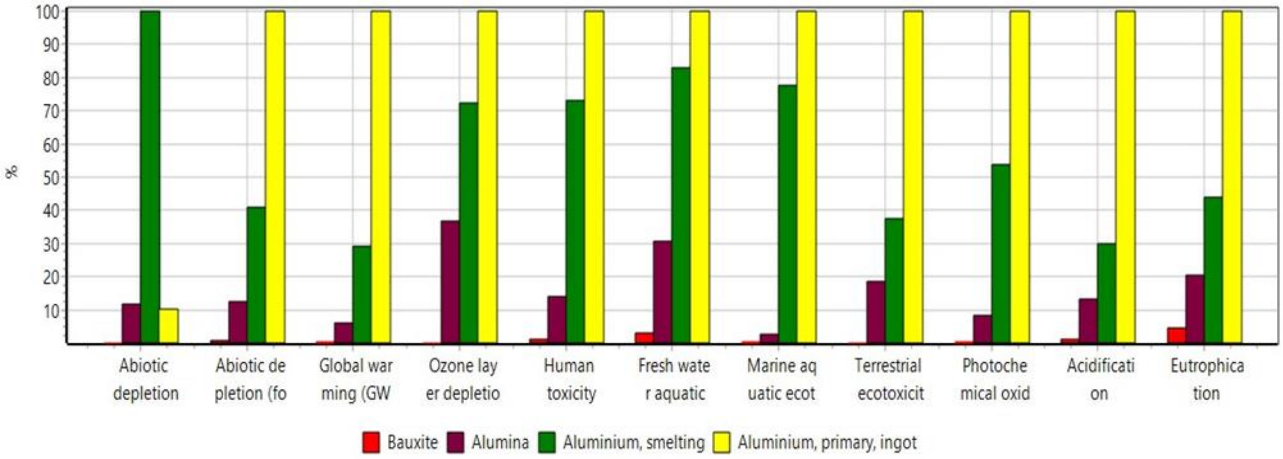
6.1 Network Diagrams.

The network diagrams provided in ***Appendix A*** to ***Appendix D*** for the processes of Bauxite, Alumina, Aluminum Smelting, and Aluminum Ingot, respectively, were generated using the CML-IA baseline V3.07 / EU25 Method. This method was chosen because of its compatibility with regional environmental data and its robustness in analyzing environmental impacts specific to European settings, making it especially useful for a thorough examination of these techniques.

6.2 Impact Assessments (Process by Process).

The impact assessments in the form of Characterization and Normalization, presented as bar graphs in ***Appendix E*** through ***Appendix H*** for Bauxite, Alumina, Aluminum Smelting, and Aluminum Ingot, respectively, were generated using the CML-IA baseline V3.07 / EU25 Method. This method was chosen because it is successful at providing a regionally relevant evaluation of environmental consequences in the European context. The bar charts provide a detailed representation of several key impact categories, including Abiotic Depletion, Abiotic Depletion (Fossil Fuels), Global Warming Potential (GWP 100a), Ozone Layer Depletion (ODP), Human Toxicity, Freshwater Aquatic Ecotoxicity, Marine Aquatic Ecotoxicity, Terrestrial Ecotoxicity, Photochemical Oxidation, Acidification, and Eutrophication. This comprehensive analysis allows for a thorough understanding of the environmental effects associated with each process.

6.3 Results of all processes using the CML-IA Baseline Method.



Method: CML-IA baseline V3.07 / EU25 / Characterisation / Excluding infrastructure processes / Excluding long-term emissions
Comparing 1 kg 'Bauxite', 1 kg 'Alumina', 1 kg 'Aluminium, smelting' and 1 kg 'Aluminium, primary, ingot';

Figure 6 - A Bar Graph Showing Results of All Processes in Characterisation Form Using the CML-IA Baseline Method.

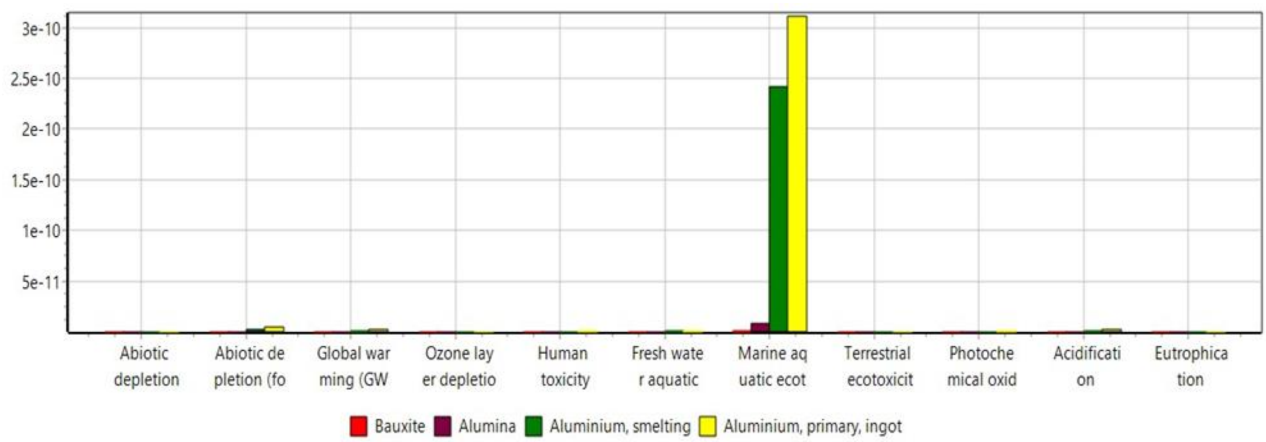
Impact assessment | Inventory | Process contribution

Characterisation | Normalisation

Skip categories: Never

Se	Impact category	Unit	Bauxite	Alumina	Aluminium, smelting	Aluminium, primary,
☑	Abiotic depletion	kg Sb eq	1.18E-11	7.22E-9	6.16E-8	6.34E-9
☑	Abiotic depletion (fossil fuels)	MJ	1.01	17.8	57.9	142
☑	Global warming (GWP100a)	kg CO2 eq	0.0672	0.821	3.96	13.5
☑	Ozone layer depletion (ODP)	kg CFC-11	3.08E-12	7.84E-9	1.54E-8	2.13E-8
☑	Human toxicity	kg 1,4-DB	0.064	0.705	3.68	5.05
☑	Fresh water aquatic ecotox.	kg 1,4-DB	0.0222	0.235	0.636	0.767
☑	Marine aquatic ecotoxicity	kg 1,4-DB	84	924	2.82E4	3.63E4
☑	Terrestrial ecotoxicity	kg 1,4-DB	4.63E-6	0.00115	0.00231	0.00616
☑	Photochemical oxidation	kg C2H4 e	2.46E-5	0.000432	0.00275	0.00509
☑	Acidification	kg SO2 eq	0.00102	0.0111	0.0246	0.0826
☑	Eutrophication	kg PO4---	0.000196	0.000884	0.00189	0.00429

Figure 7 - A Table Showing Results of All Processes in Characterisation Form Using the CML-IA Baseline Method.



Method: CML-IA baseline V3.07 / EU25 / Normalisation / Excluding infrastructure processes / Excluding long-term emissions
Comparing 1 kg 'Bauxite', 1 kg 'Alumina', 1 kg 'Aluminium, smelting' and 1 kg 'Aluminium, primary, ingot';

Figure 8 - A Bar Graph Showing Results of All Processes in Normalisation Form Using the CML-IA Baseline Method.

Impact assessment | Inventory | Process contribution

Characterisation | Normalisation

Skip categories: Never

Se	Impact category	Unit	Bauxite	Alumina	Aluminium, smelting	Aluminium, primary,
☑	Abiotic depletion		1.39E-19	8.52E-17	7.26E-16	7.49E-17
☑	Abiotic depletion (fossil fuels)		3.22E-14	5.66E-13	1.84E-12	4.5E-12
☑	Global warming (GWP100a)		1.34E-14	1.63E-13	7.87E-13	2.69E-12
☑	Ozone layer depletion (ODP)		3.45E-20	8.78E-17	1.73E-16	2.38E-16
☑	Human toxicity		8.25E-15	9.09E-14	4.75E-13	6.51E-13
☑	Fresh water aquatic ecotox.		4.28E-14	4.54E-13	1.23E-12	1.48E-12
☑	Marine aquatic ecotoxicity		7.2E-13	7.92E-12	2.42E-10	3.11E-10
☑	Terrestrial ecotoxicity		9.53E-17	2.38E-14	4.76E-14	1.27E-13
☑	Photochemical oxidation		2.91E-15	5.1E-14	3.24E-13	6.01E-13
☑	Acidification		3.63E-14	3.92E-13	8.74E-13	2.93E-12
☑	Eutrophication		1.49E-14	6.7E-14	1.43E-13	3.25E-13

Figure 9 - A Table Showing Results of All Processes in Normalisation Form Using the CML-IA Baseline Method.

