Life Cycle Analysis of remediation and utilization of bauxite residue: Evaluation of technologies from a location perspective.

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Residual resource engineering and industrial ecology

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Abstract

English

Bauxite residue or red mud is the mine waste (tailing) from the Bayer process of bauxite ore, and with 4.6 billion tonnes in reserves of the hazardous waste valorisation pathways are needed to include it as residual resource in circular economy. This study shortly benchmarks current treatment and utilization methods of the residue with focus on three technologies: De-alkalization, soil stabilization, and high performance binder (geopolymer). For each technology, processes significant to environmental impacts are identified and improvements and recommendations are suggested. It is evaluated if location-specific factors and residue composition affects the environmental impacts of the technologies. An attributional life cycle analysis using the APOS ecoinvent database and ReCiPe impact assessment method was used to evaluate each process on endpoint impact categories and compare them on midpoint impact categories. The results were discussed together with a review on some sensitive materials and processes, especially fly ash in soil stabilization and geopolymer. The "hybrid" version of the high performance binder and soil stabilization technologies have positive influence on the environment, but while de-alkalization reduce hazard risk related to bauxite landfills it also cause environmental impacts in other areas. It is argued that soil stabilization should not be credited for using fly ash because it is already used for road construction and trending to be more resource than waste. The hybrid high performance binder is therefore recommended, but the success depends on its quality which depends on bauxite residue composition, to what degree should be studied further. A break-even transport distance for each technology based on midpoint impacts and transport type show that the hybrid high performance binder product potentially can be distributed internationally without causing burden-shifting, leading to a decrease of conventional concrete production in scale with the residue production and reserves. However, there is a risk of toxic Cr(VI) leaching and alkalinity hazards that must be analysed further for the hybrid high performance binder to be marketed.

Norsk

Bauxit rester eller redmud er gruvedriften rester (tailing) fra Bayer-prosessen med bauxittmalm, og med 4,6 milliarder tonn i reserver av farlige avfallsverdier er det nødvendig å inkludere det som restressurs i sirkulær økonomi. Denne studien refererer kort til gjeldende behandlings- og utnyttelsesmetoder for residuet med fokus på tre teknologier: Avalkalisering, jordstabilisering og høytytende bindemiddel (geopolymer). For hver teknologi identifiseres prosesser som har betydning for miljøpåvirkningen, og forbedringer og anbefalinger foreslås. Det blir evaluert om stedsspesifikke faktorer og sammensetning av bauxit resten påvirker miljøpåvirkningen av teknologiene. En attribusjons livssyklusanalyse ved bruk av APOS ecoinvent-databasen og ReCiPe-konsekvensanalysemetoden ble brukt til å evaluere hver prosess på effekt kategorier for endepunkter og sammenligne dem på midtpunkt effekt kategorier. Resultatene ble diskutert sammen med en gjennomgang av noen sensitive materialer og prosesser, spesielt flyveaske i jordstabilisering og geopolymer. Den "hybrid" versjonen av høyytelses bindemiddel og jordstabiliseringsteknologi har positiv innflytelse på miljøet, men selv da avalkalisering reduserer farerisiko knyttet til fyllinger av bauxitt, forårsaker den også miljøpåvirkninger i andre områder. Det argumenteres for at jordstabilisering ikke skal krediteres for bruk av flyveaske fordi den allerede brukes til veibygging og trender til å være mer ressurs enn avfall. Det anbefales derfor å bruke det hybride høytytende bindemidlet, men suksessen avhenger av kvaliteten som avhenger av bauxit resten, i hvilken grad bør studeres nærmere. En break-even transportavstand for hver teknologi basert på midtpunktpåvirkninger og transporttype viser at det hybride høytytende bindemiddel produktet potensielt kan distribueres internasjonalt uten å forårsake byrdeforskyvning, noe som fører til en nedgang i konvensjonell betongproduksjon i skala med den årlige restproduksjonen og reserver. Imidlertid er det en risiko for giftig Cr (VI) utvasking og farer fra alkalinitet som må analyseres videre for å kunne markedsføre hybrid høyytelsesbindemiddel.

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Contents

B Inorganic Polymer LCIA   72

C Concrete sensitivity midpoint comparison   76

D Break-even transport distances and per product impacts   77

E LCIA results   81

Figures

Tables

Abbreviations

AoP	Area of Protection
APOS	Allocation at point of substitution
BR	Bauxite resiude
CF	Characterisation factor
CO2-eq	CO2 equivalents
DA	De-alkalization
DALY	Disability-adjusted life year
EOL	End of life
FU	Functional unit
GGBFS	Ground granulated blast furnace slag
HHPB	Hybrid high performance binder
HPB	High performance binder
IP	Inorganic polymer
LCA	Life cycle analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NORM	Naturally occurring radioactive material
OPC	Ordinary Portland cement
REE	Rare earth elements
RK	Rotary kiln
species.yr	Species per year (gone extinct)
SS	Soil stabilization
TBRC	Top blown rotary converter
TENORM	Technologically enhanced naturally occurring radioactive material
USD2013	United States dollar of 2013

1   Introduction to bauxite residue

Bauxite Residue

Aluminium is a low-density, corrosive-resistant, highly conductive and cheap metal with many applications (*RSC*, n.d.). It is hard to imagine a future where aluminium is not part of our everyday life. Aluminium is refined from alumina which is most often extracted from the bauxite ore through the patented "Bayer process", where 1-2 tons of the waste "bauxite residue" (BR) is produced per ton of alumina (Lyu et al., 2021). This waste is known to be hazardous and costly to manage. This study presents and discuss important aspects of valorizing bauxite residue, an idea that stems back to at least 1964 (Klauber et al., 2011), but whose potential is far from realized.

BR is often referred to as "red mud" when particle size is fine and water content high enough to make it mud-like. Its high content of iron-oxides gives the characteristic red color to the vast tailing dumpsites around the world. While BR is most often red and with fine particles, some alumina refineries separate the coarse and fine fractions into silica-rich sand and mud. Some "red" muds are also more brown and some even black in color (Evans, 2016). "Bauxite residue" is therefore more often a correct or meaningful term to use, especially because it includes both fine and coarse fractions that should otherwise be specifically distinguished between as the sand and mud fractions have different properties and therefore may serve different purposes or pose different challenges. In 2011 Power et al. (2011) estimated an annual production of 120 million tonnes BR from alumina and aluminium production and 2.7 billion tonnes of BR aggregated in landfills so far. Xue et al. (2019) estimated the BR reserves to 4.6 billion tonnes and (Lyu et al., 2021) estimated production to 200 million tonnes per year in 2018. This indicates an increase in annual BR production which is explained by the increase in alumina demand while ore quality degrades (Norgate and Jahanshahi, 2010; Sverdrup et al., 2019).

Hazard

BR is considered a hazardous material mainly because of its high alkalinity which together with its sodic content inhibits plant life (Bertocchi et al., 2006). Toxic trace metals and naturally occurring radioactive materials (NORMs) are also present in BR and poses a threat to human health (Gräfe et al., 2011). When bauxite is processed the NORMS usually double in the produced BR, this is called technologically enhanced NORMS (TENORMs). The TENORMs are sometimes close to the limit value allowed by the International Atomic Energy Authority (Evans, 2016) and therefore could become problematic if future politics change or if the BR is processed in a way that increase TENORM concentrations. BR is known to leach into the soil and groundwater surrounding the dumpsite (Liu et al., 2009; Zhu et al., 2016; Wang et al., 2019; Lyu et al., 2019), making both the TENORMs, but especially the alkalinity of the BR a local environmental threat to the surrounding ecosystem and human health.

Handling of BR

Best practice for BR storage is described in detail in World Aluminium (2015) and Power et al. (2011). Ponding and dry stacking are the most common practices. When ponding, BR is stored with a solid content of 15-30% in a cavity or behind a dam. The BR slurry (red mud) poses a threat should the dam break or spill otherwise, *e.g.* Klebercz et al. (2012) found adverse effects on the downstream ecosystem affected by the catastrophe of the Ajka red mud spill in Hungary 2010. Dry stacking is initially more expensive as it somehow involves decreasing the water content of the BR, but poses less of a risk when stored as well as lower management costs due to less volume and easier handling. Dry stacking leaves a BR in the landfill with a solid content ranging from 65-77% after a drying period of nearly a year. 80 days of summer and 160 days of winter gave 65% dry content in MOTIM, Hungary (Power et al., 2011), and World Aluminium (2015) mentions solid contents of 77% have been

claimed. Ponding was the popular practice until the 1980s and much BR is found with low solid contents, but today we see an increased popularity for dry stacking along with partial neutralization of the BR (Evans, 2016). However, according to Liu et al. (2014) and LI et al. (2018) damming (ponding) is still used the most. The technologies evaluated in this project use BR with a solid content ranging from 56-73% depending on the site and technology, meaning that they are more likely to take BR from dry stacking than from ponds or dams. Even BR that is dry stacked can be transported by pipes and pumps from the Bayer plant to the landfill.

Potential product

The interest in remediating and utilizing BR rather than storing it has been fueled by the cost, land use and environmental risks related to BR storage. At least 734 patents on BR utilization were made between 1964-2008 (Klauber et al., 2011) while the newer study by Lyu et al. (2021) mentions that over 1200 patents are made. Most researched possibilities are focusing on recovery of metals found in BR, use in cement production or as another construction material, soil amelioration or even treatment of acid mine drainage (which is an environmental hazard caused by other kinds of tailing) (Evans, 2016). Cement is responsible for 5-7% of total global CO_2 emissions (not to be mistaken with CO_2-equivalences) and about 4.2 billion tonnes cement was produced in 2016 alone (Norcem, n.d.). The demand for constructional materials that BR products may substitute is much higher than the production of BR - it is therefore imaginable that BR deposits can be emptied in the near future, *e.g.* if cement can be replaced by BR even at a moderate ratio. The "Perth to Bunbury Highway" in Australia used around 5% of the global annual BR production (Klauber et al., 2011) and may be the best example of how BR can be utilized as a product. The incorporation of BR as a residual resource is therefore an important topic related to circular economy.

Remediation of BR is necessary before use as a residual resource, which is likely why only 4 megatonne (Mt) out of 150 Mt were estimated to be used in a productive way (instead of landfilled) in 2016 (Evans, 2016). There is consensus in the scientific community that the key challenge is the strong alkalinity (Lyu et al., 2021; Jones et al., 2015; Gräfe et al., 2011; Evans, 2016; Klauber et al., 2011; Wang et al., 2018). For example, the sodic-alkaline content has adverse effects on ecosystems and must be treated if used for landfill capping, the same content can cause "formation of friable dust-prone surfaces" letting it spread by wind (Klauber et al., 2017) or cause embankment failure (Gräfe et al., 2011) *e.g.* if used as stabilizer for a road. Alkali efflorescence occur in alkaline construction materials resulting in low strength and durability of constructions (Lyu et al., 2021). As seen in appendix A the remediation technologies involve addition of other materials like quicklime (or limestone which will then undergo calcination) adding great CO_2 emissions to the carbon footprint of the treated bauxite residue (TBR).

Current handling and possible alternatives for three locations: Ireland, Romania, and Greece

This study specifically aims to recommend the best choice between three alternative technologies that all transform BR to a residual resource partaking in circular economy. The three technologies are: De-alkalization (DA), Soil stabilization (SS), and High Performance Binder (HPB). Each technology is made to valorize BR into a BR product that in this study is assumed to substitute the products or functions: Clay, stabilized road base, and concrete - respectively.

Each technology is presented in figure 1. The de-alkalization technology (DA) slake quicklime with water and mix it with BR in a thermochemical reactor with steam. It is then washed and then dried in a filter press. It has now become pre-dried de-alkalized BR.

The high performance binder (HPB) mix different inputs with BR already in the Bayer process where after it is heated in a natural gas based rotary kiln or top blown rotary converter to 1200-1300°C calcination process. It is then quenched and then depending on the next mix turns into inorganic polymer (IP) or a hybrid high performance binder (HHPB) where some

ordinary portland cement (OPC) is also in the mix. In both cases, the final product is concrete.

The soil stabilization (SS) technology mix a specific fraction of fine and coarse BR. Then mix it with the additives: Fly ash, ground granulated blast furnace slag (GGBFS), and quicklime. The final product is used for soil stabilization in road base.

The technologies are described in further detail in chapter 4 and the flow charts are available in appendix A.
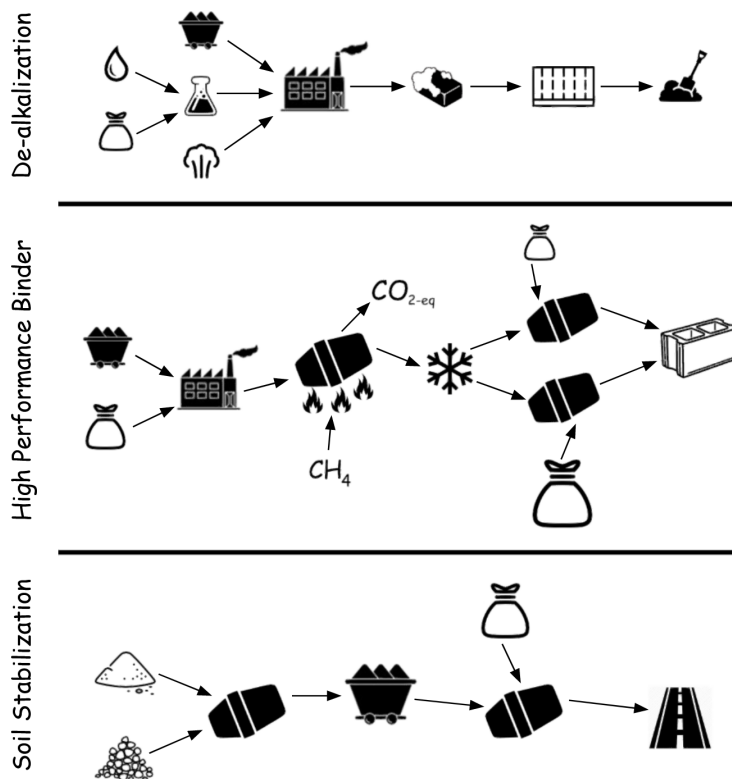
Figure 1: A simplified explanation of the three technologies in focus.

One of the technologies are potentially implemented at the ALUM, Aughinish, and AoG (Aluminium of Greece) Bayer plants in Romania (Tulcea), Ireland (Limerick), and Greece (north coast Gulf of Corinth) respectively. This study will recommend the best technology at each location. Based on the satellite photos in figure 2 all the BR landfills use mud/dry stacking which is recognized from the tractor marks in the red mud (see (World Aluminium, 2015)). The distance from plant to landfill is 3, 1-2, and 0.5 km for ALUM, AoG, and Aughinish respectively. The AoG plant itself is blurred on satellite photos (google maps), but the two other Bayer plants use pipes and pumps to transport BR to the landfill. The BR that goes from the landfill to the treatment plant is therefore assumed to have a moisture content of 30% which match with the range given by Power et al. (2011) and World Aluminium (2015).

Relevance of this study
This study is among the first comparative LCAs of multiple large volume utilizations of a residual resource, that evaluates the influence of location-specific factors. More specifically, this project evaluates three technologies and aims to find the most sustainable solution for treatment and use of BR at three different locations. This is done through a comparative life cycle
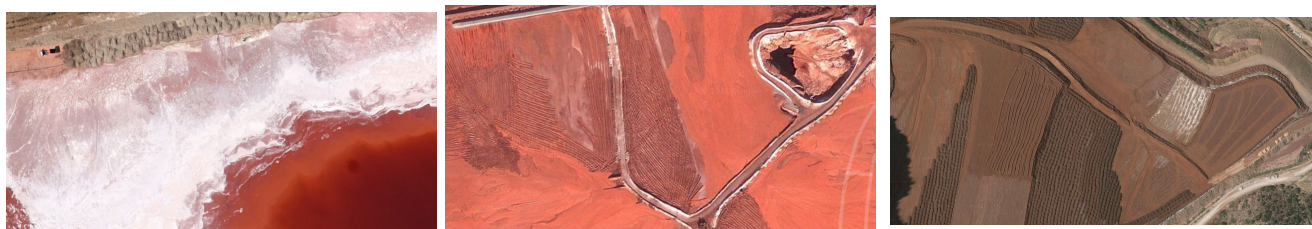
(a) A: ALUM landfill in Romania 2021 (45°09'48.1"N 28°43'58.7"E).

(b) B: Aughinish landfill in Ireland 2021 (52°37'01.5"N 9°04'29.4"W).

(c) C: AoG landfill in Greece 2021 (38°21'16.6"N 22°42'20.4"E)

Figure 2: Google Earth™ images of BR landfills at the three Bayer plants in focus. GOOGLE is a trademark of Google Inc.

analysis (LCA) where the recommended technology is based on criteria like water, energy and raw material use, as well as impacts to human health, climate, and ecosystems.

1.1   Structure and research questions

This study deviates from the more conventional structure of most scientific papers due to the mixture of a literature review and a comparative LCA of multiple life cycles with multiple alternatives.

First there is a screening of what impact categories are sensitive and what inventories in these categories are sensitive. This lead to an evaluation of the sensitive inventories and a necessary system expansion regarding the substituted products of the soil stabilization technology. When the general system is considered robust, location-specific parameters are included and discussed.

1. What inputs and outputs are of significant relevance to the environmental impacts (positive and negative) resulting from using each of the three technologies?

2. Is there a generally favorable technology when not including location-specific parameters?

3. What location-specific parameters may influence the conclusion of the LCA?

4. Can the composition of BR affect which technology is in favor?

The research questions will be discussed based on a set of impact categories further described in chapter 3.2, leading to the recommendations based on this study. Where the 2 first research questions and to an extent the 3rd can be based mostly on the life cycle impact assessment results, the conclusions must also be based on a qualitative discussion to a large degree, being increasingly more qualitative towards the 4th question. This is among other things because the attributional approach is used although the study is also of a consequential nature as well as the lack of detail in the LCI databases.

The following part of the introduction will explain how BR is initially turned into a hazardous material to give the reader a basic understanding of the chemistry which is the initial stepping stone for any innovative solution for remediation and utilization of BR. A short review of BR utilization options relevant to the three technologies studied here are then presented. The tool "Life Cycle Analysis" (LCA) is then explained as this is used to create the results the discussion is initially based on, the LCA

framework must be understood to allow a more comprehensive discussion of the ambiguous results herein presented. The LCA then begins following the ISO14040 standard for life cycle assessment framework (ISO, 2006). At this point, the reader should have the required knowledge to follow the discussion and fully understand the conclusions and recommendations made. The three technologies in question are then discussed based with and without location-specific factors to evaluate the importance of the these factors.

1.2   From ore to residue

The Bayer process is responsible for over 95% of BR production (Khairul et al., 2019). The Bayer process extracts alumina from bauxite ore somewhat the same way all over the world, the variations of the process is based on the variations of the bauxite ore composition. As seen on figure 3 the main steps from ore to alumina and residue is: Grinding of ore, desilication, digestion and clarification. At this point there are 2 products: A greenish "Bayer liquor" and the "red mud". Aluminium hydroxide precipitates from the Bayer liquor whereafter alumina can be made through calcination of the hydroxide. The composition of the red mud is dependent on the composition of the bauxite ore and the processes carried out in the Bayer plant, which as mentioned also depends on the composition of the bauxite ore. The following description of the Bayer process is mainly based on Lyu et al. (2021).

The main mineralogical phases of the bauxite ore where aluminium is bound consists of gibbsite, boehmite and diaspore. Although kaolinite is not as abundant, its silicon content will be of major importance to the alkalinity of the residue. Opal is therefore also an important phase although it does not contain aluminium. Table 1 presents a few of the main mineralogical phases relevant specifically for the alkilinity of BR. Pre-desilication and high-pressure digestion are the main processes for the formation of alkaline substances in bauxite residue. Figure 4 combined with equation 1 through 11 maps out the chemical reactions leading to the products obtained through desilication and digestion.

Table 1: Relevant ore and residue phases of bauxite (Lyu et al., 2021)

Ore phase	Formula	Residue phase	typical range (w%)	Formula
Gibbsite	$Al(OH)_3$	Calcite	2-20	$CaCO_3$
Boehmite	$\gamma - AlOOH$	Cancrinite	0-50	$Na_6Ca_2[(CO_3)_2 \mid Al_6Si_6O_{24}] \cdot 2H_2O$
Diaspore	$\alpha - AlOOH$	Diaspore	0-5	$\alpha - AlOOH$
Kaolinite	$Si_4Al_4O_{10}(OH)_8$	Kaolinite	0-5	$Al_2Si_2O_5(OH)_4$
Opal	$SiO_2 \cdot nH_2O$	Sodalite	4-40	$Na4Al3Si3O12Cl$
		Tricalcium aluminate	2-20	$Ca_3Al_2O_6$

$$3Si_4Al_4O_{10}(OH)_8 + 4Ca(OH)_2 + 4NaOH + 4Na_2CO_3 = 2Na_6Al_6Si_6O_{24} \cdot 2CaCO_3 + 18H_2O \qquad (1)$$

$$Si_4Al_4O_{10}(OH)_8 + Ca(OH)_2 + NaOH + Na_2CO_3 = Ca_3Al_2(SiO_4) \cdot (OH)_{12-4x} + NaAl(OH)_4 + Na_2SiO_3 \qquad (2)$$

$$SiO_2 \cdot nH_2O + 2NaOH = Na_2SiO_3 + (n+1)H_2O \qquad (3)$$
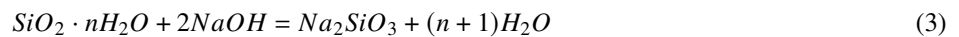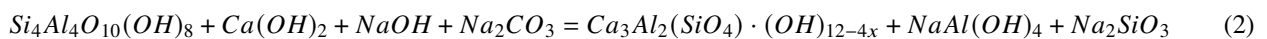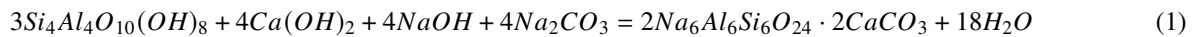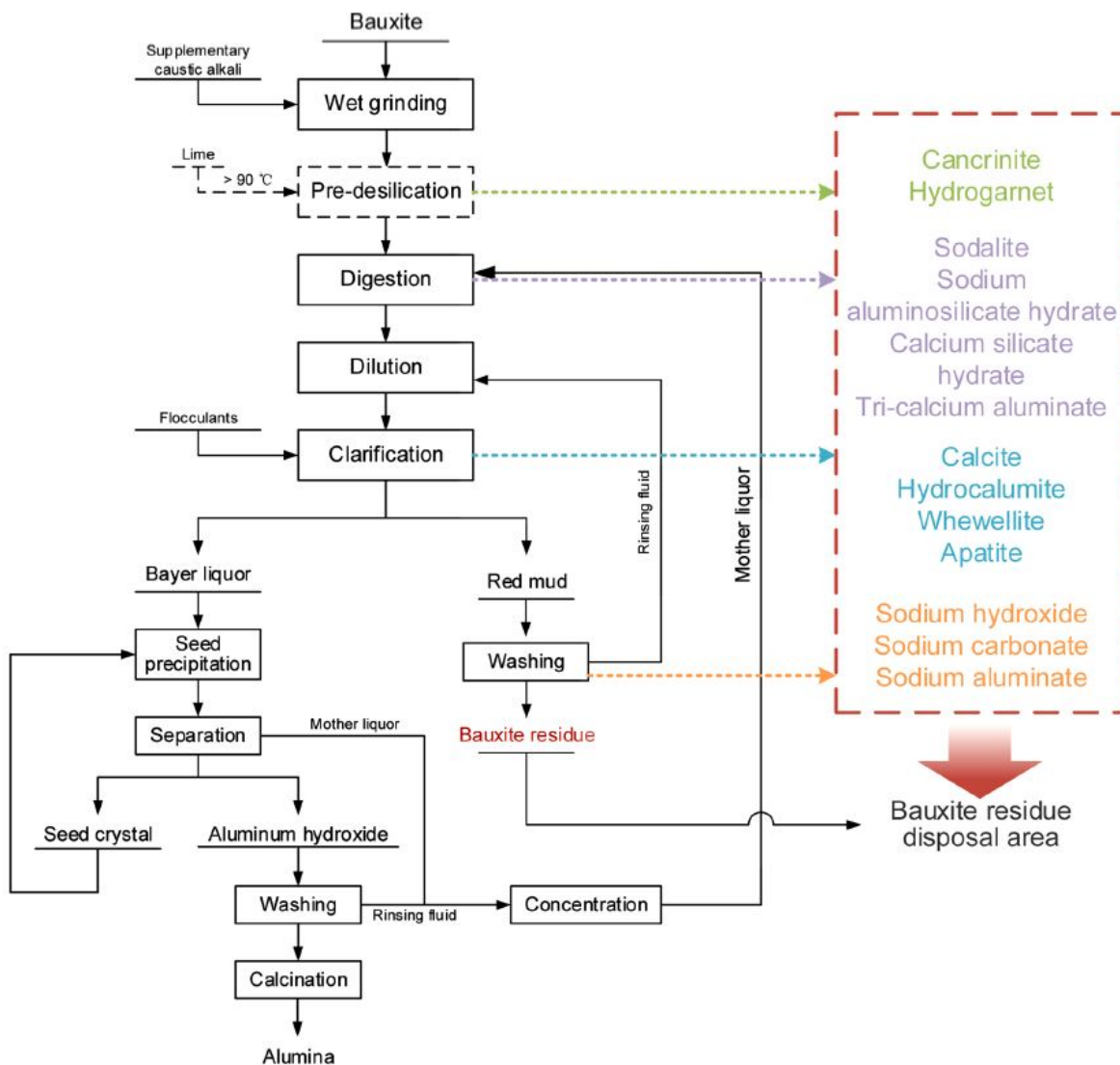
Figure 3: "Simplified flowsheet of Bayer process and schematic diagram of alkaline formation in bauxite residue" (Lyu et al., 2021).

Table 2: Bayer process parameters for treating different types of bauxite (Lyu et al., 2021).

Bauxite types	Digestion temperature (°C)	Digestion pressure (atm)	Alkali concentration (g/L)	Caustic ratio of dissolution (α)
Gibbsite	104-145	1.0-4.0	120-140	1.5-1.65
Boehmite	200-240	12-34	140-240	1.5-.175
Diaspore	220-260	28-34	250-280	1.65-1.75

$$SiO_2 \cdot nH_2O + 2NaCO_3 = Na_2SiO_3 + CO_2 + nH_2O \tag{4}$$

$$Al(OH)_3 + NaOH = NaAl(OH)_4 \tag{5}$$

$$AlOOH + NaOH + H_2O = NaAl(OH)_4 \tag{6}$$

$$3Ca(OH)_2 + 2NaAl(OH)_4 = 3CaO \cdot Al_2O_3 \cdot 6H_2O + 2NaOH \tag{7}$$

$$3CaO \cdot Al_2O3 \cdot 6H_2O + nNa_2SiO_3 = 3CaO \cdot Al_2O_3 \cdot nSiO_2 \cdot (6-2n)H_2O + 2nNaOH + nH_2O \tag{8}$$

$$Si_4Al_4O_{10}(OH)_8 + 12NaOH = 4NaAl(OH)_4 + 4Na_2SiO_3 + 2H_2O \tag{9}$$

$$2Na_2SiO_3 + 2NaAl(OH)_4 + (n-2)H_2O = Na_2O \cdot Al_2O_3 \cdot 2SiO_2 \cdot nH_2O + 4NaOH \tag{10}$$

$$3Na_2O \cdot Al_2O_3 \cdot 2SiO_2 \cdot nH_2O + 2NaX^*(Na_2X^*) = 3(Na_2O \cdot Al_2O_3 \cdot 2SiO_2) \cdot 2NaX^*(Na_2X^*) + 3nH_2O \tag{11}$$
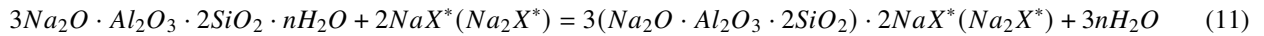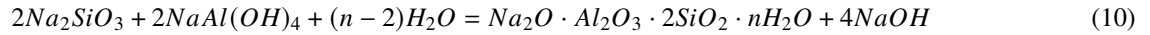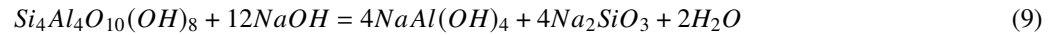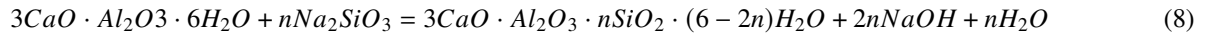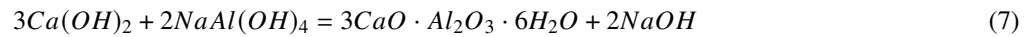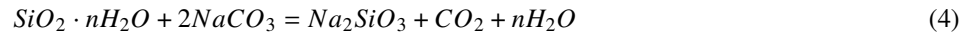
* X can be OH^-, Cl^-, CO_3^{2-} or $SO4^{2-}$

First, slaked lime ($Ca(OH)_2$) is added at above 90°C to form cancrinite and hydrogarnet from the kaolinite present in the ore (eq. 1-2). The lime also reacts with any opal present in the solution to form sodium silicate (eq. 2-3). The specifics of the digestion process of the de-silicated bauxite now depends on the bauxite type. Table 2 shows that more extreme measures are needed for the bauxite type in the following order: Gibbsite < Boehmite < Diaspore (GBD). We can therefore expect more residual alkalis like $NaOH$ and Na_2CO_3 if there is a higher concentration of diaspore as this ore-type requires higher alkali concentration and caustic ratio.

