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Comparative Life Cycle Assessment of Management and Valorization Practices for Bauxite Residue

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Abstract: The management of bauxite residue (BR) generated during alumina production, is techno-economically challenging due to its colloidal slurry form, high alkalinity, and elevated concentrations of heavy metals and radionuclides. For every tonne of aluminum produced, 2–3 tonnes of BR are generated, leading to an annual global accumulation of approximately 180 million tonnes. At present, dry disposal ("dry stacking") has become the most widely adopted management practice, although wet disposal of slurry remains in use in several regions. In this context, the present study assesses the environmental impact and the associated energy consumption of BR management following three different management and valorization practices: the wet disposal of the residue (baseline scenario), the dry disposal followed by the partial use of the dried BR in cement clinkering (current practice of the Greek aluminum industry) and the dry disposal followed by the partial use of the dried BR in a geopolymerization process. Results show that impact categories such as acidification (AC), freshwater eutrophication (FC), ozone depletion (OD), and photochemical ozone formation (POF) decrease by 21.6–77.7% under drying/valorization compared with the baseline. Dry disposal/geopolymer manufacturing presents the lowest possible environmental impact. However, the decrease of the global warming (GW) (by 12.8%), is relatively limited, while CED increases by 54.2% due to geopolymerization. Given the limited number of LCA studies available on bauxite residue management, this study explores key environmental challenges posed by current practices and identifies opportunities for improving sustainability and resource efficiency within the aluminum industry.

Keywords: red mud; dry disposal; filter pressing; geopolymerization; scenario analysis; contribution analysis

1. Introduction

Bauxite residue (BR), also known as "red mud" is generated through the high-pressure alkaline leaching of bauxite to alumina via the Bayer process [1]. It is discharged from the reactor as a slurry containing 15–30 wt.% solids, with a complex and highly variable geochemical composition that reflects the characteristics of the original bauxite feedstock. Typically, BR contains iron oxides (30–60 wt.%), aluminum hydrated oxides (10–20 wt.%), titanium oxides (traces to 25 wt.%), and various sodium-aluminum silicate phases (up to 20 wt.%) formed secondarily during the leaching process. Bauxite residue presents an increased potential environmental hazard due to: (a) its high alkalinity (pH at the range of 10.5–13); (b) fine colloidal granulometry (partially sub-micron); (c) the presence of various trace heavy metals and metalloids (including arsenic, lead, nickel, chromium and vanadium) and (d) the presence of natural occurring radionuclides (NORMs) such as ^{238}U, ^{226}Ra, 232Th and ^{40}K [1–3]. It is estimated that about 180 million tonnes of BR are produced annually, while 4 billion tonnes have been already accumulated on a global scale [4], rendering it as one of the most hazardous residues of the metallurgy industry.

The production and subsequent management of BR impacts simultaneously the ecosystems, human health and the associated resources. To date, there are two primary methods to dispose bauxite residue: wet disposal (lagooning) and dry disposal (partial removal of water content at a pre-processing stage) also referred as "dry stacking". Despite the widespread adoption of dry disposal of BR to reduce environmental impacts, wet disposal practices are still in use in several countries, notably in India where they remain extensively applied [5–7]. Evaporation ponds containing BR slurry pose various serious environmental and safety hazards, since they are susceptible to natural disasters [8]. A possible rinsing of BR slurry by rain water can cause the emission of concentrated sodium hydroxide amounts and heavy metal ions in the soil and groundwater. Lagooning, at the same time, prevents the recycling of NaOH contained in the slurry back to the Bayer reactor. After the bauxite residue accident in Ajka Hungary in 2010 [9], the scientific community focused on the impact of BR on the human health. The research conclusions presented a specific interest in residue management. Dried fugitive BR dust, despite the resulting prompt irritation of the upper respiratory tract and eyes, disposes a medium hazard—lower in comparison to urban particulate matter [9]. On the other hand, as experiments in vitro revealed, the direct contact of human cells with aqueous media containing BR material decrease their viability. The toxicity is introduced via the leaching of heavy metals and the formation of reactive oxygen species (ROS) [10]. The impact on the resources (resources scarcity) is referred to the loss of water, fossil fuels and raw materials/reagents through the production of alumina and to the amounts of raw materials contained in bauxite residue.

