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Life Cycle Assessment of Refractory Alumina Products: Use of Hotspot and Scenario Analysis as Ecodesign Support Tools

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Abstract

Refractories are advanced ceramics essential for high-temperature operations in the steel, glass, cement, and power sectors. In response to growing sustainability requirements, life cycle assessment (LCA) is increasingly applied to quantify and mitigate their environmental impacts. However, current refractory-related LCA research remains limited by the scarcity of comprehensive inventories and the lack of systematic evaluation of uncertainties affecting results and ecodesign strategies. This study addresses these gaps by presenting the first published LCAs of tabular alumina, white fused alumina, and fused cast high-alumina block production, thereby expanding the environmental knowledge base across alumina products. The analysis shows that uncertainties in characterization models can significantly influence impact-category prioritization, underscoring the need for robust interpretation frameworks. Differences in category criticality across methodological levels and LCIA methods are examined, highlighting the suitability of the Product Environmental Footprint (PEF) approach for refractory applications due to its explicit consideration of model uncertainty and comprehensive coverage of impact categories. Results indicate that alumina products significantly contribute to climate change, fossil resource depletion, particulate matter formation, acidification, freshwater eutrophication, and non-cancer human toxicity. Energy supply constitutes the main environmental hotspot, both through its direct consumption and its indirect contribution during raw material preparation. Red mud disposal is also a major contributor to impacts associated with calcined alumina production. Based on these insights, improvement strategies are proposed, demonstrating the value of LCA as an ecodesign tool. Scenario analysis for fused cast high-alumina block further quantifies the potential for impact reduction under varying operational conditions.

Keywords: LCA; alumina; refractory; fused cast; ecodesign; hotspot analysis; scenario

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1. Introduction

Refractories are ceramic materials able to withstand high temperatures and severe service conditions characterized by corrosion and thermo-mechanical loading. Their distinctive properties make them enablers of crucial processes in many industrial sectors, like metallurgy, cement, and glass manufacturing [1]. The growing emphasis on improving the environmental performance of energy-intensive industrial sectors incentivizes refractory manufacturers to supply high-performance materials with minimized environmental impact to their clients [2,3]. Life cycle assessment (LCA) has emerged as a critical tool to support decision-making towards more sustainable development [4]. LCA describes the effects of a product or service throughout its life cycle on a set of environmental domains called impact categories [5]. It can guide the design and validation of "actions for the environment" by detailing the most affected environmental categories and the processes or materials most contributing to such impacts [6]. The application of LCA within the refractory sector is relatively recent, resulting in a limited body of literature and lack of a standardized approach [7]. The present article addresses this research gap by providing a methodological guideline on LCA results interpretation applied to alumina grades and alumina-based refractories.

Alumina, or aluminum oxide, is an inorganic compound produced from bauxite refining, mainly via the Bayer process. About 90% of global alumina supply is used to produce aluminum via the Hall–Héroult process [8], with the residual quota being destined for non-metallurgical applications, such as normal and high-performance ceramics, refractories, abrasives, water treatment applications, and flame retardants [9]. A vast number of alumina-containing refractories exist, such as the unshaped calcium aluminate cement monolithics and shaped alumina-silicate and high-alumina blocks [1,10].

Only one study in the literature applied LCA to the production of alumina grades, specifically calcined (CA) and white fused alumina (WFA), meant for application in the refractory sector [11]. Two studies performed the carbon footprint (CF) analysis, hence only estimating greenhouse gas emissions. Ranaivoharilala et al. calculated the CF of CA and WFA produced in Austria, providing a contribution analysis, but without presenting the underlying inventory data [12]. Königshofer developed a simplified CF calculation method for many alumina grades, such as calcined, tabular (TA) and fused alumina, and intermediate products, such as zirconia-mullite and zirconia-alumina [13]. Besides the literature specific to refractory application, LCA applied to the production of metallurgical CA was analyzed. Indeed, the similarities in metallurgical and non-metallurgical CA production allow the direct comparison of the two manufacturing routes. Sáez-Guinoa et al. studied the effects of energy consumption, bauxite quality and bauxite transport distance on the burdens generated by alumina refining through the Bayer process [14]. The process-level inventory was compiled through thermodynamic simulations. Ma et al. compared the environmental performance of alumina production via the Pedersen and Bayer processes applied to a set of bauxite ores with different purity [9].

With regard to alumina-containing refractory products, Henry-Lanier et al. calculated the CO_2 emissions associated with the production of three calcium aluminate cements and proposed an initial approach for incorporating the use phase into the assessment [15]. Canton et al. compared the LCA of two ultra-low cement castables, made with WFA and brown fused alumina, respectively [16]. However, neither publication provided sufficient detail regarding the underlying modeling assumptions, methodological choices, or inventory data, thereby limiting the interpretability and reproducibility of their results. Königshofer calculated the simplified CF of calcium aluminate cement and fired high-alumina bricks [13]. Tang et al. applied LCA to the production of a Chinese alumina-carbon brick used in the continuous casting of steelmaking [3]. The study included uncertainty and sensitivity analysis and provided indications on the optimization of the production process. Boenzi et al. evaluated the burdens arising from the production [17] and usage in steel ladles [18] of a magnesia-alumina brick made of reactive and tabular alumina. Also, the articles provided the inventory for the production of both alumina forms. In two cases, LCA was applied to the management of end-of-life alumina bricks. Ferreira et al. compared the disposal and recycling of end-of-life alumina-zirconia bricks, calculating the potential avoided burdens from closed-loop virgin raw materials substitution [19]. The assessment was supported by a sensitivity analysis of the recycling efficiency and the transport distance to the recycling plant. Muñoz et al. quantified the environmental impacts of recycling high-alumina shaped refractories and assessed the potential benefits of substituting virgin calcined bauxite [20]. Table 1 shows the $CO_{2,eq}$ emissions arising from the production of alumina grades and alumina-containing refractory bricks reported in the literature. A critical analysis of these values is provided in Section 4.

Table 1. $CO_{2,eq}$ emissions from alumina grades and alumina-based refractory bricks production in the literature.

Product	$kgCO_{2,eq}/kg$	Geography	Source
Calcined alumina	0.7	Global [1]	[13]
	1.0	Europe	[14]
	1.7	Europe	[9]
	1.7	China	[11]
Tabular alumina	2.9	Global [1]	[13]
White fused alumina	1.0	Global [1]	[13]
	1.1	Austria	[12]
	6.0	China	[12]
	6.5	China	[11]
Magnesia-alumina sintered brick	0.9	Spain	[17]
High-alumina sintered brick	1.1	Global [1]	[13]
Alumina-carbon baked brick	2.2	China	[3]

[1] Global geographical coverage is declared in the source due to worldwide data collection [13].