Aluminium is extracted from GBD as sodium aluminate (eq. 5-6) which reacts with excess lime from the desilication phase to form tri-calcium aluminate (eq. 7). If there is more kaolinite left after desilication, this forms sodium silicate (eq. 9). The sodium silicate may react in two ways at this point. The "good" reaction occurs between sodium silicate and the tri-calcium aluminate digested from the GBD to form hydrogarnet (calcium aluminosilicate hydrate) (eq. 8). The other reaction occurs when a (too) high concentration of sodium silicate is present. This is unwanted as it leads to a reaction with sodium aluminate
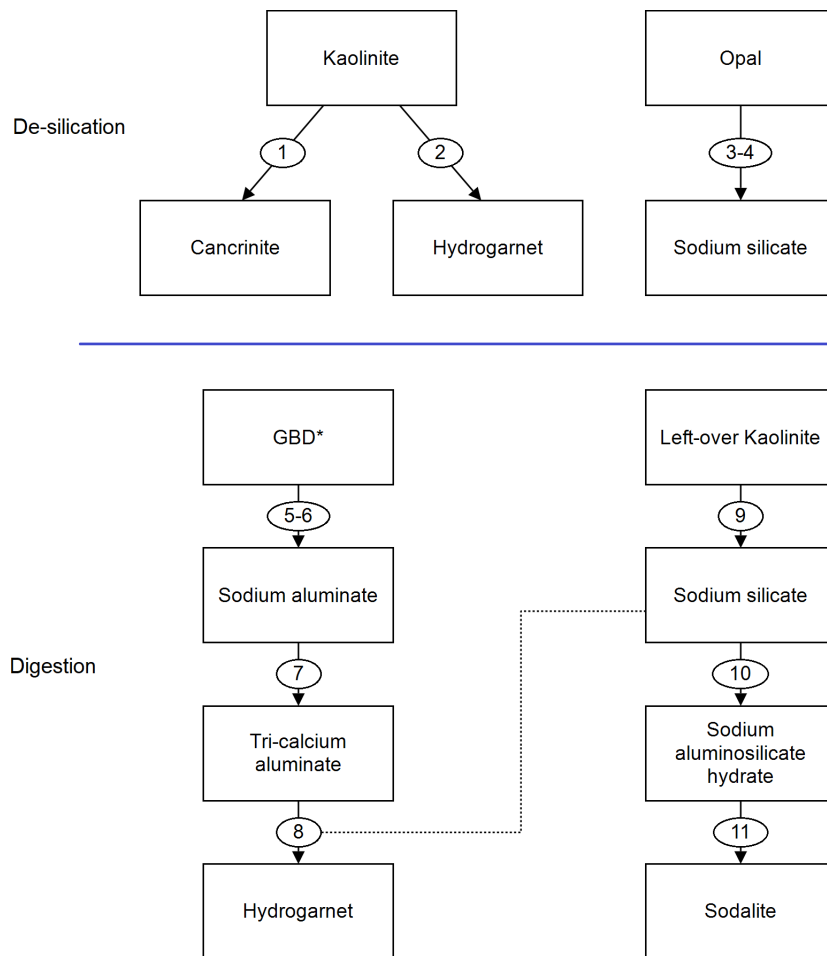
Figure 4: Map of reactions in the desilication and digestion during Bayer processing. *GBD is a combination of Gibbsite, Boehmite and Diaspore. **I intend to make this figure smaller.**

where sodium aluminosilicate hydrate precipitates (eq. 10) and then forms sodalite in a reaction with a sodium compound such as $NaOH$ or $NaCO_3$ (eq. 11). Sodalite is partly responsible for the pH buffer in BR. However, Pan et al. (2016) mentions that sodalite and cancrinite can transform to hydrogarnet in the presence of CO_3^{2-}, but if concentrations of sodalite and cancrinite are in the high end (see table 1) this is unlikely a dominant reaction.

After digestion the bauxite is further diluted and clarified in settling tanks. Here additives are added to precipitate colloidal iron, carbonates and organics from the green Bayer liquor. This also leads to the precipitation of calcite and tri-calcium aluminate amongst other minerals which will end up in the bauxite residue.

The combination of the compounds in the bauxite ore is as important to the BR composition as the composition of the bauxite ore itself. For example, quartz are not easily dissolved at low temperatures but will react with the aluminate in the caustic liquor at high temperatures to form a sodalite desilication product (Xu et al., 2008). The digestion of boehmite and diaspore type bauxite (table 2) will therefore also dissolve quartz adding to the sodium silicate production which if untreated leads to more sodalite (figure 4). A gibbsite-type bauxite with high contents of quartz is likely to leave BR with a high quartz content, but boehmite or diaspore-type bauxite may instead leave a more sodalite-rich BR meaning a waste with a stronger alkaline buffer capacity.

Another factor that may complicate the prediction of BR based on the ore is that multiple of the reactions are not instantaneous *e.g.* the desilication process usually takes 6-10 hours. The time given for the reactions to occur will affect the composition of the BR as a chain of reactions may be stopped before fully completed. This paper does not go in depth with foreseeing BR based on bauxite ore, but more knowledge on the reaction kinetics (*e.g.* reaction rate) would allow for a detailed guess on BR based on the ore composition it originated from. This in turn could help foresee how BR may be utilized in the vicinity of the mine and thereby make remediation and utilization an integrated part of the alumina production plan.

There are also other factors influencing the BR composition besides the reactions described in this chapter. For example, sodium titanate which is present in smaller concentrations (Lyu et al., 2021) can inhibit the effect of alumina extraction (Malt'ts (1991), Suss and Mal'ts (1991), Solymar et al. (1992) cited by Pan et al. (2016)), meaning that more aluminium compounds like GBD, kaolinite or hydrogarnet can be found in the BR when sodium titanate is present in the ore.

1.3 Utilization

TBR can be used for multiple beneficial purposes in the industry, figure 5 is an overview of how Klauber et al. (2011) categorised the patents invented from 1964-2008 and shows that especially the construction industry has been of interest regarding the use of BR. The increase from these 734 patents to the 1200 patents mentioned by Klauber et al. (2011) indicates the continuously increasing interest for BR utilization.

Evans (2016) estimates some 2-4.5 million tonnes of BR to be used instead of landfilled annually. Still, only as little as 1-2.5% of the annual production or 0.4~1‰ of the current BR reserves is currently utilized because of the multiple challenges complicating the use of BR. The challenges related to each of the three technologies will be presented in this chapter along with a few other BR applications. Keeping in mind that BR can be used in multiple ways is important as one use often will trade off another possible use, *e.g.* rare earth elements will not be extracted from the BR if is mixed and bound in concrete or soil stabilizer.
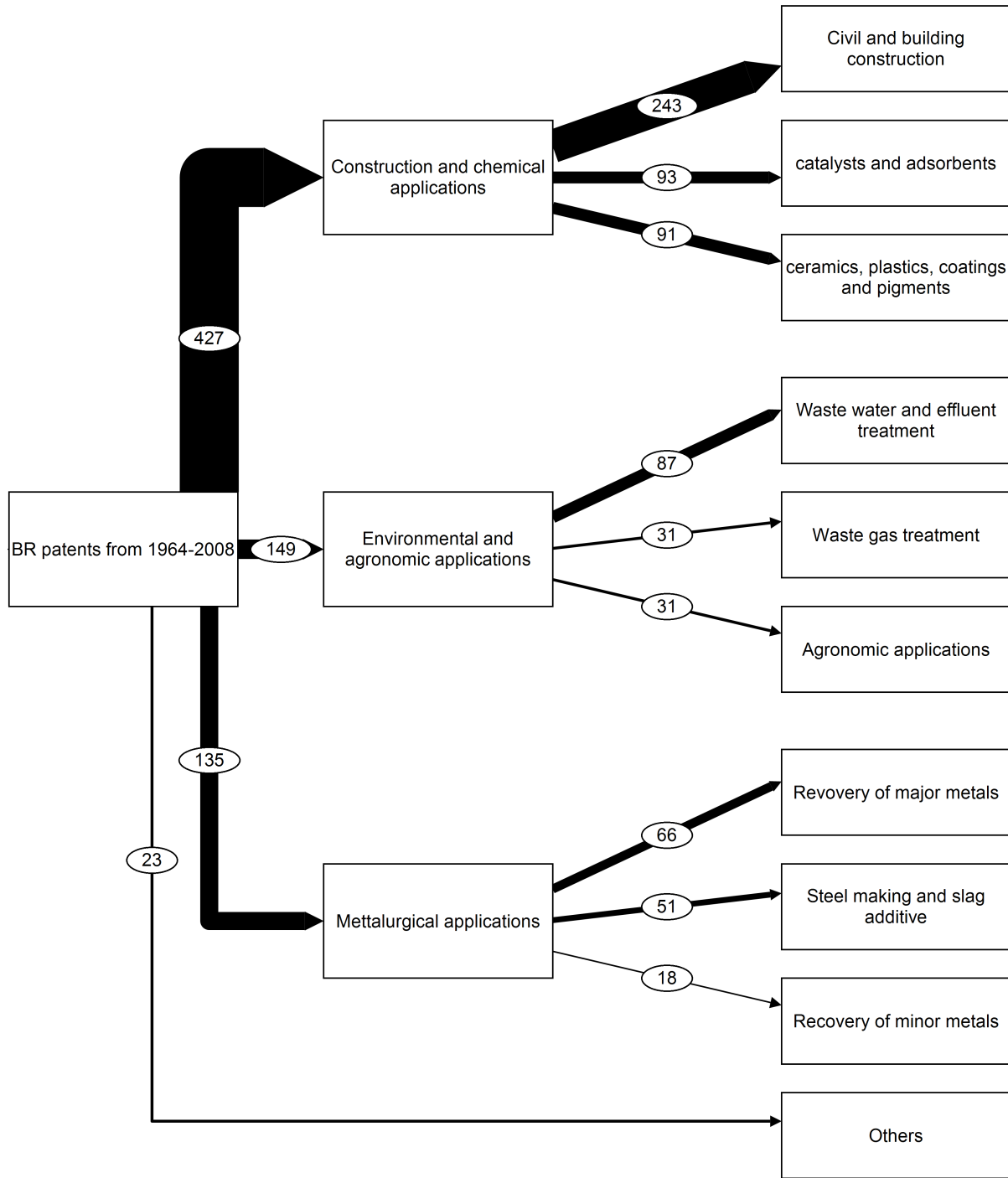
Figure 5: Distribution of patents regarding remediation and utilization of bauxite residue invented from 1964-2008. Data from (Klauber et al., 2011).

The following presentation of the challenges in BR utilization is mainly based on Evans (2016).

As also described in chapter 1.2, the composition of BR varies depending on the original bauxite and the specifics of the Bayer process. The potential applications of BR rely on the "chemical composition, mineralogy, pH, particle size distribution, morphology, and nature of the residue emanating from a particular plant" (Evans, 2016). If a suitable use is found based on these factors, it still has to be economically feasible.

It has been estimated that the cost of BR disposal is 1-3% of total production cost which is between 4-12 USD per tonne (Evans, 2016). These are 2016 estimates, but production cost are likely to increase due to decreasing ore grade, while disposal cost can be affected for better or worse by "green policies" (Ro et al., 2020). The cost for landfill remediation varies between sites. BR utilization is only economically feasible if the net cost from BR remediation and utilization is lower than the cost of landfill management. The substituted products are often easily available and at low cost meaning that it is usually difficult to get a good profit from substituting other products. Even when BR can be utilized in a seemingly economically feasible way, the following factors usually make a risk that must also be considered:

- Leaching of heavy metals (especially in construction and when extreme pH is present). It is mostly chromium VI and sometimes arsenic that is of primary concern.

- Radioactivity due to TENORMs. The EU Radiation Protection Guideline 112 recommends a radioactive level of 0.3–1 mSv/a (millisieverts per annum) for building materials. This guideline is set on expected exposure to humans rather than the radioactivity of the material itself. Many legislated limits are set on the actual radioactivity usually measured in Bq/g. Therefore, even though the radioactivity of TBR is usually under the limits in Bq/g, the product may still be an unpopular solution if humans are too exposed.

- Alkalinity or high sodium content. Besides what has already been discussed, "any waste material with a pH value above 11.5 is often considered hazardous"(Evans, 2016). Hazardous material is more expensive to manage (transport, storage etc.), but this goes for both landfill management and the processes that lead to utilization.

- Moisture level. Higher moisture levels lead to more expenses in transportation and storage, and any heating process to above 100°C (processes like calcination) also lose energy to evaporation. Frame press filters increase in popularity and can yield moisture levels of 26% or lower (see also chapter 1)

- Transport costs are as mentioned related to some of the other points, like moisture level and alkalinity. There is a growing trend of making fewer but bigger Bayer plants instead of multiple smaller Bayer plants. There is often greater distance between these plants and industrial areas as they are further away from population. This development means that transport costs will be more sensitive in the future. In this study, environmental protection is in focus, but the potential displacement of relevant industrial locations should be considered when evaluating the sensitivity of the model as transportation also will prove sensitive regarding environmental impacts.

1.3.1   De-alkalized bauxite residue as landfill cover

A BR product called Cajunite^{TM} showed advantageous over natural clay in a landfill capping in Louisiana, but clay for landfill capping has been estimated too costly if it has to be transported more than 75 km (Evans, 2016). BR clay can also be used for

amending acidic soils and some contaminated sites. When BR is used for landfill cover, especially heavy metal leaching and spreading of dust in dry locations are of concern when BR is substituting clay (Evans, 2016).

1.3.2   In soil stabilization

BR can be used for soil stabilization when constructing roads or dykes, and has been used for these purposes in several BR landfills and Bayer plants. In Australia, the company Alcoa used BR for the construction of the 70.5 km long Perth to Bunbury Highway which used approximately 5% of the global annual BR production for it's construction (Klauber et al., 2011) showing the potential for using BR in road construction. Evans (2016) mentions that the sand substitution include less CO_2 emissions, cost savings, less water usage and reduced eutrophication.

The remaining of this section is based on Patel (2019). Soil stabilization can be divided into mechanical or chemical stabilization of the soil. Mechanical stabilization happens by mixing of different soils and aggregates to achieve a matrix of low porosity, low compressibility, and high internal friction. BR may be suitable as soil stabilizer when a suitable dosage of binder is added. Addition of binder is categorised as chemical stabilization as it alters the soil properties by additives or chemicals (Patel, 2019). Lime, cement, and fly ash are often used as additives. The soil stabilization technology in this study use lime, fly ash, and GGBFS (ground granulated blast furnace slag) as additives.

Lime addition is especially useful in fine-grained soils where it reduce plasticity index (PI) by flocculation of clay minerals. In soils, the calcium in lime will also react with silica in the pore water due to the increased pH from the lime, this reaction creates cement which gives a stronger soil - since BR is likely to have high contents of silica (see table 1) it is also likely that the effect of lime is enhanced with BR. Quicklime is more reactive than hydrated lime, so demand of quicklime would be 75% of that of hydrated lime (Patel, 2019).

Fly ash is pozzolanic and some is also "self-cementing". Fly ash that is not self-cementing needs addition of lime or cement to make a cementitious product. The addition of sodium silicate also allows fly ash to become a geopolymer. Patel (2019) mentions that generally 8-16% (dry w/w) fly ash is added to coarse soils for effective stabilization.

Cement is among the most widely accepted additives for soil stabilization of most soils as long as there is absence of certain salts that disrupts setting time and organic content is <2%. The concentration of cement needed when used as soil stabilizer is around: 5%–10% in gravels, 7%–12% in sands, 12%–15% in silts, and 12%–20% in clays, meaning that finer soils needs more cement (Patel, 2019).

Multiple materials can be used for soil stabilization, and the choice of material is dependent on the characteristics of the soil that needs stabilization as well as the availability of materials at the location. As discussed in the LCIA, this LCA is very sensitive to the choice of substituted product which makes the results of the soil stabilization technology uncertain since substitution of gravel or cement would result in very different impacts. Choosing the material that is most likely substituted by the treated BR will make a more certain recommendation for the given location. This is further discussed in chapter 5.2.4.

1.3.3   As geopolymers: Inorganic polymers and high performance binder

Inorganic polymers (IP) or the hybrid high performance binder (HHPB) are geopolymers. Geopolymers are "an amorphous alkali aluminosilicate binder formed by the reaction of an aluminosilicate precursor, such as metakaolin, with an alkali(-silicate) solution." (McLellan et al., 2011). When knowing about geopolymers together with the potential of having metakaolin (calcined kaolinite) from chapter 1.2, converting BR into a geopolymer seems a natural choice. When aluminosilicate is mixed with an alkali solution it activates the polymerisation reactions where "tetrahedral Al and Si are connected via oxygen bridges" as shown in figure 6 - the material is then used as a binder to fixate aggregates in a strong matrix - just like concrete. An inorganic polymer is a "supergroup" of geopolymers by having some materials (like more Fe) that lead to desirable properties (better binding) (McLellan et al., 2011).
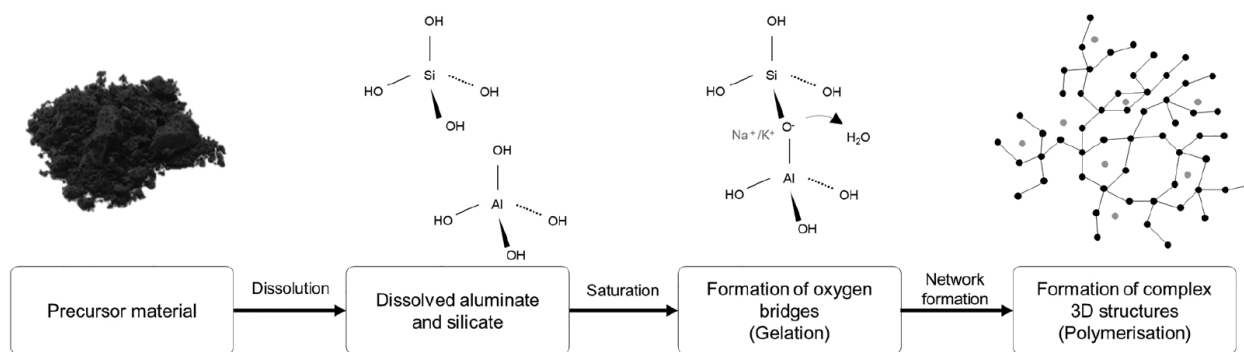
Figure 6: Simplified inorganic polymerization process (McLellan et al., 2011).

The challenges with IP or HPB are overcoming the hazards of TENORMS, heavy metal leaching and especially the high alkalinity (Evans, 2016), and avoidance of burden shifting when remediating the BR for use as product. McLellan et al. (2011) lists a number of studies where BR is used as a filler material in geopolymer products along with binders like metakaolin, GGBFS, fly ash, rice husk ash, and ferronickel slag where BR improves mechanical properties to a certain degree as long as BR concentration is not too high.

C. Fergusson (2014) cite multiple investigations by Barbhuiya et al. (2006-2009) on the matter of concrete and cement strength and attributes when replacing some OPC with the TBR called "Bauxsol raw material". Bauxsol raw material has been treated with additives resulting in a pH of 9-10 and alkalinity ±1,000 mg/L. Using TBR to substitute 20% of OPC resulted in a concrete comparable in strength to the ordinary OPC product with no substitution. The TBR lacked pozzolanic properties which caused a compressive strength decrease in a cement paste. But when the cement paste contained only 20% TBR, it passed the requirements for a class 52.5 (MPa) cement according to the standard on criteria of common cement: BS EN 197-1:2000. TBR can also be used to substitute 10-15% of sand in cement which additionally improves the durability properties like resistance to acidic silage effluents which is important in the agricultural industry.

Dimas et al. (2009) mentions that the Si and Al compounds in BR has a poor reactivity which inhibits the potential for obtaining binding properties found in BR. However, McLellan et al. (2011) mentions that thermal, chemical, and chemo-mechanical (or a combination hereof) treatments are promising alternatives for making the potential binder-components in BR more reactive. Hertel et al. (2016) transformed BR into a reactive slag (useful as geopolymer) by heating it to 1100°C in the presence of small

quantities of carbon and silica followed by quenching – similar to the base case scenario for IP and HHPB in this study. From this, he was able to make cement with >40MPa compressive strength with only a small addition of carbon and SiO_2. The success of the polymer is ascribed to the increase of reactivity of the silica-rich amorphous phase in BR.

Inorganic polymers are often good quality and is a valorised residual resource when based on BR which fits well with the goals of this study. However, the activating alkali solution (often sodium silicate) used in the IP version of HPB has major environmental impacts as shown in appendix B and by McLellan et al. (2011). Therefore, the HHPB seems a more promising technology than the IP already before a LCIA is conducted, as the HHPB deliberately tries to eliminate the sodium silicate from the geopolymer creating process.

Lastly, it is important to consider if the substitution product (BR product) is truly able to substitute ordinary concrete products already on the market. The EN 197-1 standard (CEN, 2000) categorise concrete by compressive strength, where standard strength is compressive strength 28 days after setting has started. The compressive strength and other factors describing the quality of the BR product should be tested, quantified, and used for comparison to what products, or rather functions of the product, can be substituted.

1.3.4   Other utilizations

As seen in figure 5, there are multiple different possible pathways for utilizing BR. However, using one method may disable the use of another, meaning that there is usually a trade-off in BR utilization.

Recovery of the metal subcategory "rare earth elements" (REE) has been developed for BR as REEs do not dissolve during the Bayer process and thereby has an increased concentration in the BR. Elements like lanthanides, scandium and yttrium are essential for products like electric and hybrid cars, wind turbines and fluorescent lights. All are products that are essential for a sustainable infrastructure as well. Based on findings by Deady et al. (2016), Evans (2016) estimates that annually 100,000 tonnes of REEs are produced along with BR but not extracted. When BR is mixed with sand or the like, the concentration of REEs decrease and it is likely that it becomes less economically attractive to extract the REEs from the BR.

BR has also been successfully used for heavy metal sorption, phosphate removal, industrial waste water and solids treatment and multiple treatments of contaminated soil at spill sites and mining sites ((McConchie et al., 1999; C. Fergusson, 2014). Some of the properties that make BR useful for these functions are also what may be beneficial as landfill capping.

2   Introduction to life cycle analysis

Unless other authors are referenced, the introduction to life cycle analysis (LCA) is based on Hauschild et al. (2018):

2.1   Why is LCA useful?

Life cycle analysis (LCA) is a tool that enables a holistic interpretation of the environmental consequences resulting from the choice(s) analysed in the LCA. The term "Life cycle" is an analogy. A product and that of a living being. In a LCA a product
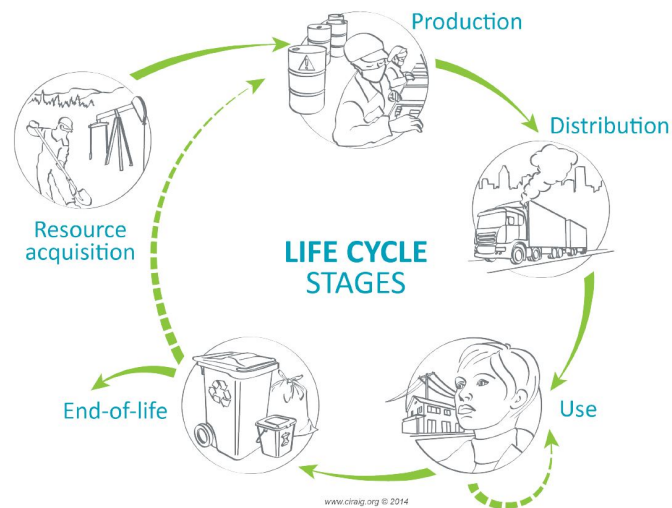
Figure 7: Stages of a product's life cycle (Beaulieu et al., 2015)

or service undergoes stages throughout its life cycle (see figure 7) – each stage has inputs and outputs from other life cycles. *E.g.* An aluminium can was made of aluminium that had to be mined and then processed into being a can – this is usually the resource acquisition and production stages. The can is then used, *e.g.* as a soda can we drink from, but first it has to be transported to the consumer - this is the distribution and use stages. After use the can is discarded, either as waste, recycled, or reused. The can may only be recycled or reused to a limited degree until it's quality renders it unusable at its "end of life". It is natural to think of LCA as an evaluation of the life cycle of a product or service, but it is often better to think of it as the life cycle fulfilling a certain function. *E.g.* the can fulfilling the function of "storing a small volume of beverage until consumed" - in this way, the function can be compared to products or services sharing this function, like plastic bottles. The description of the function is called the functional unit (FU) and is a vital part of any LCA.

It is important to stress that LCA is giving a holistic interpretation. If multiple potential environmental impacts are not considered, a solution for one environmental issue may lead to a problem in another, *e.g.* only using biofuel to satisfy the global energy demand may be good for short-term CO_2 emissions, but will be catastrophic for land use and terrestrial ecosystems – this is called "burden shifting".

Every emission and used resource through the life cycle is ideally mapped in a LCA, and when possible, with geographical location of them. This list of flows (resources in, and emissions out) make out the life cycle inventory (LCI). These flows are then put in mathematical models that are based on proven causalities and empirical relations. Here they are computed into impact categories that allows for a better overview of what the potential consequences are, if the function in question is performed. The ability to turn thousands of connected processes, consumptions of resources, and emissions into a few comprehensible categories is what makes LCA such a useful tool. The quantitative nature of the LCA allows for an easy comparison between different life cycles and therefore is a valuable tool for decision making related to sustainable development. However, the enormous number of inputs and outputs are also the weakness of LCA, as it is impossible to ensure correct and precise data for every process, in fact most processes are averages which includes uncertainties. A LCA without a proven robustness through sensitivity analysis is therefore useless as an initial LCA often have ambiguous or even wrong results.

The inputs to a life cycle are in the form of materials, energy, or raw resources while the outputs are emissions (from energy

production or directly from chemical reactions like CO_2 from calcination), products, or waste streams. These physical flows connect "unit processes" which are sometimes called the building blocks of a LCA. A unit process is describing the conversion of the input flows into whatever output flows are produced. In continuation of the building block metaphor, the flows work like mortar that connects the bricks. The goal of any LCA is to monitor the relevant unit processes and flows throughout the life cycle to understand the impacts of the function (usually product or service) on the natural environment (ecosphere) and human society (technosphere).

To systematically "build" or explain the life cycle and determine what is the relevant part of it, the LCA is always split into four phases: Definition of goal, definition of scope, life cycle inventory, life cycle impact assessment, and interpretation.

2.2   Relevant choices in the 4 phases of LCA

2.2.1   Definition of goal and scope

The scope defines what unit processes are accounted for in the life cycle inventory. There is a near-infinite amount of activities down- and upstream to any activity, but eventually going too much down- or upstream becomes irrelevant as illustrated in example 1.