In this context, several life cycle assessment (LCA) studies have been so far focused on the quantification of the environmental impact and the energy consumption in respect of various practices for the management or the valorization of BR slurry. The environmental impact of the residue neutralization (to a pH at the range of 8–9) using sea water instead of lime was investigated via two LCA scenarios: one with the cradle at the bauxite mine and the other with the cradle at the bauxite residue pond. The analysis indicated that neutralization with sea water is beneficial in terms of carbon dioxide emissions (kg of CO_2/kg of neutralizing agent) and electricity consumption which are reduced by 80% and 66% respectively. On the other hand, the fuel usage increases by 12 times due to the increased transportation requirements of bauxite residue loads to the sea [11]. The environmental footprint through the use of BR as co-calcined or pre-vitrified component in Portland cement was assessed at midpoint level considering 18 impact categories. The majority (14) of them, including the global warming potential (GWP) (kg CO_2-eq m^{-3}), decreased by up to 19% (the WP decreased by 17.7%). At the same time, the ionizing radiation potential (kg Co-60-eq m^{-3}), that revels the artificial radioactivity, increases by 93% due to the existence of NORMs in the residue [12]. The comparative potential environmental impact of BR when used as component in a geopolymerization process and in Portland cement was investigated as a function of GWP, terrestrial acidification, water consumption, mineral resources scarcity and fossils resources scarcity. A thermodynamic algorithm was used for the estimation of impact categories values at a upscaled (industrial level). GWP and water consumption when BR is used as geopolymer binder were estimated at 457.9 kg CO_2-eq and 6.95 m^3. The respective values in case of BR as a Portland component were 1208.8 kg CO_2-eq and 2.85 m^3 [13]. The ReCiPe hierarchic endpoint method used for the estimation of the environmental impact through the synthesis of a mortar material containing BR and blast furnace slag (BFS) as the main components. Various indicators presenting the effect on human health, biodiversity and resources scarcity summarized to a single impact value that correlated to the chemical composition of the mortar. It was found out that the total impact value decreases by the BR /BFS mass ratio increase (optimum ratio 3:1) [14]. Recently, more importance is given to the metallurgical treatment of BR. According to thermodynamic simulation data, the use of the residue as a raw material for the production of pig iron, reduces the mineral scarcity and the water consumption, however, it presents a negative effect on two major indicators: The warming potential and the fossil resource scarcity which are increased by 33.6% and by 45.5%, respectively. A conventional industrial electric furnace and solid carbon as reducing agent were considered as the main processing parameters [15]. A life cycle assessment approach used to estimate the environmental impact generated by the BR valorization through the simultaneous extraction of iron and the use of the secondary metallurgical residue as a geopolymer component. The most significant impact categories are the direct emissions of CO_2, which account for 36% of climate change contribution, and the use of boric acid as a reagent, which accounts for 34% of climate change, 73% of acidification, 68% of freshwater eutrophication, and 77% of freshwater toxicity [16].

Despite the extensive literature available on the topic, there remains a lack of LCA-related studies that evaluate the environmental impact of currently implemented management practices in comparison to alternative valorization routes. To this end, the current gate-to-gate LCA study examines the environmental impact, using a number of key impact categories, and the cumulative energy demand in respect of three different management and valorization practices: (a) the wet disposal which is defined as the baseline scenario (WDB—wet disposal baseline); (b) the dry disposal/partial valorization of the dried residue as a clinker component (DDC—dry disposal clinkering) and (c) the dry disposal/partial valorization of the dried residue as geopolymer component (DDG—dry disposal geopolymerization). The impact of the management practices (a) and (b), which are currently industrially followed, will be investigated comparatively with the proposed valorization practice (c). Furthermore, this study analyzes the contribution of individual processing stages to overall environmental impacts in order to identify environmental hot spots and prioritize areas for improvement. To the best of our knowledge, this LCA study is the first to evaluate geopolymerization as a novel valorization option that supports a near-zero-waste approach within the aluminum industry. Overall, the present study examines management and valorization options that promote sustainability and resource efficiency within the aluminum industry, thus supporting more responsible and eco-friendly bauxite residue management.

2. Materials and Methods

According to the ISO 14040–14044 standard series [17,18], an LCA study follows four key steps: goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation. Each of these steps is explained in detail below.

2.1. LCA Methodology

The main goal of the present LCA study is to quantify the energy consumption and greenhouse gas footprint of the management of bauxite residue generated in an alumina production plant following a gate-to-gate approach. In this context, three different scenarios for the management of a bauxite residue generated in an alumina production plant are examined: (a) the WDB—wet disposal baseline; (b) the DDC—dry disposal clinkering and (c) the DDG—dry disposal geopolymerization.

2.2. System Boundaries and Functional Unit

The generation of the slurry during the thickening process is the entry gate, while the exit gates are alternatively: (a) the wet disposal of the slurry in a pond (WDB); (b) the disposal of the dried BR in the pond and its partial use in the cement clinkering process (DDC) and (c) the disposal of the dried BR in the pond and its partial use in in a geopolymerization process (DDG) (Figure 1).

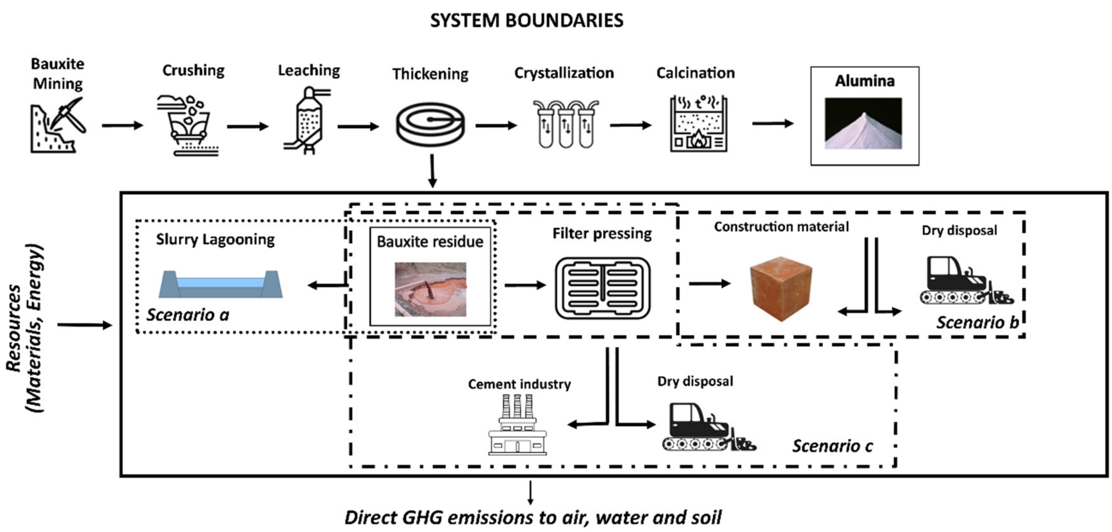

Figure 1. The gate-to-gate system boundaries considered in the study for the management of the bauxite residue.