Within this context, the present study intends to tackle two main research gaps identified in the literature. First, LCA is applied to products that were not addressed in the previous literature, hence improving the coverage of existing alumina products. Specifically, the first published LCAs of TA, WFA and fused cast high-alumina block production are presented here, along with an updated and comprehensive evaluation of CA production. Scenario analysis is applied to the manufacturing of high-alumina blocks to estimate the range of potential environmental impacts under varying production conditions. Second, this article contributes to the development of a standardized methodological framework by providing guidance to refractory stakeholders on the interpretation of LCA results and their application in ecodesign. The intrinsic biases and methodological uncertainties of LCA are examined, and their influence on the identification of critical environmental impact categories and hotspot processes is evaluated. Based on LCA findings, ecodesign strategies are suggested for all alumina products. This article is a revised and expanded version of a paper entitled "Life Cycle Assessment of Refractory Materials: Using Environmental Data to Enhance Production Routes and Product Design for Sustainability", which was presented at UNITECR 2025, Cancun, in October 2025 [21].

2. Materials and Methods

LCA consists of four phases: goal and scope definition, inventory analysis, impact assessment and interpretation [5,22].

2.1. LCA Goal and Scope

The goal and scope phase involves defining the purpose and the methodological framework of the LCA. In this article, cradle-to-gate LCA is applied to the production of three alumina types and high-alumina refractory block with a reference unit of "1 ton of product". Cradle-to-gate refers to the analysis of a partial product life cycle, including raw materials extraction and transformation, up to the production factory gate. The product system is divided into foreground and background systems. The core processes directly controlled or influenced by the decision-maker within the LCA study constitute the foreground portion [23]. Instead, the processes reflecting the broader industrial economy that fall outside the decision-maker's direct control represent the background system. In all cases, products manufactured in China are considered. System boundaries and multifunctionality are modeled through a simple cut-off approach and mass allocation.

2.1.1. Product System of Alumina Grades Production

CA, TA and WFA are among the most commonly used types of alumina in refractory applications [24,25]. Generic alumina products made in China with state-of-the-art production methods are modeled, with no specific quality requirement set.

CA is primarily produced through the Bayer process, in which bauxite ore is refined to extract aluminum oxide [26]. First, bauxite rock is digested in hot sodium hydroxide solution to dissolve aluminum-bearing minerals and precipitate hydrated alumina. Then, the hydrated alumina is calcined in rotary kilns or fluidized bed calciners to remove water and produce metallurgical CA. Additional purification steps may be necessary to produce non-metallurgical grade; however, they fall outside the system boundaries, as their environmental impact is considered negligible. TA is a high-quality sintered alumina characterized by large corundum crystals. It is produced by firing pelletized CA at 1800–1900 °C in shaft kilns [27]. In detail, after being ground and agglomerated, CA is dried and sintered. The finishing treatments include crushing, grinding, and packaging. WFA is a nearly pure alumina product obtained by melting CA in an electric arc furnace [28]. The Higgins furnace is the most widely used for this process, as it promotes the development of a well-defined crystalline structure with large crystals [28]. Fused alumina undergoes pouring and casting to form alumina grains. In this study, the ingot casting method is applied, with molten alumina being poured into large cast-iron molds and slowly cooled. The solidified blocks are then crushed into the desired aggregate size and packaged. The production routes of CA, TA and WFA are represented in Figure 1, with the inventory of mass and energy flows detailed in Table 2.

The production route, particularly the thermal stabilization treatments, directly influences the thermo-mechanical properties of alumina. While CA is generally considered a lower-performance grade, TA and WFA exhibit comparable properties, and the preferred grade is determined by the specific operational requirements of the application [10,25,27].

2.1.2. Product System of High-Alumina Refractory Block Production

Alumina-silicate refractories are classified into fireclay and high-alumina products, with the latter containing at least 42% alumina [1]. High-alumina refractories are further classified into four subcategories based on their purity and the corresponding main raw materials. The purest grade, with over 80% alumina, is usually produced from bauxite, corundum and calcined, sintered or fused alumina [1]. In this article, the cradle-to-gate LCA of a 95% high-alumina fused cast block produced from CA is presented. Electrofused refractories are generally characterized by high density and low permeable porosity, which guarantees enhanced resistance to corrosion, erosion and high temperatures [10,29,30]. Their production involves three main steps, namely melting, casting and cooling [29,31].

A detailed flowchart of fused casting, adapted to the high-alumina block, is presented in Figure 2. The related inventory of mass and energy flows is presented in Table 3.

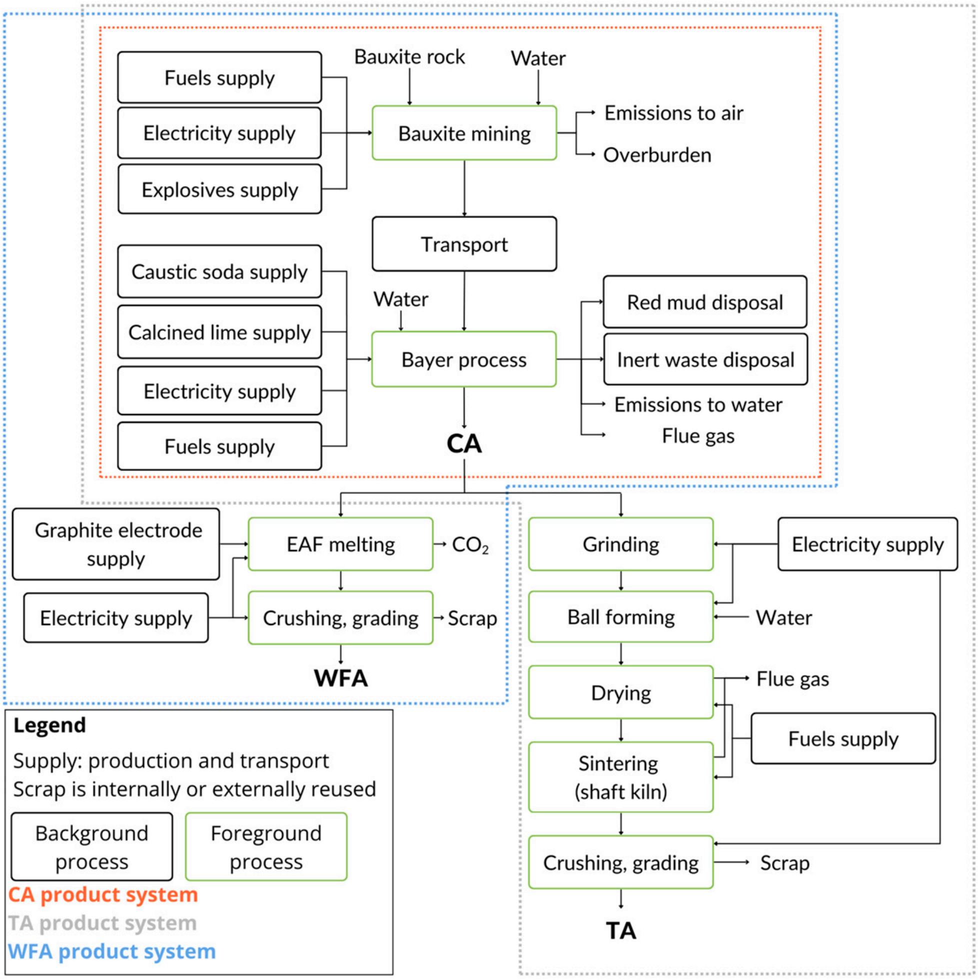

Figure 1. Production flowchart of calcined (CA), tabular (TA) and white fused (WFA) alumina.