6.4 Results of all processes using the TRACI Method.

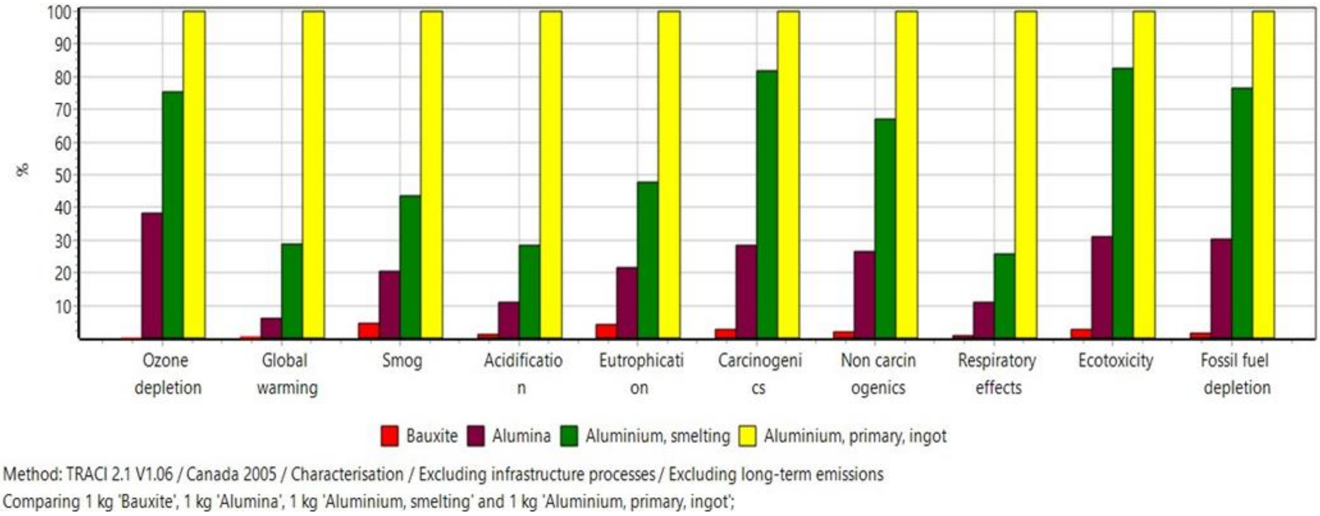


Figure 10 - A Bar Graph Showing Results of All Processes in Characterisation Form Using the TRACI 2.1 Method.

Impact assessment | Inventory | Process contribution

Characterisation | Normalisation

Skip categories: Never

Se	Impact category	Unit	Bauxite	Alumina	Aluminium, smelting	Aluminium, primary,
☑	Ozone depletion	kg CFC-11	3.14E-12	8.98E-9	1.77E-8	2.35E-8
☑	Global warming	kg CO2 eq	0.0669	0.811	3.95	13.7
☑	Smog	kg O3 eq	0.0373	0.165	0.352	0.81
☑	Acidification	kg SO2 eq	0.00128	0.0111	0.0285	0.101
☑	Eutrophication	kg N eq	6.96E-5	0.000353	0.000778	0.00163
☑	Carcinogenics	CTUh	1.08E-9	1.15E-8	3.29E-8	4.03E-8
☑	Non carcinogenics	CTUh	1.04E-8	1.43E-7	3.64E-7	5.41E-7
☑	Respiratory effects	kg PM2.5 e	2.14E-5	0.000402	0.000933	0.0036
☑	Ecotoxicity	CTUe	0.201	2.37	6.28	7.6
☑	Fossil fuel depletion	MJ surplus	0.151	2.69	6.78	8.88

Figure 11 - A Table Showing Results of All Processes in Characterisation Form Using the TRACI 2.1 Method.

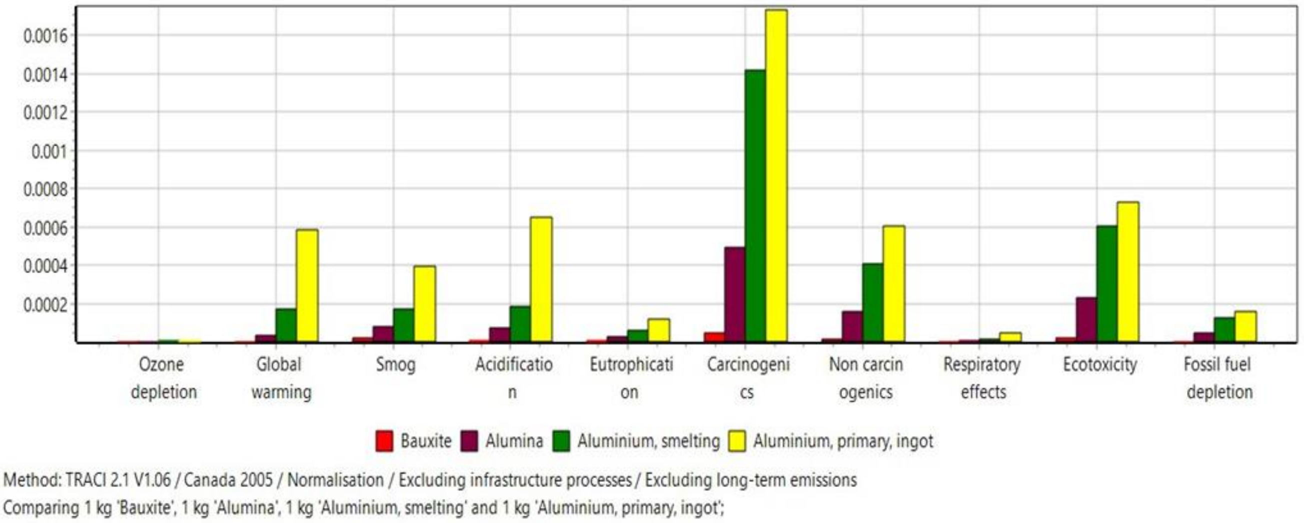


Figure 12 - A Bar Graph Showing Results of All Processes in Normalisation Form Using the TRACI 2.1 Method.

Se	Impact category	Unit	Bauxite	Alumina	Aluminium, smelting	Aluminium, primary,
☑	Ozone depletion		7.84E-10	2.24E-6	4.43E-6	5.87E-6
☑	Global warming		2.85E-6	3.45E-5	0.000168	0.000584
☑	Smog		1.82E-5	8.07E-5	0.000172	0.000396
☑	Acidification		8.27E-6	7.19E-5	0.000185	0.000651
☑	Eutrophication		5.11E-6	2.59E-5	5.72E-5	0.00012
☑	Carcinogenics		4.64E-5	0.000493	0.00142	0.00173
☑	Non carcinogenics		1.16E-5	0.00016	0.000405	0.000603
☑	Respiratory effects		2.91E-7	5.46E-6	1.27E-5	4.89E-5
☑	Ecotoxicity		1.93E-5	0.000228	0.000603	0.00073
☑	Fossil fuel depletion		2.7E-6	4.81E-5	0.000122	0.000159

Figure 13 - A Table Showing Results of All Processes in Normalisation Form Using the TRACI 2.1 Method.