Based on the 'gate-to-gate' approach, the functional unit (FU) considered in this LCA study is 1 tonne of BR as produced (in slurry form) in the thickener installation in a alumina production plant in Central Greece. For the Greek alumina facility with an average annual production of approximately 900,000 tonnes of BR slurry, the by-product consists of around 270,000 tonnes of dry solids. mainly oxides and unreacted minerals and 630,000 tonnes of alkaline leachates, rich in sodium hydroxide and residual soluble soda. The chemical composition of the BR material taken into account in this study is presented in Table 1.

Table 1. Chemical composition of BR on dry basis and contents of water and NaOH in slurry and dried forms [19].

Content of Main Elements Expressed as Oxides on Dry Basis (wt.%)								
Al_2O_3	Fe_2O_3	SiO_2	TiO_2	CaO	Na_2O	K_2O	MgO	L.O.I
15.65	45.58	6.96	7.07	14.84	3.26	0.07	0.19	6.42
Typical Contents of Water and NaOH Expressed as Na_2O (wt.%)								
							Water	Na_2O
BR at slurry form							70	4–6
BR after the filter-press processing							25	1–3

2.3. Data Collection

Data from various sources were collected for the establishment of the life cycle inventory including: (a) primary data by a Greek alumina production company concerning the management of the BR slurry and the mass balance calculations through the whole procedure; (b) secondary data obtained by the European reference Life Cycle Database (ELCD) and other commercial platforms (i.e., Ecoinvent 3.8); (c) literature data concerning the methodology used for the construction of the geopolymers and the physicochemical characteristics of the raw materials involved in the geopolymerization process. Data gaps were addressed using estimations, assumptions, or supplementary data sources to ensure the completeness and reliability of the analysis. In few cases of information lack, a limited number of assumptions, following quoted in detail, were taken into account.

2.4. Scenario Analysis of Bauxite Residue Management

Scenario analysis was used in this LCA study to address uncertainties in source data and impact assessments. Recognized as a primary approach to identify and evaluating potential alternative future developments within a product chain, it focuses on emission reduction, energy conservation, and sustainability [20]. Scenario analysis has been extensively used in metal-based LCA studies to identify critical parameters that influence future development and to promote long-term sustainability, particularly within industrial waste management systems [20–22]. Furthermore, it serves as a valuable decision-making tool by evaluating potential outcomes and their practical implications. The scenarios examined in this study specifically considered the management of the produced waste/by-product during the aluminum production (i.e., bauxite residue) in order to evaluate aspects such as energy savings, waste reuse, and reduced environmental impact into soil and water systems. The overall flowchart presenting the three investigated scenarios (baseline, current and proposed) for the management of the bauxite residue is displayed in Figure 2.

WDB (Wet disposal): According to WDB, which consists the baseline scenario of this comparative study, the total amount of the slurry generated through the Bayer process, after its thickening, is transferred through pipelines to the evaporation pond. Unprocessed wet BR contains a high content of moisture (70 wt.%) and a high concentration of NaOH (4–6 wt.% expressed as Na_2O) macroscopically observed as an extremely alkaline dense suspension.

DDC (Dry disposal-clinkering): This scenario is the currently applied practice of the Greek aluminum industry in cooperation with the cement industry. This management procedure includes the following steps (Figure 3):

- The filtration taking place into four filter-presses each composed by 156 frames-filters and a filtration area of 750 m^2 [23]. The dewatering is performed at 30 min cycles. The dried BR (DBR) solid stream, described as iron-alumina or commercially as Bauxaline®, discharged with moisture between 26–28%, while the liquid steam, rich in NaOH, is returned to washers, and re-introduced to the Bayer cycle.
- The disposal of DBR in the stacking area nearby to the metallurgical plant, where it is resurfaced using excavators, skid-steer loaders and articulated trucks. A proportion of the initial amount (14%) is transferred with trucks to the harbor of the Company (Agios Nikolaos) and subsequently with general cargo ships to domestic cement production companies.
- The addition of DBR, as a component, at an amount percentage ≤5% in the Portland clinker manufacturing process. Prior to its addition in the clinker, the material is in-situ dried for further moisture removal at the level of 18–22 wt.%.
- The treatment of the filtrate liquor which collected into 2 tanks with total volume of 380 m^3. About the 67.5 wt.% of the filtrate, which is rich in NaOH, is reintroduced in the Bayer cycle, while the remaining liquid is rejected into the sea through a submarine pipeline.