Table 2. Life cycle inventory of tabular (TA) and white fused alumina (WFA) production. Reference unit: 1 ton.

	Unit	TA	WFA
Input			
Calcined alumina	ton	1.05	1.05
Electricity	kWh	-	1622
Coal	MJ	2044	-
Graphite electrodes	kg	-	3.6
Bulk bag	kg	1.3	1.3
Wooden pallet	n.	0.07	0.07
Output			
Product	ton	1	1
CO_2 (to air)	kg	-	13

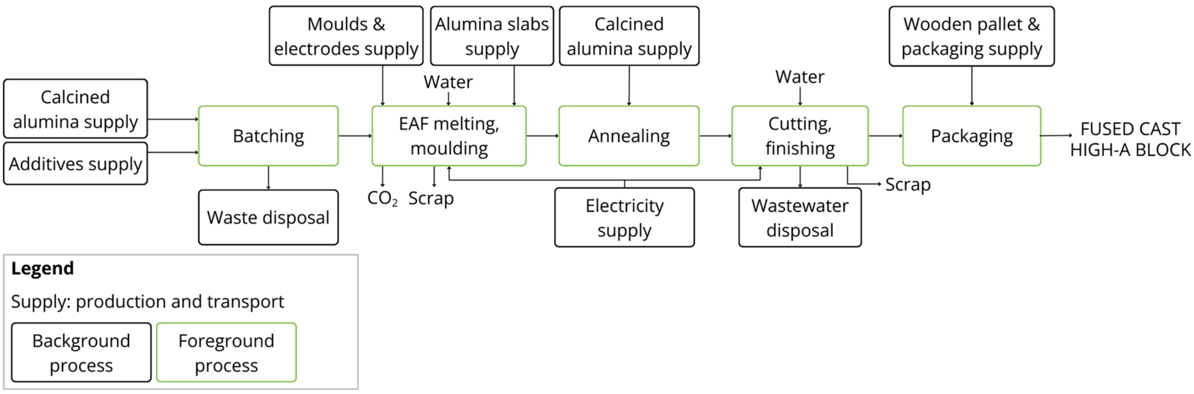

Figure 2. Production flowchart of fused cast high-alumina refractory.

Table 3. Aggregated inventory of fused cast high-alumina block production. Reference unit: 1 ton.

	Unit	Value
Input		
Calcined alumina	kg	2159
Additives	kg	91
Electricity	kWh	3348
Graphite (molds & electrodes)	kg	40
Coating (molds & electrodes)	kg	5
Road transport (raw materials)	tkm	1656
WFA for slabs (consumable)	kg	58
Annealing CA (consumable)	kg	14
Water	m^3	0.2
Wooden pallet	n.	0.2
Plastic for packaging (mix)	kg	0.6
Cardboard for packaging	kg	0.4
Waste (packaging of raw materials)	kg	6.3
Output		
Alumina block	kg	1000
CO_2 (to air)	kg	66.5

Electrofused alumina blocks are produced by melting raw materials, mainly CA, either virgin or recycled, in an electric arc furnace, generating a highly fluid bath of molten oxides. The molten material is then poured into molds (graphite in the present case) to shape the blocks. A sacrificial header is added to the mold to act as a liquid reservoir during solidification, feeding the block as it shrinks. After casting, the pieces are demolded to undergo annealing by slowly cooling in an insulating alumina-based medium to relieve internal stresses. Finally, the solidified blocks are machined, and their headers are removed to expose the dense, homogeneous part of the block, ensuring high dimensional accuracy and excellent material quality for use in demanding furnace applications. It has to be underlined that incorporating internal scraps improves overall yield; therefore, plants typically maintain 20–30% fused cast grog in the feed to facilitate production of high-grade blocks. Finally, blocks undergo quality control and packaging. The core processes just described constitute the foreground system. The supply of energy, raw materials, packaging and consumables, such as graphite electrodes and molds, and annealing alumina media, represents the background system.

2.2. Life Cycle Inventory

The life cycle inventory (LCI) represents the product system through a list of mass and energy flows. Ecoinvent version 3.9.1 “cut-off by allocation” is chosen as the reference commercial database to model background processes. Primary data and existing literature are used to model the foreground system.

2.2.1. Alumina Grades Production

The life cycle inventories of alumina grades are compiled from literature data. Based on data availability, partially aggregated inventories are built. Bauxite mining and CA production inventories are approximated from primary data collected by the International Aluminium Institute in 2019 [32]. The Bayer process is modeled as an integrated system, precluding detailed analysis at the unit-process level (Table S1, Supplementary Materials). Table 2 shows the inventories for the production of 1 ton of TA and WFA.

For WFA production, a yield of 95% is assumed, with energy intensity and electrode consumption in the electric arc furnace melting taken from [28]. The national Chinese electricity grid mix of 2020 is adopted. Graphite electrodes are supposed to be fully oxidized into carbon dioxide. The cooling water for the electric arc furnace is assumed to be continuously recirculated in a closed system. The consumption of iron molds is put outside the system boundaries due to a lack of information. A standard comminution circuit including primary crushing and grinding is considered. Its energy consumption is approximated from primary data, and its contribution to the total energy consumption is found to be negligible (<1%). For TA production, a yield of 95% is considered. The total energy consumption is approximated as 35% of that of WFA production [33], following the approach of [17]. Coal is chosen as the heat source. For all alumina products, the inventory includes the consumption of packaging materials, i.e., 1.5-ton plastic bulk bags and wooden pallets. The models for CA and WFA production constitute an update of those presented in [11].

2.2.2. High-Alumina Refractory Block Production

The inventory for producing 1 ton of high-alumina fused cast blocks is presented in Table 3. The values are derived from primary data collected at production plants over a one-year operating period. To ensure that the inventory remains representative rather than case-specific and to respect confidentiality constraints, these primary data were adjusted before being made publicly available.

The production is assumed to take place in China, with Chinese CA as the main raw material. The global production yield is 44%, resulting from 40% mass loss at the machining stage (mainly related to the sacrificial header), 20% rejection rate at the final quality control and minor mass loss during electrofusion. Both cutting residues and rejected blocks are pre-consumer scraps, which are commonly closed-loop recirculated to substitute virgin alumina. This is made possible by the material’s ability to retain its properties unchanged after multiple melting cycles. Eventual surplus scrap is likely to be open-loop recycled as an alumina source in other products within the production plant. However, external recycling is generally not practiced because it is not economically viable. In this model, scraps are considered to be recyclable waste, and a simple cut-off allocation is applied, hence not attributing them any burden. The choice is in line with the polluter pays principle and is further justified by the lack of clear open-loop recycling options. Nevertheless, future research should explore alternative allocation methods that assign a portion of the environmental burdens to scraps. The benchmark inventory described in

Table 3 considers a worst-case scenario with 100% consumption of virgin CA, meaning no closed-loop recirculation of scrap. About 5% of the feed is represented by additives. The electrofusion generates CO_2 emissions due to feed and electrode oxidation, and fines, which are reused in the plant. Electricity is the only energy source and is modeled through the 2020 Chinese grid mix (approximately 60% hard coal and 20% hydropower as the main sources). Almost all electricity is employed for melting, with negligible contribution from block cutting (<2%). Consumables include electrodes and molds, which are made of graphite and a coating, annealing CA powder, and WFA slabs intended for mold placement. All consumables are either reused in the plant or sold as scraps. The water employed for cooling the electric arc furnace is closed-loop recirculated, while the quota used for cooling the cutting saws is consumed, treated and disposed of. Finished blocks are packed on wooden pallets and protected with cardboard and plastic wrapping.