6.5 Results of all processes using the ReCiPe2016 Endpoint (H) Method.

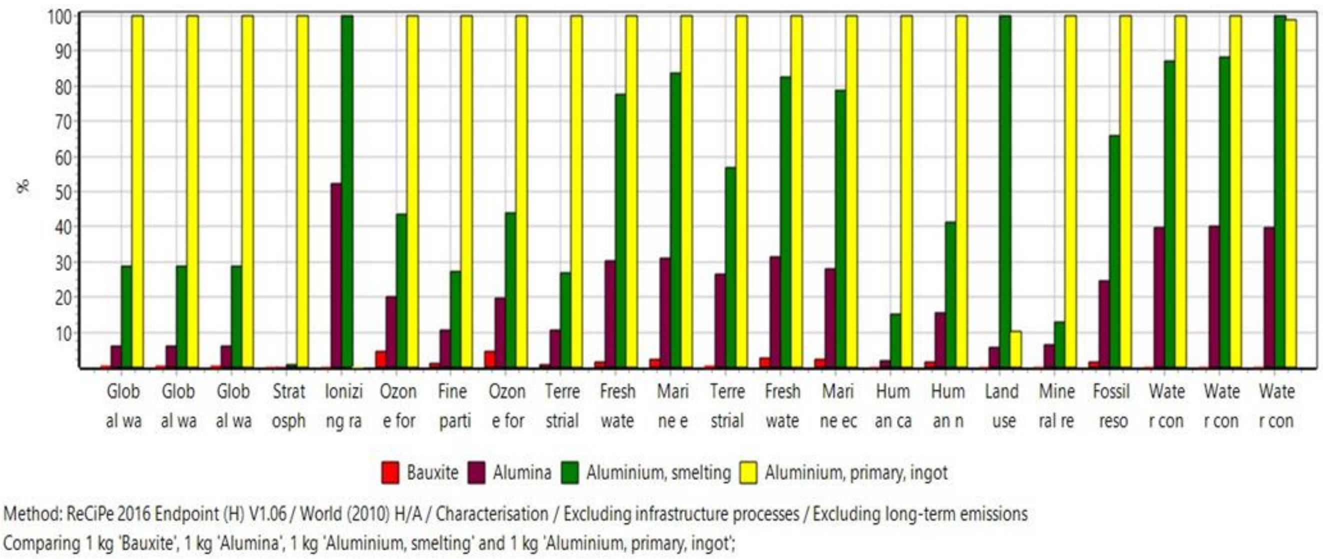


Figure 14 - A Bar Graph Showing Results of All Processes in Characterisation Form Using the ReCiPe2016 Endpoint (H) Method.

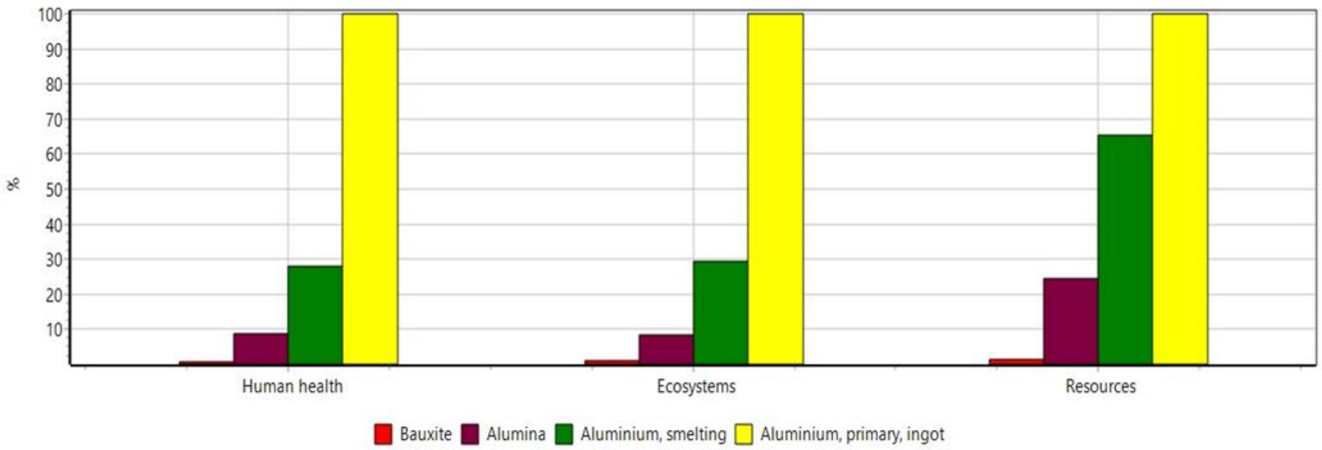
Impact assessment | Inventory | Process contribution | Setup

Characterisation | Damage Assessment | Normalisation | Weighting | Single score

Skip categories: Never

Se	Impact category	Unit	Bauxite	Alumina	Aluminium, smelting	Aluminium, primary, ingot
☑	Global warming, Human health	DALY	6.3E-8	7.83E-7	3.76E-6	1.31E-5
☑	Global warming, Terrestrial ecosystems	species.yr	1.9E-10	2.36E-9	1.13E-8	3.96E-8
☑	Global warming, Freshwater ecosystems	species.yr	5.19E-15	6.45E-14	3.1E-13	1.08E-12
☑	Stratospheric ozone depletion	DALY	9.12E-12	6.69E-11	5.97E-10	6.63E-8
☑	Ionizing radiation	DALY	5.54E-17	3.8E-11	7.24E-11	2.98E-14
☑	Ozone formation, Human health	DALY	1.37E-9	6.1E-9	1.33E-8	3.05E-8
☑	Fine particulate matter formation	DALY	1.58E-7	1.73E-6	4.4E-6	1.62E-5
☑	Ozone formation, Terrestrial ecosystems	species.yr	1.95E-10	8.72E-10	1.94E-9	4.41E-9
☑	Terrestrial acidification	species.yr	1.77E-10	1.98E-9	5.05E-9	1.87E-8
☑	Freshwater eutrophication	species.yr	6.37E-13	1.23E-11	3.15E-11	4.07E-11
☑	Marine eutrophication	species.yr	6.33E-16	9.44E-15	2.55E-14	3.03E-14
☑	Terrestrial ecotoxicity	species.yr	4.24E-14	3.19E-12	6.79E-12	1.2E-11
☑	Freshwater ecotoxicity	species.yr	2.73E-13	3.31E-12	8.72E-12	1.06E-11
☑	Marine ecotoxicity	species.yr	5.56E-14	6.73E-13	1.88E-12	2.39E-12
☑	Human carcinogenic toxicity	DALY	1.98E-10	3.44E-9	2.51E-8	1.65E-7
☑	Human non-carcinogenic toxicity	DALY	4.83E-9	5.45E-8	1.47E-7	3.55E-7
☑	Land use	species.yr	8.22E-16	2.39E-13	4.26E-12	4.43E-13
☑	Mineral resource scarcity	USD2013	7.25E-9	0.000401	0.00079	0.00617
☑	Fossil resource scarcity	USD2013	0.0104	0.162	0.435	0.662
☑	Water consumption, Human health	DALY	2.96E-14	4.29E-10	9.35E-10	1.07E-9
☑	Water consumption, Terrestrial ecosystem	species.yr	1.97E-16	2.62E-12	5.76E-12	6.54E-12
☑	Water consumption, Aquatic ecosystems	species.yr	1.75E-20	1.2E-16	3.01E-16	2.97E-16

Figure 15 - A Table Showing Results of All Processes in Characterisation Form Using the ReCiPe2016 Endpoint (H) Method.



Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/A / Damage assessment / Excluding infrastructure processes / Excluding long-term emissions
Comparing 1 kg 'Bauxite', 1 kg 'Alumina', 1 kg 'Aluminium, smelting' and 1 kg 'Aluminium, primary, ingot';

Figure 16 - A Bar Graph Showing Results of Damage Assessment of All Processes Using the ReCiPe 2016 Endpoint (H) Method.

Impact assessment | Inventory | Process contribution | Setup

Characterisation | Damage Assessment | Normalisation | Weighting | Single score

Skip categories: Never

Se	Damage category	Unit	Bauxite	Alumina	Aluminium, smelting	Aluminium, primary, ingot
☑	Human health	DALY	2.27E-7	2.58E-6	8.34E-6	2.99E-5
☑	Ecosystems	species.yr	5.63E-10	5.23E-9	1.84E-8	6.28E-8
☑	Resources	USD2013	0.0104	0.162	0.436	0.668

Figure 17 - A Table Showing Results of Damage Assessment of All Processes Using the ReCiPe 2016 Endpoint (H) Method.