Example 1: Treating aluminium scrap: The treatment needs energy, this energy is among other things from biowaste. Biowaste is a by-product agriculture, like carrot production. The production of the carrot is actually in the inventory for "treatment of aluminium scrap" in the ecoinvent database (Wernet et al., 2016) because of this connection, so the background inventory is quite detailed. However, energy and resources are inputs in the carrot production, one of the many resources are phosphorous, this is also part of the database. Some of the phosphorous is mined in Africa and transported to the carrot-farm in Europe. A mine worker in Africa use safety-shoes and a helmet on the job, something he would not have needed if the phosphor mine was not needed. What is the impact of his extra pair of shoes, is it relevant for the impact of aluminium scrap treatment?

Since it is impossible to include every activity up- or downstream of the life cycle in focus (along with not wanting to waste time and resources on it) it is important to clarify when activities are no longer deemed relevant and therefore not included - this is especially important for comparisons as a larger scope usually results in larger impacts. "Cradle-to-grave" or "cradle-to-gate" are terms often used to describe that all activities upstream of the life cycle (from "cradle") are included until the product's end of life ("grave") or until the product leaves the responsibility of the producer or company ("gate"). But as just discussed there is an infinite amount of activities linked to the life cycle, so these terms are practically impossible to fulfill.

Although the LCA model is inevitably wrong, it is only a tool for answering the goal of the LCA. Therefore, the scope is determined to allow the LCA to fulfil its goal at minimum effort for the LCA practitioner. This usually means that only the most sensitive processes in the inventory need to be discussed and perhaps altered to be more case specific, as they cause the results that may change the conclusion of the LCA. A LCA is considered robust when the conclusion remains the same despite the uncertainties of the inventory's processes. This makes the goal of the LCA a very important definition.

The LCA goal describes the purpose of the LCA. According to the ISO standards[1]a goal definition should include:

1. Intended applications of the results

2. Limitations due to methodological choices

3. Decision context and reasons for carrying out the study

4. Target audience

5. Comparative studies to be disclosed to the public - this study is already public and needs no comparative study disclosed to the public.

6. Commissioner of the study and other influential actors.

Point 1-3 are important to the decisions made during the LCA. The "intended applications of the results" are explaining what the study aims to answer. It is important to remember that the LCA is meant to answer only its own goal - it can be misguiding in answering other questions. A LCA will always be limited by the choice of methodology used, among others whether the LCA is attributional or consequential (see chapter 2.2.4). The reason for carrying out the study is mentioned to reveal where the LCA is useful – this LCA compares 3 different technologies meaning that it will be robust to the extent necessary for these technologies, but it may not include data that allows for a fair comparison to other technologies.

Point 4-6 deal with how the LCA is communicated. Due to the ambiguous nature of LCAs, it should be transparent for the reader who could have influenced the LCA and who it is meant to influence so that the reader may be critical to the context the LCA was conducted in.

Defining the goal and scope includes setting a functional unit as well as making decisions on the methodology of the study. Both will be described in the following chapters.

2.2.2 Functional unit

LCA's are always made to help decision-making for a more "green economy" or sustainable future, both socially and environmentally (United Nations Enviroment Programme, 2011). However, the goal should be more specific than that - in this study, the goal is to compare the environmental sustainability of three different technologies related to the remediation and utilization of BR. The functional unit (FU) must then describe a flow or use that leads to the environmental impact categories we wish to study (defined by the scope). The FU should be as precise as possible to fit the goal of the LCA, but a too specific FU may inhibit comparison with other life cycles and a broader use. It is important when comparing life cycles of the same FU, that the FU describes the function rather than the quantity of the products or services. This is especially important to the quality of compared products. 1 ton of concrete with a low compressive strength cannot be compared to concrete with a high compressive strength unless it is mentioned that the substituted concrete was used in a context where a low compressive strength meets the needed requirements to fulfil its function. *E.g.* is the function of the concrete to build bridges or furniture? Compressive strength may not be of equal importance between the two functions.

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[1]("ISO STANDARDS ARE INTERNATIONALLY AGREED BY EXPERTS - Think of them as a formula that describes the best way of doing something" (*ISO - Standards*, n.d.). Following the ISO standards also makes a LCA more comprehensive for other LCA practitioners and allows for easier comparisons as LCAs are performed in a similar structure.)

2.2.3   Cut-off, system expansion and allocation

Unit processes usually have more than one useful output, this is called a "multifunctional process". *E.g.* The production of wooden constructions also produces woodchips and sawdust which can be burned for energy or used in other products like particleboards or wood pulp. This means that we avoid cutting down new trees for burning or creation of other products when a house of tree is built. To understand the impacts of producing the wooden constructions the secondary product should therefore be included as well. Defining how multifunctionality is modelled is a vital choice for most LCAs, but especially in this study as we are in fact working on converting a waste flow into a secondary function of alumina production. Different solutions for modelling of multifunctional processes are found in the ISO 14044 standard. System expansion using crediting is used in this study, but all solutions are described in the following.

"Cut-off" or "sub-division" of a unit process is preferred when the inputs and internal processes of the unit process can be divided so that the primary function can be modelled without the inputs and outputs of the secondary function. This can be done for a factory producing chocolate where the chocolate production can be separated from the production and use of the packaging. If the goal of the study is to evaluate the chocolate (without caring about how it is packed), the processes of plastic production and packaging would be cut off (not accounted for) so that the chocolate could be compared to another chocolate without comparing how it is packaged. When producing alumina, the co-production of BR cannot be cut off as the BR production is an inevitable co-product of alumina. Instead of cutting process out of the system, the system must be expanded.

System expansion means that more unit processes are included in the life cycle to make the model fairer in terms of the primary function's impacts. This means that the modelled life cycle of a wooden construction includes the use of sawdust in its most likely applications ("inclusion") or subtracts the impacts that would have most likely happened if the function of the sawdust were to be fulfilled otherwise (perhaps by incineration of fossil fuels) ("crediting" or "substitution"). The use of inclusion or substitution can lead to opposite results, but as long as they are used consistently when comparing two life cycles, the comparative LCA of the two should end up with similar conclusions.

Allocation or partitioning is the last suggested solution for multifunctionality by the ISO 14044 standard. If a unit processes cannot be subdivided and there are no reasonable processes to use for substitution and crediting, the inputs and emissions of the unit process are shared between the products of the process. This means that the impacts of the secondary product may look very different from those of the primary product although one cannot exist without the other. When allocating the impacts to the products, it is done based on a parameter (unit) shared by both products. While it could be by weight or volume for most products, it is most popular to allocate based on the economic value of a product since the economic value is assumed to be the incentive of making the product in the first place. BR is expected to have a very low value or no value at all and products using BR would therefore not be allocated any of the impacts related with its production. Allocation is often the preferred method in the background inventory (ecoinvent) when using the methodology "allocation at point of substitution" (APOS).

While allocation at the point of substitution is used in this study by using APOS generated inventories in the foreground LCI, allocation is not performed manually. Instead system expansion is used to credit avoided impacts from the substituted products to the BR treatment and utilization life cycle. However, if this LCA is to be implemented in the ecoinvent database, it may be converted to an allocation scheme together with alumina production rather than system expansion. See figure 8 to better follow the coming explanation of APOS and how system expansion in this study converts to allocation in a future ecoinvent database using the APOS methodology:
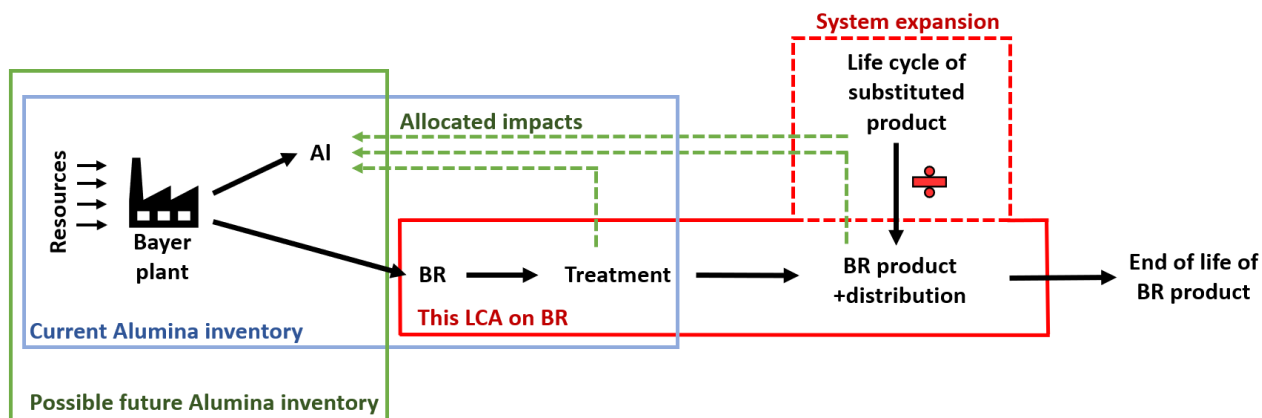
Figure 8: Simplified overview of the current (blue) and possible future inventory (green) setup for Alumina production in the APOS ecoinvent database, and how this LCA (red) use system expansion (dotted red) to calculate allocated impacts (dotted green) in the possible future alumina inventory.

The production of alumina is unavoidably multifunctional with the production of BR. The waste treatment of BR as a secondary product must therefore be included in the alumina life cycle as well. When the BR is remediated and utilized this too should be included in the life cycle of alumina production as it is an effect of alumina production. Currently, the production of alumina only has alumina as a useful output while the rest of the outputs from the process are waste and emission flows - this is currently an *included* system expansion where the treatment of BR is allocated to alumina production. But if the waste is further treated and utilized as a product by one of the technologies in this study, this too is a secondary function of the alumina producing process including the substitution of another product. The treatment of the BR must therefore still be included, but the processes needed for the substituted product can also be subtracted from the life cycle of alumina production which thereby gives credit to the use of the waste since other impacts are now avoided through the product substitution. In other words, the impacts of the waste, both good and bad, are allocated to the point where another product is substituted. Allocation at the point of substitution (APOS) avoids allocating the impact of the treatment within the treatment system but allocates the impacts of by-products (clay, stabilized road base, or concrete) together with the primary product (alumina). This study focuses on finding the balance between included impacts in the remediation of BR and the substituted product impacts resulting from the utilization of the remediated BR. Eventually, both benefits and impacts from remediation and utilization of the BR found in this study may be allocated with alumina production resulting in a more sustainable profile for Bayer process productions - this is the point as it motivates for circular economy and sustainable development.

2.2.4   Attributional or consequential LCA

LCA is not a single method, but more a family of methods where the different approaches can be put into subgroups (Ekvall, 2020). While using cut-off, system expansion, or allocation can vary between unit processes in the same LCA, the choice of an attributional or consequential LCA regards the entire analysis. The attributional and consequential LCA have different input data which ultimately leads to different perspectives of the problem. This often leads to very different conclusions so it is important to discuss why a specific kind of LCA approach is used. The two are described here by United Nations Enviroment Programme (2011):

1. "Attributional approach: System modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule."

2. "Consequential approach: System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit."

Hauschild et al. (2018) also describes the two approaches as a way to answer two different questions: "What environmental impact can be attributed to product X?" (attributional). "What are the environmental consequences of consuming product X?" (consequential). The consequential LCA seeks to discover how the market changes when a product or service is added or removed to the market. System expansion is usually the consequence when a product is added or removed, *e.g.* more wooden houses leads to more wood chips and therefore less trees being cut for burning. However, more trees are cut for construction. It is already evident that consequential LCA quickly becomes complicated to model as it tries to predict the market response. For the same reason it also uses marginal background processes. A marginal process is the process that is either removed or employed as an effect of the change caused by the change in the system. This usually makes a big difference in regards to energy consumption as a new production leads to a short-term increase in energy demand – such demands are met by burning of natural gas or other fossil fuels since the establishment of renewable energy takes longer and are less easily adjusted to new demands. Using marginal energy consumption may lead to "spikes" of emissions due to very specific political choices or the like (*e.g.* next power plant should be coal-based) which may bring much confusion to a comparative LCA. Although an ideal consequential analysis would be closest to reality, it has many uncertainties and its results can be counterintuitive – therefore it is often the attributional approach that is preferred for most studies.

The attributional approach can answer how much an activity is to "blame" for the environmental impacts. It uses average background processes rather than marginal, *e.g.* it assumes that a new production is not to blame for the change in energy demand and therefore the average of the energy grid in the region defined by the LCA scope is used as energy consumption in the model, although in reality the energy may come from more specific sources. An attributional LCA also does not consider future consequences of adding or removing a product from the system – it does not consider that the system changes at all. The attributional approach can therefore be seen more as a "snapshot" of the situation, which in multiple regards is wrong because there will undoubtedly be a consequence in some scale. However, it is often easier to comprehend the results of an attributional LCA and it is also often considered a more "fair" distribution of blame, as illustrated by example 2.

Figure 9: Illustration of the idiom "Straw that broke the camel's back". It illustrates the cumulative effect of small actions resulting in a sudden large reaction.

If any of the technologies can successfully substitute a construction material, it will have significant consequences in the market because of the amount that can be substituted (BR production is 200 million tonnes per year). Therefore, it would not be wrong to use a consequential approach. However, the goal is also to compare each technology with each other based on a spatial context. A consequential approach may then quickly become so complex that no useful answers can be gained as each technology leads to different market changes and data that is needed for a precise estimation of the market dynamics are hard to come by. The attributional or "blaming" approach is therefore preferred in this study to see how much each technology is to blame for the environmental impacts it causes depending on what energy mix it will use. It is therefore important to remember that the "snapshot" of the system gained by the attributional approach is limited

in showing what may happen to the system when the product is introduced. Sensitivity analysis can help discuss some of the model's limits, and other consequences are discussed qualitatively.

> Example 2: Imagine there is only one camel in a town. The townsfolk are moving, but want to bring their hay. One guy puts his hay on the back of the camel. Another adds his hay as well. Soon, everyone is putting their hay on the back of the camel. When the last and poorest man puts his one straw on the back of the camel, its back breaks rendering the camel unable to carry any hay. Is it the fault of the man with one straw that the camel broke its back or should the blame be distributed by how much weight each and everyone put on the camel? This example is inspired by Majeau-Bettez (2020) and known as the "straw that broke the camel's back" see figure 9.

2.3   Life cycle inventory

Once the goal and scope have been defined the life cycle inventory (LCI) is aggregated. The LCA practitioner finds data for the life cycle inventory *foreground system* and connects it to the LCI *background system*.The LCI can be divided in two:

- **Foreground inventory:** The foreground system consists of activities that can be affected by the stakeholder of the LCA (Reinhard et al., 2019). In the case of this study, the foreground system is the activities carried out during the remediation and utilization of the BR, described in detail in table 3, 5, and 4, and simply illustrated in figure 1.

- **Background inventory:** The countless activities linked to the foreground inventory system are not manually build by the LCA practitioner but build up as a database that automatically is connected to the foreground system by being part of the foreground inventories. The background system is huge (ecoinvent has more than 10,000 inventories (Wernet et al., 2016)), and consists mostly of generic and averaged activities.

Inventories are split in "market" inventories that are an average of multiple "transformation" inventories. A transformation inventory is a unit process that transforms inputs to different outputs, a market inventory is a collection/average of multiple transformation inventories of the same category. *E.g.* an often used market inventory is the energy mix {ReR} (Europe without Switzerland), it combines the market inventories for each energy grid in European countries, and each of those have combined the energy inventories relevant for its country so that Denmark have more wind power and Norway more hydro power. The {ReR} market inventory is therefore an energy consumption expected to be of a mix of energy sources from all of Europe. Even transformation inventories are often an average to find the "typical" inventory, *e.g.* the typical life cycle of one generic windmill.

The LCA practitioner finds data for the LCI foreground system and connects it to the LCI background system. This is often done by having appropriate market inventories in the foreground system which are already build up from the background system database (ecoinvent in this study). While this allows for a very comprehensive model, the market values in the foreground LCI comes with a lot of uncertainty.
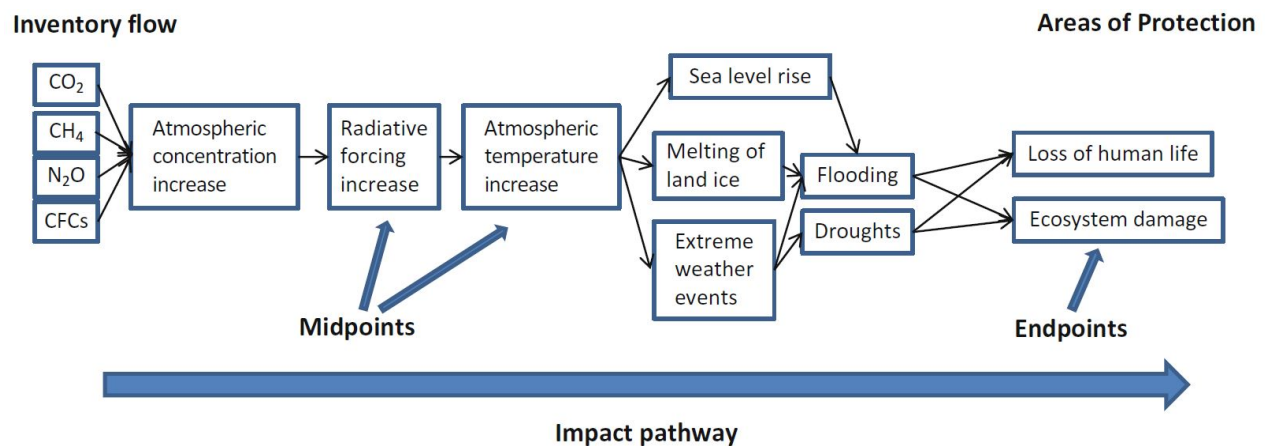
Figure 10: "Simplified impact pathway for global warming connecting elementary flows from the LCI to the AoP" (Hauschild and Huijbregts, 2015).

2.4   Life cycle impact assessment

Every activity in the LCI consists of inflows and outflows. Some outflows are as products to the technosphere and some outflows are direct emissions to the environment. Some inflows are extracted resources and some are remediated waste like BR is in this study. Waste utilized as or in a product is calculated as a negative emission thereby resulting in a good result on the impact assessment. The life cycle impact assessment (LCIA) converts all the emissions and resource extractions into a number of impact scores that represent the impact on areas of interest like global warming or ecotoxicity which can be further converted to impacts on an "area of protection" (AoP) which represents what we ultimately seek to avoid damaging (Hauschild and Huijbregts, 2015).

The impacts are mathematically represented through characterization factors (CF) at "mid-" or "end-" point level. A CF is a value with a certain unit that allows multiple emissions to be represented together. Units can be CO_{2-eq} or DALY (disability adjusted life year) and represents an effect on the environment or society. The endpoint level CF are typically the AoP (Dewulf et al., 2015): Natural Environment, Human Health, and Natural Resources. These endpoint impacts are aggregates of midpoint values. Midpoint values are calculated with midpoint CFs and substance emissions. CFs are calculated by different methods, which is why it is important for a transparent LCA to document which method is used to obtain LCIA results as different methods give different results from the same LCI. Figure 10 is a simplified example illustrating how emissions aggregated from the LCI create impacts that are represented by CFs at midpoint level and are then further calculated to CFs at the endpoint level.

(Hauschild and Huijbregts, 2015) mentions that midpoint and endpoint impacts are complimentary. While endpoint CFs provide better information on the overall impact from the LCI, the midpoint CFs are more certain due to less conversions but also seems less relevant for a decision maker as they do not directly describe the AoP. *E.g.* many politicians talk of global warming, because it leads to an increase in extreme weather events and sea level rise that leads to destruction of the natural environment and endangers human lives. While the latter categories are what we really care about, global warming measured in CO_{2-eq} (carbon dioxide equivalents) is a measurement closer to the source of the problem and therefore more certain.

The LCIA rarely gives an unambiguous result which especially makes the discussion of the presented CFs important. An
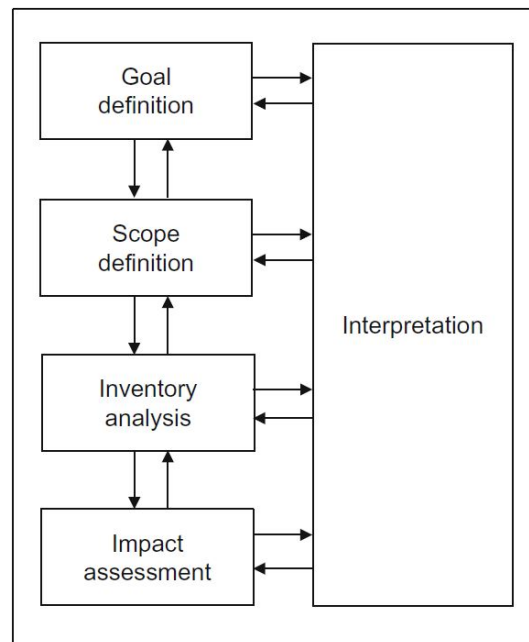
Figure 11: Iterative phases of life cycle assessment (Hauschild et al., 2018)

example could be incineration of organic waste. The carbon in the waste is "green" CO_2 after combustion as it belongs to the biogenic carbon cycle (Hauschild et al., 2018) and incineration of the biowaste therefore leads to a positive result for global climate change if it will substitute fossil energy. However, the more and more scarce resource, phosphorous, will go to waste in the process resulting in negative impacts on resource scarcity. Depending on the goal of the LCA, the right impact categories should be presented. LCIA is a tool *to help* decision making, it is not meant to stand alone when the decision is made but rather work as an argument in a bigger discussion.

2.5   The iterative process of interpretation

Interpretation is *not* the "last step" of a LCA as LCAs are not worked out in a linear manner. Each of the previous steps are interpreted along with what have been found in the other steps as illustrated by figure 11. In practice, a sensitivity analysis is performed to find the most sensitive parameters which are then evaluated and their sensitivity analysed again. Multiple iterations should help identify the largest uncertainties of the LCA. As long a the focus is to reduce uncertainty of key processes, the best precision can be made with minimum work effort. Multiple iterations are especially important when deciding where to cut off the model. As mentioned, the real world life cycle network is nearly, if not actually, infinite, but when included processes have small enough impacts they are considered neglectable, *e.g.* if their highest impact score is less than 0.1% of the total impact made to that category, it is unlikely that anything upstream of that process will change the conclusion of the LCA. That is why this iterative process is necessary to ensure that the scope and LCI is defined in a way that allows a fair representation of the real system and also to ensure the LCIA represents those impact categories that are relevant to the goal.

"A final limitation worth keeping in mind is that, while LCA can tell you what (product system) is better for the environment, it cannot tell you if better is "good enough". It is therefore wrong to conclude that a product is environmentally sustainable, in absolute terms, with reference to a LCA" (Hauschild et al., 2018). Therefore, keep in mind that it is the comparison of the technologies that are in focus.

3   Life cycle assessment: Goal and scope

Each phase is described based on the ISO standard requirements listed by Hauschild et al. (2018) to ensure that all details are included.

3.1   Goal definition

1. Intended applications of the results
The goal of this LCA, as for the study as a whole, is to evaluate the environmental impacts from implementing one of the three technologies: De-alkalization, soil stabilization, or high performance binder, as well as the utilization of the treated bauxite residue product and its potential substitution of another product or function.

2. Limitations due to methodological choices
As this is an attributional LCA and not consequential, the industry is not assumed to change if a technology is implemented. Not including this in the LCIA must be mentioned due to the size of the alumina industry and the fact that treated BR can influence the impacts of the construction industry. To clarify the importance of this, example 3 describes a situation this LCA is not able to evaluate.

3. Decision context and reasons for carrying out the study
The study is a master's thesis connected to the RemovAl project (*RemovAL – Removing the waste streams from the primary Aluminum production in Europe*, n.d.).

4. Target audience
The LCA targets a scientific audience, not necessarily with expert knowledge of the LCA framework, but with a technological and scientific foundation. It is meant to broaden the environmental perspective and knowledge in the RemovAl project and therefore anyone of relevance in the RemovAl project is also a targeted audience.

5. Comparative studies to be disclosed to the public
This is not needed, as this study already is disclosed to the public.

6. Commissioner of the study and other influential actors.
The study is commissioned by the Norwegian University of Science and Technology (NTNU). Other influential actors are the supervisors of the study, including supervisors from the Technical University of Denmark (DTU), and the pilot plants from where the flow charts of the technologies were made. The flow charts are assumed to be precise without further evaluation of the mass and energy flows.

Example 3: Imagine technology "A", it remediates environmental impacts, but not as well as another technology "B". However, technology A is economically more feasible than technology B, and therefore encourages more people in the industry to use it. Although technology B had better results per kg of waste treated or per product produced, technology A ends up treating more kg of waste and substituting more products on the market and therefore the *total* negative impact reduction in the industry is now better for technology A than B, although the comparative LCIA showed better results for technology B.

3.2   Scope definition

1. Deliverables

This LCA delivers both three LCIs and multiple LCIAs, they are further explained in chapter 2.3 and 5.1 respectively. Based on these and combined with the literature review in the first part of this paper, this study also delivers a qualitative discussion of the technologies and give recommendations on which technologies are best suited based on a spatial context.

2. Object of the assessment

The objective is to remove BR from BR landfills in a meaningful way or avoid putting it there in the first place. Although a lot of work is put into the evaluation of the substituted products, it is the removal of BR that is the priority objective and the utilization of the treated BR is only an effect of the economic incentive created by having treated BR at hand. Because of this, remediation will not occur without being followed by a utilisation which is described in the functional unit (FU):

FU: Remediation and utilisation of 1 ton bauxite residue in an acceptable quality in reference to the substituted product in the year 2021.

This FU along with the approach that incorporates the negative waste flow in the LCI allows both for a comparison of each technology with one another and an evaluation if the technology is more beneficial than "business as usual". Unlike many other FUs, this FU does not specify location, because the study aims to compare life cycles at different locations. The time period for inventories in ecoinvent version 3.5 are mostly valid until 2018, but was used with the assumption that the industry has not changed much. The time is also not set as a time horizon as the attributional approach is used to capture a "snapshot" of the situation. In a longer time frame the new products will have consequences for the market which the attributional approach cannot predict. The term "acceptable quality" demands that the treated BR is of a quality similar to that of whatever concrete is substituted.

3. LCI modelling framework and handling of multifunctional processes

An attributional approach is used, but in contrast to the conventional view on the attributional approach, when subdivision is unavailable system expansion is used rather than allocation in the foreground LCI (see chapter 2.2.1). The background LCI is from the ecoinvent database version 3.5 where "allocation at point of substitution" (APOS) is used for multifunctional processes. This is especially important as the utilization process of treated BR is a "specialty production".

A speciality production is an activity that has a material for treatment as an input, but which is not a treatment activity" (Weidema et al., 2013). The ecoinvent guidelines state that "Materials for treatment should as far as possible not be used as inputs to activities that are not treatment activities, i.e. speciality productions should only be used when unavoidable." The goal of this LCA is to redirect the usual waste flow, and therefore making the foreground inventory of each technology into a specialty production, is unavoidable.

A LCA for each of the three technologies will reveal if they are in fact improving the current environmental situation. Instead of comparing them to a "business as usual" scenario, which would be a comparison to the "Redmud from bauxite digestion {GLO}| market for" inventory in ecoinvent, this inventory is added to the LCI for each technology as a negative waste flow thereby acting as an inflow from waste to the technology inventory and back in the technosphere.