Production Scenarios for High-Alumina Blocks

Scenario analysis is carried out on high-alumina block production to assess how environmental impacts vary under different operating conditions and to inform ecodesign strategies by identifying parameters that deliver the greatest improvements with minimal change. Raw material production and direct energy use are typically the main environmental hotspots of refractory products [7]. Accordingly, scenarios are developed to examine the influence of changes in both the quality and quantity of CA and electricity. Rather than applying a generic sensitivity analysis, the scenarios are constructed from actual plant configurations and from realistic ranges of parameters that could be modified as part of potential improvement strategies. In this system, the factors affecting the raw material contribution are the source of CA and the production yield, which is principally influenced by design-related mass loss and rejection rates (cf. Section 2.2.2). For energy use, a single scenario evaluates the impact of switching to a more sustainable electricity mix. Table 4 presents the modeling assumptions of the six scenarios considered.

Table 4. Description of fused cast high-alumina block production scenarios.

Parameter	Benchmark (Worst-Case)	Scenario 1 (Recycled)	Scenario 2 (NG-CA)	Scenario 3 (Design)	Scenario 4 (Rejection)	Scenario 5 (Hydro)	Scenario 6 (Best-Case)
CA source	100% virgin (hard coal)	50% recycled–50% virgin (hard coal)	100% virgin (natural gas)	100% virgin (hard coal)	100% virgin (hard coal)	100% virgin (hard coal)	30% recycled–70% virgin (natural gas)
Mass loss by block design	40%	40%	40%	20%	40%	40%	20%
Rejection rate	20%	20%	20%	20%	10%	20%	10%
Electricity source	National grid mix	National grid mix	National grid mix	National grid mix	National grid mix	Hydropower	Hydropower
Production yield (global)	44%	44%	44%	59%	50%	44%	67%

The "Benchmark" scenario corresponds to the inventory shown in Table 3 and reflects the worst-case production setup. Scenarios 1 and 2 involve consuming low-impact CA sources. In Scenario 1, half of the virgin CA is replaced with closed-loop scrap with a 1:1 substitution factor, under the assumption that the production process remains unchanged. The recirculated scrap undergoes crushing to achieve the required grain size. In Scenario 2, 100% of natural-gas-based virgin CA (NG-CA) is consumed. The LCA characterized impacts of NG-CA production are provided in the Supplementary Materials (Table S2). Scenarios 3 and 4 examine how production yield affects LCA impacts. The global yield is calculated upon the mass loss at the cutting stage, typically ranging from 20% to 40%; the rejection of damaged blocks, which generally falls between 10% and 20%; and minor losses during melting. Maximizing production efficiency requires reducing cutting residues through precise mold and block design while also lowering the rejection rate by controlling the cooling process to prevent cracking from rapid tension release. Scenario 3 assumes a reduced mass loss by design (20%), while Scenario 4 focuses on lowering the rejection rate to 10%. These changes affect the inventory differently. Reducing the number of blocks produced influences the entire process chain, whereas limiting the cutting-related mass loss mainly affects the batching and melting stages. Casting and subsequent treatments remain unchanged, as their inventories depend on the number of blocks processed rather than the treated mass. The distinction is reflected in the resulting production yields: 59% in Scenario 3 and 50% in Scenario 4. Scenario 5 evaluates the effects of replacing the standard coal-based (~60%) national electricity grid mix with a mix based mainly on hydropower (87%). Lastly, Scenario 6 includes all the described improvements as the best-case scenario, with the recycled alumina content limited to 30% to respect the availability of closed-loop scrap.

2.3. Life Cycle Impact Assessment and Results Interpretation

Life Cycle Impact Assessment (LCIA) converts the inventory flows into impacts on a set of environmental categories (characterization), which are eventually normalized and pondered, and ultimately interpreted. The LCA results presented in Section 3.1 are calculated in LCA for Experts software (version 10.9.0.31), applying the impact assessment method EF 3.1, which is part of the European Product Environmental Footprint (PEF) framework [4]. Results interpretation is oriented towards the identification of environmental hotspots to shape effective ecodesign strategies.

Hotspot Analysis

Hotspot analysis supports LCA results interpretation and ecodesign by highlighting environmental improvement opportunities and prioritizing the most effective actions [34,35]. Following the PEF methodology [36], the hotspot analysis applied in this study includes four main steps

- Identification of the most relevant impact categories;
- Evaluation of processes' relative contribution;
- Design of impact reduction actions;
- Quantification of actions' potential burden reduction through LCA.

Relevant impact categories can be identified in different ways depending on the methodological framework applied. In some cases, target categories are directly defined in the LCA goal and scope by the commissioning party. For instance, climate change is often of interest due to the current decarbonization efforts in many industrial sectors. When no such requirements are set, relevant categories are defined as those most affected by the product system under study. The assessment is typically conducted at the normalization or weighting stage, as these steps ensure consistent units over the environmental categories. Normalization compares characterized results with a reference situation, while weighting adjusts the normalized results according to the relative importance of each category on the overall environmental footprint. The inherent uncertainties in normalization and weighting factors may affect LCA results by misleading the comparison among impact categories and their prioritization [35]. Therefore, this study compares the four highest normalized impact categories with those contributing to at least 80% of total weighted impacts (PEF framework), to assess the reliability of the two approaches and their implications for ecodesign. Special attention is given to human toxicity burdens, which are often seen as critical in the Bayer process due to red mud disposal [37,38].

Once the meaningful environmental domains are identified, the processes' relative contribution to the global burdens is analyzed. Hotspot processes show high characterized impacts and cumulatively contribute to at least 80% of the most relevant impact categories. Then, actions aimed at reducing the overall burdens are designed to target these hotspots. Each potential action is validated through LCA by comparing its environmental performance to the benchmark case.

3. Results

3.1. LCIA Characterization Results

Tables 5 and 6 describe the EF 3.1 midpoint characterization results of alumina grade and high-alumina block production, respectively, expressed per ton of product.

Table 5. LCIA characterized results of CA, TA and WFA production. EF3.1, reference unit 1 ton.