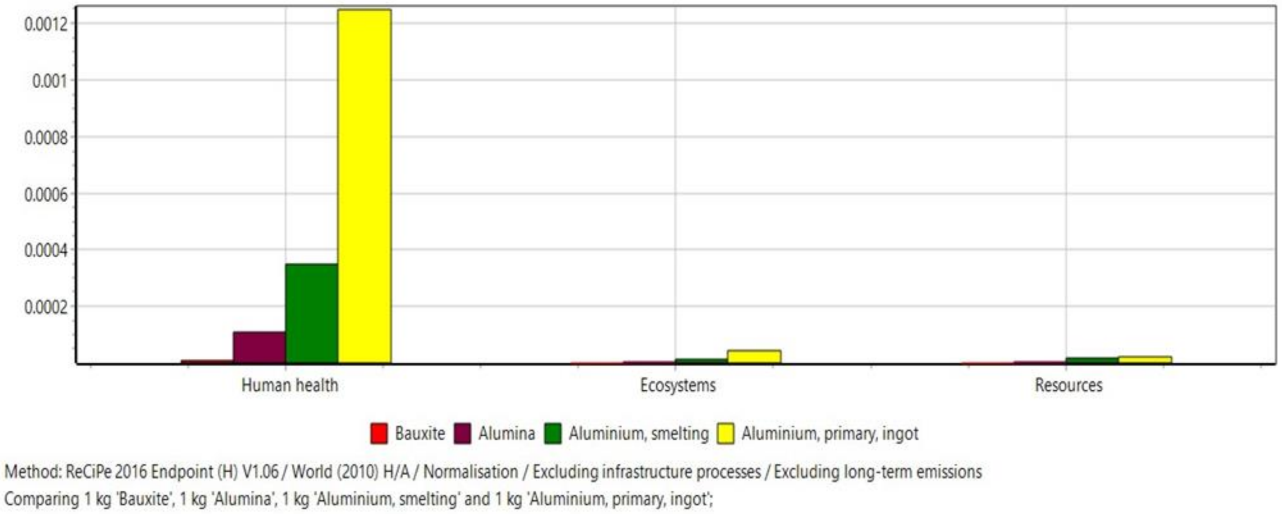


Figure 18 - A Bar Graph Showing Results of All Processes in Normalisation Form Using the ReCiPe2016 Endpoint (H) Method.

Impact assessment | Inventory | Process contribution | Setup

Characterisation | Damage Assessment | Normalisation | Weighting | Single score

Skip categories: Never

Se	Damage category	Unit	Bauxite	Alumina	Aluminium, smelting	Aluminium, primary, ingot
☑	Human health		9.47E-6	0.000107	0.000348	0.00125
☑	Ecosystems		3.8E-7	3.54E-6	1.24E-5	4.25E-5
☑	Resources		3.7E-7	5.8E-6	1.56E-5	2.38E-5

Figure 19 - A Table Showing Results of All Processes in Normalisation Form Using the ReCiPe2016 Endpoint (H) Method.

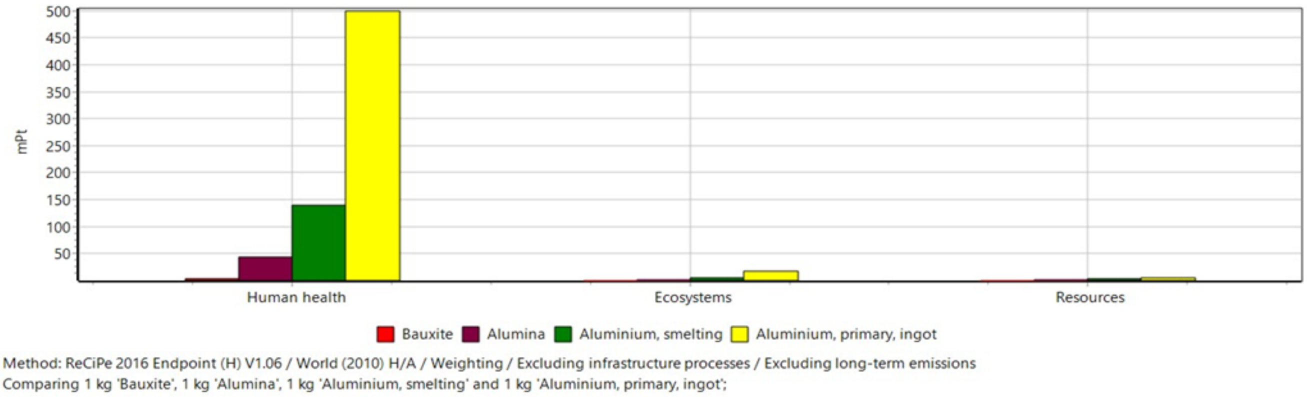


Figure 20 - A Bar Graph Showing Results of All Processes in Weighting Form Using the ReCiPe2016 Endpoint (H) Method.

Impact assessment | Inventory | Process contribution | Setup

Characterisation | Damage Assessment | Normalisation | Weighting | Single score

Skip categories: Never

Se	Damage category	Unit	Bauxite	Alumina	Aluminium, smelting	Aluminium, primary, ingot
	Total	mPt	4.01	45.6	147	521
☑	Human health	mPt	3.79	43	139	499
☑	Ecosystems	mPt	0.152	1.42	4.97	17
☑	Resources	mPt	0.0739	1.16	3.11	4.77

Figure 21 - A Table Showing Results of All Processes in Weighting Form Using the ReCiPe2016 Endpoint (H) Method.

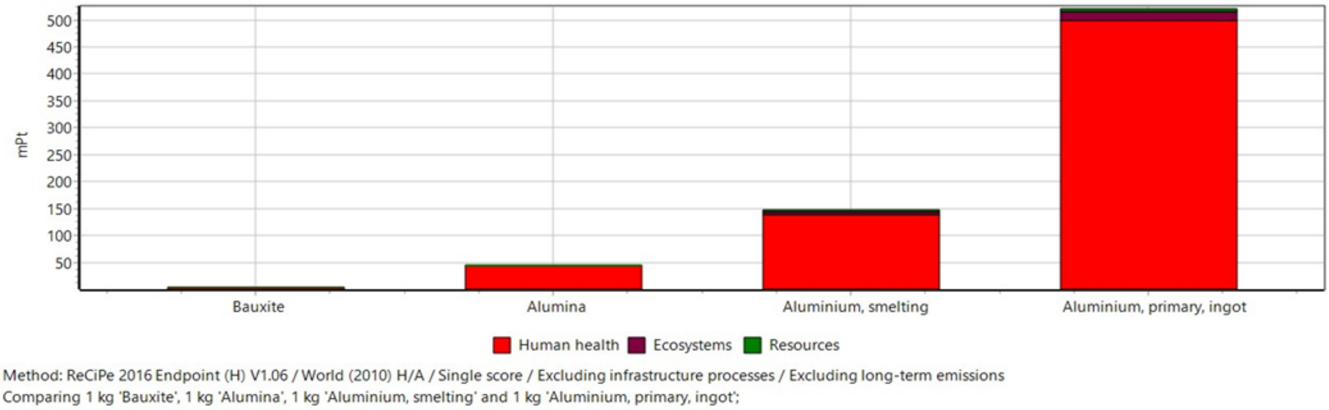


Figure 22 - A Table Showing Results of Single Score of All Processes Using the ReCiPe 2016 Endpoint (H) Method.

Impact assessment | Inventory | Process contribution | Setup

Characterisation | Damage Assessment | Normalisation | Weighting | Single score

Skip categories: Never

Se	Damage category	Unit	Bauxite	Alumina	Aluminium, smelting	Aluminium, primary, ingot
	Total	mPt	4.01	45.6	147	521
☑	Human health	mPt	3.79	43	139	499
☑	Ecosystems	mPt	0.152	1.42	4.97	17
☑	Resources	mPt	0.0739	1.16	3.11	4.77

Figure 23 F- A Table Showing Results of Single Score of All Processes Using the ReCiPe 2016 Endpoint (H) Method.