4. System boundaries

According to Hauschild et al. (2018), the system boundaries should ideally be set so that only elementary flows (resources and emissions) cross the system boundary borders - in other words, the entire technosphere should be included. As seen in figure 12 this has not been considered necessary in this study as the comparison between the technologies are in focus and therefore a lot of the processes in the technosphere are irrelevant to include as they are the same for all technologies. End of life (EOL) treatment of the treated BR product after its use stage is assumed to be the same as for the substituted product and is therefore not included. The system boundaries start after the Bayer process when BR is at hand and end when the BR product has been transported to the site where it is utilized. The included upstream and downstream activities within the described scope in this LCA are initially all the activities from the ecoinvent database (version 3.5).
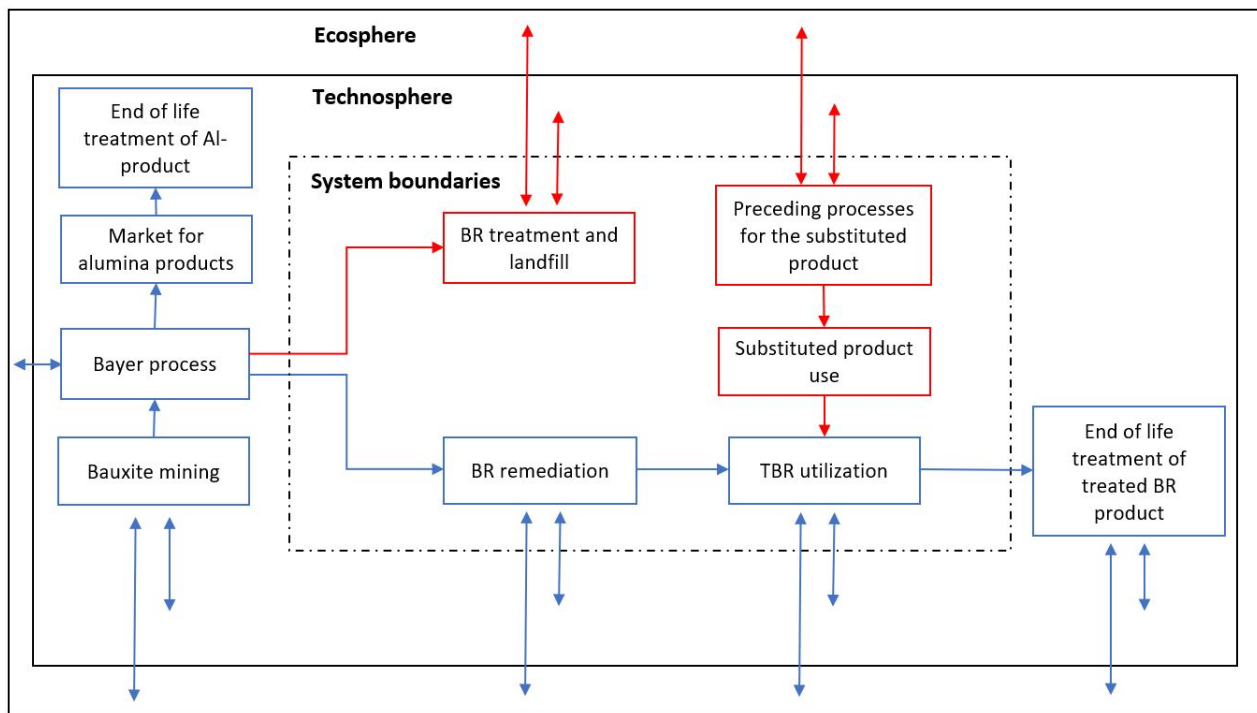
Figure 12: A simplified presentation (aggregation) of what processes are included in the system boundaries. Red flows and processes are mathematically negative in impact calculations as these are the avoided processes when the system is expanded by substitution. Flows between eco- and technosphere and unit processes within the scope are obtained from the background LCI (ecoinvent).

5. Representativeness of LCI data

The geographical representativeness of the LCI data is mainly based on the regional mix of market inventories and the energy grid of the location. Market mix's have been prioritized in the following order: RER (Europe without Switzerland), GLO (global), a European country except for switzer land, and lastly RoW (rest of world). For the LCIA each technology is mostly

build as a European inventory. In the initial iteration an averaged energy grid shows that the energy consumption of the actual processes are not as sensitive as some of the materials used or substituted. The information gathered for the LCI is site specific for the technologies in their country, but production and transport of many of the processes that make the foreground system are of an industry-averaged type where most often RER is used. Another important factor for geographical representativeness is the transport distance and transport type between sources of inputs to the treatment plant (like quarries) and from treatment plant to customer. This will be thoroughly discussed in chapter 6.0.2.

The time-related representativeness of the LCI is based on the value choice: Hierarchist (*cf.* chapter 5.1) which has a 100-year time horizon for impacts. Besides that, the time horizon is short - as shown in figure 12 the disposal phase is not included. The potential emissions during the "use" phase for soil stabilizer, concrete or clay are included for a 100-year time horizon. Concrete is known to absorb CO_2 during it's full life time and even after disposal (Xi et al., 2016), this is not included in this study as no literature have been found on the CO_2 sorption or nature of carbonation in concrete based on treated BR. For all products a long lifetime is expected (over 50 years) and the delay of landfilling treated BR after it is used as product, is assumed to cause less impacts in the future than now due to the development of sustainable technologies and policies agreed by many nation leaders in the Paris agreement as well as the focus on sustainable development goals (SDGs). The processes used in the foreground system are valid until 2018, although the flows of the technologies evaluated are measured or calculated in 2020 and 2021.

The technological representativeness of the LCI is not very specific. The BR (red mud) treatment process from the ecoinvent database is one average of different treatment and disposal sites across the globe using a mix of the technologies described in chapter 1. The sensitivity between using different processes for sensitive inventories (like concrete or soil stabilization methods) have been tested and shown significant differences that are given as uncertainties in the final LCIA results. The technological representativeness is therefore based mostly on the choice of substituted product and transportation types and encompass multiple technologies to give the range of uncertainty for impacts.

6. Preparation of the basis for the impact assessment

This study use ReCiPe as assessment method which is further described in chapter 5.1, but not all the impact categories in this method are included in the study as some are insignificant compared to the other impact categories. This is presented in chapter 5.2.2 and figure 14.

While this study focus on midpoint categories, it also use the endpoint (AoP) units. Therefore, "endpoint categories" that are usually damage to; human health, ecosystem quality, and resource availability, are now presented as divided in midpoint categories. Therefore, you can find the midpoint category global warming impacts for multiple AoP in the "endpoint categories".

The endpoint impact categories are used for a screening of sensitive inventories in the three technologies, because the common units related to areas of protection are minimized to three instead of the otherwise thirteen different units in the midpoints categories. This is because the endpoint impact categories are less precise than the midpoint impact categories because they are scaled by characterisation factors. Therefore, the final comparison of technologies and evaluation of location-specific factors use midpoint impacts.

It must be emphasized that the carcinogenic and non-carcinogenic toxicity impacts are important results. The reason they are not included in figures is because the toxicity values are of a magnitude that makes it difficult to compare and evaluate the rest of the categories with each other. Toxicity is further discussed in chapter 5.2.1.

Included impact categories:

Initial screening with **endpoints**:

- Human health related categories

  Global warming, Human health

  Fine particulate matter formation

  Human non-carcinogenic toxicity (not in figures but discussed in chapter 5.2.1)

  Human carcinogenic toxicity (not in figures but discussed in chapter 5.2.1)

- Species related categories

  Global warming, Terrestrial ecosystems

  Ozone formation, Terrestrial ecosystems

  Terrestrial acidification

  Freshwater eutrophication

  Land use

- Resource scarcity

  Mineral resource scarcity

  Fossil resource scarcity

Analysis with **midpoints**:

- Global warming

- Ozone formation, Human health

- Fine particulate matter formation

- Ozone formation, Terrestrial ecosystems

- Terrestrial acidification

- Freshwater eutrophication

- Land use

- Mineral resource scarcity

- Fossil resource scarcity

- Water consumption

Excluded impact categories:

Initial screening with **endpoints**:

- Human health related categories

  Stratospheric ozone depletion

  Ionizing radiation

  Ozone formation, Human health

  Water consumption, Human health

- Species related categories

  Global warming, Freshwater ecosystems

  Marine eutrophication

  Terrestrial ecotoxicity

  Freshwater ecotoxicity

  Marine ecotoxicity

  Water consumption, Terrestrial ecosystem

  Water consumption, Aquatic ecosystems

Analysis with **midpoints**:

- Stratospheric ozone depletion

- Ionizing radiation

- Marine eutrophication

- Terrestrial ecotoxicity

- Freshwater ecotoxicity

- Marine ecotoxicity

- Human carcinogenic toxicity

- Human non-carcinogenic toxicity

(7.) Special requirements for system comparisons and a **(8.) critical review** has not been conducted in this study. The **(9.) Reporting of results** are intended for internal use by NTNU, DTU and the RemovAl project.

The resulting inventories of this LCA are intended to be used specifically for comparing the specific technologies in this study, they can *not* be used as a generic "remediation and utilization of BR" technology as these technologies varies greatly in matter of inputs and outputs. The LCA is also not complete in terms of evaluating the impacts of toxicity from the BR products and can therefore *not* say if a BR product is better than it's substituted product in regards to toxicity.

4 Life cycle Inventory and description of the 3 technologies

This section presents the LCI for each of the three technologies. Flowsheet for the de-alkalization technology is given by the ALUM treatment pilot plant in Romania (RO) and the soil stabilization technology flowsheet from the Aughinish treatment pilot plant in Ireland (IR). Flowsheets for the high performance binder technology are received from both the Romanian and Irish plant as well as from the AoG (Aluminium of Greece) plant in Greece (GR), so due to a change in values this leads to multiple LCIs. Instead of showing each one, the different values are given in the following order: RO/IR/GR, when they appear in the LCI table for the high performance binder technology (table 5).

Processes that occurs in all life cycles relevant for the comparison or processes that are similar between the substituted technology and BR technology are not part of the LCI as it makes not difference to the comparison, *e.g* curing of asphalt in the soil stabilization technology - curing of asphalt will happen in any case. The ecoinvent inventories that describes energy consumption also includes a fraction of the inputs and emissions necessary to construct a power plant or windmill. Similarly, the construction of the BR remediation facility will vary depending on the technology used. It is assumed that somewhat similar constructions are needed for mixing and heating of the BR. The vast amount of BR that will go through the plant indicates that the difference in construction of the remediation plants of different technologies is neglectable, and the environmental impact from construction compared to the use-phase of the plant is also assumed neglectable.

The difference in moisture between BR input and the treated BR product is included in the LCI only as off-gas H_2O. The BR inventory is assumed to have a 30% moisture content as all three BR landfills related to the pilot plants use dry stacking (see chapter 1). Treated BR products are assumed to be in wet weight when transported.

4.1 De-alkalization

There are multiple methods for de-alkalization of BR (Lyu et al., 2021). In short, de-alkalization is about neutralizing the buffer created during the desilication and digestion in the Bayer process, usually done by a mixture of precipitation, washing and neutralization with acid of the buffer compounds in the BR. The technology in focus in this paper de-alkalize the BR by adding lime and then heating to 95-98°C. This method is similar to alkali recovery through calcification, a method described in detail by Wang et al. (2018): "The intention of the calcification process is to replace the sodium oxide in the sodium aluminosilicate hydrate in bauxite residue with calcium oxide. This will change the phase structure and transform Bayer bauxite residue (mainly sodium aluminosilicate hydrate) into a calcified product (calcium aluminosilicate hydrate based), thus removing the alkali." The method is more efficient at higher temperatures, although the alkali removal efficiency stops improving after

160°C. Wang et al. (2018) found a Na_2O content in the calcified solids of 1.5% when calcination happened at 100°C and 0.33% when at 160°C. Where Wang et al. (2018) and Lyu et al. (2021) focus on the aluminium recovery, the de-alkalization technology in this paper focus on the de-alkalized BR substituting clay as the aluminium recovery is not part of the given flow charts.

Table 3: LCI of **de-alkalization** technology based on flowsheets from the ALUM plant in Romania.

Inputs	ecoinvent label	Amount	Unit	Comment
Bauxite Residue	Redmud from bauxite digestion {GLO}| market for	1425.87	kg	30% moisture content assumed. Therefore, for 1 tonne dry BR 1/0.7~1.4 tonne wet BR. According to the flowsheet a 44% moisture content is found in input BR, but only 1 inventory exists in ecoinvent, so an equal amount of moisture content is assumed for the sake of comparability between technologies.
BR moist		785.71	kg	
Steam (water)	Steam, in chemical industry {RER}|production	120	kg	Of the different available steam inventories in ecoinvent, this inventory had the best match for steam input based on descriptions of every steam inventory.
Lime	Quicklime, milled, packed {RER}| market for quicklime, milled, packed	200	kg	
Wash water	Tap water {RER}| market group for	1100	kg	From reslurry process and filter press see appendix A.
Total energy	Electricity, medium voltage {RER}| market group for	32.92	kWh	
Outputs				
Pre-dried de-alkalised solids		1200	kg	This output may substitute a range of products, see discussion in chapter 5.2.4.
Evaporated water		100	kg	
Avoided products				
Clay	Clay {RoW}| clay pit operation	1200		Output is pre-dried de-alkalized bauxite residue which is assumed to be used road base and therefore replace clay (not gravel due to grain size of BR).

4.2   Soil stabilizer

Soil stabilization and implementation of BR in the technique has been described in chapter 1.3.2. Flow data from the pilot plant in Aughinish (IR) show that the BR input is divided in 2 fractions: coarse and fine. 46% of the BR is the coarse fraction and has particle sizes similar to sand. 54% is the fine fraction (mud) with particle sizes similar to clay. This is not part of the LCI as there is only one BR inventory in ecoinvent. However, it may be of importance to the quality of the final product as well as where soil stabilization is possible due to BR composition.

For the LCIA, 3 different scenarios of soil stabilization is compared: (1) Gravel is excavated nearby and transported to the location where soil stabilization is needed, here it is grinded and replaces the current soil or is dumped on top. (2) The current soil is mixed with additives until stable, in this study cement is used because it is often the preferred method for chemical soil stabilization. (3) The current soil is replaced by BR mixed with fly ash, GGBFS, and lime. Bauxite residue mixed with fly ash and GGBFS (ground granulated blast-furnace slag) and quicklime can act as a soil stabilizer with similar properties to soil mixed with cement if the fly ash has pozzolanic and self-cementing properties or lime is added to achieve mentioned properties (Patel, 2019).

Scenario 1 is based on mechanical soil stabilization without additives, where different sized soil fractions are mixed to impart incompressibility and internal friction between the soil particles in a dense packed matrix. However, sand and gravel used as stabilized soil is often held together by a smaller dose binder (Patel, 2019). Therefore, using BR may substitute the quarry and transport processes related to using sand and gravel for soil stabilization. The "suitable dose of binder" PATEL201919 that should be added to the aggregates for a good stabilization is in the BR soil stabilization technology: Lime, fly ash, and GGBFS which have binder properties, so in the comparison of the two technologies it could be assumed that the same amount of these materials is used including the water from the moisture in BR. It may be very different how easy sand is acquired from location to location, but it is assumed that sand is acquired from gravel/sand quarries. An uncertainty of the foreground LCI of scenario 1 is then the gravel/sand quarry inventory which represents the quarry operation of gravel and sand, but does not specify the proportion of gravel or sand produced. It is likely that crushing gravel into sand requires a higher energy demand than simply making gravel, and this uncertainty is not quantified in the LCIA in this study.

Scenario 1 and 3 assume a replacement of the soil and therefore have no uncertainty related to soil type at the location. But in scenario 2 cement concentration should be 5-20 %w/w depending on the soil type, *cf.* chapter 1.3.2. Therefore, input of cement is compared to the FU which refers to the utilization of 1 ton dry BR. 1 ton dry BR is mixed with the additives: Fly ash, GGBFS, and lime, and totals ~1.35 tons of soil stabilizing product. If cement is mixed with the current soil instead of adding BR soil stabilizing product, 5-20% of the 1.35 tons equals that 67.5-270 kg OPC would be used for chemical stabilization.

Table 4: LCI of the **soil stabilization** technology based on flowsheets from the Aughinish plant in Ireland.

Inputs	ecoinvent label	Amount	Unit	Comment
Bauxite Residue	Redmud from bauxite digestion {GLO}| market for	1425.87	kg	30% moisture content assumed. Therefore, for 1 tonne dry BR 1/0.7∼1.4 tonne wet BR.
Fly ash	Fly ash and scrubber sludge {Europe without Switzerland}| treatment of fly ash and scrubber sludge, hazardous waste incineration	270	kg	Added as a negative waste generation in SimaPro. The currently used ecoinvent label also includes emissions to air from incineration, meaning some of the upstream processes of fly ash generation that should not be subtracted are currently subtracted.
GGBFS (Ground granulated blast-furnace slag)	Ground granulated blast furnace slag {GLO}| market for	60	kg	The documentation for the label is better described when looking up one of the two processes included in the market process
Lime	Quicklime, milled, packed {RER}| market for quicklime, milled, packed	20	kg	
Energy (electricity)	Electricity, medium voltage {RER}| market group for	19.5	kWh	
Outputs				
Stabilized soil	Gravel, crushed {RoW}| production	1000	kg	
Avoided products				
Gravel	Gravel, crushed {RoW}| production	1000	kg	
OR				
Cement	Cement, unspecified {Europe without Switzerland}| market for cement	67.5-270	kg	Depending on the soil that needs stabilization 5-20%w/w cement is added to the soil for stabilization.

4.3   High performance binder

The third evaluated technology in this paper produces high performance binder from BR. Ordinary Portland cement (OPC) is a fine powder that mainly consist of lime and argillaceous materials that contain alumina, silica and iron oxide - a description very similar to the fine BR (red mud), if lime is added. The final product of this technology is assumed to replace finished concrete.

First, BR is mixed with a carbon source (charcoal), $CaCO_3$ (limestone), and SiO_2 (silica sand). The pilot plant used a SiO_2 product with a purity >99%, but the ecoinvent database only has an inventory of a >85% purity, therefore a higher mass is assumed in the industrialized model than given in the pilot plant flowsheets. The addition of non-pure industrial silica sand (x)

is calculated in equation 12 where the actual input of industrial silica sand (assumed purity of 85%) has to be higher than the input was of more pure sand used in the pilot plant (99% and calculated as ~100%). The amount of pure SiO_2 added in the pilot plant (y) allows for a calculation of the ratio between SiO_2 and sandy material. This ratio must stay constant to ensure the effect of silicium sand. The equation shows the amount of non-pure silica sand needed in order for the concentration ratio to stay constant:

$$x \ kg \ silica \ sand = \frac{1000 kg BR}{\frac{1000 kg \ BR}{y \ kg \ SiO_2} \cdot 0.85 - 0.15}$$

(12)

The HPB technology can be performed in different ways. The calcification can be performed in a top blown rotary converter (TBRC) or a rotary kiln (RK) where it is heated to 1200-1300 °C using methane as energy supply. No specifics on the efficiency of the two options are given, but TBRC have long been recognised for its usefulness in pyrometallurgical metal recovery (Whellock and Matousek, 1990) and the rotary kiln is normally used in the production of Portland cement. They are therefore assumed equally able to support the pyrometallurgical processes. According to the flowsheets from the pilot plants, the RK always use less than 2476 MJ per ton input of BR while the energy consumption varies for the TBRC. The option that consumes least energy is chosen at each location for the model.

Next, the hot material from the calcination process is quickly cooled down in either a water or air quencher. The air quenching technology allows for heat recirculation of 80% energy and therefore saves methane input, while the water quenching is assumed to be faster and therefore cheaper. Energy savings from air quenching (E_s) is calculated in equation 13, where 33% of the added energy (E_{in}) stays in the material and the rest is already recirculated. Of energy in the material, 80% is now also recirculated if air quenching is used leading to the following calculation of energy savings from air quenching:

$$E_s = E_{in} \cdot 33\% \cdot 80\% = E_{in} \cdot 26.4\%$$

(13)

After quenching, the treated BR will be mixed in a concrete mixer with the concrete aggregates (sand and gravel). The options are then to add sodium silicate to make Inorganic Polymers (IP) or instead add GGBFS and some OPC along with a few additives which results in a hybrid product of Portland cement and BR combined (see table 5).

Table 5: LCI of the **High Performance Binder** technology based on flowsheets from multiple locations. The values are shown for each location in the following order: Romania/Ireland/Greece, where input of CH_4 assumes lowest energy consuming option of either rotary kiln (RK) or top blown rotary converter (TBRC). BR and carbon source input are the same value for all locations. * marks a "lesser process" in the hybrid high performance binder, see discussion chapter 5.2.5.

Inputs	ecoinvent label	Amount	Unit	Comment
Base technology				
Bauxite Residue	Redmud from bauxite digestion {GLO}| market for	1425.87	kg	30% moisture content assumed. Therefore, for 1 tonne dry BR 1 /0.7~1.4 tonne wet BR.
Carbon source	Charcoal {GLO}| production	24.6	kg	Carbon content purity in pilot plants is 89% and in ecoinvent purity is 78-90%.
SiO2 source	Silica sand {GLO}| market for	93 /120 /263	kg	Silica sand is assumed to have a purity of 85%. Flowsheets from the pilot plants use 99% - therefore more silica sand is added to adjust so the concentration of SiO2 stays the same. See equation 12
CaCO3	Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill	196 /268 /336	kg	this is limestone, *not quicklime*.
CH4	Methane, 96% by volume, from biogas, high pressure, at user {RoW}| market for methane, 96% by volume, from biogas, high pressure, at user	(Water quenching: 2360/2476 /2476) (Air quenching: 1737/1817 /1728)	MJ	Either a Top Blown Rotary Converter (TBRC) or a rotary kiln (RK) is used. The least energy consuming option is chosen for each side: TBRC /RK /RK.
Electricity	Electricity, medium voltage {RER}| market group for	57.3/60.3 /67.8	kWh	
Inorganic polymers (case 1)				
Sodium silicate (SiO2 /Na2O, 75% H2O) Autoclave synthesised	Sodium silicate, without water, in 48% solution state {RER}| market for sodium silicate, without water, in 48% solution state	283/301 /335	kg	A 25% solution is used, so 25 /48=52% mass is needed of the 48% solution to obtain the same mass of pure sodium silicate. The 48% solution market in ecoinvent is related to hydrothermal production of sodium silicate (whereas 37% solution is from furnace).
Sand (0-4 mm)	Sand {GLO}| market for	2589/2748 /3066	kg	
Gravel (4-16mm)	Gravel, round {RoW}| market for gravel, round	3416/3626 /4046	kg	
Electricity	-		kWh	Same as normal concrete production. So neglectable

Hybrid (case 2)				
*Water	Tap water {RER}| market group for	564 /599 /668	kg	
*NaOH	Sodium hydroxide, without water, in 50% solution state {GLO}| market for	24.9/26.5 /29.5	kg	Today sodium hydroxide (NaOH) is produced by the chloralkali process (according to Wikipedia). This market process combines the chloralkali process using membrane, diaphragm or mercury cells.
*Super plasticizer	Plasticiser, for concrete, based on sulfonated melamine formaldehyde {GLO}| market for	10.0/10.6 /11.8	kg	Superplasticizer and plasticizer is not produced in similar ways. "Plasticizers are commonly manufactured from lignosulfonates, a by-product from the paper industry. Superplasticizers have generally been manufactured from sulfonated naphthalene condensate or sulfonated melamine formaldehyde, although newer products based on polycarboxylic ethers are now available." (Wikipedia). In this LCA they are assumed similar.
*GGBFS	Ground granulated blast furnace slag {GLO}| market for	235 /249 /278	kg	
Hemihyrate	n/a	5.0/5.3 /5.9	kg	According to wikipedia: "A hemihydrate, or semihydrate, is a hydrate whose solid contains one molecule of water of crystallization per two molecules, or per two unit cells." Therefore, this can be many substances. But its concentration compared to the overall concrete production is low and hemihydrate is assumed neglectable and not part of the LCI.
*Limestone fines	Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill	125 /132 /148	kg	*not quicklime.*
Ordinary Portland cement (52.5 N)	Cement, Portland {Europe without Switzerland}| market for	235 /249 /278	kg	
Sand (0-4 mm)	Sand {GLO}| market for	4047/4296 /4793	kg	.
Gravel (4-16)	Gravel, round {RoW}| market for gravel, round	5339/5668 /6323	kg	
Electricity	-		kWh	Same as normal concrete production. So not included.

Outputs	ecoinvent label	Amount	Unit	Comment
Base case				
H2O (off-gas), **Air quenching**	Water	351 /376 /417	kg	
H2O (off-gas), **Water quenching**	Water	380 /407 /451	kg	**Notice!** Only one of these water outputs is used. Depends if air or water quenching is used. Air quenching is used in every figure in this report.
CO2	Carbon dioxide	203 /234 /265	kg	Direct emissions from calcination process.
Inorganic polymers (case 1)				
Concrete	Lean concrete {RoW}| production, with cement CEM II/B	7634/8104 /9040	kg	Lean concrete is the least impacting concrete inventory of multiple tested. "Concrete block {DE}| production, U" can be used for highest impacting inventory to give a range of uncertainty (except for GWP where "Concrete, sole plate and foundation {RoW}| concrete production, for civil engineering, with cement CEM II/B " is highest). See figure 25.
Hybrid (case 2				
Concrete	Lean concrete {RoW}| production, with cement CEM II/B	11976/12713 /14183	kg	

4.4   Sensitive materials in foreground LCI

Besides fly ash which have already been presented and discussed in relation to soil stabilization and it's pozzolanic attributes in chapter 1.3.2, lime and Portland cement have also shown to be very sensitive to the LCIA.

4.4.1   Lime

Calcium carbonate ($CaCO_3$) is commonly found in nature and can be mined as *limestone*. When limestone is heated it undergoes thermal decomposition (calcination) where it releases CO_2 and forms calcium oxide (quicklime) (see eq. 14). 44% of the limestone mass is converted to CO_2 in the calcination process, which makes it very important to differentiate between these two materials.

$$CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)} \tag{14}$$

4.4.2   Portland cement and concrete

The high performance binder technology enables bauxite residue to be utilized as part binder part aggregate in concrete mix - either without or partly with OPC. Understanding how concrete is conventionally produced is important if we are to understand the impacts of reusing bauxite residue to substitute conventional concrete on the market. The following chapter is based on Nelson (1990).

Production of Portland cement needs two types of raw material: calcareous materials (lime) and argillaceous materials (minerals with high contents of clay) containing alumina, silica and iron oxide. The material is grinded fine and put in a cement kiln. From a global warming perspective when making concrete, the most important process is the calcination of the limestone into quicklime and CO_2. When processed, Portland cement has four major compounds: Tricalcium silicate (Ca_3SiO_5), dicalcium silicate (Ca_2SiO_4), tricalcium aluminate ($Ca_3Al_2O_6$), and tetracalcium aluminoferrite ($Ca_4Al_2Fe_2O_{10}$).

Of these four, the two silicate compounds usually make up 80% of the total cement and these react with water to make the hydration products known as *Portlandite*. Important for this LCA is that mixing water with a dry concrete mix to create concrete blocks changes the mass as water is chemically bound to the cement in the hydration process. However, as the mass changes the absolute volume decreases because the absolute density of the hydrated cement increases. But the bulk volume of the finished concrete may slightly increase as an effect of an increased porosity in the concrete. The ecoinvent database has inventories of different kinds of concrete blocks in either mass or volume, so comparing these inventories to the dry concrete mix received by remediating the bauxite residue includes many uncertainties. It is assumed that they finished BR concrete always have a density of 2400 kg/m^3 and the substituted concrete products are calculated based on their given density as well. It is then assumed that all described densities are bulk density.

5   Life cycle impact assessment

5.1   LCIA method: ReCiPe

The "ReCiPe 2016 Endpoint (H) V1.03 / World (2010) H/A" has the endpoints, and "ReCiPe 2016 Midpoint (H) V1.03 / World (2010) H" the midpoints, shown in figure 13. The "(H)" means the "hierarchist" values are assumed when calculating the CF from the LCI. "The hierarchist perspective is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms" (National Institute for Public Health and the Environment, 2017). Important for this LCA is that the hierarchist version:

- Has a 100 years time horizon (fitting with the scope).

- Calculates resource scarcity based on "ultimate recoverable resource" which is "the amount available in the upper crust of the earth that is ultimately recoverable", which by UNEP (2011) is set to 0.01% of the total resource found in the crust of the earth down to a 3 km depth.

- Includes impacts on terrestrial ecosystems.

- Is the only ReCiPe version that includes climate-carbon feedback for non-CO_2 compounds (like CH_4) in the global warming midpoint CF (CO_{2-eq}) which is important when evaluating methane input in the HPB.

The hierarchist may be described as the most neutral view compared to the individualist (I) view (optimistic) and the egalitarian (E) view (pessimistic or precautionary). *E.g.* the time horizon is 20, 100 and 1000 years for I, H, and E respectively (National Institute for Public Health and the Environment, 2017), meaning that the effect of green house gasses (GHG) will have a greater impact in the E view rather than I, as it is calculated over a greater time. It is not quite as simple as that though, as the H view includes climate-carbon feedback for more GHGs and therefore could show greater impacts on global warming than the E view. All midpoint and endpoint CFs are presented in the ReCiPe 2016 v1.1 report (National Institute for Public Health and the Environment, 2017).