Impact Category	Unit	CA	TA	WFA
Acidification	Mole of H^+ eq.	13.6	16.7	23.0
Climate Change, total	kg CO_2 eq.	1750.5	2123.7	3421.89
Ecotoxicity, freshwater, total	CTUe	6803.0	7721.1	11,473.7
Eutrophication, freshwater	kg P eq.	0.9	1.0	1.2
Eutrophication, marine	kg N eq.	1.9	2.3	3.8
Eutrophication, terrestrial	Mole of N eq.	20.7	24.5	40.6
Human toxicity, cancer, total	CTUh	7.1×10^{-6}	7.5×10^{-6}	7.8×10^{-6}
Human toxicity, non-cancer, total	CTUh	1.0×10^{-4}	1.1×10^{-4}	1.2×10^{-4}
Ionizing radiation, human health	kBq U235 eq.	29.5	32.2	97.9
Land Use	Pt	4877.5	5522.7	8105.7
Ozone depletion	kg CFC-11 eq.	6.4×10^{-5}	6.8×10^{-5}	7.0×10^{-5}
Particulate matter	Disease incidences	1.9×10^{-4}	2.3×10^{-4}	3.2×10^{-4}
Photochemical ozone formation, human health	kg NMVOC eq.	6.1	7.2	11.4
Resource use, fossils	MJ	2.0×10^{4}	2.5×10^{4}	4.2×10^{4}
Resource use, mineral and metals	kg Sb eq.	1.6×10^{-3}	1.8×10^{-3}	2.8×10^{-3}
Water use	m^3 world eq.	330.6	357.1	525.5

Among the alumina grades, CA production exhibits the lowest environmental impacts, while WFA shows the highest. This outcome was expected, given that CA serves as the raw material for the production of TA and WFA, which consequently bear additional environmental burdens from further processing steps. WFA production is more impactful than TA due to its higher energy intensity. Concerning climate change, $CO_{2,eq}$ emissions range from 1.7 to 3.4 tons per ton of alumina. It is underlined that the cradle-to-gate LCA results presented in Table 5 are intended to provide an overview of the environmental performance of the alumina grades rather than a direct comparison. Indeed, owing to their different thermo-mechanical properties, each grade provides distinct technical advantages for specific applications and may deliver varying service lifetimes when used in the same application. Therefore, any direct comparison must account for these considerations.

The production of alumina blocks results in higher environmental impacts compared to alumina grades, as expected due to the more complex manufacturing process and broader system boundaries. A total of 7.9 tons of $CO_{2,eq}$ are emitted per ton of blocks.

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Table 6. LCIA characterized results of fused cast high-alumina block production. EF3.1, reference unit 1 ton.

Impact Category	**Unit**	**High-A Block**
Acidification	Mole of H^+ eq.	54.4
Climate Change, total	kg CO_2 eq.	7879.8
Ecotoxicity, freshwater, total	CTUe	30,224.8
Eutrophication, freshwater	kg P eq.	2.7
Eutrophication, marine	kg N eq.	8.8
Eutrophication, terrestrial	Mole of N eq.	94.9
Human toxicity, cancer, total	CTUh	1.7×10^{-5}
Human toxicity, non-cancer, total	CTUh	2.7×10^{-4}
Ionizing radiation, human health	kBq U235 eq.	219.9
Land Use	Pt	22,247.8
Ozone depletion	kg CFC-11 eq.	1.6×10^{-4}
Particulate matter	Disease incidences	7.5×10^{-4}
Photochemical ozone formation, human health	kg NMVOC eq.	27.8
Resource use, fossils	MJ	98,897.6
Resource use, mineral and metals	kg Sb eq.	8.6×10^{-3}
Water use	m^3 world eq.	1218.2

3.2. Hotspot Analysis

3.2.1. Identification of Critical Impact Categories

The first step of hotspot analysis entails identifying the environmental domains most affected by the studied product system. To assess how the LCIA method influences hotspot analysis, the four categories with the highest normalized impacts are compared with those contributing to at least 80% of the global weighted impacts (cf. Section Hotspot Analysis). Detailed normalized and weighted impacts, along with category hierarchies, are provided in the Supplementary Materials (Tables S3–S5).

Across all alumina products, the same patterns emerge. Non-cancer human toxicity consistently shows the highest normalized impact, followed by freshwater eutrophication and particulate matter. The fourth most affected category is cancer human toxicity for CA and TA, and fossil resource use for WFA and high-alumina blocks. At the weighting stage, the critical categories remain consistent across products. Six categories are identified as meaningful, with their relative importance being reversed compared with normalization. Climate change dominates the weighted impacts, alone covering 27–30% of the global burdens, followed by particulate matter and fossil resource use (each ~15%). Acidification, freshwater eutrophication and non-cancer human toxicity complete the list of relevant categories.

3.2.2. Alumina Grades: Processes' Relative Contribution

Figure 3 illustrates the processes' relative contribution to alumina grades production. The reported values represent the processes' average contribution, calculated as the mean across the environmental domains identified as significant in Section 3.2.1.

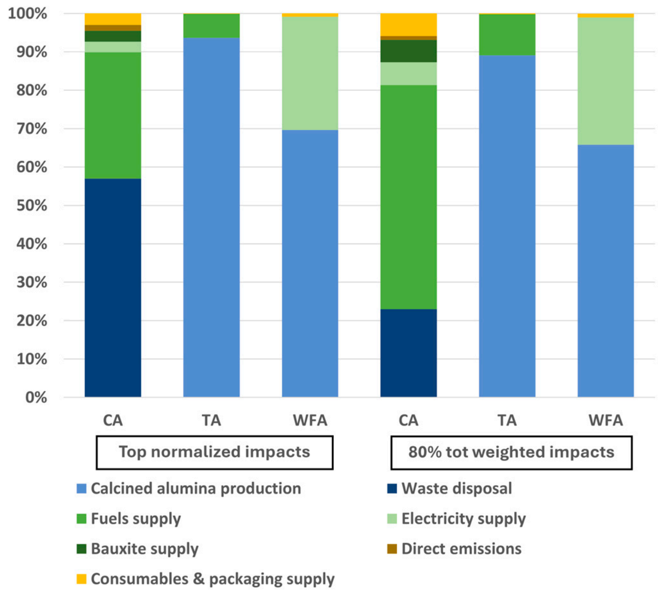

Figure 3. CA, TA and WFA production: processes' relative contribution to the categories with the highest normalized values (**left**) and those contributing to over 80% of weighted impacts (**right**). EF3.1.

On average, CA production contributes to about 90% and 70% of the normalized environmental impacts associated with TA and WFA production, respectively. A negligible variation of share is observed at the normalization and weighting stages (5%) due to CA contributing less to the highest-weighted impact categories, i.e., climate change and acidification (about 86%), than to the top normalized categories (98% for non-cancer human toxicity and 91% for freshwater eutrophication). Energy supply, in the form of electricity for WFA and heat in TA, is responsible for the residual burdens at both normalization (29% for WFA, 6% for TA) and weighting levels (33% for WFA, 11% for TA). The contribution of packaging material supply is negligible in all cases due to the low quantity of consumed material. The same consideration applies to the supply of graphite electrodes for WFA. CA is therefore recognized as the primary environmental hotspot for TA and WFA production, followed by energy supply.