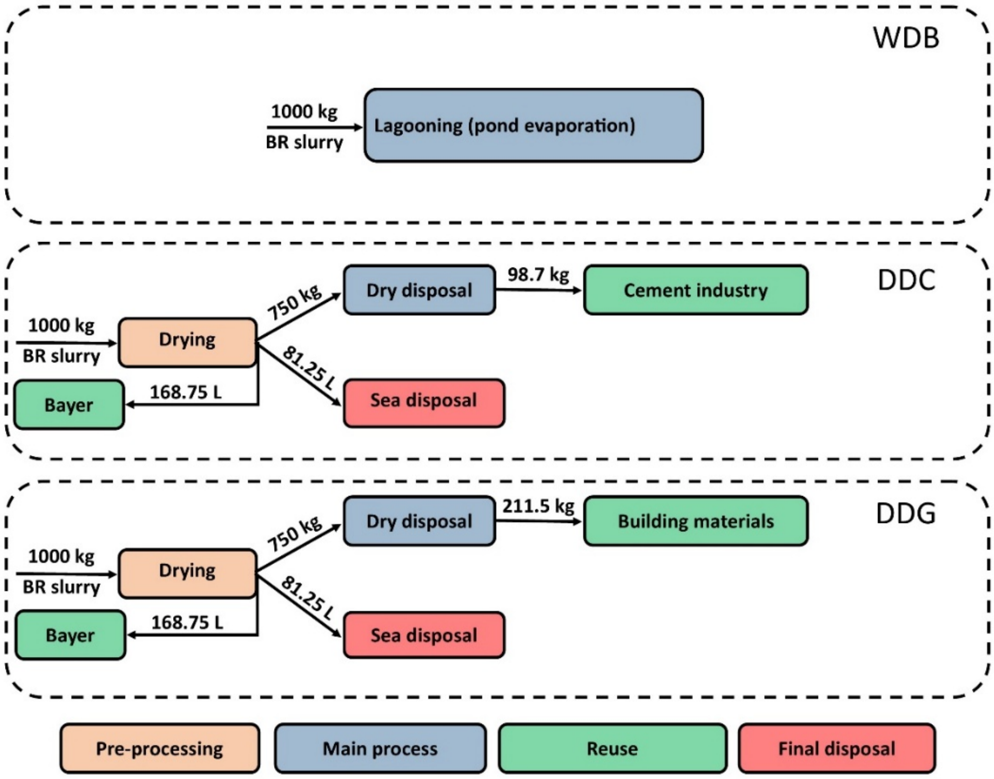

Figure 2. Overall flowsheet describing the investigated BR management scenarios.

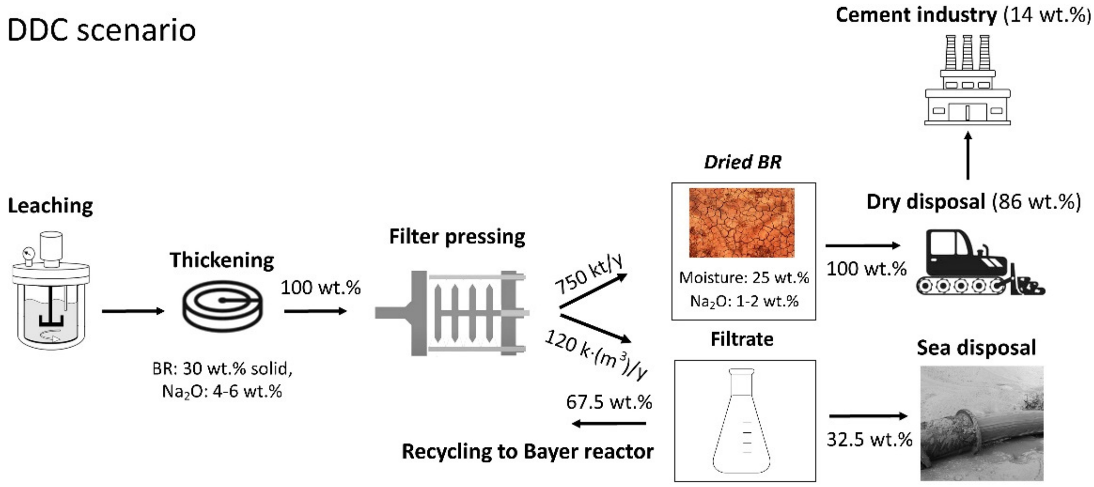

Figure 3. Flowsheet and mass balance of the dry disposal/clinker manufacturing (DDC) scenario.

DDG (Dry disposal-geopolymerization): According to this proposed scenario, the BR slurry, following its dewatering through filter press drying, is subsequently valorized as a component in construction materials. (Figure 4). A geopolymer material containing an equal ratio amount of BR and FeNi slag and an optimum tensile strength (40 MPa) was defined as the end-building-product. FeNi slag is the main solid residue of a Greek ferronickel production Company in Central Greece and its main components (wt.%) are: SiO_2: 38.85, FeO: 32.50, Fe_2O_3: 4.03, MgO: 8.49, Al_2O_3: 6.92, CaO: 4.95, Cr_2O_3: 3.10 [24]. The use of ferronickel slag as a geopolymerization component has been well established experimentally [25,26]. The geopolymer is synthesized via the alkaline activation of the BR-FeNi slag mixture using a 10 M NaOH solution and a curing duration of 7 days [27].