In this study, the endpoint impact categories are evaluated based on the midpoint categories that, when aggregated, will result in an endpoint impact category (area of protection). In the first iteration of the LCIA, the results presented are in the endpoint units: DALY, Speciec.yr, and USD2013, but evaluated as midpoint impact categories (Global warming, fine particulate matter formation etc.). The normalisation to the endpoint units enables an easier comparison of the different impacts categories which is useful when finding the sensitive categories, whose sensitive inventories are evaluated. *E.g.* The first iteration of de-alkalization shows that global warming is the highest impacted midpoint category for the human health AoP and that the most sensitive inventory here is quicklime.

DALY is described by WHO (n.d.) as: "One DALY represents the loss of the equivalent of one year of full health." This means that it is not based on how lethal an impact is, but rather on how it affects life quality for humans. **Species.yr** is described by National Institute for Public Health and the Environment (2017) as: "number of species lost integrated over time" in ecosystems. An impact of 1 species.yr therefore means that we expect 1 species to reach extinction every year. **USD2013** describes the "surplus cost potential" (SCP) of a resource in US dollars in the year 2013. SCP is derived from surplus ore potential which is predicted based on the current and expected future extraction of the resource. Any mineral extraction leads to a decrease in ore grade as it is assumed that the highest concentration ores are extracted first (National Institute for Public Health and the Environment, 2017). Any "wasted" mineral or resource is therefore measured as an expected monetary future loss due to the increased cost of extraction - the unit for this measure is then USD2013.

The substituted products are the most sensitive inventories of the first iterated LCIA. A range of uncertainty is added to the model by presenting a range of potential scenarios related to the life cycle of BR remediation and utilization. The technologies are then compared using midpoint category units, so that fewer CFs are included and the values more relevant for each category. *E.g.* using CO_{2-eq} as unit for the global warming potential describes the amount of radiative forcing an emissions has equivalent to what is caused by 1kg of CO_2 over the cause of 100 years (hierarchist) instead of the damage to human health or ecosystems/species (National Institute for Public Health and the Environment, 2017). The units used for each midpoint category is given in table 6.

Table 6: Units for midpoint categories in the ReCiPe impact assessment method. Except for water consumption given in m^3, all units are "equivalence of" unit.

Impact category	Global warming	Stratospheric ozone depletion	Ionizing radiation	Ozone formation, Human health	Fine particulate matter formation	Ozone formation, Terrestrial ecosystems
Unit	kg CO$_2$	kg CFC-11	kBq Co-60	kg NOx	kg PM$_{2.5}$	kg NOx
Impact category	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity
Unit	kg SO$_2$	kg P	kg N	kg 1.4-DCB	kg 1.4-DCB	kg 1.4-DCB
Impact category	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Land use	Mineral resource scarcity	Fossil resource scarcity	Water consumption
Unit	kg 1.4-DCB	kg 1.4-DCB	m^{2}a crop	kg Cu	kg oil	m^3
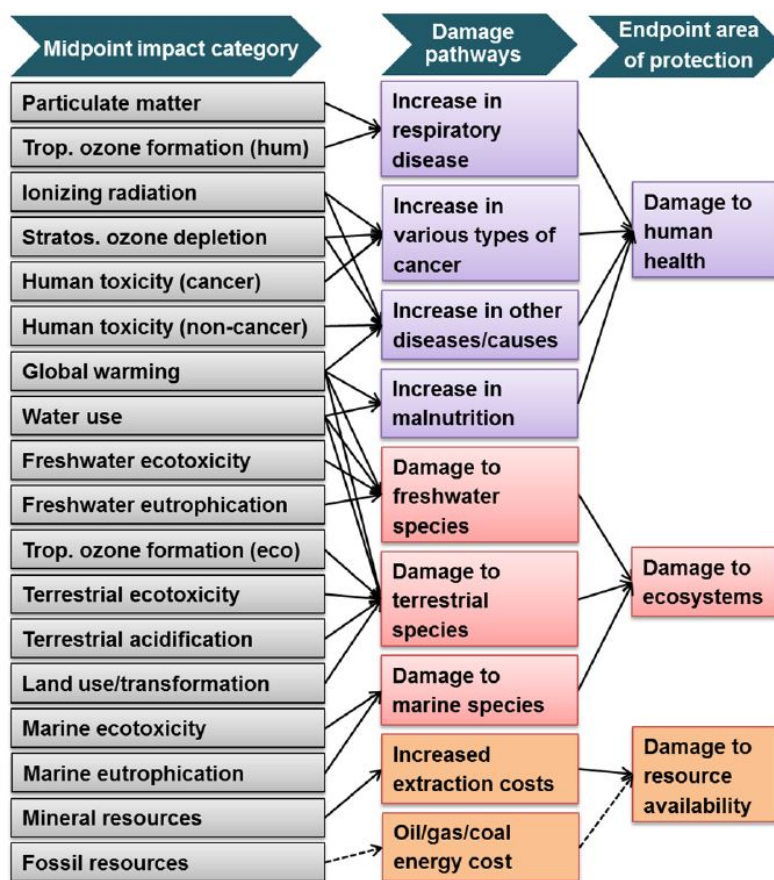
Figure 13: "Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection." (National Institute for Public Health and the Environment, 2017)

5.2   LCIA results

5.2.1   Flawed model results: Carcinogenic and non-carcinogenic toxicity

For all the technologies "human carcinogenic toxicity" is affected more than all other DALY based categories combined – mainly by the negative BR landfill process, see appendix **??**. A closer look on the LCIA reveals that almost the entire carcinogenic toxicity impact is caused by the high Chromium VI concentrations in BR. According to the model, BR removal is therefore a major benefit for human carcinogenic toxicity, but the model is very unrealistic in this matter. The LCI is set up so that BR impacts are negative inputs, in other words, the model *very incorrectly* believes that hazardous compounds in the BR are not moved but simply 'disappears' from the landfill they were in. This is very unlike the real scenario where the BR is washed or mixed with aggregates and additives and then moved away from a controlled landfill - possibly even closer to human society, *e.g* under roads or as construction material as soil stabilizer or concrete. In contrast to the LCIA results, the potential for adverse toxicity impacts are either similar to landfilling BR or possibly worse.

Leaching dynamics of metals in BR has been studied by Rubinos and Barral (2013) who concludes that: "Cr is of particular concern since relatively high concentrations of this metal were dissolved in acidic media." However, the relative high concentrations in solution (mobile Cr VI) are an effect of an initial high concentration rather than high mobility of the Cr VI. Rubinos and Barral (2013) mentions that Cr would only be released under "extreme acidic conditions". In a sequential extraction procedure, more than 80% of the Cr were in the residual phase while the rest was bound to Fe and Al hydroxides. The "Redmud from bauxite digestion RoW| treatment of, residual material landfill" inventory assumes a leaching of Cr to water corresponding to 18.77‰ of total BR weight. Rubinos and Barral (2013) observed a Cr leaching corresponding to 20.93‰ of total BR weight, but in extremely acidic conditions. In pH 6 he observed a leaching of 1.35‰ . Depending on the pH of the natural environment, ecoinvent's assumption on Cr leaching may be well over a factor 10 off results from sequential extraction analysis, depending on the time horizon.

Therefore, the *potential* impact on human carcinogenic toxicity is considered extremely high, which is in contrast to the LCIA results in this study. But the *actual* impact is very uncertain and possibly not as hazardous as the potential impact presented from the ecoinvent inventory. Also, when BR is mixed with different aggregates before becoming a product, the concentration of toxic compounds decrease and there is also a chance that the more stable soil/aggregate matrix immobilizes hazardous compounds to some degree similar to how the toxic compounds in fly ash can be immobilized in concrete (Tang et al., 2020). Nonetheless, the Cr VI leaching potential is extremely concerning and must be studied for each possible BR product before any products can be marketed with a good conscience!

While this discussion focused on the carcinogenic toxicity which is almost entirely from Cr(VI), a similar discussion for the non-carcinogenic toxicity can be made where sodium silicate, concrete, and fly ash inventories have non-carcinogenic toxic impacts because of Zn (Zinc), while fly ash inventory because of V (Vanadium). Because of the extreme values and their ambiguity in the toxicity categories, human carcinogenic toxicity and human non-carcinogenic toxicity is left out of results for the rest of the LCIA - but the toxicity is still a major concern and no products should be distributed before the toxicity has been thoroughly studied and actual leaching ensured safe.

5.2.2   Initial sensitivity screening using endpoint values

Figure 14 presents the impacts on all midpoint categories in ReCiPe but characterized as endpoint values with the units: DALY, Species.yr, and USD2013. The figure is *not* used for comparison of the technologies but as an initial screening of the sensitive categories. The list of impact categories included in chapter 3.2 point 6, is partly based on the significance of impacts presented in figure 14.

The high performance binder technology presented is the *hybrid* high performance binder in Greece, using a rotary kiln, air quenching, and substituting lean concrete. This is chosen based on the discussion in chapter 5.2.4 and 5.2.5.

As mentioned, characterizing midpoint values as endpoint values (impacts on AoP) allows for an easier screening of the significant impact categories. For example, table 6 shows that the midpoint category unit for "ionizing radiation" is kBq Co-60$_{eq}$ and "global warming" is in kg CO$_{2-eq}$, these different units are not comparable. By showing the results in figure 14 in endpoint units (DALY, species.yr, and USD2013) the approximate magnitude of the impact in each category now becomes comparable within each of the three AoP. Figure 14 gives an obscured picture of the actual emissions and the impacts on each impact category, because the sum of flows from the LCI each are scaled by different CFs to show the midpoint impact and then scaled again to show the endpoint impact of the category. These multiple CF are subjective to some degree and differ depending on choices like what impact assessment method is used and the "value choice" which in this LCA is the "hierarchist" (see chapter 5.1). But as seen in figure 14 the *magnitude* of the impacts on human health (DALY) from ionizing radiation and global warming are extremely different: Global warming is of concern compared to "Ionizing radiation" which in comparison is negligible. This way, the endpoint values are used to find what midpoint categories are of importance and thereby which midpoint categories should be included. Later in the discussion (chapter 4.1, 5.2.4, and 5.2.5) the magnitude of each foreground inventory process within the life cycle of each technology is likewise evaluated with endpoint units to find what processes are sensitive to impacts on AoP and which are not. The sensitive parameters will then be the relevant discussion points when the technologies are compared, where midpoint units are finally used for a less obscure result to each midpoint category.

Hybrid high performance binder has significantly higher impacts (both positive and negative) than its competing technologies. This is mainly caused by the high volumes of substituted product, except for impacts on land use which is discussed in chapter 5.2.5. Following the FU, each technology is evaluated based on the remediation of 1 ton BR, and the hybrid HPB technology is creating a much larger volume of substituted product (concrete) per input of BR than the other technologies. Since larger non-BR volumes are included, the hybrid HPB technology is less sensitive to the BR landfill inventory than the competing technologies.

In the following chapters, a sensitivity analysis is made for each technology based on the impact categories of importance in figure 14.
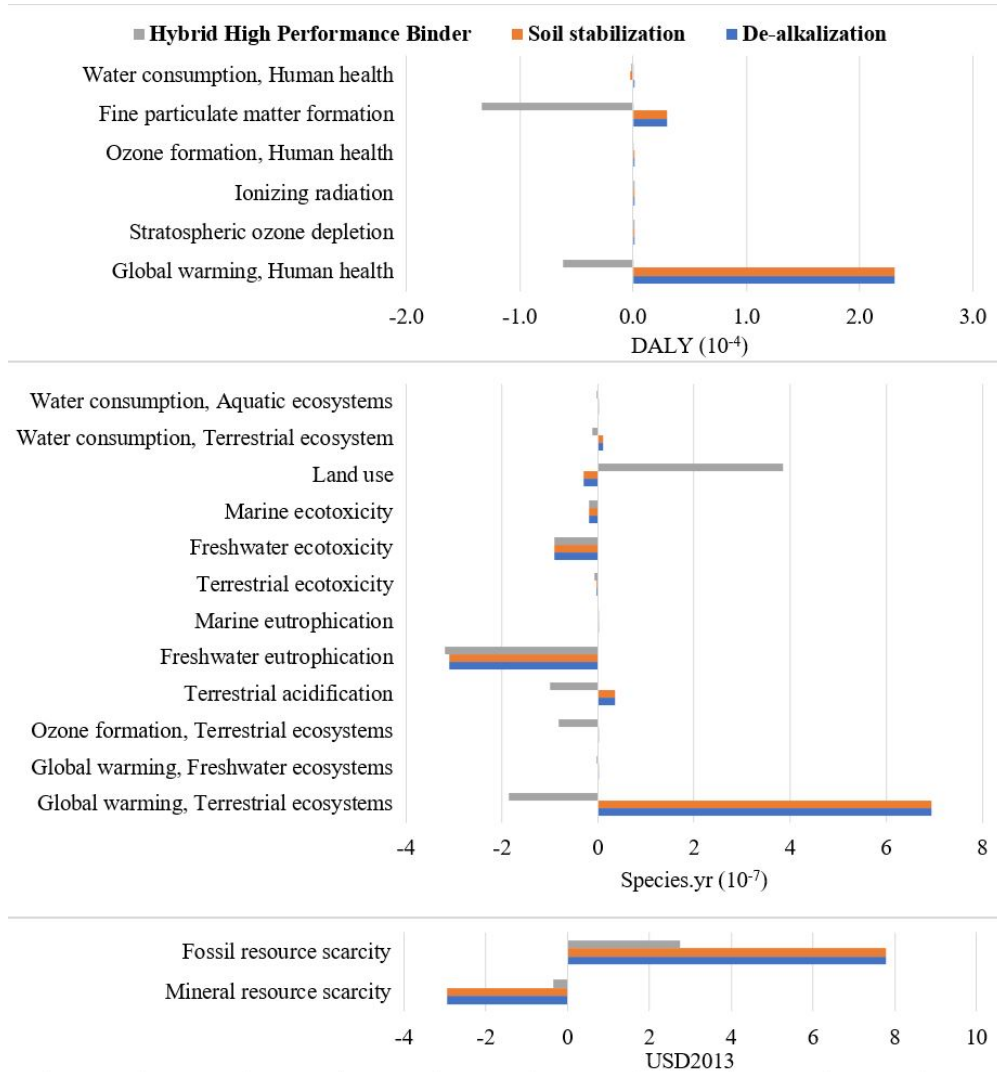
Figure 14: Total impact from technologies to each impact category from the ReCiPe method (except resource scarcity). Marked by bold text are the categories that are significantly greater in impact according to the ReCiPe LCIA.

5.2.3   De-alkalization
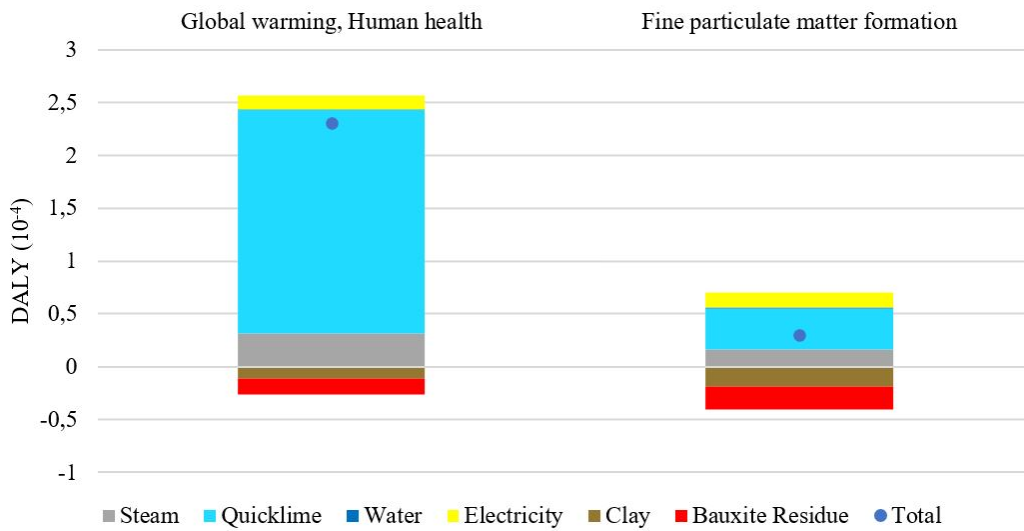
Figure 15: Relevant ReCiPe DALY results of De-alkalization
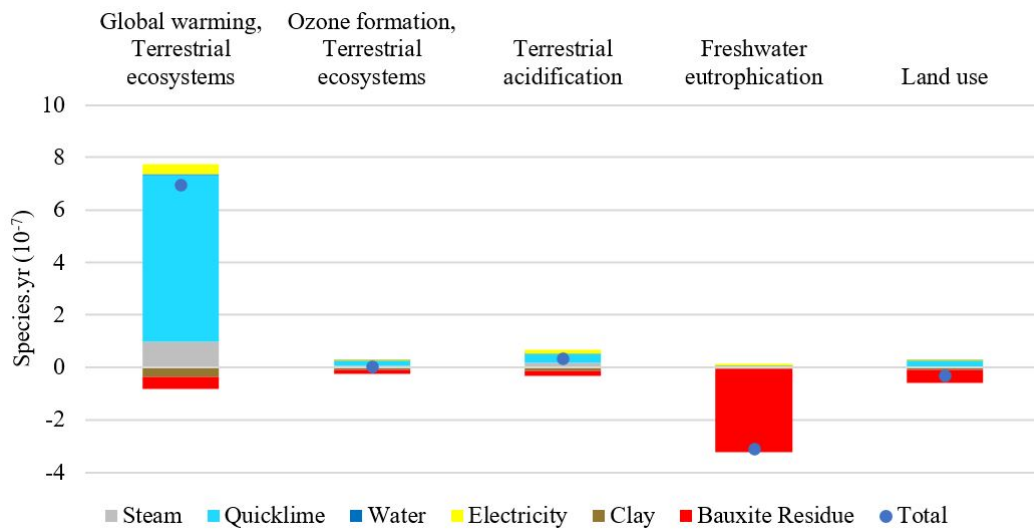
Figure 16: Relevant ReCiPe species results of De-alkalization
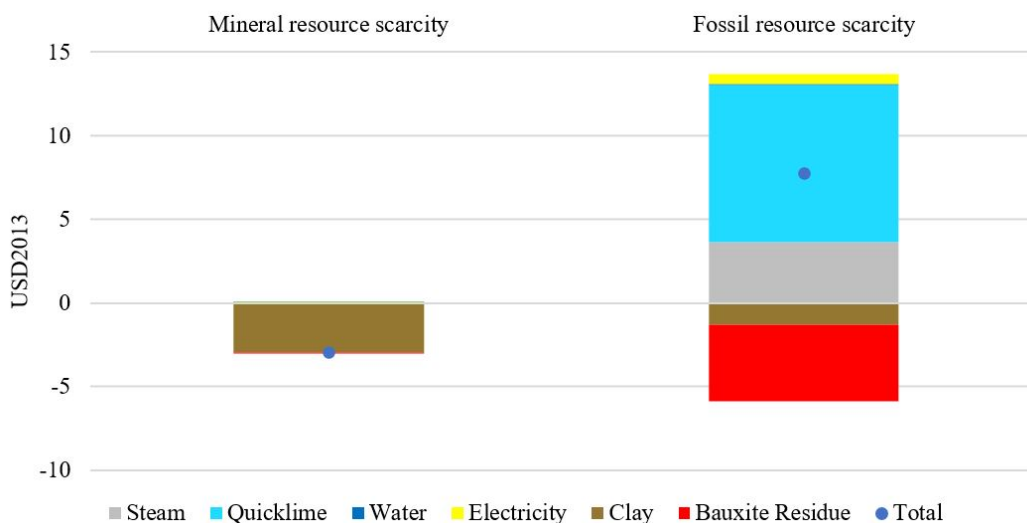
Figure 17: ReCiPe results for impacts on mineral scarcity of De-alkalization

The figures show that substitution of clay using BR would have positive effects on the environment if not for the immense use of quicklime in the de-alkalization remediation process along with the steam input. The steam process is based on the average technology used in chemicals and plastics industry in Europe and it's impacts mainly depends on the heat needed for steam production in boilers. If the steam is generated in a combined heat and power plant, some of the impacts may be allocated to the energy from the power plant.

The use of quicklime have greater impacts than the avoided products and waste for all categories but "freshwater eutrophication", "land use", and "mineral resource scarcity" especially in the categories related to global warming and GHGs. The quicklime process itself is the main driver for the impact on global warming. As described in equation 14 the creation of quicklime releases great amounts of fossil CO_2 to the atmosphere, which is also revealed in a midpoint network analysis where "Quicklime, in pieces, loose RoW|production" is responsible for 91.6% of CO_{2-eq} emissions from de-alkalization. 92.3% of this is direct emissions from the inventory itself, meaning that 84.6% of the CO_{2-eq} emissions from production of de-alkalized bauxite residue is from the chemical reaction when creating quicklime. Due to the nature of the chemical process, these emissions are not location or time specific. There should be good argumentation for using quicklime if the substituted products do not substitute GHG emissions in greater amounts somewhere else in the life cycle.

Such an argument could be that de-alkalized BR pose less of a hazard risk than non-treated BR in case of spills. As described in chapter 1 BR is mainly hazardous due to its high alkalinity which caused harm in the Ajka spill 2010. However, LCAs should follow the "best estimate" principle meaning that spills and accidents with very high environmental impacts are not included if they occur rarely. So a benefit of the de-alkalization method, which is a major risk reduction at BR landfills, is not shown in the LCIA results.

The product of this technology is called "de-alkalized solids". It can replace clay as a construction material, but BR is also known to have remediating effects on contaminated soil (PAHs/VOHs and heavy metals), acid mine drainage and waste water from municipal or industrial facilities (Klauber et al., 2011). The de-alkalization of BR could therefore be a middle-step towards a utilization of BR that could be beneficial and show positive results in a LCIA if such inventories were made. Such a

scenario should be a study by itself if the specific situation is relevant. However, the use of de-alkalized BR for these purposes will likely only use a fraction of the volume of BR available and therefore leave high volumes of BR in the landfills thereby not fulfilling the purpose of removing it in the first place. Therefore, the most likely product substituted continues to be clay.

Freshwater eutrophication is the only included impact category where de-alkalization of BR seems to make a significant improvement, except for substitution of clay in mineral resource scarcity which is insignificant compared to the negative impacts on fossil resource scarcity. For freshwater eutrophication, it is the removal of bauxite residue leading to a removal of phosphorous that gives this result. And since it is unlikely that phosphorous is affected by de-alkalization, phosphorous will eventually leak when the de-alkalized BR is used in soils. In contrast to the LCIA results, the potential eutrophication impact therefore stays the same regardless of de-alkalizing the BR or not.

It is primarily quicklime that disqualifies de-alkalization from being better than business as usual. Lyu et al. (2021) mentions that BR alkalinity can be neutralized to a pH of 8.2-9.0 by mixing the BR with seawater (10-20 times more seawater than BR by volume) for 30 minutes. The seawater discharged back to sea has not shown adverse effects on marine ecology. Seawater neutralization may be possible for AoG (Greece) and Aughinish (Ireland) as they are in the vicinity of the ocean. Using seawater neutralization may greatly benefit the de-alkalization technology, but another LCA should be made to test for burden-shifting when using this technology - however, methods for evaluating impacts on marine ecosystems are not yet incorporated in the LCA framework.

In conclusion to the sensitivity of de-alkalization, the quicklime, steam, and bauxite residue are the most sensitive processes. Impacts from quicklime exceeds the avoided impact from substituting clay with BR making the current de-alkalization technology worse than a "business as usual" scenario independent of location, unless enough BR-clay is used for a specific treatment purpose that outweighs the impacts made by quicklime. The impact reductions from BR removal are unlikely realistic as different compounds still leak, just in a different location. If possible, a study on seawater neutralization should be carried out to improve the technology by removing the quicklime input. However, different means than LCA is currently needed for evaluation of marine impacts as well as quantifying the impacts from alkalinity.

5.2.4   Soil stabilization
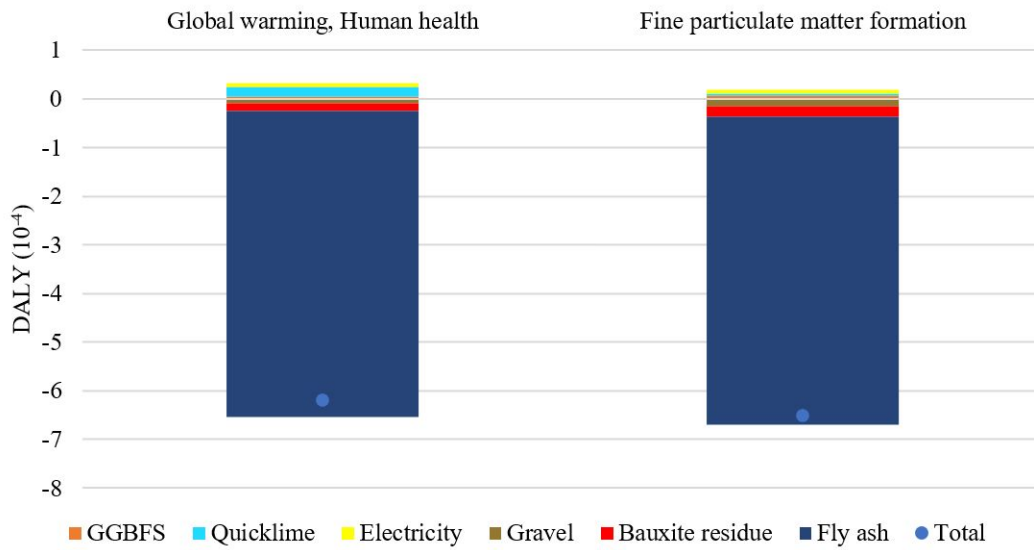
Figure 18: Relevant ReCiPe DALY results of soil stabilization
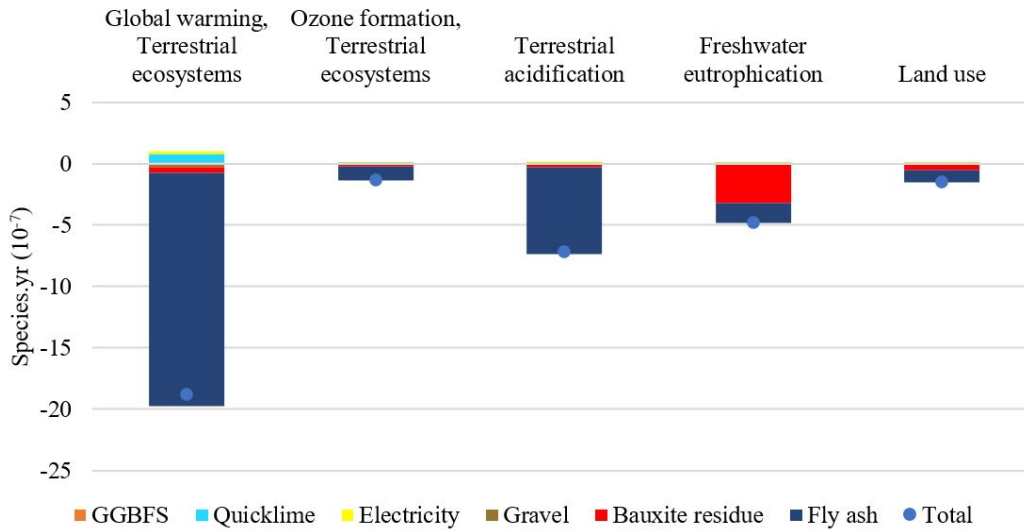
Figure 19: Relevant ReCiPe Species.yr results of soil stabilization
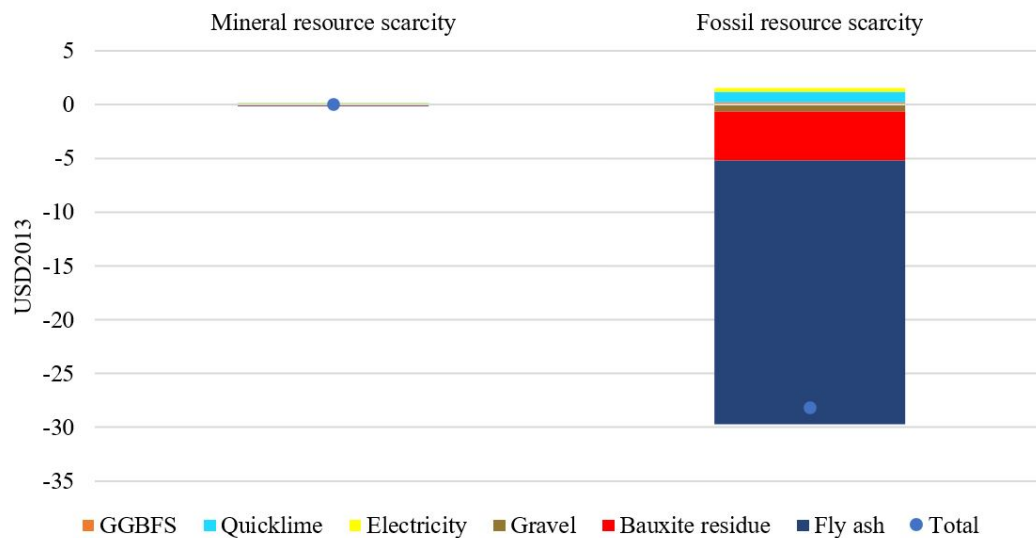
Figure 20: ReCiPe results for impacts on mineral scarcity of soil stabilization

Fly ash is by far the most sensitive inventory for the soil stabilization (SS) technology. In the LCIA presented in figure 18, 19, and 20 fly ash is assumed to be a waste, which similar to the case of BR "disappears" when used as soil stabilization. While EEA (2007) mentions that most residues from coal combustion are not considered hazardous, Al-Mayman et al. (2017) presents potential high concentrations of toxic heavy metals in fly ash (like Cr and As), but also mentions that the toxic materials may be immobilized by "waste stabilization" such as using fly ash in cement like done by Tang et al. (2020). Besides the toxicity of fly ash that is immobilized when the pozzolanic and self-cementing properties of fly ash is activated, there is a major saving in energy from heat production for the conventional remediation before landfilling of fly ash that makes fly ash utilization beneficial to use. Because of the waste stabilization that occurs when soil is stabilized, freshwater eutrophication impacts, in contrast to de-alkalization of BR, may be reduced if phosphor compounds become immobilized in the soil matrix after stabilization.