Regarding CA production, a significant difference in the burden share at the normalization and weighting stage is observed in Figure 3. The highest normalized impact categories are mainly driven by waste disposal (57% of total burdens) and fuel supply (33%). Waste disposal corresponds to the management of red mud, i.e., the residue of Bayer digestion containing gangue and undissolved minerals. Red mud disposal accounts for 86% of non-cancer human toxicity, 94% of cancer human toxicity and 47% of freshwater eutrophication. These effects are mostly caused by the alkalinity of the mud and the potential leaking of toxic and heavy metals [37–39]. Fuel supply mostly refers to hard coal, which covers 85% of the energy demand and 96% of the fuel-related burdens. Electricity, bauxite, and consumables supply each contribute to approximately 3% of the total normalized environmental impacts. Consumables' share is primarily attributed to quicklime and soda production, with packaging materials playing only a minor role. At the weighting stage, the burden distribution shifts notably: fuel supply increases to 58% of total impacts, while waste disposal decreases to 23%. Also, 6% of the impacts are attributed individually to electricity, bauxite and consumables supply. The reduced relevance of red mud disposal results from the low weighting factor assigned to human toxicity and its limited contribution to acidification, climate change, particulate matter and fossil resource use (around 1%). Conversely, fuel supply emerges as more dominant, generating approximately 75% of impacts within these categories. Overall, fuel supply and red mud disposal are key environmental hotspots in CA production, though LCIA methodological biases constrain a precise assessment of their actual contribution.

3.2.3. High-Alumina Refractory Block: Processes' Relative Contribution

Figure 4 shows the processes' relative contribution to fused cast high-alumina block production. The reported values represent the processes' average contribution, calculated as the mean across the environmental domains identified as significant in Section 3.2.1.

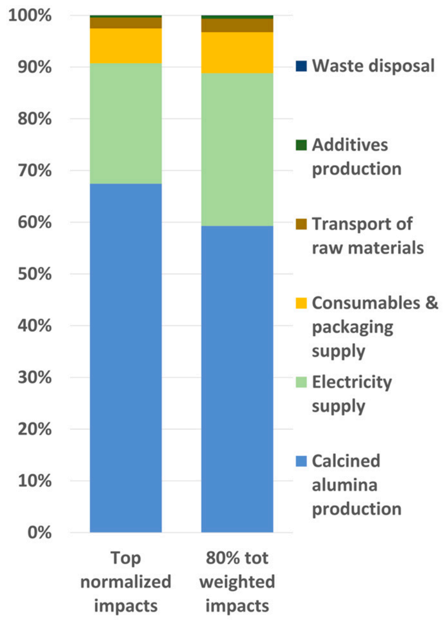

Figure 4. Fused cast high-alumina block production: processes' relative contribution to the categories with the highest normalized values (**left**) and those contributing to over 80% of weighted impacts (**right**). EF3.1.

At the normalization level, critical impact categories are affected mainly by CA production (67%) and electricity supply (23%). The supply of consumables and packaging generates 6% of the burdens, primarily due to the production of CA and WFA. Negligible impacts (<3%) arise from additives supply, transport of raw materials, and waste disposal. As observed for alumina grades, the share of burdens attributed to CA decreases at the weighting stage (−7%) due to the lower relevance of toxic impacts and the reduced contribution to climate change, fossil resource use and acidification burdens. Globally, the results are consistent with those obtained for TA and WFA production, with CA supply and electricity as the main hotspots.

3.3. Scenario Analysis on High-Alumina Block Production

Six scenarios are considered for fused cast high-alumina block manufacturing to quantify the environmental performance of various production setups (Section Production Scenarios for High-Alumina Blocks). Figure 5 compares the impacts of each scenario, expressed as percentages relative to the benchmark case.

Table 7 summarizes the key outcomes of scenario interpretations, with full results provided in the Supplementary Materials (Table S6). It reports the average burden reduction across meaningful impact categories, the maximum reduction achieved, and any associated trade-offs. The best-case production setup modeled in Scenario 6 reduces overall burdens by an average of 77% relative to the benchmark. This reduction is lower than the total cumulative gains observed across Scenarios 1–5 due to the lower recycled content and the partial overlap of certain improvement actions. For instance, higher production efficiency decreases total energy demand, thereby limiting the additional benefits of switching to a lower-impact electricity mix. Acidification, climate change, particulate matter, and marine eutrophication decrease by over 80%, while water use increases by 142%. The reductions in acidification and particulate matter align with the use of natural-gas-based CA (Scenario 2), whereas the changes in marine eutrophication, climate change and water use reflect the influence of hydroelectricity consumption (Scenario 5).

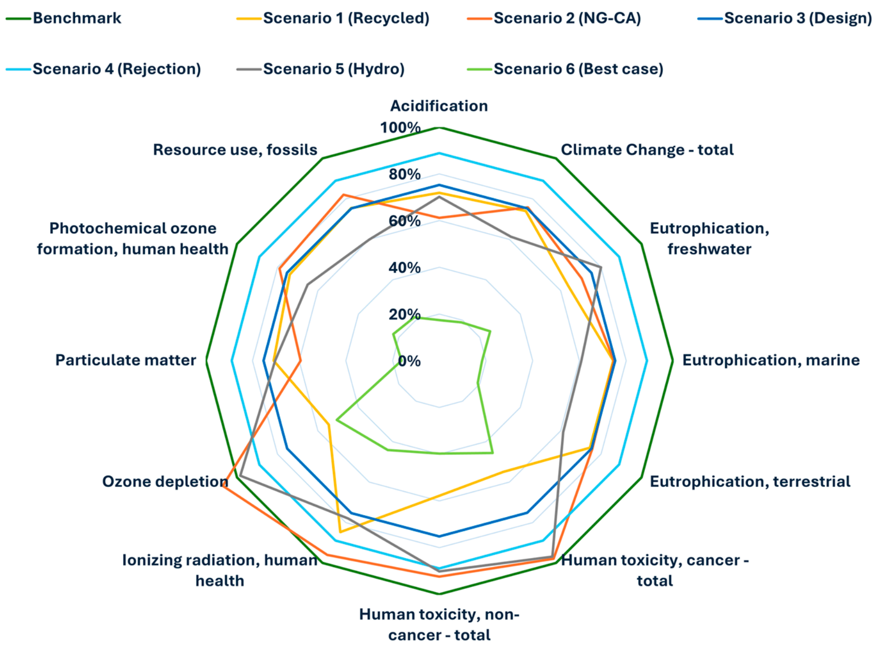

Figure 5. LCIA characterized results for fused cast high-alumina block production scenarios, expressed as relative values to the benchmark model. EF 3.1.

Table 7. LCIA results interpretation of fused cast high-alumina production scenarios. Maximum and average reduction on benchmark model and trade-off effects. EF 3.1.

Scenario	Average Reduction in Meaningful Categories	Maximum Reduction	Increased Impacts
Scenario 1 (recycled)	31%	−45% cancer human toxicity & ozone depletion	None
Scenario 2 (NG-CA)	26%	−40% acidification & particulate matter.	Negligible +7% on ozone depletion.
Scenario 3 (design)	25%	All reductions comprised in the range 23–25%.	None
Scenario 4 (rejection)	11%	All reductions comprised in the range 10.5–11%.	None
Scenario 5 (hydro)	28%	−40% marine eutrophication & fossil resource use.	+284% water use.
Scenario 6 (best-case)	77%	−83% particulate matter & acidification.	+142% water use.