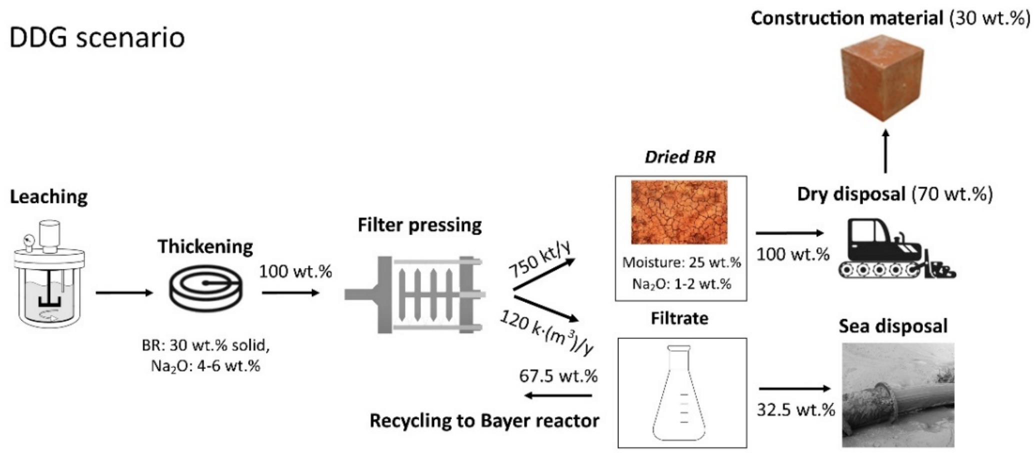

Figure 4. Flowsheet and mass balance of the dry disposal/geopolymer manufacturing (DDG) scenario.

2.5. Life Cycle Inventory

The main LCI data for the three scenarios representing the management and valorization practices for bauxite residue are provided in Table 2. All inventory data were based on primary information obtained for the period 2018–2020 and subsequently validated and revised using energy and mass balance calculations. All inputs have been scaled to the functional unit of 1 tonne of bauxite residue slurry as produced in the thickener installation of the alumina production plant under study.

Table 2. Main inventory data of the three BR management and valorization scenarios investigated in this study.

Parameter	Material	Unit *	Scenarios		
			WDB	DDC	DDG
Material resources (Input)	Gypsum	kg	4.3	-	-
	Geomembrane	m^2	0.43	-	-
	Sand/gravel	kg	225	-	-
	Limestone	kg	-	17.6	-
	Clay	kg	-	4.7	-
	Iron ore	kg	-	1.2	-
	Bauxite residue re-used (dry)	kg	-	54.6	110
	FeNi slag	kg	-	-	110
	NaOH pellets	Kg	-	-	17.6
	Tap water	L	-	11.4	26.4
Energy resources (Input)	Electricity (grid mix)	MJ	44.3	79	96
	Thermal (fossil)	MJ	-	22.5	36
	Fossil fuel (diesel)	MJ	41.9	19.1	15.2
Marketable Products	Clinker	kg	-	52	-
	Geopolymer (40 MPa)	kg	-	-	264

* per functional unit.

2.6. Determination of LCA Impact Categories

To quantify the environmental life cycle impacts, the ILCD (International Life Cycle Data system midpoint) method with 5 impact categories was selected. Additionally, the impact category of the cumulative energy demand (CED), as an energy flow indicator, was assessed [28] (Table 3). The ILCD midpoint methodology is well adapted to supply chains of industrial products and to their respective residues/by-products, while it presents a lower percent uncertainty in respect to the end-point techniques [29,30]. The OpenLCA software (1.10.3) was selected for the performance of the comparative life cycle assessment of the current study.

Table 3. Impact categories selected for the current LCA study.

Impact Category	Abbreviation	Unit of Measurement
Acidification	AC	Mole H^+-eq.
Fresh water eutrophication	FC	kg P-eq.
Global warming (100 years)	GW	kg CO_2-eq.
Ozone depletion	OD	kg CFC-11-eq.
Photochemical ozone formation	POF	kg C_2H_4-eq.
Cumulative energy demand	CED	MJ-eq.

2.7. Key Assumptions

A number of assumptions were done in order to ensure the integrity and the comparativeness of the scenarios investigated. As such, the contributions of land use and infrastructure are not taken into account due to their negligible influence to the environmental impact in comparison to the produced residues, by-products and building materials. The disposal area occupies a surface of 410 acres, where an amount of about 900 kt of BR in annually transferred. The water amounts collected through the evaporation ponds or through the filter-press system are partially recycled (by 70% in respect to their initial volume). The filtrate liquor originated by the filter-press system is continuously re-introduced to the Bayer process cycle irrespective of the weather conditions and unpredictable breakdowns. A 1 $kg \cdot m^{-3}$ filtrate liquor density is considered. The energy demand of the processes is covered by electric energy provided by the Hellenic Electricity Distribution Network Operator originating from the following energy mixture: lignite combustion (12.4%), oil combustion (8.3%), natural gas combustion (40.9%), photovoltaic power (9.7%), wind power (20.4%), hydroelectric power (7.2%) and biomass combustion (0.93%) [31]. The building (geopolymers) materials plant is in vicinity to the alumina production plant. The materials and residues transport into and in vicinity to the building materials plant were not taken into account due to their low impact. Technical data concerning the chemical composition of the raw materials and the alkaline activator solutions and, as well as, the synthesis conditions were obtained from literature. The transport of the FeNi slag from its production site to the building materials plant (distance: 81.4 km) is performed via vehicles with capacity 16–32 tonnes and EURO 5 vehicle emission standards. It should be noted that the use of certain assumptions introduces a limitation to the study, as they simplify processes such as land use, infrastructure, and local transport. However, these parameters are expected to have negligible influence on the overall outcomes as shown in previous LCA studies [32,33], and their inclusion primarily ensures consistency and comparability among the scenarios.

3. Results and Discussion

The LCA results per functional unit i.e., 1000 kg of processed BR slurry for AC, FE, GW, OD, POF, CED according to the three case studies for the management of the residue are presented in Table 4.

Table 4. Calculated values of the environmental impacts and the cumulative energy demand regarding three different scenarios investigated for the management of the bauxite residue.