However, for the multiple arguments *for* using fly ash in general, here are important arguments *against* using fly ash with BR. The following discussion makes the following arguments: (i) BR mixed with fly ash cannot be compared to gravel not mixed with fly ash, (ii) fly ash soon risks losing its label as waste, (iii) fly ash should not partake in a comparison where it is used in both scenarios. Lastly it is discussed how: (iv) Cement substitution is highly unlikely. These arguments are then represented by scenarios whose impacts are illustrated in figure 21.

BR mixed with fly ash cannot be compared to gravel not mixed with fly ash. The quality of the road depends on the technique used for soil stabilization. Where road base composed of gravel and sand is usually referred to as an "unbound" road base, the addition of binders (e.g. cement, fly ash, lime) will make a base referred to as "bound". According to Titi et al. (2018), when unbound base course layers experience fatigue cracking and rutting, it is amongst other things due to: "low elastic modulus of the base layer ... lack of adequate particle angularity and surface texture (poor interlocking), and degradation under repeated loads" and low shear strength. A good mix has the opposite properties and can result in a good road base. But in any case, the addition of fly ash help bind the aggregates due to its pozzolanic and self-cementing properties, which strengthens the road base and reduce the risk of experiencing above mentioned issues. Camargo et al. (2012) compared

an unbound road base using gravel aggregates with a road base using recycled asphalt bound with cementitious high carbon fly ash. The addition of fly ash significantly increased CBR (California Bearing Ratio, which indicates the base strength) and decreased plastic strain in laboratory tests, although field tests showed less promising results. These findings strongly indicate that addition of binders like fly ash makes the road base capable of receiving more stress (heavier and more frequent loads) than if it was an unbound base. On the extreme sides of the "spectre" of bound and unbound road bases are a gravel base and concrete base, it is intuitive that a concrete base is stronger than a gravel base. Because of the benefits gained from mixing fly ash in road base soil, the quality of BR mixed with fly ash is not comparable with gravel *not* mixed with fly ash, except in the case where non-mixed gravel is of such quality it simply cannot benefit from binders. Therefore, it is assumed that a road base using gravel along with the same mix of fly ash, lime, and GGBFS will have the same quality as when BR is mixed with these additives and vice versa.

Fly ash soon risks losing its label as waste. Since fly ash is a by-product of coal combustion, the utilization of fly ash demands that energy is produced from coal. Ghassemi et al. (2004) describes that coal mining creates significant amounts of tailings leading to some of the environmental impacts this study specifically aims to decrease. The impacts from the production of fly ash are allocated to the energy production process because it is a waste product. But to quote Hauschild et al. (2018) on allocation of multi-functional processes: "...where the value of the co-product is zero, its allocated share of the inputs and outputs also becomes zero in accordance with the fact that a zero-value output is not a co-product but waste and should be modelled as such." Therefore, if at some point in the future there is an unmet demand for fly ash in road construction and therefore a value, it will and should be attributed some fraction of the impacts from coal combustion as it no longer can be defined as a waste. Weil et al. (2009) also discuss the issue for residue-based geopolymers and mentions that: "applications should preferentially favour secondary resources which are not already used as raw materials". In 2004 less than 10% of the European generated fly ash was put in temporary storage and under 2% in landfills - the rest was utilized in construction material or civil works, or used for restoration and filling material in mines, quarries, and pits (EEA, 2007). Therefore, there is a high risk that fly ash in the near future will be considered a product with environmental impacts similar to the impacts originally desired to avoid!

Fly ash should not partake in a comparison where it is used in both scenarios. The very reason that fly ash "risk" loosing its label as a waste, is because it is already a resource that, among other purposes, is specifically used with gravel to stabilize soil in road construction as also described in chapter 1.3.2. Therefore, including fly ash in the system expansion where conventional road stabilization also use fly ash, would in a broader perspective be counting the benefits of using fly ash *twice* - because the benefits already should be included in the road stabilization life cycle that is substituted. The additives added to the BR in the LCI description of soil stabilization (table 4) can therefore be excluded from the comparative LCIA to "business as usual".

Cement substitution is highly unlikely. Another common option for soil stabilization is the use of cement (see chapter 1.3.2). 21 shows the uncertainty of the impacts that depends on the amount of cement needed for a fine or coarse soil type. While cement in SS was already in 1959 considered a more affordable option when distance to a quarry exceeded ~16km (~10 miles) (Fisher et al., 1959) it is not the most environmentally beneficial option. However, if cement is used for soil stabilization, it would be to a location far enough from quarries that neither gravel or BR is affordable to transport. Therefore, whether cement is already used or not depends on the distance of the soil stabilization site from a quarry, and since at least two of the treatment plants are near a quarry, cement will never be substituted because the transport is economically infeasible.

The above discussion can be depicted by three scenarios:

1. BR substitutes gravel in soil stabilization, it is assumed that fly ash and other additives are already used in conventional soil stabilization. The comparison of SS and "business as usual" therefore boils down to BR substituting gravel in 1:1 dry weight. Therefore, fly ash and the additives are *excluded* from the comparison to "business as usual".

2. BR substitutes gravel in soil stabilization, it is assumed that fly ash is not conventionally used in the area and the addition of additives now improve the BR soil matrix to a level better or comparable to the conventional high quality unbound road base. Therefore, fly ash and additives are *included* in the comparison with "business as usual".

3. BR substitutes cement in the unlikely case that it is economically feasible at the soil stabilization location although it was not earlier feasible to use gravel. The amount of cement used depends on soil type.
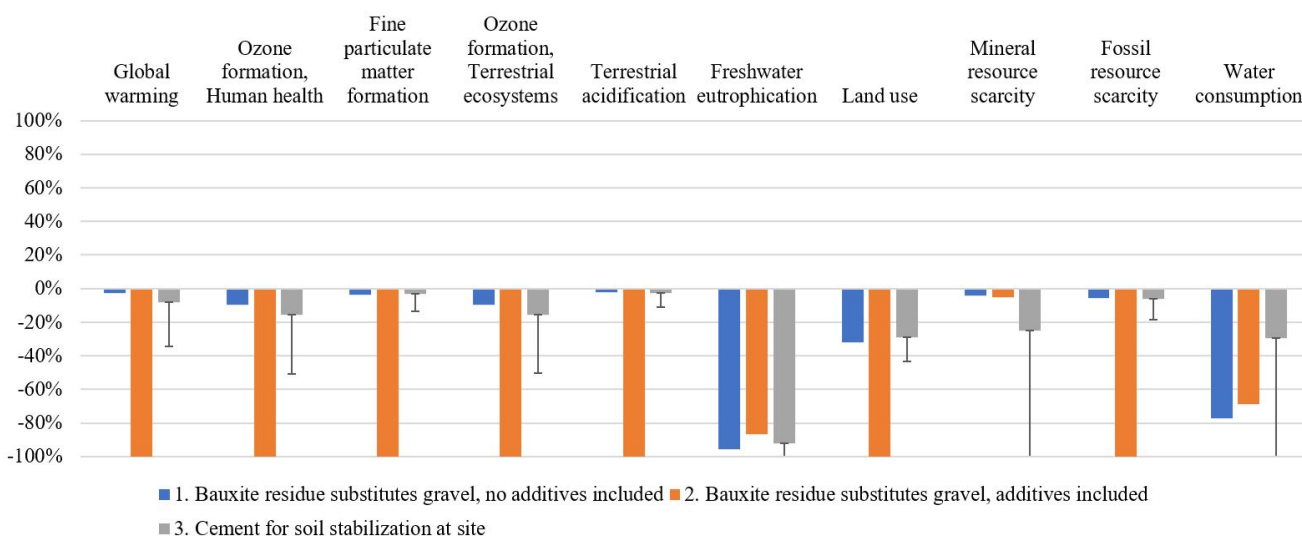
Figure 21: Midpoint ReCiPe LCIA of 3 alternative soil stabilization scenarios.

Based on this chapter's discussion and presented literature on fly ash, it is most likely that fly ash is already used in road base construction together with gravel, at least when higher quality is desired. Fly ash is also not recommended by other authors as it is already gaining the traits of a valued resource rather than a waste. Therefore, scenario 1 in figure 21 is the most likely and most fair life cycle to use for comparison with the other technologies. However, it is presented with the uncertainty that it could be considered as scenario 2 in some cases depending on the situation and very much a matter of a somewhat subjective perspective.

5.2.5 High Performance Binder

The are two alternatives for the high performance binder technology (HPB): "inorganic polymers (IP)" and "hybrid high performance binder" (HHPB), they share a "base" technology which is presented in chapter 4 and discussed below. In this chapter the two alternatives are initially evaluated based on generic (non-location dependent) processes to reveal if one is generally more sustainable than the other. The HPB scenario from Greece is used throughout this discussion. The sensitivity of HPB location is later discussed.

Also, note that due to the many different processes included in the foreground LCI of HHPB, multiple lesser processes has been aggregated to one category: "lesser processes" which in combination seems to have an impact (figure 22, 23, and 24), are considered insignificant to the final conclusion of the LCA due to their individual low impact relative to the other processes. Processes aggregated to the "lesser processes" category are marked with a * symbol in table 5 and their individual impacts can be seen in Appendix **??**.

Base scenario: Quenching and heating
As can be seen from figure 22 and 23, the methane input in the base scenario has a significant impact on fossil resource scarcity. This impact is reduced by 26.4% (see equation 13) if air quenching is used over water quenching because heat generated from this methane is recirculated when air quenching is used, therefore air quenching is recommended.

Comparison of IP and Hybrid
Figures for a ReCiPe endpoint LCIA of IP can be found in appendix B along with a comparative midpoint LCIA of the IP and HHPB. The substitution of concrete blocks is marginally the greatest impact for both the IP and hybrid technology. In the HHPB technology this is followed by OPC, methane, and direct emissions (calcification process) as seen in figure 22, 23, and 24. OPC is not used for the IP technology which lowers its emissions, but the substitution of concrete is also significantly lower which affects the substituted impacts even more per FU. With small variations between the pilot plants, the hybrid scenario has an output of 157~160% more concrete product than IP. This is an effect of the extra aggregates and additives added in the HHPB. The impact of these extra aggregates and lesser processes show little sensitivity compared to the substitution of concrete making the high volume production HHPB preferred over IP in a non-location based LCIA. A "per tonne BR product" comparison is also made in appendix B and the HHPB is still superior to IP.

The main reason for IP to be worse than HHPB is also the main contributor to the environmental impacts only found in the IP technology: Sodium silicate. An investigation of the background LCI shows that sodium silicate production has high emissions of CO_2 (93% of global warming impact from IP production), sulphur dioxide, and particulates $<2.5\mu m$ (responsible for 58.5 and 21.6% of fine particulate matter formation, respectively). In the ecoinvent database sodium silicate production is consuming much energy and heat due to the high temperatures needed for the chemical reactions shown in equation 15 which also emits CO_2 directly from its own process.

McLellan et al. (2011) propose using waste soda from the Bayer process for alkali activation of the aluminosilicate instead of using sodium silicate (*cf.* chapter 1.3.3). According to the LCIA in appendix B, if sodium silicate production was completely neutral in terms of environmental impacts (*i.e.* substituted by waste soda), IP would benefit the environment compared to a "business as usual" scenario. If high quality concrete is substituted, HHPB would have best results per FU due to high volume production, while IP would have the best results per tonne product produced. If IP is possible without using sodium silicate it is therefore worth studying further, but the new scenario would need a new LCA.

When sodium silicate *is* used, which is the case of the current technology, it must substitute a high quality concrete to be better than "business as usual" in most impact categories, but even then cannot avoid burden-shifting in land use and water consumption. Fossil resource scarcity is also only barely avoiding burden-shifting when high quality concrete is substituted (see appendix B). However, if IP is able to substitute the highest quality concrete and HHPB only the lowest, then IP becomes the better alternative in all other categories per tonne concrete produced. But in all other cases IP using sodium silicate is not

advised.

$$Na_2CO_3 + xSiO_2 \rightarrow Na_2O \cdot xSiO_2 + CO_2 \tag{15}$$
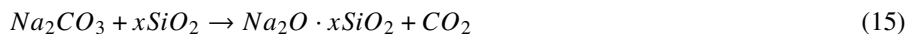
In conclusion to this chapter, the high performance binder technology is best using air quenching and the hybrid version. Air quenching is preferred over water quenching as it enables recirculation of heat and thereby decrease demand of methane and improves fossil resource scarcity. The hybrid version results in much higher amounts of concrete substitution and the additional inputs needed are not as environmentally damaging as the substitution of concrete is beneficial. Also, the sodium silicate needed for the IP technology has significant impacts and its use is therefore best seen eliminated from the treated BR product's life cycle.

Endpoint sensitivity on hybrid high performance binder
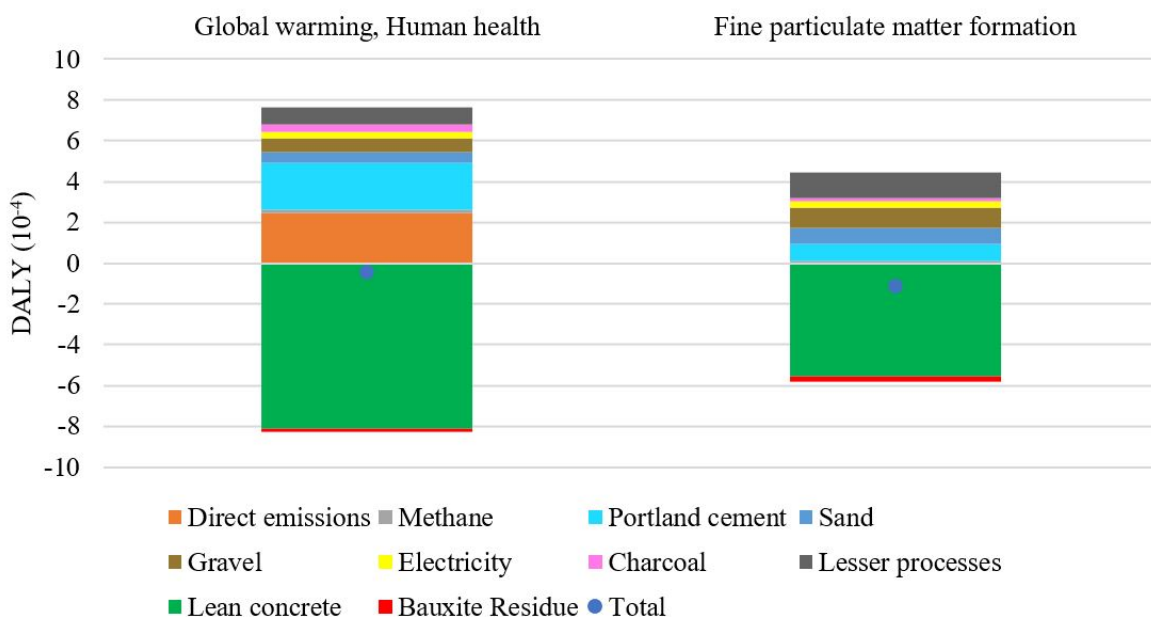
Figure 22: Relevant ReCiPe DALY results of High Performance Binder
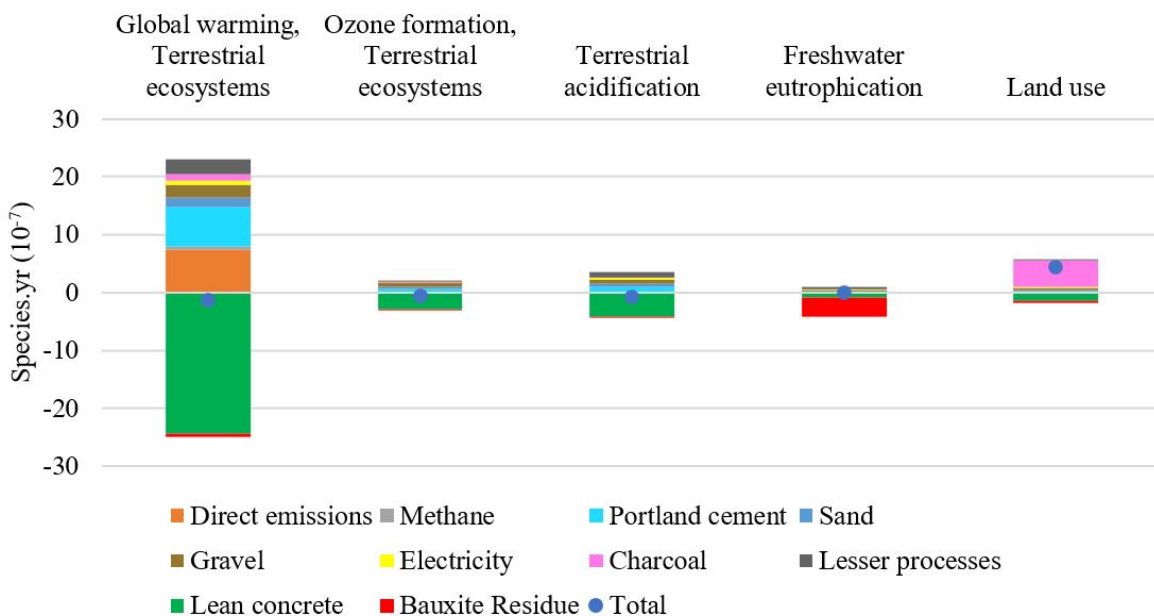
Figure 23: Relevant ReCiPe species results of High Performance Binder
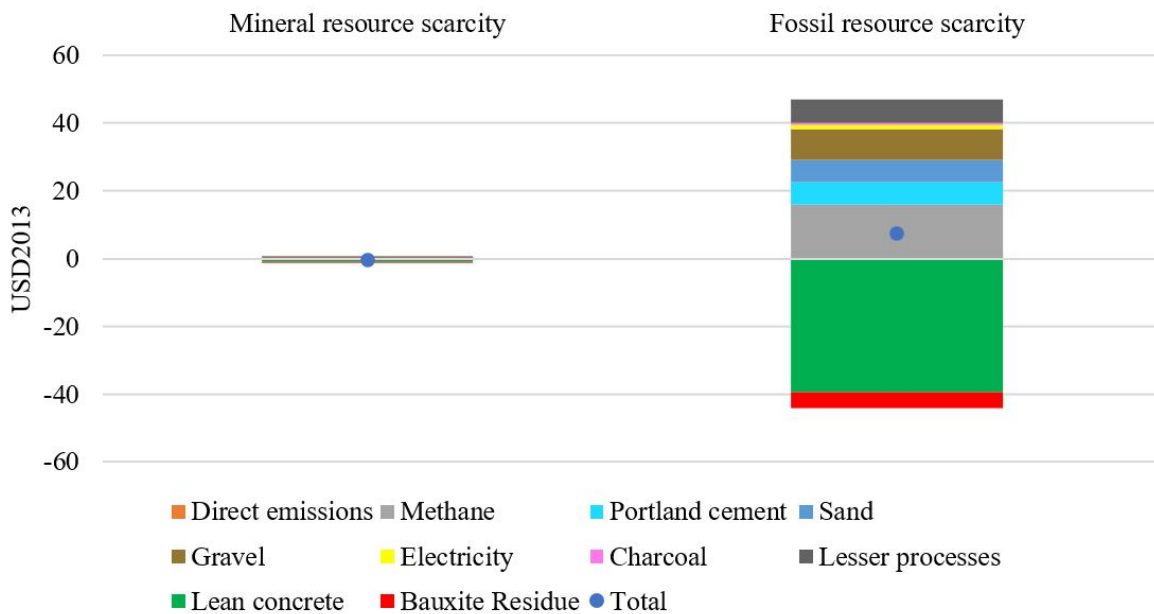
Figure 24: ReCiPe results for impacts on mineral scarcity of High Performance Binder

Figure 22, 23, and 24 show greatest sensitivity to the choice of substituted concrete. The figures presented use "Lean concrete" for substitution, which is the ecoinvent concrete process found to have the smallest absolute impact among the relevant concrete processes tested (see figure 25). In the following, the substituted concrete process is evaluated along with the processes related to charcoal and Portland cement which are also sensitive. The direct emissions are based on data from the pilot plants and

considered precise. Natural gas, cement, and the high volume of aggregates (in that order) are the main responsible for the impacts on fossil resource scarcity. The methane input is significantly impacting fossil resource scarcity because of it being a natural gas, which is a fossil resource.

Sensitivity of concrete process chosen for substitution

The HPB is assumed to replace standard concrete – not lightweight or frost resistant concrete which are produced differently and need different inputs. *E.g.* the "Lightweight concrete block, expanded clay RoW| production" demands a significantly higher input of clinker for production than the concrete processes shown in figure 25 (see appendix C for lightweight concrete midpoint impacts). The concrete processes evaluated are all "CEM II/B" meaning that there is an additive content of 21-35% of fly ash, slag, or limestone in the cement used for the concrete production. Assuming a 10% cement content, this is 2.1-3.5% additives. In comparison, HPB concrete has 3-12% additives depending on whether treated BR is counted as an additive or not. The reason for substituting "CEM I/B"-cement based concrete is because treated BR concrete product would likely fit under a similar category of concrete.

The concrete inventories presented in figure 25 are all sensitive to the clinker process where a lot of CO_2 emissions are from limestone decarbonation and from heat processes. This is responsible for a major part of the environmental impacts where concrete is to blame. It is seen from the results that if HPB substitutes lean concrete, it is not near as beneficial as if it substitutes concrete used for sole plates and foundations or a concrete like the German concrete block; "Concrete block {DE}". Since the HPB product's quality is unknown the highest and lowest impacts from figure 25 is used as uncertainty in the comparison of the three technologies - the uncertainty is greatest for land use and minimal in water consumption but otherwise range from 50-100% in other categories, showing just how significant the substituted concrete quality is since it is also the most sensitive parameter.
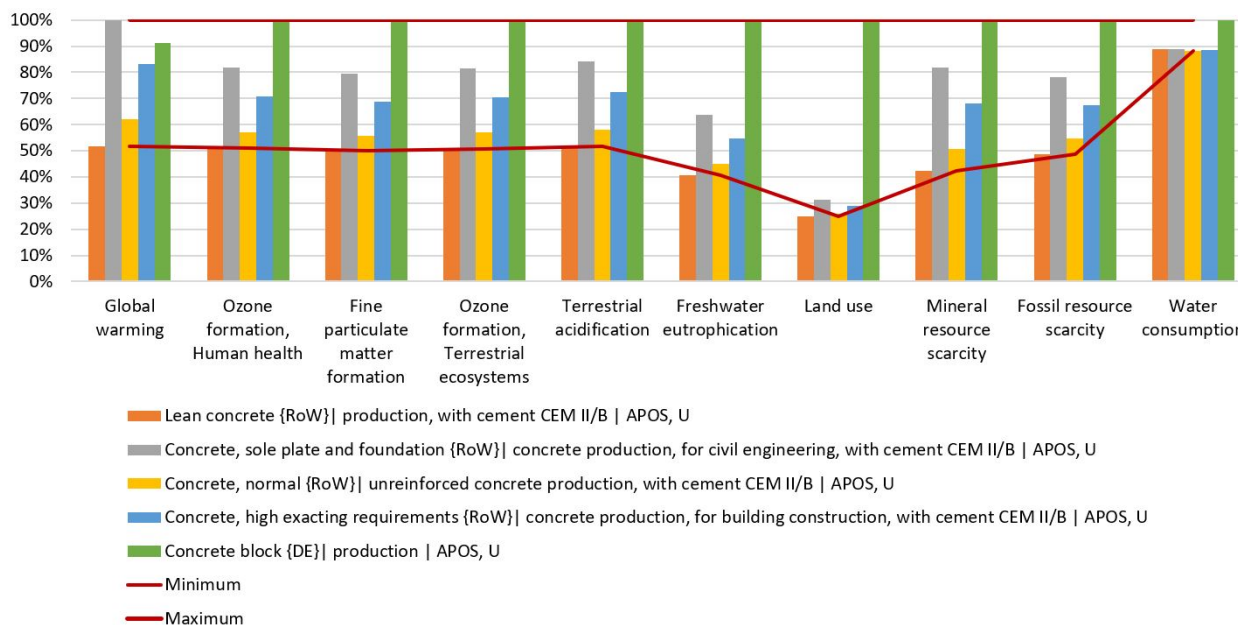
Figure 25: Impact of 4 concrete processes relative to the highest impact in a ReCiPe midpoint category. In combination they show the possible range of impacts from concrete substitution.

Portland cement affects global warming the most because of the clinker process. "Clinker {Europe without Switzerland} | production" is responsible for 85.6% of the total CO_{2-eq} from the Portland cement inventory. The main emissions are CO_2 (98%). Fine particulate matter is also mostly affected by clinker (45.8% of total category impact). The substances affecting fine particulate matter is mainly sulphur dioxide (46.5%), nitrogen oxides (32.2%) and particulates <2.5μm (19.3%). The global warming impacts from clinker production will not vary with location or time as it is quite fixed to the chemical reactions in clinker production, but fine particulate matter impacts may decrease as energy sources become more sustainable.

Charcoal affects land use marginally more than any other process and is responsible for burden shifting in this category. However, a LCIA presents the *potential* impacts of a life cycle and ReCiPe's assessment method of land use is only assessing the change to agricultural or urban land, and excludes forestry (Mattila et al., 2011). Therefore, the actual impact from charcoal on land use is assumed to be marginally smaller than the results in figure 23. However, it does show that charcoal from sustainable forestry is important to avoid the burden-shifting.

High Performance Binder recommendation

From the results of the LCIA, the HHPB technology is barely beneficial to the environment for most categories when the substituted concrete product is of a low quality (see also figure 26). The lowest quality concrete substitution experience burden shifting in fossil resource scarcity. However, if high quality concrete is substituted it will result in great improvements on all impact categories except freshwater eutrophication, land use, and mineral resource scarcity as the concrete process hardly impacts these categories (figure 23 and 24). The potential impact on land use due to the charcoal use is not near the actual impact which is significantly smaller when sustainable forestry is used and phosphor will potentially immobilize in the bound concrete matrix. The hybrid high performance binder is therefore recommended over both IP and business as usual, but it should be noted that there will be burden-shifting to impacts on fossil resource scarcity if the quality of the substituted concrete is not at an adequate level.