7. Interpretation and Discussion.

7.1. Analysis of Network Diagrams (CML-IA Baseline Method).

The environmental impact analysis of aluminum production, from bauxite mining to aluminum ingot, demonstrates significant CO_2-equivalent (CO_2 eq) emissions at each stage, quantified using the CML-IA Baseline Method. Bauxite extraction emits 0.0672 kg CO_2 eq/kg, primarily from maritime freight (0.0476) and diesel trains (0.00773). Alumina refining generates 0.821 kg CO_2 eq/kg, mostly from fuel oil (0.393 kg), natural gas (0.108 kg), and bauxite transport (0.177 kg). Aluminum smelting emits 3.96 kg CO_2 eq/kg, primarily due to power use. Emissions from the production chain total 13.5 kg CO_2 eq/kg, with electricity (5.86 kg) and natural gas (1.34 kg) being the main sources. The findings show that the refining and smelting stages are responsible for the majority of emissions, emphasizing the importance of lowering energy and fossil fuel consumption in order to reduce environmental effects.

7.2. A detailed analysis of the impact of all processes using the CML-IA Baseline Method.

Based on the provided data, environmental impact assessments for various stages in the aluminium production process (Bauxite, Alumina, Aluminium Smelting, and Aluminium Primary Ingot) were analyzed using the CML-IA baseline V3.07 / EU25 Method in both Characterisation and Normalisation forms. In the Characterisation stage, which presents absolute impact values, the results show that the Aluminium Primary Ingot stage consistently has the highest environmental burden across most impact categories. For example, Aluminium Primary Ingot has the highest Global Warming Potential (GWP100a) at 13.5 kg CO_2 eq, while the Bauxite stage has the lowest at 0.0672 kg CO_2 eq. Similar to this, aluminum primary ingot is the most resource-intensive and environmentally impactful stage in the depletion of the ozone layer (2.13E-8 kg CFC-11 eq) and the abiotic depletion of fossil fuels (14.5 MJ). On the other hand, the Bauxite extraction stage consistently exhibits the lowest impacts, as seen in categories such as Acidification (where Bauxite shows the lowest value of 0.000196 kg SO_2 eq) and Human Toxicity (where it scores 0.000168 kg 1,4-DB eq compared to 5.05 kg 1,4-DB eq for Aluminum Primary Ingot).

The patterns remain mostly similar during the Normalisation stage, which measures these impacts in comparison to global or regional baselines. Aluminium Primary Ingot continues to have the highest normalised impacts in areas such as global warming and ozone layer depletion, while the extent of its difference from other stages is less noticeable. The bauxite process, on the other hand, remains the least impactful, with consistently lower normalised values. This shows that, even when compared to reference values, Bauxite mining has a lower environmental impact than the other phases of aluminum manufacturing.

Overall, both Characterisation and Normalisation results demonstrate that bauxite mining is the most environmentally friendly stage of the aluminum production process, with reduced impacts in crucial categories such as global warming, fossil fuel depletion, and toxicity. Aluminium Primary Ingot, on the other hand, is the least sustainable alternative because of its high environmental effect, particularly in energy-intensive and climate-relevant categories. From a sustainability approach, prioritizing improvements in the Aluminum Primary Ingot stage is recommended to achieve a lower environmental footprint.

7.3. A detailed analysis of the impact of all processes using the TRACI Method.

Based on the data provided, environmental impact assessments for several stages of the aluminum manufacturing process (bauxite, alumina, aluminum smelting, and aluminum primary) were conducted using the TRACI 2.1 V1.06 / Canada 2005 approach in both Characterisation and Normalisation forms. The data from the Characterization stage, which provides absolute impact values, shows that the Aluminium Primary stage consistently has the largest environmental load across most impact categories. Aluminium Primary has the largest Global Warming Potential (GWP) of 13.7 kg CO_2 eq, whereas Bauxite stage has the lowest at 0.0669 kg CO_2 eq. Similarly, Aluminium Primary has the highest Ozone Depletion Potential (2.35E-8 kg CFC-11 eq) and Fossil Fuel Depletion (8.88 MJ excess), indicating a significant resource usage and environmental impact. The bauxite stage had the lowest environmental impact, including Carcinogenics (1.08E-9 CTUh) and acidification (0.00128 kg SO_2 eq), indicating a lesser burden.

In the Normalisation stage, in which scales impact relative to reference baselines, these trends remain consistent. Aluminium Primary continues to have the highest normalised impacts in key categories like global warming and ozone depletion, however the difference between stages is less noticeable when scaled to regional or global levels. The Bauxite process has the least impact on the normalised assessment, consistently presenting lower values. This shows that, as compared to other steps of aluminum manufacturing, bauxite extraction has a comparatively low environmental impact.

Overall, both Characterisation and Normalisation results indicate that Bauxite extraction is the most environmentally favorable stage in the aluminum production process, showing lower impacts across key categories like global warming, fossil fuel depletion, and toxicity. In contrast, Aluminium Primary emerges as the most environmentally burdensome stage, with significant implications, notably in energy-intensive and climate-related categories. From a sustainability perspective, it is recommended to prioritize efficiency and impact reduction in the Aluminium Primary stage to reduce the overall environmental foot-print and address key environmental challenges associated with aluminum production.

7.4. A detailed analysis of the impact of all processes using the ReCiPe 2016 Endpoint (H) Method.

The ReCiPe 2016 Endpoint (H) Method assesses environmental impacts through key stages from characterization to single score. In characterization, the process from Bauxite to Aluminium primary ingot reveals significant impacts, particularly in human health and ecosystem damage. For example, Bauxite shows a human health impact of 6.3E-8 DALY and ecosystem impact of 1.9E-10 species.year. Moving further down the production chain, the primary aluminium ingot stage displays much higher impacts, with human health at 1.31E-5 DALY and terrestrial ecosystems at 8.91E-8 species.year, highlighting the substantial increase in environmental bur-den as raw materials are processed into refined products.

In damage assessment, impacts are grouped into human health, eco-systems, and resources. Human health damage increases significantly from 2.27E-7 DALY for bauxite to 2.99E-5 DALY for aluminum primary ingot. Ecosystem damage is also increasing, with species loss going from 5.63E-10 to 6.28E-8 each year. This phase focuses on the increasing environmental and health costs associated with the various production processes. Resource depletion is also intensifying, with economic costs growing from 0.0104 USD2013 for bauxite to 0.668 USD2013 for aluminum ingot, highlighting the increased environmental and economic toll along the production chain.

Through normalization, these impacts are contextualized against global averages, showing that Bauxite's human health impact is 9.47E-6 while Aluminium primary ingot reaches 0.00125, indicating a much more severe effect relative to global reference values. Weighting assigns more importance to human health impacts, leading to a significant single score difference; Bauxite totals 4.01 mPt, while Aluminium primary ingot scores 521 mPt. This high single score for Aluminium primary ingot reflects its intense resource and energy demands, emphasizing the need for targeted interventions in these high-impact stages to mitigate overall environmental impacts across the material's lifecycle.

8. Conclusion.

This study evaluated the environmental impacts of aluminum production for EVs using the CML-IA Baseline, TRACI, and ReCiPe 2016 Endpoint (H) methods. Across all processes, the Aluminum Primary Ingot step was identified as the most environmentally damaging, owing to its high emissions and energy requirements. Using the CML-IA approach, total emissions reached 13.5 kg CO_2 eq/kg, with smelting providing 3.96 kg CO_2 eq/kg and electricity accounting for a large share (5.86 kg CO_2 eq in total). The ingot stage exhibited the highest impacts in categories like ozone depletion (2.13E-8 kg CFC-11 eq) and fossil fuel depletion (14.5 MJ). The TRACI 2.1 analysis showed overall emissions of 13.7 kg CO_2 eq/kg, with smelting and refining contributing the most to the global warming potential (GWP).

The ReCiPe Endpoint results supported these findings by emphasizing significant impacts on human health (1.31E-5 DALY) and ecosystem degradation (8.91E-8 species/year) during the ingot production stage. Furthermore, resource depletion increased from 0.0104 USD2013 in the bauxite stage to 0.668 USD2013 during ingot production, indicating rising economic and environmental costs across the production chain.

These findings indicate that smelting and refining are critical areas for improvement, as their heavy emissions and energy consumption pose challenges for manufacturers. The reliance on fossil fuels and electricity in these processes leads to substantial environmental impacts and heightened regulatory and financial pressures, especially in regions with strict carbon pricing and emission reduction targets.