Impact Category *	Abbr.	Scenarios		
		WDB	DDC	DDG
Acidification (Mole H^+-eq.)	AC	55.1	36.5	31.5
Fresh water eutrophication (kg P-eq.)	FE	8.32×10^{-5}	2.32×10^{-5}	1.85×10^{-5}
Global warming (100 years) (kg CO_2-eq.)	GW	264	225	232
Ozone depletion (kg CFC-11-eq.)	OD	1.12×10^{-4}	7.35×10^{-5}	6.243×10^{-5}
Photochemical ozone formation (kg C_2H_4-eq.)	POF	3.05×10^{-5}	2.38×10^{-5}	2.06×10^{-5}
Cumulative energy demand (MJ-eq.)	CED	86.2	124.6	134.2

* per FU^{-1}.

The results indicate that dry disposal technique followed by the partial use of dried BR as a geopolymerization component (DDG) presents the lowest total environmental impact, while at the same time requires the highest amount of energy. On average, both valorization scenarios (DDC and DDG) reduce environmental impacts compared with wet disposal. Across the four categories of acidification, eutrophication, ozone depletion, and photochemical ozone formation, DDC achieves an average reduction of about 40%, while DDG achieves a higher average reduction of nearly 49%. In direct comparison, the DDG scenario provides greater reductions in all four categories. However, DDC records a slightly higher decrease in GWP (15.5% vs. 12.8%), which indicates a relative advantage in terms of environmental performance. However, both scenarios result in increased cumulative energy demand which highlights the trade-off between reduced environmental burdens and higher energy requirements due to expansion of the associated system boundaries (Figure 1). More specifically, the variation (%) of the impact categories in case of dry disposal/clinker manufacturing and dry disposal/geopolymer manufacturing as a function of the baseline scenario (WDB) is presented in Figure 5. The implementation of case studies DDC and DDG cause a significantly lower fresh water eutrophication (decreasing by 72.3% and 77.7%), acidification (decreasing by 33.9% and 43.6%), ozone depletion (decreasing by 33.6% and 43.4%) and photochemical ozone formation (decreasing by 21.6% and 30.6%). Global warming, which consists a long-term environmental indicator, presents a slighter decrease (15.5% and 12.8%), while cumulative energy demand increases by 42.7% and 54.2% due to the involvement of an additional stage (clinkering or geopolymerization) in the whole management practice. However, at the same time, an intermediate-product (cement clinker) or an end-product (building material) is synthesized.

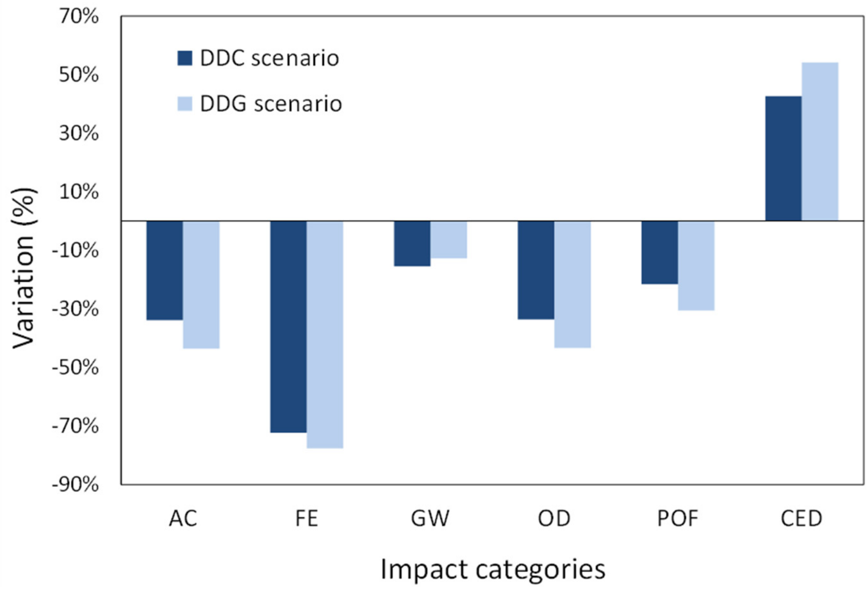

Figure 5. Variation (%) of the impact categories of the DDC and DDG scenarios in relation to the baseline WDB.

The direct disposal of the BR in evaporation ponds consists of a single-stage process which contributes by 100% to the five studied impact categories and to the cumulative energy demand. The implementation of DDC and DDG is further more complex including 4 different processing and management stages. A common pressure filtration technique is initially applied under the same conditions (pre-processing). The largest proportions of the dried BR amounts, 86.8% in case of DDC and 71.8% in case of DDG, are transferred to dry disposal (main process). The third stage (residue reuse) is differentiated in two cases. An amount of dried non-disposed BR is added as a component either in Portland clinker, or in a geopolymer building material. Finally, an equal volume (81.25% L/t of BR) of liquor is not re-introduced in the Bayer reactor and rejected to the sea (final disposal) (Figures 3 and 4).