5.3   Comparison of technologies on a generic level
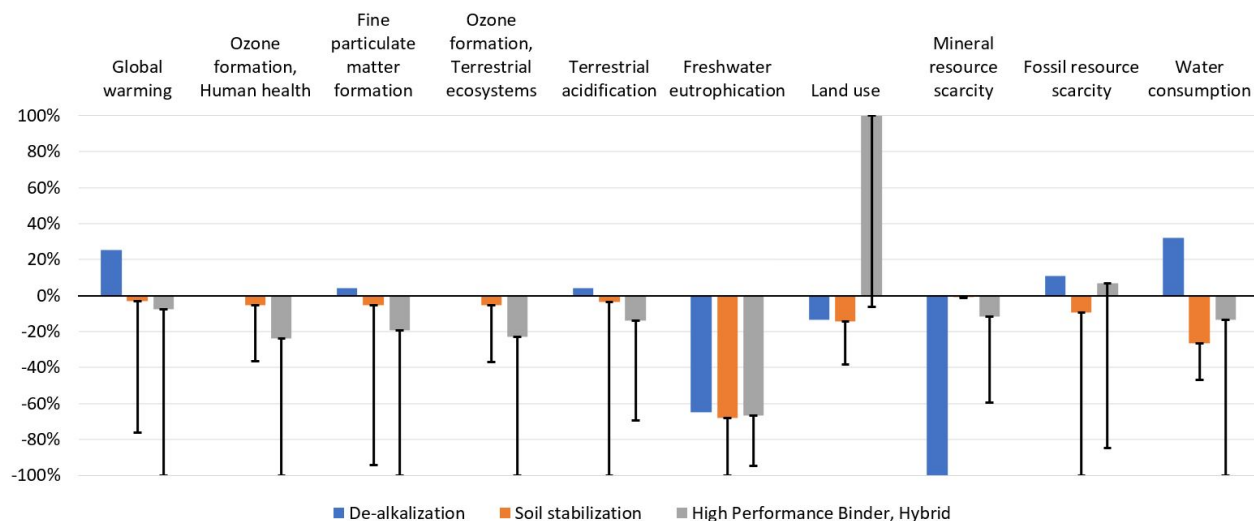
Figure 26: Comparison of ReCiPe midpoint impacts of the three technologies: De-alkalization (DA), soil stabilization (SS), and hybrid high performance binder (HHPB). The HHPB is from AoG in Greece assumed to use air quenching and a rotary kiln for the hybrid product. The error bars depicts whether high or low quality concrete is substituted (HHPB) and whether fly ash and additives are included in the comparison (SS).

Figure 26 shows that de-alkalization (DA) is not better than soil stabilization (SS) or the hybrid high performance binder (HHPB) technology when compared on the FU, except for saving more mineral resource scarcity. If de-alkalization was done to improve mineral resource scarcity it would unavoidably result in heavy burden-shifting to multiple other categories that are much more sensitive than the mineral resource scarcity (see figure 17, 16, 15). Therefore, de-alkalization continues to be the least recommended technology.

Whether SS or HHPB is the most beneficial choice depends on the substituted product. SS has great benefits if it is assumed that fly ash was not originally used for soil stabilization at the site where the bauxite residue is mixed with the soil. In other words, it must be emphasized that it is *not* the use of bauxite residue that makes soil stabilization a good choice, but rather the use of fly ash - an additive that may also benefit HHPB both in terms of pozzolanic and self-cementing properties, and impact assessment (depending on the view/opinion on fly ash) if it was simply added to the HHPB mix. The HHPB is also guaranteed beneficial in all categories except for toxicity, land use, and fossil resource scarcity. The only way to avoid burden shifting for resource scarcity is by ensuring an adequate quality of the concrete substitution product.

When evaluating the technologies aside from the LCIA, the hybrid high performance binder is recommended over soil stabilization because the inclusion of fly ash is expected to be fair only in rare situations - if ever. Meanwhile, the review in chapter 1.3.3 presents how the chemically useful components of bauxite residue have their potential fulfilled when treated as the bauxite residue is treated in the high performance binder technology. The bauxite residue therefore functions more like a "binding aggregate" than just aggregates in the high performance binder where it is simply aggregates in soil stabilization, based on the current knowledge of the two technologies.

6   Location-specific LCIA

First, the location specific parameters that may alter the conclusion are discussed: Energy demand, transport of product and inputs, and ratio of input/output based on BR composition. Simapro was used to evaluate what processes had high impacts in the background LCI and found that energy and transport is significant there. This indicates that the energy grid could be sensitive to the conclusion and transport as well if included. Transport and BR composition is then further discussed specifically in relation to each location: Romania, Ireland, and Greece.

6.0.1   Energy

Energy demand in the *foreground* LCIs is not sensitive for electricity input in any of the technologies compared to other inventories in the foreground LCIs. However, energy consumption in the *background* LCI is a significant part of the global warming potential due to its connection to every production along the product chain. But electricity is often traded internationally meaning that the electricity market inventory for "{ReR}" (Europe without Switzerland) is the best approximate for the actual electricity. Likewise, the priority of ReR, GLO, a European country (not Switzerland), and then RoW for every inventory in the foreground LCI also limits the uncertainty related to what energy grid is used for the production of inputs to the foreground LCI since each input then use the most relevant energy mix available.

In conclusion, the energy mix is a relevant factor for almost any LCA, *but* despite its significance in the background LCI, the uncertainty is fairly low because the energy mix already is a best approximate to the region (Europe).

6.0.2   Transport

Transportation in the background LCI is also significant, and since the background LCI is an indicator of what to expect in every inventory (as it is a total of many inventories intertwined) this indicates that transport included in the foreground LCI would be significant as well if included. The impact of 1tkm (tonne kilometre) for three different types of transport is presented in table 7. The sensitivity of transport types will also be discussed.

Table 7: Midpoint impacts from 1tkm transport of 3 different ecoinvent processes: Truck ("Transport, freight, lorry >32 metric ton, euro4 RER| market for transport, freight, lorry >32 metric ton, EURO4"), barge ("Transport, freight, inland waterways, barge RER| market for transport, freight, inland waterways, barge"), and ship ("Transport, freight, sea, transoceanic ship GLO| market for").

Unit	Impact category	Truck	Barge	Ship
(10^{-2}) kg CO2 eq	Global warming	8.991	4.561	1.138
(10^{-4}) kg NOx eq	Ozone formation, Human health	4.080	5.163	1.469
(10^{-4}) kg PM2.5 eq	Fine particulate matter formation	1.221	0.912	0.621
(10^{-4}) kg NOx eq	Ozone formation, Terrestrial ecosystems	4.182	5.210	1.480
(10^{-4}) kg SO2 eq	Terrestrial acidification	2.687	2.512	1.896
(10^{-6}) kg P eq	Freshwater eutrophication	7.037	5.979	1.529
(10^{-3}) m2a crop eq	Land use	6.767	2.157	0.076
(10^{-4}) kg Cu eq	Mineral resource scarcity	1.414	1.447	0.138
(10^{-2}) kg oil eq	Fossil resource scarcity	3.267	1.343	0.360
(10^{-4}) m3	Water consumption	2.900	1.925	0.337

Significance of FU

When comparing the technologies in this study the FU is "per tonne BR remediated and utilized" and not "per tonne treated BR product" although there is a very high production volume. Until now the high performance binder has had an advantage from the FU by producing more substitution product (concrete) compared to the soil stabilization that produce much less. The advantage is a result of the substituted product being more sensitive than the goal: Removal of BR. So when comparing equal amounts of the removal of BR, the difference in the more sensitive product risk giving an obscure presentation of the impacts because they mainly rely on the product. Figure 27 is a comparison of the HHPB and SS based on "per tonne product" but otherwise the same uncertainties as already discussed. It shows that SS-l is in fact better than HHPB-l *per tonne product*, indicating that products are likely to be transported further without burden-shifting. However, when concrete quality increases the HHPB continues to be the best technology.
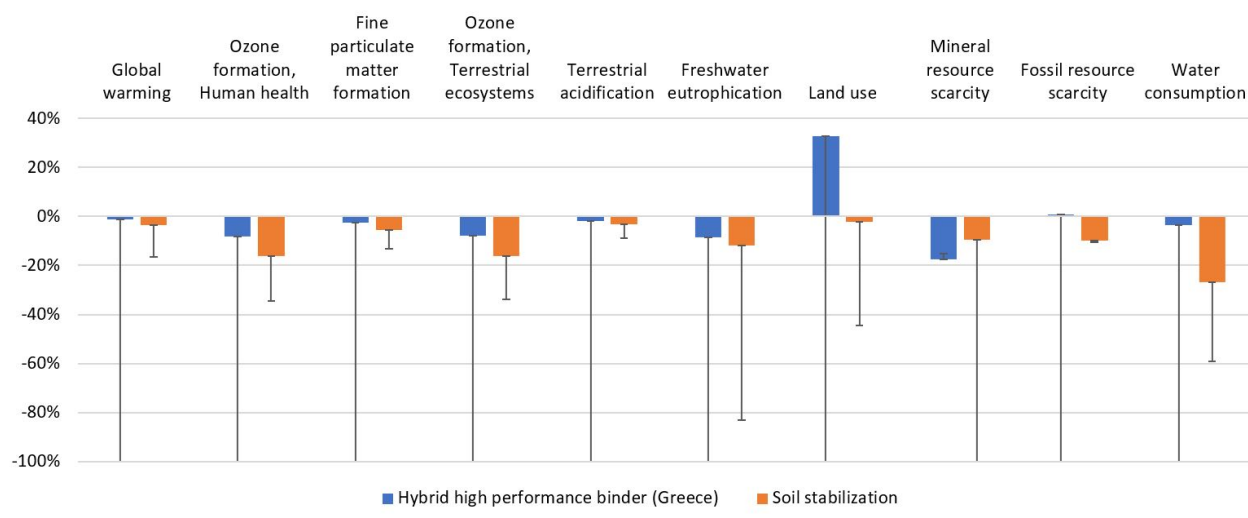
Figure 27: Comparison of hybrid high performance binder (Greece) and soil stabilization midpoint impacts "per tonne product".

Table 8: Break-even distance in *km* for transport by truck of 1 tonne bauxite residue product calculated using equation 16. Highlighted cells are deciding the break-even distance to avoid burden-shifting. A figure of the numbers as well as the P_i values is given in appendix D.

Impact category	De-alkalization	Soil stabilization *excluding* additives	Soil stabilization *excluding* additives	Hybrid high performance binder of low quality (Greece)	Hybrid high performance binder of high quality (Greece)	Hybrid high performance binder of low quality (Romania)	Hybrid high performance binder of high quality (Romania)	Inorganic Polymer of low quality (Greece)	Inorganic Polymer of high quality (Greece)
Global warming	0	143	4187	52.1	689	70.2	707	0.0	427.5
Ozone formation, Human health	0	222	1374	112	473	118	479	12.7	373.1
Fine particulate matter formation	0	261	4776	122	635	131	644	0.0	242.1
Ozone formation, Terrestrial ecosystems	0	221	1379	107	466	113	472	7.6	366.5
Terrestrial acidification	0	234	7104	125	620	135	630	0.0	314.6
Freshwater eutrophication	43882	47200	56834	4756	6745	5651	7640	5412.6	7401.5
Land use	336	616	1383	0	28.8	0	0	0.0	0.0
Mineral resource scarcity	59689	361	656	742	3766	746	3770	861.6	3886.0
Fossil resource scarcity	0	238	2419	0	258	0	245	0.0	31.4
Water consumption	0	1682	2838	102	761	159	818	0.0	0.0
Minimum distance	0	143	656	0	28.8	0	0	0.0	0.0

When transport of the product is included in the LCA scope the HPB is 'punished' because more product needs transport per FU "tonne BR remediated and utilized". Not including transport in the comparison of the technologies is therefore unfair with the current FU. It is important to also consider that different types of transport have different impacts. If an overall avoidance of burden-shifting is desired a technology should be beneficial in the same categories as those the transport process impacts. But naturally, the *magnitude* of the impacts must also be evaluated, *e.g.* a slight burden-shifting in mineral resource scarcity may be worthwhile if all other categories are significantly improved.

Transport of product

The transport cost/impact per tonne product results in a higher impact for the HPB than the SS. In table 8, the break-even point distance of transportation by truck *per tonne bauxite residue product* is calculated based on the impacts in the different impact categories for ReCiPe midpoint. This is seen in equation 16, where P_i is environmental impact from production of 1 tonne BR product on impact category i and T_{ir} is the accumulated impact on impact category i for transport of one tonne BR product with transport types r_0 through r (see table 7 for 3 examples), which gives the break-even distance x:

$$\frac{P_i \frac{1}{t}}{\sum_{r_0}^{r}(T_{ir})\frac{1}{t \cdot km}} = x\ km \tag{16}$$

From table 8 it can be seen that in the rare case where soil stabilization includes fly ash and additives for comparison and therefore have high impact benefits **(SS-h)**, the product can be transported the furthest without making burden-shifting

compared to the "business as usual" scenario. Burden-shifting happens if the product is transported further than the break-even distance. Soil stabilization excluding the fly ash and additives resulting in low impact benefits **(SS-l)** can still be transported further than high performance binder substituting high quality concrete **(HHPB-h)**, because of the charcoal impacts on land use. This indicates, that *per tonne product* soil stabilization could be a better alternative to high performance binder if charcoal is not sustainably obtained. However, if the charcoal is from sustainable forestry, then fossil resource scarcity is the next bottleneck - and this would allow HHPB-h concrete to be transported ~100km further than bauxite residue for SS-l. Again, depending on the substituted product or perspective on fly ash, both soil stabilization and the hybrid high performance binder can be the best alternative.

Different means of transportation is available at the different sites, *e.g.* it is possible to transport by ship straight from the treatment plant in Greece and Ireland, but in Romania a truck or barge must be used first. Therefore, the geographic location of the pilot plant can have significant impact on the environmental impacts because the different means of transportation have significantly different impacts on the environment as seen in figure 28.
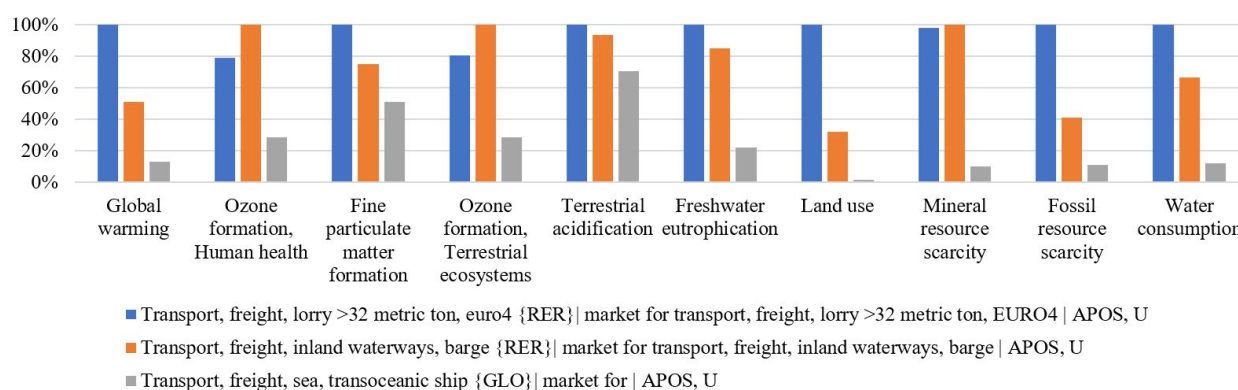
Figure 28: ReCiPe midpoint comparison of three transport inventories from ecoinvent of unit 1tkm: Truck in Europe carrying over 32 tonnes, barge used in shallow water, and large ships.

It is assumed that the bauxite residue substitution product is in greatest demand where population density is high since such cities tend to construct more buildings and roads. A short description of transport to potential markets/cities for the products are therefore described below. The transport of the high volume aggregates from quarry to treatment plant are also relevant to consider for the transport impacts. A potential transportation scenario is then presented for each location using equation 16.

Romania's ALUM plant is located 2km from an industrial harbour in the Saint George Branch which leads to the Danube river. The Danube river runs through 10 countries in Europe. A quarry called "Cariere Bididia" lies right in the eastern outskirts of Tulcea where ALUM resides (5 km from ALUM). Transport of aggregates could originate from this quarry resulting in low transport distance to the plant, and equally low transport distance for gravel to soil stabilization sites meaning that cement is not substituted by the soil stabilization technology.

Possible transport: Approximately 350km by barge on the Danube river, then 64km truck to Bucharest (only barely possible for SS-h and HHPB-h also assuming charcoal is sustainable). Can also be transported on barge 120km to the Black Sea where use of ship is available *e.g* to Istanbul. There is at least 10,000km transport left in ship for HHPB-h assuming charcoal is sustainable and 6,000km left for SS-h.

Ireland's Aughinish BR treatment plant has direct access to the sea through the deep water channel: Shannon Estuary, and approximately 50km to the North Atlantic Ocean. The quarry called "Roadstone, Joseph Hogans" is an 8.4 km drive south from Aughinish.

Possible transport: 35km to Limerick by ship or barge or approximately 170km to Galway by ship. From Limerick the Shannon river continues north for another 360km passing multiple settlements.

Greece's Aluminium of Greece (AoG) owned by Mytilineos also has direct access to the Gulf of Corinth. If products are transported by ship it must sail through the Corinth canal, a total trip of approximately 120km if done in straight lines to and from the canal. No quarries have been found near AoG, but the area is also blurred on Google Maps which has been used for this evaluation.

Possible transport: 120km by barge (or mix of barge and ship) to Athens. Or ~100km to Patras by ship.

This LCA is based on the data flow charts from the bauxite residue treatment pilot plants and therefore assumes that aggregates are mixed at the plant. However, if aggregates are mixed at the construction sites, transportation impacts will decrease, especially for the hybrid high performance binder that can be transported ~1200km instead of 258km from AoG by truck (land use aside, having fossil resource scarcity as bottleneck) or ~4000km by ship (terrestrial acidification becomes bottleneck).

Concluding on transport of high volume production, getting the product on a ship is a major benefit, allowing high quality substitution product to be distributed internationally without burden-shifting. The FU has also shown to potentially have influence on the possible outcome of a LCA. Table 8 shows a significant difference between HHPB-h and SS-h, in contrast to figure 26 which is based on the FU. These different results are the effect of producing high or low volumes of product which only becomes more significant when only highly impacting transport methods are available, *e.g.* when there is no water in the vicinity of the plant. The table (8) is also affected by which impact categories are affected by the transportation method. There will be no utilization of the product if it cannot be distributed and thereby no reduction in BR landfilling, so the break-even distance for every category should be evaluated in each scenario for SS and HHPB: Is fly ash included, what is the quality of the concrete, what transport types are available etc.. Such an analysis will tell what product to make at each site.

6.0.3   Bauxite residue composition

As described in chapter 1.2, bauxite residue composition can vary greatly depending on the bauxite residue landfill. The only difference between the BR treatment flow charts from Romania, Ireland, or Greece is a difference in input which is based on the difference in BR composition (see appendix A). Therefore, a comparative analysis of the HHPB in Romania and Greece is made to see if the difference in inputs and thereby BR composition also makes a significant difference for the environmental impacts.

First, the inputs in both the inorganic polymer (IP) and hybrid extension of the base scenario have the same input per mass treated bauxite residue. The difference between the Romanian and Greek flow charts is therefore only inputs in the base scenario, the amount of output, consumption of methane, and off-gas CO_2. The final production volume of treated bauxite residue from the base scenario can be calculated by the following equation, where the "carbon source" (charcoal) is excluded

since it combusts during the calcination process:

$$V_{BR-treated} = BR_{dry} \cdot 88.5\% + SiO_2 + CaCO_3 \cdot 56\% \tag{17}$$

The input of dry bauxite residue stays constant between the two plants (due to FU), while the input of SiO_2 and $CaCO_3$ change. As mentioned in chapter 1.3.3, Hertel et al. (2016) made the BR more reactive by heating and quenching in the presence of carbon and silica. It has also been discussed that the calcination of $CaCO_3$ resulting in quicklime (CaO) is relevant for cement as binder. Therefore, the input of SiO_2 and $CaCO_3$ is certainly related to the composition of the bauxite residue in terms of how much is needed to make it more reactive and better as binder.

The output of treated bauxite residue from the base scenario affects how much final product is made by $\frac{output\ kg}{218\ kg}$. So freshwater eutrophication and land use is more affected in Ireland's HHPB because the input of bauxite residue (freshwater eutrophication sensitivity) and charcoal (landfill sensitivity) are higher *per output final product*, but this difference is not significant for any conclusion as seen in figure 29.
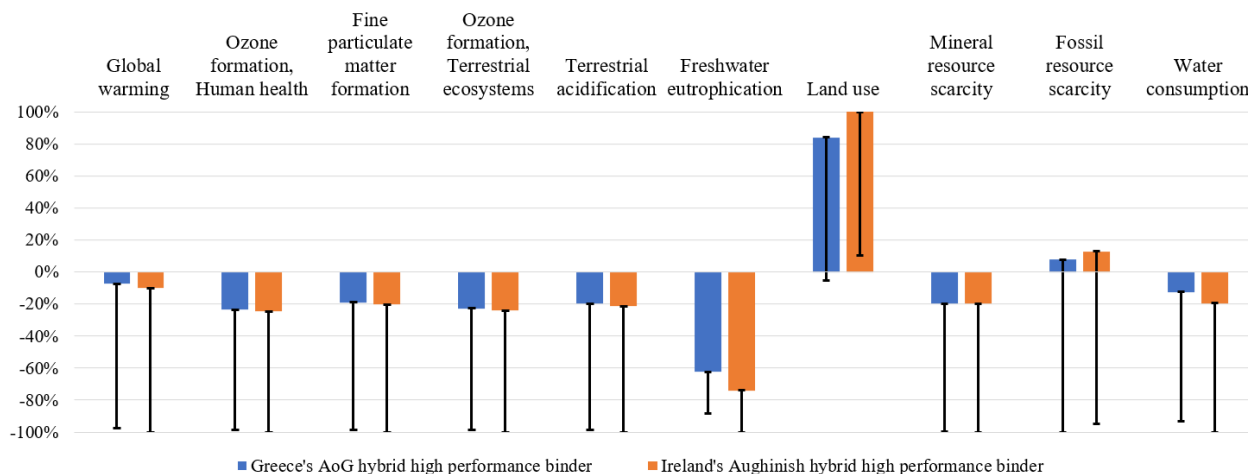
Figure 29: Hybrid high performance binder using air quenching and Rotary kiln. The hybrid high performance binder in both Greece and Romania is compared for highest or lowest impact from concrete substitution *per tonne product*.

It should be noted, that the calculated input of SiO_2 in equation 12 has not been included in the calculation of treated bauxite residue output from the base scenario. Although the purity of silica in the silica sand input also affects product volume it is likely to affect the final product quality more and is therefore an insignificant detail compared to the quality of the product.

Based on the findings from the literature review in chapter 1.2 and 1.3.3, the composition of BR is likely to affect the quality of the concrete to some extent. The properties shared between cement and BR gives a potential for BR to be a "binding aggregate" rather than just an aggregate. But if the treated bauxite residue has insufficient binding properties to substitute concrete of adequate quality, it may be better used for soil stabilization in nearby locations to avoid impacts on fossil resource scarcity. Therefore, the composition of the BR is potentially the most sensitive parameter although no data yet exists to support this statement. The quality of the product based on bauxite residue composition should be evaluated in a future study as this can have significant impacts on the choice of technology.

In conclusion to this chapter, based on the changes found in the flow charts from the different treatment plants, bauxite residue composition does not make significant changes in this LCIA's impacts by altering the amount of different inputs. However, if the composition of bauxite residue affects the quality of the concrete product then it is the *most sensitive* factor for the entire LCA.

7   Gaps of knowledge and future studies

A major gap of knowledge in this study is the lacking capability of modelling impacts from: (i) Alkalinity, (ii) Toxicity, (iii) and radioactivity. These points are shortly discussed here:

As mentioned in chapter 1, alkalinity is the main reason BR is considered hazardous. However, the alkalinity is not modelled in the LCIA and no quantitative discussion have been made regarding this main issue. It is possible that stabilization of BR can remediate hazards from alkalinity which would be a benefit to the soil stabilization and high performance binder technologies. The de-alkalization technology may also be much more beneficial than the LCIA informs in terms of neutralizing the alkalinity.

Toxicity has also shown to be inadequately modelled as discussed in chapter 5.2.1 and the immobilization of both Chromium VI, Zinc, and Vanadium should be studied for any specific BR product before it is marketed. If more time was available the USEtox impact assessment method would have been implemented as well and maybe shown interesting results related to human- and ecotoxicity.

While radioactivity from the TENORMs are below limit values, the variation of BR composition is likely to also regard TENORMs. The impacts of radioactivity is highly location-dependent, so depending on where the BR product is expected to be located it should also be analysed for radioactivity.

The uncertainties related to leaching in BR landfills and the general uncertainties from the ecoinvent inventory having averaged a scenario that varies so much from landfill to landfill, also makes any BR LCA using this ecoinvent inventory less reliable because the "business as usual" scenario is uncertain.

8 Conclusion

Location-specific factors have not been relevant for the conclusion of this LCA - the choice of best technology is more related to the substituted function, being soil stabilization with or without fly ash for the soil stabilization (SS) life cycle, or the quality of concrete for the hybrid high performance binder (HHPB) life cycle. However, it is still uncertain if the composition of the BR affects the quality of concrete. In case the concrete is of inadequate quality the SS technology is preferred over the HHPB although it may still only be distributed a short range. Therefore, although the conclusion remains the same in the non-location/generic LCIA and location-specific LCIA in this study it may change when the composition's impacts on quality is studied further. Also, the geography is relevant when transport is included and options should be considered when transporting high volume products since the impact varies greatly between types of transportation *e.g.* trucks and ships.

In most of the discussed scenarios, the hybrid high performance binder (HHPB) is recommended over the other technologies for every location, as long as it has an adequate, but not necessarily very high, product quality. De-alkalization (DA) is not recommendable due to high input of quicklime. Its treatment of alkalinity and decrease of risk may be arguments for making it worthwhile instead of business as usual. However, compared to the other technologies in question DA is least likely to immobilize the toxic compounds because it does not have binding properties, and the other technologies also decrease risk of spills by solidifying the BR.

HHPB is also considered better than soil stabilization (SS). Fly ash may become a by-product of coal combustion rather than a waste thereby sharing the impacts of coal combustion. It is also already used in road construction of similar quality to the soil stabilizing technology. It is therefore only fair that the SS life cycle system expansion only consists of gravel being substituted by BR while the rest is similar to "business as usual. This perspective also reveals that it is not the use of BR that is a benefit in SS but the use of fly ash making the technology slightly irrelevant as fly ash is already reaching its limits of use in the industry. The new perspective on SS is still better than business as usual, but only slightly. Therefore, the BR in SS cannot be transported far without resulting in burden shifting.

The HHPB is also preferred over the inorganic polymer (IP) mainly due to the use of sodium silicate in IP. The only scenario where IP is preferred over HHPB is if the HHPB is of minimal quality while IP is of the highest quality. The use of waste-soda instead of sodium silicate may also alter the conclusion, but that scenario requires further studying as it is a whole new life cycle.

The most sensitive parameter in HHPB is its production volume - resulting in both good and bad impacts related to concrete substitution and transport. However, if aggregates to the HHPB are mixed at the construction site, the adverse transport impacts decrease to a level where the HHPB product can be distributed internationally by ship without burden-shifting, if the product is of good quality. Such a scenario would likely result in all concrete within the feasible transport radius to be substituted by the hybrid high performance product and significantly reduce multiple environmental impacts - especially on global warming by substituting a great fraction of the otherwise used cement. *But*, the use of any BR product should be studied concerning its actual ability to cause toxic or radioactive impacts on its surrounding environment and how much the potential alkalinity hazards can be contained.