8.1. Implications for Manufacturers.

The significant environmental impact of the smelting and refining steps, mainly from the usage of fossil fuels and electricity, highlights the critical need for cleaner energy sources. Heavy emissions imply stricter regulatory scrutiny and increased costs due to carbon pricing.

9. Suggested Mitigatory Measures.

To address the high environmental impacts of aluminum production, manufacturers should adopt renewable energy sources for smelting to reduce electricity-related emissions, which account for 5.86 kg CO_2 eq. Energy efficiency improvements in refining might dramatically reduce natural gas-related emissions, which generate 1.34 kg CO_2 eq. Furthermore, increasing aluminum recycling can reduce emissions by up to 90% compared to original manufacturing, making it a feasible option for lowering the carbon footprint. Sustainable transportation options, like reducing emissions from maritime freight (0.0476 kg CO_2 eq) and diesel trains (0.00773 kg CO_2 eq), are crucial. Implementing these techniques will assist manufacturers in lowering production costs, meeting strict environmental requirements, and aligning with the worldwide shift to sustainable, low-emission electric vehicles.

10. References.

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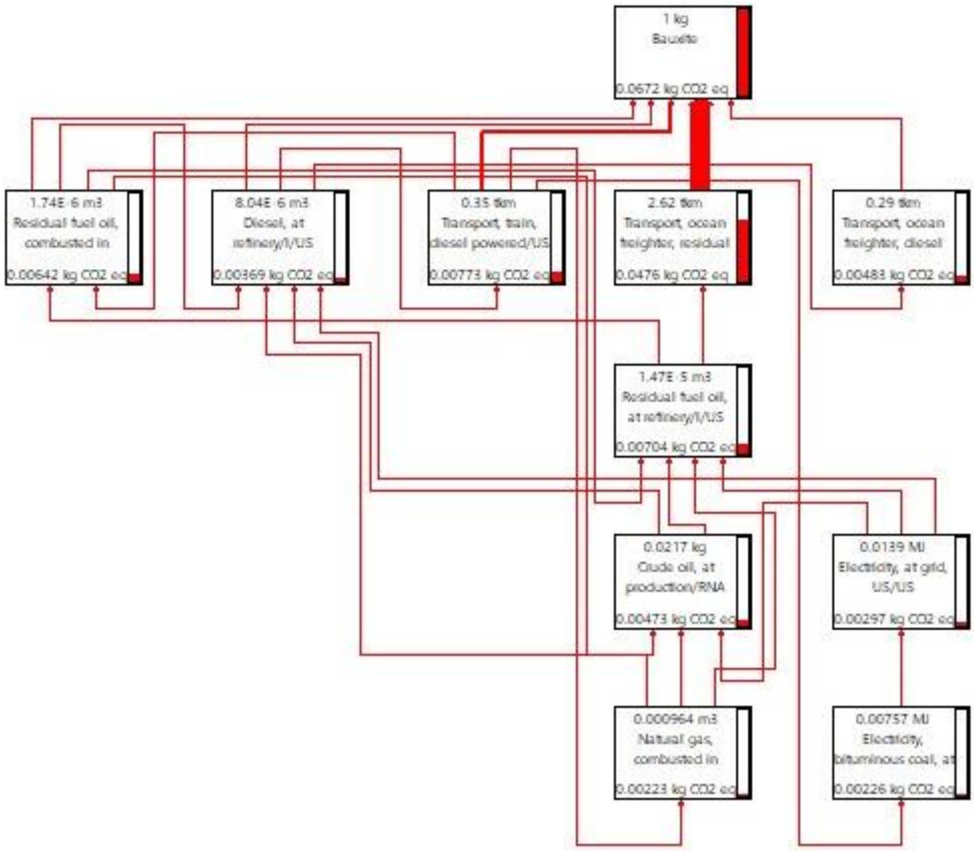
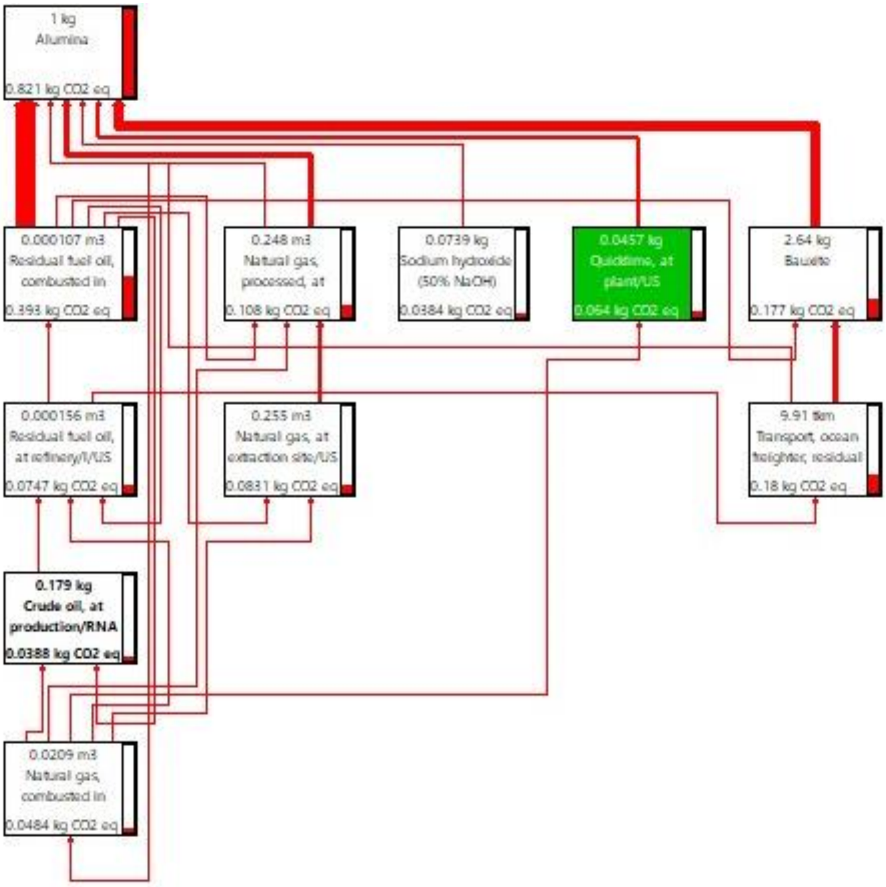
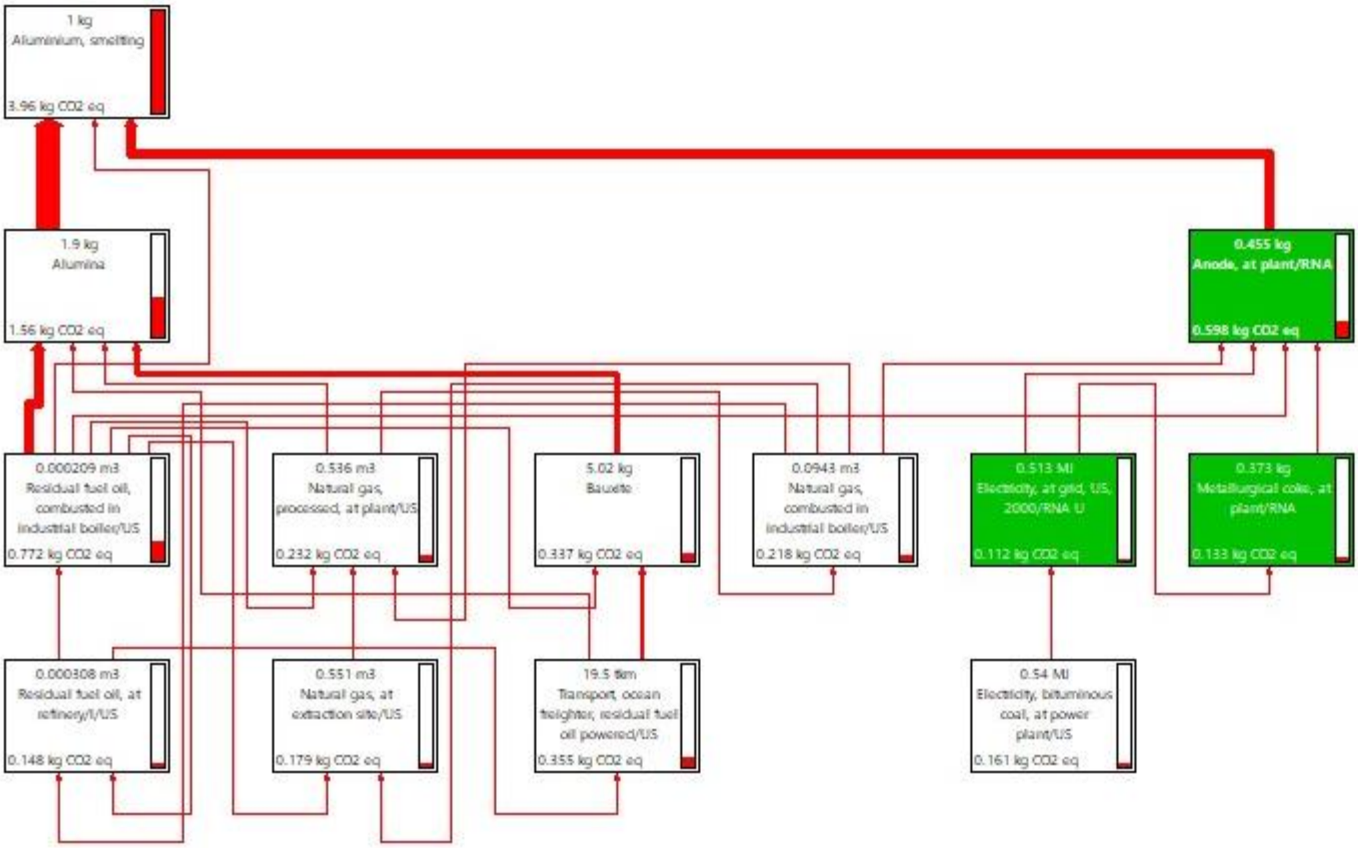
Appendix A.