The contribution of each individual stage on the five examined environmental impact categories and on the cumulative energy demand through the implementation of DDC and DDG (Figures 6 and 7). The dried BR disposal (main process) presents the higher effect on the impact categories of: acidification (57.3% and 47.7%), ozone depletion (48% and 35.3%) and photochemical ozone formation (60.6% and 54.1%). Filtration (pre-processing stage) affects crucially (70.5% and 68.3%) the global warming indicator. The partial residue reuse stage contributes between 16.2% and 17.4% at all studied environmental impact categories when BR is used as an additive in cement clinker and between 20.9% and 30.1% when it used as a component in building geopolymer material. The increased contribution of the reuse stage in second case should be attributed to the complexity of the geopolymerization process involving the use of various environmentally impacting reagents such as sodium hydroxide and the requirement for thermal energy [34]. The final disposal stage contributes significantly to the fresh water eutrophication (37.4% and 45.5%) and ozone depletion impact categories (28.8% and 37.7%).

Concerning the effect of each processing stage on the cumulative energy demand, it is clearly observed that filtration presents the higher impact (66.8% and 61.8%) due to the increased requirement for electrical energy supplying the filter-press system. Nevertheless, residue reuse stage contributes at significant extent (18.1% and 26.8%) on CED value.

Based on the obtained comparative LCA results, the environmental impact of “dry disposal” and “residue reuse” processes could be further reduced through the mitigation of the transportation stage effect [35]. Conventional vehicles such as dump trucks and articulated haulers that transfer the dried BR to the disposal site or to the clinker plant could be replaced by electric vehicles [36]. The use of a conveyor belt is alternatively proposed for the transportation of dried bauxite residue to the disposal site. Additionally, the installation of roof protection over the residue pond/lagoon and the use of capping layers is also suggested in order to avoid drainage and leaching phenomena and therefore further minimize the impact of the management processes into the environmental [37]. In this sense, the environmental impact categories and the CED values of the pre-processing stage could potentially be decreased by the replacement of the filter-pressing by less energy-consuming processes such as screw pressing and geotextile dewatering bags. However, he implementation of either approach requires extensive technical testing and a detailed capital investment assessment to evaluate feasibility and performance. On the other hand, although, the optimization of the geopolymerization technique is currently in progress, modifications throughout the entire production sequence such as the application of microwave treatment to precursor materials and the increased incorporation of aggregates into the raw material mix, are expected to offer more sustainable construction materials [38]. Taking this fact into consideration, and in alignment with the results obtained in this study, the dry disposal combined with geopolymer manufacturing demonstrates a lower overall environmental impact compared to the currently implemented practice of dry disposal with clinker production.

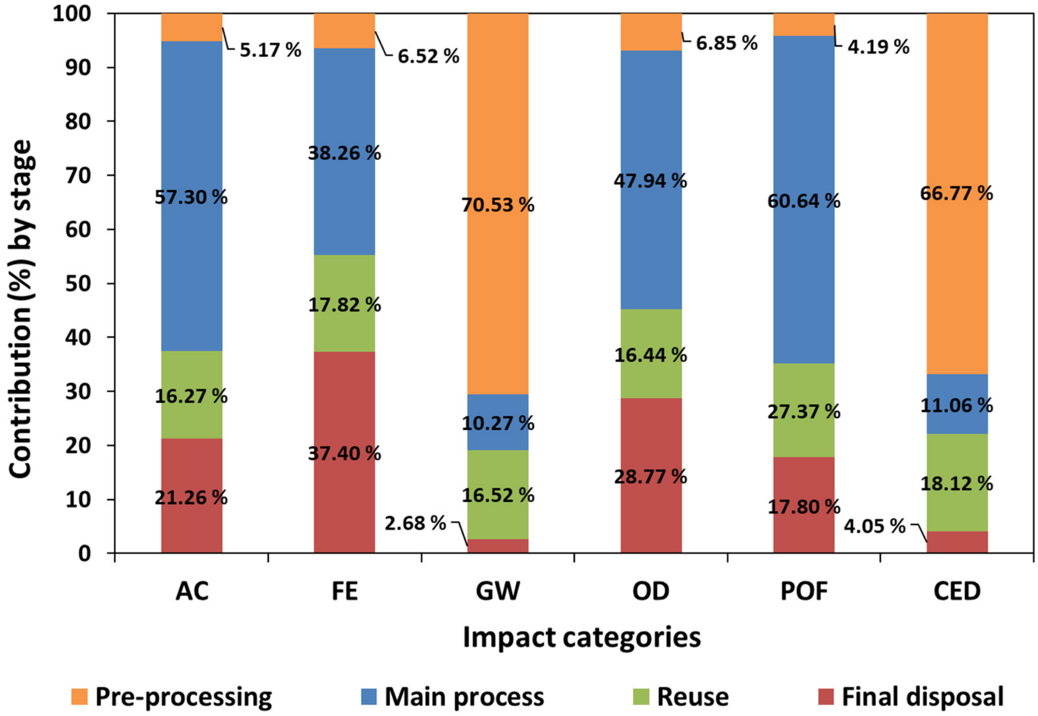

Figure 6. Contribution analysis of different processes to the five midpoint impact categories and to the cumulative energy demand according to DDC scenario.