4. Discussion

Among the alumina grades, CA production generates the lowest environmental impacts and WFA the highest. This result was expected, given that both WFA and TA are derived from CA. The supply of fuels for CA sintering causes the additional impacts of

TA production (approximately 10%). Similarly, the supply of electricity required by CA melting generates roughly 30% of WFA burdens. These results provide an overview of the environmental performance of the alumina grades rather than a direct comparison. The higher energy intensity of TA and WFA production is linked to their higher purity and enhanced thermo-mechanical properties, which improve wear resistance and extend service life in use [10,25,27]. Consequently, direct product comparison and ecodesign strategies involving alumina grade substitution should consider both environmental impacts and technical performance to avoid misleading conclusions.

In terms of absolute values, the impact on climate change of CA production is consistent with the literature [9,40,41]. The lower CF reported by Königshofer for non-metallurgical CA and WFA production (0.7 ton $CO_{2,eq}$/ton CA and 1.0 ton $CO_{2,eq}$/ton WFA, Table 1) likely result from narrower system boundaries and lower emission factors attributed to the energy supply [13]. This conclusion aligns with Ranaivoharilala et al., who found that the same WFA production route in China generates five times more $CO_{2,eq}$ emissions than in Europe (6.0 vs 1.1 ton $CO_{2,eq}$/ton WFA) due to the differences in the national electricity mix [12]. The preliminary climate change impact of WFA presented in [11] overstated due to the overestimation of the melting energy intensity. The $CO_{2,eq}$ emissions calculated for TA production are consistent with [13].

A comparison with existing literature is not feasible for high-alumina blocks, as no prior studies have examined fused cast products, and their process and energy requirements differ substantially from the sintered or baked bricks typically reported.

4.1. Critical Use of Hotspot Analysis and Methodological Limitations

The present study applies hotspot analysis to alumina products to establish guidelines for LCA results interpretation in the refractory sector. In detail, it outlines the optimal approach for selecting relevant impact categories and identifying process hotspots to be prioritized in ecodesign strategies.

Results interpretation should account for the relative robustness of each impact category, acknowledging that certain categories exhibit higher uncertainty due to challenges in modeling cause–effect pathways. For instance, the robustness of ecotoxicity and human toxicity indicators is often questioned due to the incomplete characterization models and the large number of uncharacterized flows [42]. Consequently, several LCA guidelines, such as the Harmonization of LCA Methodologies for Metal Guidance, applicable to metallurgical alumina, recommend excluding these categories from decision-making [40,43]. In parallel, previous refractory-focused studies highlight the limited reliability of mineral resource depletion metrics due to the scarcity and uncertainty of characterization factors for crucial raw materials [44,45]. Within the PEF framework, normalization does not consider the uncertainty of the results, as it just scales characterized results to a reference situation. Weighting, by contrast, evaluates the relative importance of each category on the overall environmental performance by integrating its perceived criticality and its methodological robustness [46,47]. This approach assigns the highest weighting factor to climate change, reflecting both strong scientific reliability and great societal concern, while toxicity-related categories use the lowest weighting factor due to their limited robustness. Similarly, mineral resource use is considered a weak category and hence is attributed a low weighting factor. For these reasons, the PEF approach of selecting critical impact categories that contribute to at least 80% of weighted impacts is here considered to provide a sound and transparent basis for interpreting LCA of alumina products and, by extension, refractories. It adequately accounts for methodological uncertainties and variable robustness of characterization models while preserving a comprehensive assessment that avoids excluding categories a priori. The explicit 80% threshold further enhances consistency and limits practitioners' subjectivity.

This study demonstrates that normalization and weighting significantly affect the prioritization of impact categories for both alumina grades and high-alumina block. Although the same categories emerge as critical across products and methodological levels, their relative importance shifts between normalization and weighting.

Non-cancer human toxicity consistently shows the highest normalized impacts for all products, primarily due to the leaking of toxic elements from red mud disposal. However, its relevance decreases substantially at the weighting stage. At weighting, climate change registers the highest impact, followed by particulate matter, fossil resource use, acidification, freshwater eutrophication, and ultimately, non-cancer human toxicity. To ensure the robustness of these results, the environmental impacts of CA production were recalculated using the ReCiPe 2016 v1.1 Midpoint (H) method (Table S7, Supplementary Materials). Due to the absence of midpoint weighting factors, the identification of critical impact categories relies solely on normalized results. Under this framework, cancer human toxicity and freshwater and marine ecotoxicity rank among the categories with the highest normalized scores. This outcome confirms that toxicological impacts remain influential not only at different methodological levels but also when assessed through an alternative LCIA methodology.

The results are consistent with the existing literature on refractories [7,48]. Specifically, the manufacturing of alumina and alumina-based refractories is demonstrated to highly affect freshwater eutrophication, toxicity categories, particulate matter and climate change [3,9,19].

The environmental performance of alumina grades and alumina-containing refractories is largely driven by direct and indirect energy consumption. Direct energy demand, in the form of fuel for TA and electricity for WFA, accounts for 11% and 33% of their respective burdens. Indirect energy use mostly originates from the supply of CA, which constitutes the main hotspot for both TA and WFA. This is primarily due to hard coal, responsible for 58% of CA's burdens. The result on energy supply being the dominant contributor to CA impacts, regardless of its source, is consistent with the literature [9,49]. Regarding climate change, the 74% share of $CO_{2,eq}$ emissions attributed to hard coal supply in this study aligns with the range of 65–72% reported in [14].

For the production of fused cast high-alumina block, burdens stem mainly from direct electricity consumption (30%) and calcined alumina supply (59%), leading to a global contribution from direct and indirect energy use exceeding 65%. The high relevance of CA supply also explains the consistency of the most relevant categories across alumina grades and high-alumina block.

4.2. Interpretation of Scenario Analysis on Alumina Block Production

Scenario analysis is applied to fused cast high-alumina block production to evaluate how key parameters influence LCA results, define the range of potential impacts arising from different operating conditions, and support ecodesign. The scenarios target CA and electricity supply, identified as the main hotspots of this production route (Section 3.3). Scenarios 1–4 compare strategies aimed at reducing the burdens associated with CA, either by lowering its consumption or by using less impactful alumina sources. Increasing the acceptance rate proves more effective than improving block design, although the rejection rate varies in a restricted range (10–20%), which limits the maximum achievable improvement (Figure 5). On the contrary, proper block design can yield larger gains because it allows higher mass reduction (typically 20–40%). In addition to reducing upstream raw-material impacts, improved production efficiency also reduces energy demand by lowering the treated mass, thereby addressing both main hotspots simultaneously. Across all CA-oriented scenarios (1–4), substituting the alumina source is more effective than merely reducing its consumption. When closed-loop recirculated scrap is consumed, the achievable substitution is constrained by scrap availability, which is inversely proportional to the production yield. For instance, the 44% yield in Scenario 1 allows a 50% substitution rate, while only 30% replacement is feasible in Scenario 6 (67% yield). Externally sourced recycled alumina could increase scrap availability and allow higher substitution rates, but the net benefit may be offset by the impacts arising from its recycling and transport. Using low-impact virgin CA enables full substitution, making the potential burden reduction depend on the geographical and technical context of its production (Scenario 2). In this study, 50% internal scrap content guarantees slightly higher burden reduction than 100% substitution with natural-gas-based CA (31% vs 26%). The optimal strategy would combine the two options, using all available closed-loop scrap and sourcing the residual virgin CA from low-impact production. This option would guarantee approximately 40–45% burden reduction. Future research should verify whether secondary alumina could offer additional advantages, as scrap remelting may be energetically convenient compared to CA melting.