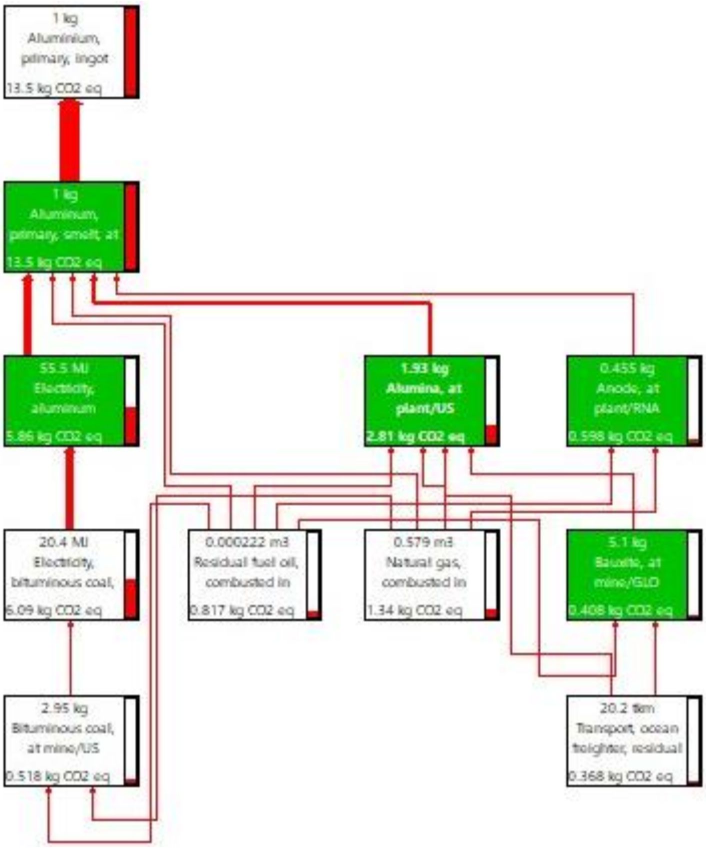
Appendix B.



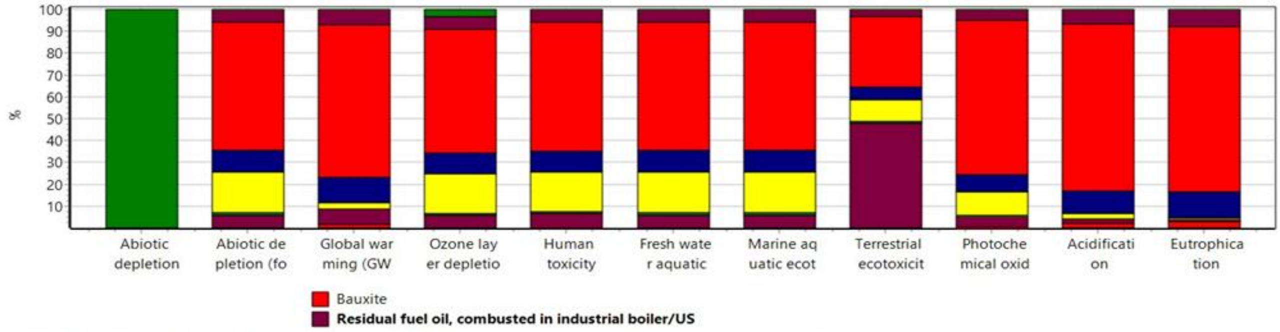
Appendix C.



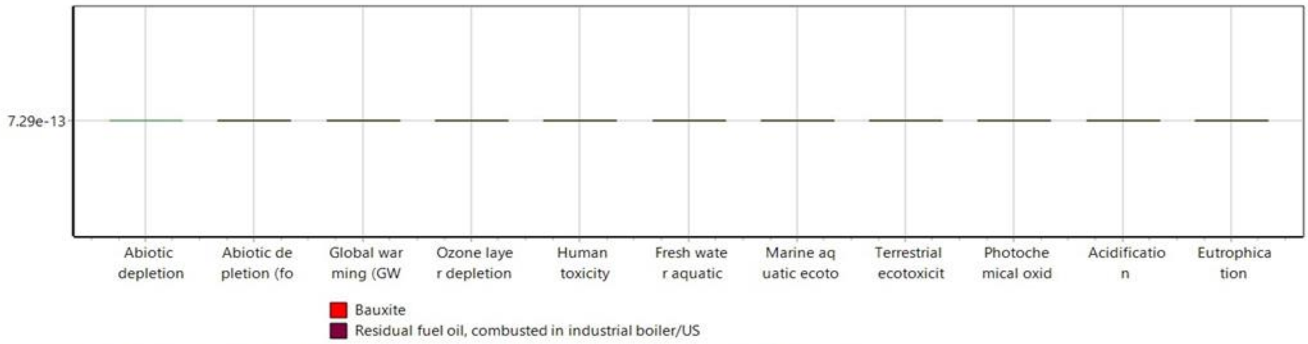
Appendix D.



Appendix E.



Method: CML-IA baseline V3.07 / EU25 / Characterisation / Excluding infrastructure processes / Excluding long-term emissions
Analysing 1 kg 'Bauxite';



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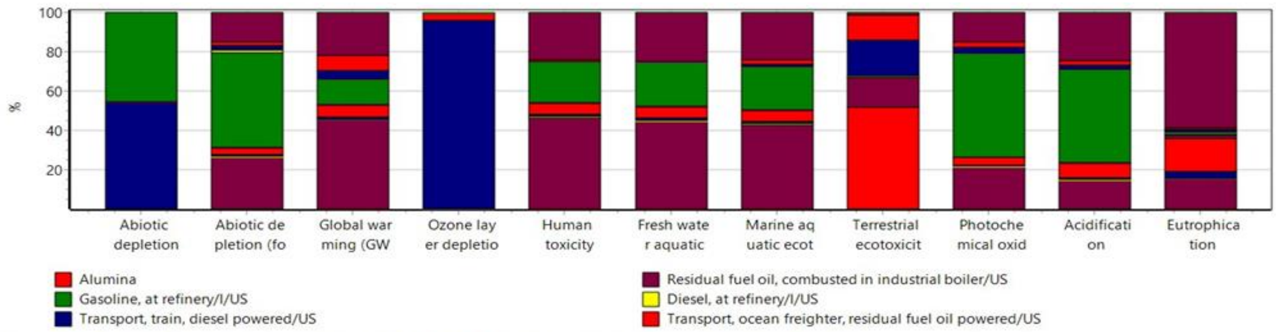
Analysing 1 kg 'Bauxite';

Appendix F.