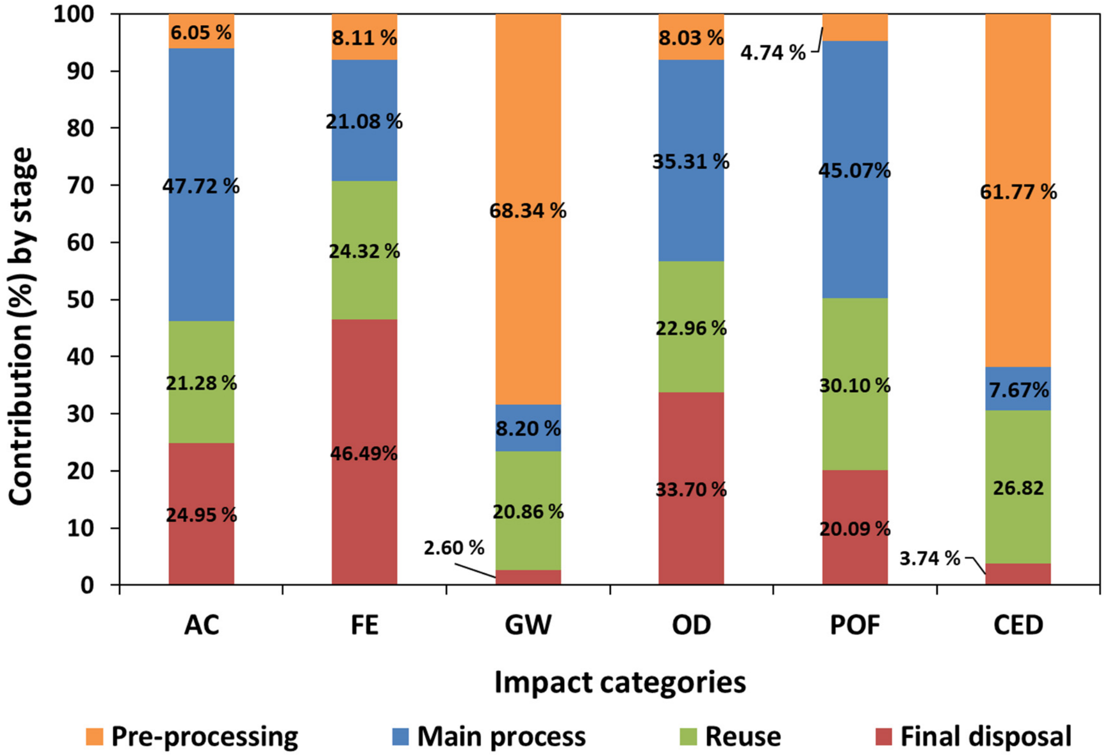

Figure 7. Contribution analysis of different processes to the five midpoint impact categories and to the cumulative energy demand according to DDG scenario.

4. Conclusions

The environmental impact of the bauxite residue management was comparatively assessed via a gate-to-gate life cycle methodology taking into account three case studies: The wet disposal of the as-received bauxite residue slurry which is defined as the baseline scenario (WDB), the disposal of the dried BR and its partial valorization in the cement clinkering process (DDC) and the disposal of the dried BR and its partial valorization in in a geopolymerization process (DDG). DDG presents the higher environmental benefit followed by the DDC practice. Fresh water eutrophication (FC), ozone depletion (OD) and acidification (AC) categories are reduced by 77.7%, 43.3% and 43.6%, respectively by applying the DDG. On the other hand, the cumulative energy demand is minimum in case of WDB. CED value increases by 42.7% and by 54.2% through the implementation of case studies DDC and DDG. However, wet disposal poses human health and safety threats since sodium hydroxide and traces of heavy metal(loid)s can be easily exposed to the soil and groundwater. The replacement of the current energy mixture by renewable energy re-sources could significantly reduce the energy requirement. It should be noted that the alumina production plant, which is also proposed as an installation for the geopolymers fabrication, is in proximity to a wind turbines power network.

Useful data were extracted concerning the contribution of each processing stage on the whole environmental impact. The residue management according to DDC and DDG consists of four stages: the press-filtering (pre-processing), the dry disposal (main process), the dried residue reuse and the sea disposal of the wastewater (32.5 vol%/final disposal) generated through the filtering process. Dry disposal and press-filtering consist the most environmental impacting stages in both DDC and DDG. Dry disposal significantly effects on the acidification (57.3% and 47.7% for DDC and DDG, respectively), ozone depletion (48% and 35.3%) and photochemical ozone formation (60.6% and 54.1%) categories. Press-filtering is noticeably impacting on the global warming (GW) category (with a contribution percentage around 70%).

Finally, the findings of this study are crucial for guiding sustainable residue management strategies in the alumina industry. In this context, special emphasis is given to the significance of process optimization, particularly in the press-filtering and dry disposal stages, which are shown to be the dominant contributors to environmental impacts in both the current and proposed management and valorization scenarios. Future improvements in these areas, along with the adoption of low-carbon or renewable energy sources could substantially reduce the environmental footprint associated with bauxite residue valorization. However, this study is subject to some limitations. The gate-to-gate boundaries applied do not fully capture upstream and downstream impacts across the entire life cycle. Some assumptions, particularly those related to energy mixes and transport requirements, may affect the accuracy of the results. Moreover, the availability of detailed process data for geopolymerization was limited to experimental and literature sources, which may not fully represent large-scale industrial conditions. Future research should therefore extend to cradle-to-grave assessments, investigate alternative dewatering technologies, optimize geopolymerization processes, and integrate renewable energy sources to enhance sustainability outcomes.

Overall, this comparative assessment provides valuable data and insights for decision-makers and stakeholders that aim to promote the proper implementation of more sustainable and responsible management practices for bauxite residue, thus contributing to the decarbonization of alumina production and the broader construction materials sector.

Author Contributions

A.F. and G.B.: conceptualization, methodology, software; A.F. and M.S.: data curation; M.S. and A.F.: writing—original draft preparation; A.F. and M.S.: investigation; G.B.: supervision; G.B.: software, validation; G.B.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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