Scenario 5 focuses on the second hotspot of fused cast block production: electricity supply. Shifting from the coal-based Chinese electricity grid mix to mainly hydroelectricity reduces overall burdens by approximately one-third (−28%), on average. However, the shift triggers a rebound effect, significantly increasing water use to the point that it becomes one of the meaningful categories contributing to 80% of the weighted impacts. This result proves that electricity influences not only the magnitude of the environmental impacts but also which domains are most affected. Hence, changing the energy source may generate unexpected burden shifts to other impact categories. Therefore, any potential improvement measure, even if perceived as environmentally effective, must be systematically evaluated through LCA.

4.3. Ecodesign Recommendations

Ecodesign recommendations are drawn for alumina grades and high-alumina block production, combining the outcomes of scenario and hotspot analyses. Fuel supply is the main hotspot of CA production, therefore indicating that improvement strategies should aim at reducing energy intensity and shifting to lower-impact fuels. For instance, replacing hard coal with natural gas can reduce the impacts by roughly one-third (Table S2, Supplementary Materials). Alternatively, the electrification of the production route, coupled with renewable electricity, has been identified as particularly effective in previous studies [14]. Adopting innovative solutions for improved red mud management could support additional impact reductions, particularly for human toxicity and ecotoxicity. However, the feasibility of this option remains uncertain given the extensive past efforts already devoted to this issue. Optimization efforts for TA and WFA production should prioritize decreasing the consumption of virgin CA. Increasing production yield appears challenging due to the already high process efficiency (95%), and the marginal improvements are likely to bring limited benefits. More effective alternatives include using less-impactful CA or secondary alumina. In parallel, both products could benefit from cleaner energy mixes, for instance, replacing hard coal with natural gas in TA production or using renewable electricity sources for WFA.

Ecodesign recommendations for fused cast high-alumina block production were already introduced in Section 4.2. Environmental performance is mainly driven by CA and electricity supply; therefore, improved production and energy efficiency is central to limiting impacts. Further reduction can be achieved by adopting low-impact alumina sources and green electricity. It is noted that strategies yielding proportionally greater burden reduction do not necessarily lead to the largest overall improvements, due to technical limitations. For example, although improving rejection yield is more efficient than optimizing refractory block design, its limited variability constrains the maximum improvement achievable. Similarly, the substitution of virgin CA with closed-loop scrap is restricted by global production yield and the resulting scrap availability. In any case, yield improvements always ensure lower energy demand. In parallel, adopting renewable electricity sources, such as hydropower, can greatly enhance the environmental performance of fused cast high-alumina block production. Still, attention must be paid to avoid unintended burden shifts, including potential rebound effects.

4.4. Future Research

Despite the novelty of the inventories provided in this article, future research should focus on their improvement and updating. In detail, the dataset of CA production should be adapted to non-metallurgical grades by incorporating the refining treatments applied to Bayer alumina. The inventories of TA and WFA should be revised and expanded to include the treatments currently overlooked, such as ball-forming and purification. In all cases, providing process-level data would allow more detailed analyses of environmental hotspots and operational criticalities. Additional primary data collection is also needed for fused cast high-alumina block production to increase the representativeness of the inventory across product grades and operational setups. More extensive geographical coverage should also be addressed in future studies by regionalizing the manufacturing route of alumina products.

The variability of impact scores observed in the commercial database used for modeling background processes highlights the need to constantly update the calculations to guarantee the reliability of LCA results and their compatibility with other studies. With respect to ecodesign, scenario analyses should be systematically applied across all production routes to refine and strengthen improvement strategies. Priority areas include evaluating the technical and environmental feasibility of electrifying CA production, as well as assessing whether scrap remelting in high-alumina block manufacturing could reduce overall energy demand compared to the use of virgin alumina.

In parallel, future research should tackle several methodological LCA challenges, such as improving toxicity characterization models, establishing a harmonized methodological framework for refractory materials, and applying uncertainty analysis more systematically. In the case of high-alumina block production, the effect of the allocation approach should also be studied by considering scrap as a co-product and allocating it an appropriate share of the burdens.

5. Conclusions

Rising environmental awareness is driving the integration of environmental considerations into economic decisions, promoting both the production and usage of lower-impact products. The refractory sector is gradually adapting to this transition and applying LCA as an ecodesign support tool. Nevertheless, a harmonized modeling approach has yet to be established, and the environmental performance of numerous refractory products remains unexplored. This study tackles both challenges by performing the LCA of alumina grades and fused cast high-alumina block production. The key outcomes of the article could be summarized as follows:

- New inventories and LCAs are provided for TA, WFA and fused cast high-alumina block production.
- The PEF approach is recommended for results interpretation, as it ensures a comprehensive analysis of the environmental performance while accounting for intrinsic

biases and uncertainties in LCIA methods. The primary challenge of alumina products lies in accurately quantifying toxicity impacts.

- Alumina products generate meaningful impacts on climate change, fossil resource use, particulate matter, acidification, freshwater eutrophication, and non-cancer human toxicity.
- Fuel supply and red mud disposal are the main hotspots of CA production. Environmental burdens could be reduced by changing the energy source, reducing energy demand or applying improved red mud management options.
- CA and energy supply are the main hotspots for TA and WFA production. Improvement strategies include using recycled or low-impact alumina sources, optimizing the production yield, and relying on greener energy sources.
- CA and electricity supply are the main hotspots of fused cast high-alumina block production.
- The scenario analysis on fused cast high-alumina block production illustrates how to build scenarios, incorporate technical constraints, and interpret the main outcomes. The highest burden reduction is achieved by replacing virgin CA with closed-loop scrap, followed by enhancing production yield and substituting the Chinese grid mix with hydropower.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18062790/s1, Table S1. Life cycle inventory of calcined alumina production in China. Reference unit: 1 ton. Adapted from [32]. Table S2. LCIA characterized results and reduction over benchmark of CA production, Natural gas scenario. EF 3.1, reference unit 1 ton. Table S3. LCIA normalized and weighted results of calcined (CA), tabular (TA), and white fused alumina (WFA) production. EF3.1, reference unit 1 ton. Table S4. LCIA normalized and weighted results of fused cast high-alumina block production (benchmark). EF3.1, reference unit 1 ton. Table S5. Most relevant impact categories on normalized (top) and weighted (bottom) impacts for alumina products. EF3.1. Table S6. LCIA characterized results of fused cast high-alumina block production scenarios. EF3.1, reference unit 1 ton. Table S7. LCIA characterized and normalized results of calcined (CA) production. ReCiPe 2016 v1.1 Midpoint (H), reference unit 1 ton.

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Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
CF	Carbon footprint
PEF	Product environmental footprint

A	Alumina
CA	Calcined alumina
TA	Tabular alumina
WFA	White fused alumina
NG	Natural gas

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