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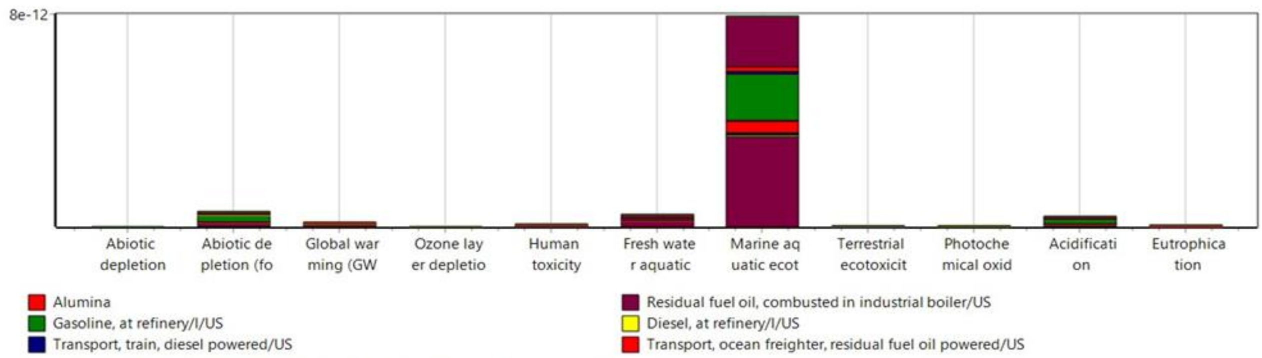

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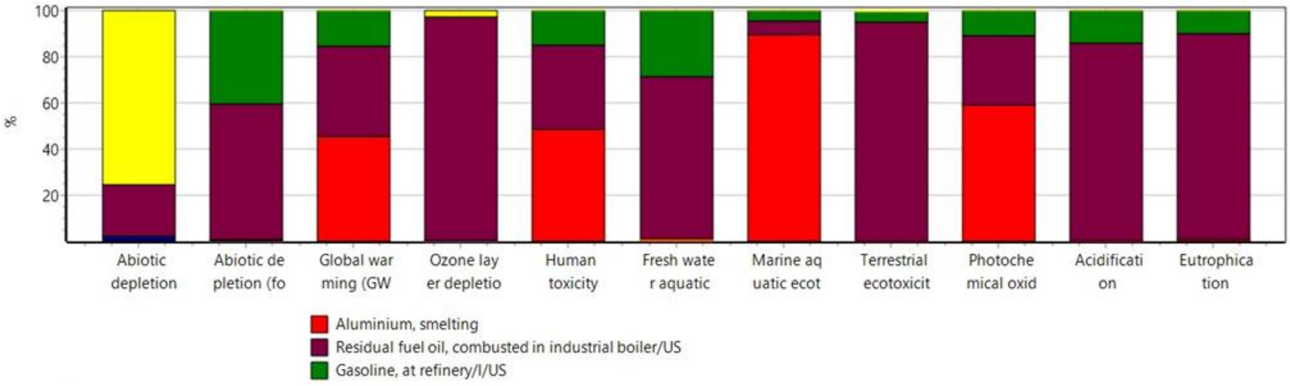
Analysing 1 kg 'Alumina';

Appendix G.



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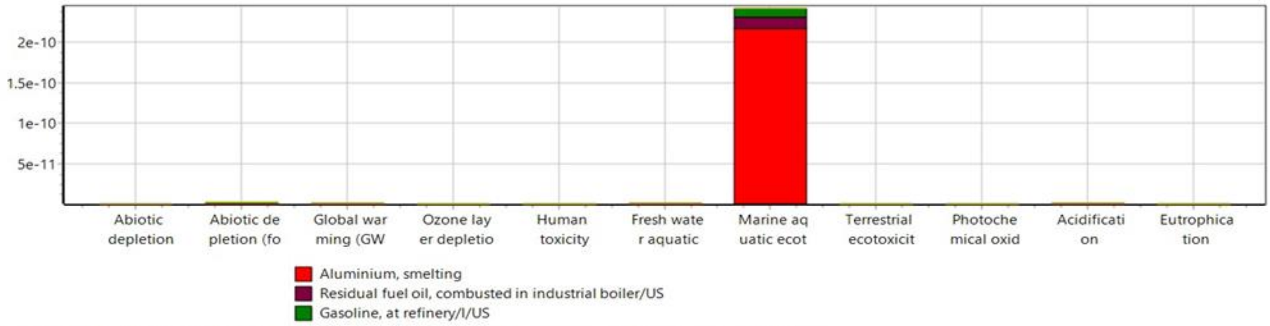
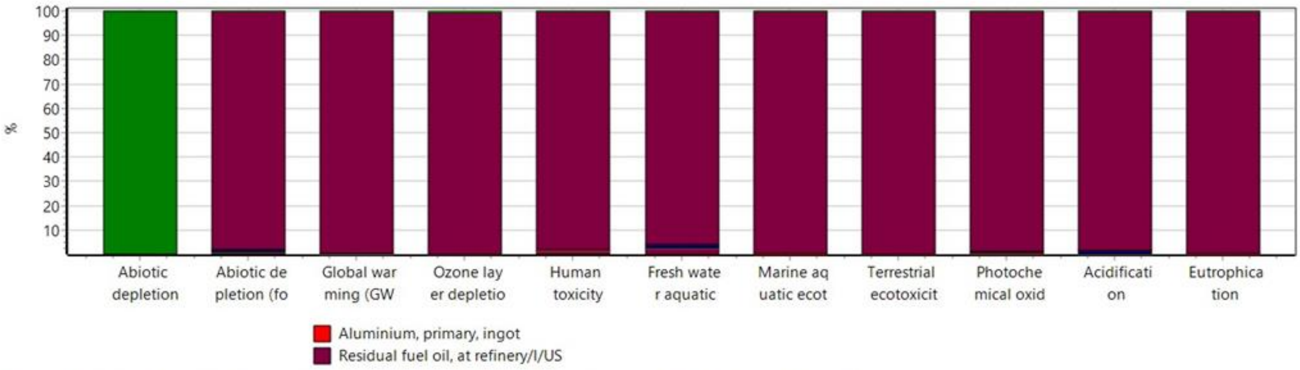


Method: CML-IA baseline V3.07 / EU25 / Normalisation / Excluding infrastructure processes / Excluding long-term emissions
Analysing 1 kg 'Aluminium, smelting';

Appendix H.



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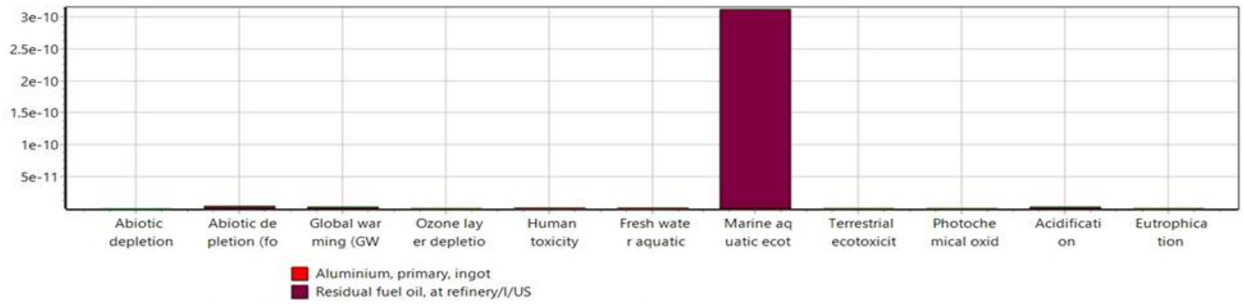

Method: CML-IA baseline V3.07 / EU25 / Normalisation / Excluding infrastructure processes / Excluding long-term emissions
Analysing 1 kg 'Aluminium, primary, ingot';