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Appendices

A   Flow charts

A.1   De-alkalization flow chart from ALUM (Romania)

A.2   Soil stabilization flow chart from Aughinish (Ireland)

2. Soil stabilization technology

System boundary

BR materials   **Base materials**

Bauxite residue course fraction (sand)

Farmed Bauxite residue fine fraction (mud)

Mixer
25 °C
19.5 kWh*

Bauxite residue*
1
*0,54t Farmed BR
0,46t Sand BR

Moisture 27%-30%

Fly ash
0.27

GGBFS
0.06

Lime
0.02

*To be defined considering the actual plant to be used in the pilot
Aughinish BR

Mixer
25 °C
26.33 kWh*

*To be defined considering the actual plant to be used in the pilot

1.35t

material	tons	%
mud	0.54	40.0%
sand	0.46	34.1%
PFA	0.27	20.0%
GGBFS	0.06	4.4%
Lime	0.02	1.5%
total	1.35	

Water (only if necessary)
25 °C
3.24 kWh*
0.00675 t

*Regular sprinker truck 150 kW net power. Use for 1min to spray asphalt emmulsion over 1 t of material

Grader
25 °C
17.69 kWh*
1.35675t

*Regular grader 163 kW net power (215 HP). Use for 5min to lay down 1 tone

Compaction
25 °C
10.53 kWh*
1.35675t

*Regular roller compactor 97kW net power. Use for 5min to lay down 1 tone

Curing asphalt tack coat
25 °C
3.26 kWh*

A.3   High Performance Binder - base scenario

Base scenario for High Performance Binder

Moisture	Dry BR	Carbon source (89% C)	SiO₂ source		CaCO₃	

Moisture: 500.0 / 500.0 kg / 500.0

Dry BR: 1000.0 / 1000.0 kg / 1000.0

Carbon source (89% C): 24.6 / 24.6 kg / 24.6

SiO₂ source: 78.0 / 100.0 kg / 215.0 ; 93.0454 / 119.76 kg / 262.917

CaCO₃: 196.0 / 267.9 kg / 336.2

Bayer process

Part of Bayer process: Mixer

Note: The first two steps are part of the Bayer process, probably ignore the energy consumption in these processes.

1799 / 1893 kg / 2076

Part of Bayer process: Filter press (Moisture grav 25%)   0 kwh/t

175 / 152 kg / 106

Filtrate

Order:
Romania
Ireland
Greece

If you recirculate the water, a water pump is needed that can give the pressure of tap water. You can assume that we need 30l/kg of TBR in the process, with an aimed pressure of 6 bar

1623 / 1741 kg / 1970

Pellitizer (Eirich)   5 kWh

1623 / 1741 kg / 1970

Pre-heating (Cyclone dryer, in cement industry)   0 MJ

Off-gas (H2O)   348 / 371 kg / 417

The energy supply for 'Pre-heating' is from 'Heat', which is recycled from high temperature off-gases. The preheater in cement is a cyclone dryer, if it requires energy the one's from cement can be

TBRC (1200-1300 °C) (Top blown rotary converter, CH₄ and air as energy supply)   2360 / 2497 MJ / 2834

Or

Rotary kiln (1200 °C)   2476 / 2476 MJ / 2476

1276 / 1370 kg / 1553

Off-gas (mainly CO2)   202.9 / 234.5 kg / 264.6

33% of energy   Heat   1265 / 1338 MJ / 1519

Off-gas (mainly CO2)   202.9 / 234.5 kg / 264.6

33% of energy   Heat   1265 / 1338 MJ / 1519

H₂O , 30l/kg of TBR

Or

623 / 659 MJ / 748

Heat

1073 / 1135 kg / 1288

Air quenching (grate cooler)   ?   kWh

Water quenching (pump, 6 bar)

Water is recycled

80% of the heat from Air quenching can be reused

If air quenching is considered, the produced heat can be used for 80% in the calcination process, then a similar cooler has to be installed as for cement (grate coolers) or a hatch air granulation setup. The calculations on the right show that air granulation is not necessary as the heat from the process can dry the matetrial. However, it can reduce the required energy for melting the material as the material will enter at a higher temperature.

The granulation setup did not consume any power in our case, because it was just city water going through small nozzles, increasing the speed of the water.

1073 / 1135 kg / 1288

1101 / 1165 kg / 1323

Ball mill (25% more energy as cement)   55.3 kWh

Dryer (105°C) or offgas heat

Off-gas (H2O)   29 / 30 kg / 34

39kWh/t for cement Ball mill to obtain 4000 cm²/g

1073 / 1135 kg / 1288

Using the water granulation (quenching) step, our material has only a water content of 2.6 %. However, the excess heat at the upscaling is quite good to dry all the red mud and treated red mud. So here we assume no energy consumption (yes!).

Ball mill (25% more energy as cement)   55.33 kWh

1073 / 1135 kg / 1288

TBR_Air (4000 cm²:g)

TBR_Water (4000 cm²/g)

A.4   High Performance Binder - Inorganic Polymer

Case 1: Inorganic Polymers (1 m³) - not optimised

TBR_water or air	Sodium silicate (SiO₂/Na₂O, 75% H2O) Autoclave synthesised	Sand (0-4 mm)	Gravel (4-16)

342 kg   171   kg   814 kg   1074 kg
               89   52%

Concrete Mixer   ? kWh/t   (Same as OPC based concrete)

2401 kg

Concrete   2400 kg or 1m3 concrete output is what the original inputs are based on

A.5   High Performance Binder - Hybrid

Case 2: Hybrid (1 m3) - not optimised

Water	Superplasticizer	Hemihyrate	Ordinary portland cement (52.5 N)	Gravel (4-16)

TBR_water or air	NaOH	GGBFS	Limestone fines	Sand (0-4 mm)

218 kg   113 kg   5 kg   2 kg   47 kg   1 kg   25 kg   47 kg   811 kg   1070 kg

Concrete mixer   kWh/t (Same as OPC based concrete)

2339 kg

Concrete   2400 kg/m3

B   Inorganic Polymer LCIA

B.1   Inorganic Polymer Endpoint impacts

B.2   Inorganic Polymer and hybrid high performance binder comparison

Midpoint comparison of inorganic polymer and hybrid high performance binder (Greece) based on functional unit.

Midpoint comparison of inorganic polymer and hybrid high performance binder (Greece) based on functional unit. **No sodium silicate included!**
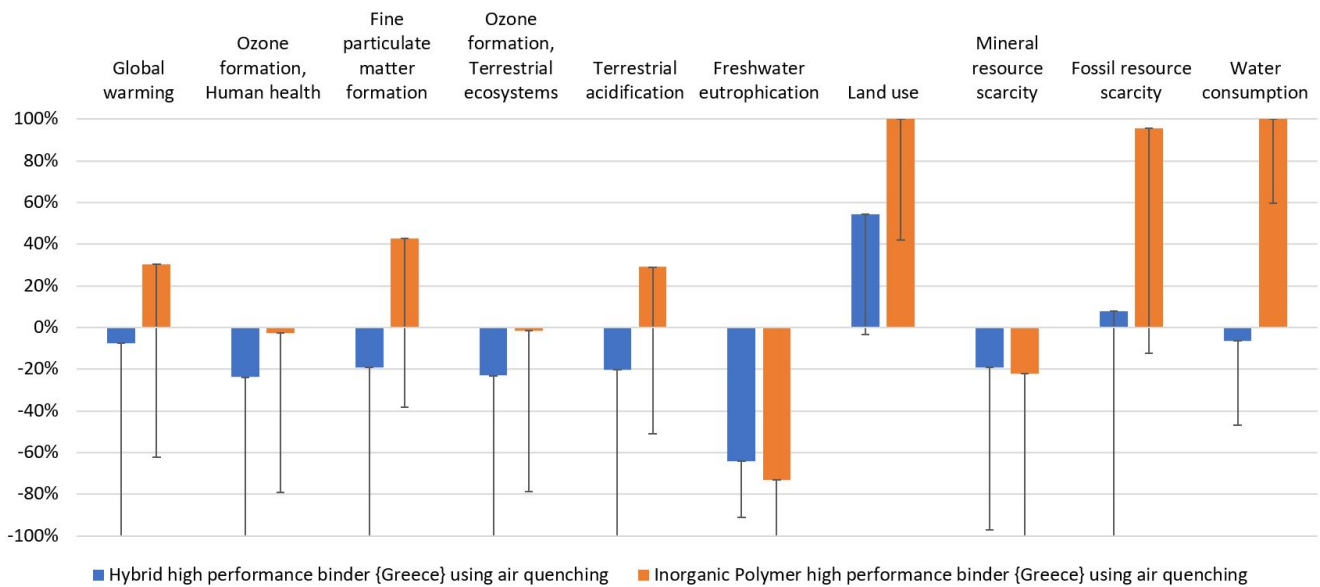
Midpoint comparison of inorganic polymer and hybrid high performance binder (Greece) based on *per tonne product*.
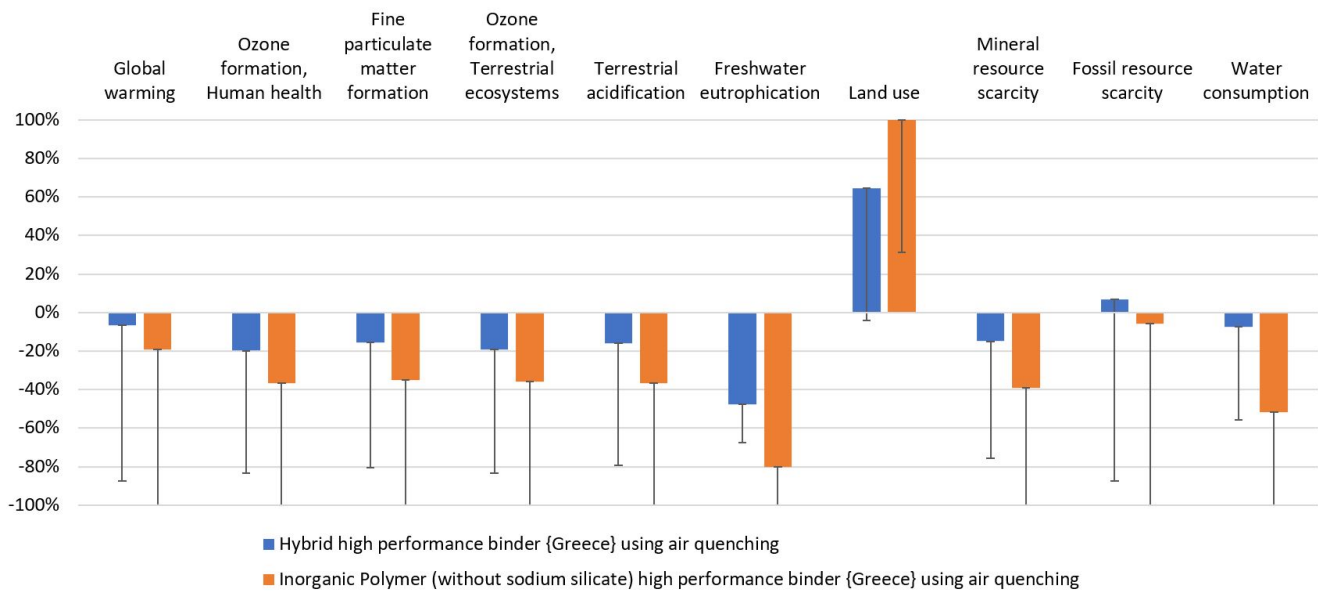
Midpoint comparison of inorganic polymer and hybrid high performance binder (Greece) based on *per tonne product*.**No sodium silicate included!**

C   Concrete sensitivity midpoint comparison

Impact category	Unit	Lightweight concrete block, pumice [DE] production | APOS, U	Lean concrete {RoW} production, with cement CEM II/B | APOS, U	foundation {RoW} concrete production, for civil engineering, with cement CEM II/B | APOS, U	Concrete, normal {RoW} unreinforced concrete production, with cement CEM II/B | APOS, U	Concrete, high exacting requirements {RoW} concrete production, for building construction, with cement CEM II/B | APOS, U	Concrete block [DE] production | APOS, U	Autoclaved aerated concrete block {RoW} production | APOS, U	Min	Average	Max
(mass or volume)	kg or m3(-4)	1 kg	4.44444 m	4.16667 m3	4.21941 m3	4.13223 m3	1 kg	1 kg	Not lightweight & autoclave		
Global warming	kg CO2 eq	0.227169	0.061518	0.11874186	0.073631959	0.098638409	0.108213	0.466196	0.061518	0.09013	0.118742
Stratospheric ozone depletion	kg CFC11 eq	3.37E-08	1.12E-08	1.66E-08	1.23E-08	1.46E-08	2.45E-08	7.94E-08	1.12E-08	1.79E-08	2.45E-08
Ionizing radiation	kBq Co-60	0.009224	1.34E-03	1.95E-03	1.45E-03	1.69E-03	0.002812	0.011788	0.001335	0.002074	0.002812
Ozone formation, Human health	kg NOx eq	0.000452	0.000152	0.00024487	0.00017089	0.000212003	0.000299	0.000735	0.000152	0.000226	0.000299
Fine particulate matter formation	kg PM2.5 eq	0.00018	6.25E-05	9.96E-05	6.98E-05	8.61E-05	0.000125	0.000382	6.25E-05	9.38E-05	0.000125
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.000458	0.000154	0.00024798	0.000173225	0.000214768	0.000304	0.000746	0.000154	0.000229	0.000304
Terrestrial acidification	kg SO2 eq	0.000441	0.000142	0.00023139	0.000159833	0.000199475	0.000275	0.000808	0.000142	0.000209	0.000275
Freshwater eutrophication	kg P eq	4.37E-05	9.54E-06	1.50E-05	1.06E-05	1.29E-05	2.35E-05	6.45E-05	9.54E-06	1.65E-05	2.35E-05
Marine eutrophication	kg N eq	3.05E-06	6.26E-07	9.80E-07	6.94E-07	8.45E-07	1.58E-06	4.78E-06	6.26E-07	1.1E-06	1.58E-06
Terrestrial ecotoxicity	kg 1,4-DCB	0.384295	0.144441	0.18373883	0.1505523	0.16887551	0.407289	0.63062	0.144441	0.275865	0.407289
Freshwater ecotoxicity	kg 1,4-DCB	0.003057	0.000825	0.00114457	0.000879937	0.00102056	0.002491	0.00428	0.000825	0.001658	0.002491
Marine ecotoxicity	kg 1,4-DCB	0.004386	0.001204	0.00166066	0.001282057	0.001483739	0.003631	0.006224	0.001204	0.002418	0.003631
Human carcinogenic toxicity	kg 1,4-DCB	0.006942	0.001297	0.00180678	0.001388425	0.001610668	0.005886	0.00966	0.001297	0.003591	0.005886
Human non-carcinogenic toxicity	kg 1,4-DCB	0.094813	0.026549	0.0361531	0.028148818	0.03244499	0.081308	0.1261	0.026549	0.053929	0.081308
Land use	m2a crop eq	0.017441	0.001084	0.00135071	0.001121897	0.001250366	0.00434	0.006741	0.001084	0.002712	0.00434
Mineral resource scarcity	kg Cu eq	0.018891	0.000313	0.0006065	0.000375432	0.000503908	0.000741	0.001787	0.000313	0.000527	0.000741
Fossil resource scarcity	kg oil eq	0.025555	0.008677	0.01386702	0.009704682	0.01198041	0.017768	0.064984	0.008677	0.013223	0.017768
Water consumption	m3	0.001713	0.001452	0.00144985	0.001443385	0.001446515	0.001635	0.001908	0.001443	0.001539	0.001635

D   Break-even transport distances and per product impacts

D.1 P_i values - impacts for *per tonne product*

Unit	Impact category	De-alkalization	Soil stabilization, additives excluded	Soil stabilization	High performance binder (Greece) min quality	High performance binder (Greece) max quality	High performance binder (Romania) min quality	High performance binder (Romania) max quality	Inorganic poylymer min quality	Inorganic poylymer max quality
kg CO2 eq	Global warming	165.4532	-12.8649	-376.4462	-4.6840	-61.9078	-6.3092	-63.5330	18.7905	-38.4333
kg NOx eq	Ozone formation, Human health	0.0130	-0.0904	-0.5608	-0.0459	-0.1929	-0.0483	-0.1953	-0.0052	-0.1522
kg PM2.5 eq	Fine particulate matter formation	0.0317	-0.0319	-0.5830	-0.0149	-0.0775	-0.0160	-0.0786	0.0330	-0.0296
kg NOx eq	Ozone formation, Terrestrial ecosystems	0.0135	-0.0925	-0.5765	-0.0449	-0.1950	-0.0471	-0.1972	-0.0032	-0.1533
kg SO2 eq	Terrestrial acidification	0.1101	-0.0629	-1.9088	-0.0335	-0.1665	-0.0363	-0.1693	0.0484	-0.0845
kg P eq	Freshwater eutrophication	-0.3088	-0.3321	-0.3999	-0.0335	-0.0475	-0.0398	-0.0538	-0.0381	-0.0521
m2a crop eq	Land use	-2.2757	-4.1707	-9.3569	3.0604	-0.1952	3.6372	0.3816	5.6331	2.3775
kg Cu eq	Mineral resource scarcity	-8.4377	-0.0511	-0.0927	-0.1049	-0.5324	-0.1054	-0.5330	-0.1218	-0.5493
kg oil eq	Fossil resource scarcity	14.3744	-7.7880	-79.0367	0.6686	-8.4220	1.0909	-7.9997	8.0647	-1.0259
m3	Water consumption	0.7499	-0.4879	-0.8231	-0.0296	-0.2207	-0.0462	-0.2373	0.4724	0.2813

D.2   Impacts from 1tkm use of a truck

Impact category	De-alkalization	Soil stabilization, additives excluded	Soil stabilization	High performance binder (Greece) min quality	High performance binder (Greece) max quality	High performance binder (Romania) min quality	High performance binder (Romania) max quality	Inorganic poylymer min quality	Inorganic poylymer max quality
Global warming	0.0	143.1	4186.9	52.1	688.6	70.2	706.6	0.0	427.5
Ozone formation, Human health	0.0	221.6	1374.4	112.4	472.8	118.3	478.7	12.7	373.1
Fine particulate matter formation	0.0	261.2	4776.4	122.4	635.3	131.0	643.9	0.0	242.1
Ozone formation, Terrestrial ecosystems	0.0	221.1	1378.6	107.4	466.3	112.7	471.6	7.6	366.5
Terrestrial acidification	0.0	234.1	7103.7	124.7	619.6	135.0	629.9	0.0	314.6
Freshwater eutrophication	43881.7	47199.6	56834.3	4756.5	6745.4	5651.3	7640.2	5412.6	7401.5
Land use	336.3	616.3	1382.8	0.0	28.8	0.0	0.0	0.0	0.0
Mineral resource scarcity	59689.0	361.5	655.7	742.0	3766.4	745.8	3770.2	861.6	3886.0
Fossil resource scarcity	0.0	238.4	2419.2	0.0	257.8	0.0	244.9	0.0	31.4
Water consumption	0.0	1682.5	2838.4	102.1	761.2	159.3	818.4	0.0	0.0
Minimum distance	0.0	143.1	655.7	0.0	28.8	0.0	0.0	0.0	0.0
Minimum distance (not 0)	336.3	143.1	655.7	52.1	28.8	70.2	244.9	7.6	31.4

D.3   Impacts from 1tkm use of a barge

Impact category	De-alkalization	Soil stabilization, additives excluded	Soil stabilization	High performance binder (Greece) min quality	High performance binder (Greece) max quality	High performance binder (Romania) min quality	High performance binder (Romania) max quality	Inorganic poylymer min quality	Inorganic poylymer max quality
Global warming	0.0	282.1	8254.2	102.7	1357.4	138.3	1393.1	0.0	842.7
Ozone formation, Human health	0.0	175.2	1086.1	88.8	373.6	93.5	378.3	10.0	294.8
Fine particulate matter formation	0.0	349.7	6394.2	163.9	850.5	175.4	862.0	0.0	324.1
Ozone formation, Terrestrial ecosystems	0.0	177.4	1106.4	86.2	374.3	90.4	378.5	6.1	294.2
Terrestrial acidification	0.0	250.5	7599.6	133.4	662.8	144.4	673.9	0.0	336.6
Freshwater eutrophication	51647.4	55552.4	66892.2	5598.2	7939.1	6651.4	8992.3	6370.4	8711.4
Land use	1054.8	1933.2	4337.2	0.0	90.5	0.0	0.0	0.0	0.0
Mineral resource scarcity	58300.2	353.1	640.5	724.8	3678.8	728.5	3682.5	841.5	3795.5
Fossil resource scarcity	0.0	579.8	5884.0	0.0	627.0	0.0	595.6	0.0	76.4
Water consumption	0.0	2534.4	4275.6	153.8	1146.7	240.0	1232.8	0.0	0.0
Minimum distance	0.0	175.2	640.5	0.0	90.5	0.0	0.0	0.0	0.0
Minimum distance (not 0)	1054.8	175.2	640.5	86.2	90.5	90.4	378.3	6.1	76.4

D.4　Impacts from 1tkm use of a ship

Impact category	De-alkalization	Soil stabilization, additives excluded	Soil stabilization	High performance binder (Greece) min quality	High performance binder (Greece) max quality	High performance binder (Romania) min quality	High performance binder (Romania) max quality	Inorganic poylymer min quality	Inorganic poylymer max quality
Global warming	0.0	1130.7	33087.3	411.7	5441.3	554.5	5584.2	0.0	3378.1
Ozone formation, Human health	0.0	615.6	3817.5	312.3	1313.3	328.5	1329.5	35.2	1036.2
Fine particulate matter formation	0.0	513.0	9381.4	240.4	1247.8	257.4	1264.7	0.0	475.5
Ozone formation, Terrestrial ecosystems	0.0	624.5	3894.4	303.5	1317.3	318.2	1332.1	21.5	1035.4
Terrestrial acidification	0.0	331.7	10064.9	176.6	877.9	191.3	892.5	0.0	445.8
Freshwater eutrophication	202007.4	217280.9	261633.8	21896.1	31052.1	26015.5	35171.4	24916.6	34072.6
Land use	29852.8	54712.7	122747.8	0.0	2560.9	0.0	0.0	0.0	0.0
Mineral resource scarcity	609971.5	3693.9	6701.1	7583.1	38489.9	7621.6	38528.3	8804.4	39711.2
Fossil resource scarcity	0.0	2160.8	21928.6	0.0	2336.7	0.0	2219.5	0.0	284.6
Water consumption	0.0	14488.4	24442.2	879.3	6555.1	1371.9	7047.7	0.0	0.0
Minimum distance	0.0	331.7	3817.5	0.0	877.9	0.0	0.0	0.0	0.0
Minimum distance (not 0)	29852.8	331.7	3817.5	176.6	877.9	191.3	892.5	21.5	284.6

E   LCIA results

De-alkalization Endpoint

Impact category	Unit	Total	Bauxite residue, remediation and utilization (RO) | de-alkalization	Steam, in chemical industry [RER] production | APOS, U	Quicklime, milled, packed [RER] market for quicklime, milled, packed | APOS, U	Tap water [RER] market group for | APOS, U	Electricity, medium voltage [RER] market group for | APOS, U	Clay [RoW] market for clay | APOS, U	Redmud from bauxite digestion [GLO] market for | APOS, U
Global warming, Human health	DALY	0.00023	0	3.17E-05	0.000212	3.72E-07	1.32E-05	-1.2E-05	-1.5E-05
Stratospheric ozone depletion	DALY	1.14E-08	0	4.12E-09	1.16E-08	1.02E-10	4.11E-09	-2.9E-09	-5.7E-09
Ionizing radiation	DALY	1.03E-07	0	7.55E-09	3.79E-08	1.09E-09	6.42E-08	-3.3E-09	-4.5E-09
Ozone formation, Human health	DALY	1.78E-08	0	3.68E-08	1.23E-07	8.69E-10	2.55E-08	-6.9E-08	-9.9E-08
Fine particulate matter formation	DALY	2.99E-05	0	1.63E-05	3.89E-05	4.49E-07	1.47E-05	-1.8E-05	-2.2E-05
Human carcinogenic toxicity	DALY	-0.006629	0	1.08E-06	1.57E-06	4.29E-07	2.88E-06	-8.2E-06	-0.00663
Human non-carcinogenic toxicity	DALY	-8.88E-05	0	9.82E-07	1.91E-06	8.27E-08	2.95E-06	-7E-06	-8.8E-05
Water consumption, Human health	DALY	1.75E-06	0	5.87E-08	1.51E-07	2.45E-06	2.38E-07	-1.5E-07	-1E-06
Global warming, Terrestrial ecosystems	species.yr	6.95E-07	0	9.58E-08	6.38E-07	1.12E-09	3.99E-08	-3.5E-08	-4.6E-08
Global warming, Freshwater ecosystems	species.yr	1.9E-11	0	2.62E-12	1.74E-11	3.07E-14	1.09E-12	-9.5E-13	-1.2E-12
Ozone formation, Terrestrial ecosystems	species.yr	2.62E-09	0	5.33E-09	1.79E-08	1.26E-10	3.64E-09	-9.9E-09	-1.4E-08
Terrestrial acidification	species.yr	3.5E-08	0	1.64E-08	3.65E-08	3.49E-10	1.31E-08	-1.4E-08	-1.8E-08
Freshwater eutrophication	species.yr	-3.1E-07	0	2.39E-09	2.1E-09	2.03E-10	1E-08	-3.9E-09	-3.2E-07
Marine eutrophication	species.yr	2.09E-12	0	4.13E-13	6.19E-13	4.02E-14	1.84E-12	-5.5E-13	-2.8E-13
Terrestrial ecotoxicity	species.yr	-1.23E-09	0	5.41E-10	6.77E-10	1.16E-11	1.59E-10	-1.6E-09	-9.8E-10
Freshwater ecotoxicity	species.yr	-8.98E-08	0	1.02E-10	2.03E-10	1.13E-11	3.89E-10	-6.3E-10	-9E-08
Marine ecotoxicity	species.yr	-1.94E-08	0	2.72E-11	4.68E-11	2.38E-12	7.99E-11	-1.4E-10	-1.9E-08
Land use	species.yr	-3.03E-08	0	3.03E-09	2.23E-08	1.17E-10	4.97E-09	-8.9E-09	-5.2E-08
Water consumption, Terrestrial ecosystem	species.yr	1.05E-08	0	3.28E-10	1.08E-09	1.49E-08	1.21E-09	-9.1E-10	-6.1E-09
Water consumption, Aquatic ecosystems	species.yr	4.56E-13	0	1.55E-14	4.88E-14	6.66E-13	5.27E-14	-4.9E-14	-2.8E-13
Mineral resource scarcity	USD2013	-2.932817	0	0.002206	0.008129	0.000961	0.004847	-2.94132	-0.00764
Fossil resource scarcity	USD2013	7.782524	0	3.643958	9.417437	0.019633	0.584265	-1.30627	-4.5765

De-alkalization Midpoint

Impact category	Unit	Total	Bauxite residue, remediation and utilization (RO) | de-alkalization	Steam, in chemical industry [RER] production | APOS, U	Quicklime, milled, packed [RER] market for quicklime, milled, packed | APOS, U	Tap water [RER] market group for | APOS, U	Electricity, medium voltage [RER] market group for | APOS, U	Clay [RoW] market for clay | APOS, U	Redmud from bauxite digestion [GLO] market for | APOS, U
Global warming	kg CO2 eq	248.1797	0	34.2016	228.0141	0.401052	14.25789	-12.4342	-16.2608
Stratospheric ozone depletion	kg CFC11 eq	2.15E-05	0	7.76E-06	2.19E-05	1.93E-07	7.75E-06	-5.50E-06	-1.07E-05
Ionizing radiation	kBq Co-60 eq	12.12442	0	0.890081	4.460749	0.128994	7.566187	-0.3866	-0.53499
Ozone formation, Human health	kg NOx eq	0.019511	0	0.040397	0.13491	0.000955	0.027967	-0.07551	-0.10921
Fine particulate matter formation	kg PM2.5 eq	0.047585	0	0.026003	0.061995	0.000714	0.023432	-0.02908	-0.03548
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.020311	0	0.041291	0.138606	0.000976	0.028202	-0.07711	-0.11165
Terrestrial acidification	kg SO2 eq	0.1652	0	0.077144	0.172186	0.001646	0.061754	-0.06492	-0.08261
Freshwater eutrophication	kg P eq	-0.463192	0	0.00357	0.003134	0.000303	0.015005	-0.0059	-0.47931
Marine eutrophication	kg N eq	0.001227	0	2.43E-04	0.000364	2.37E-05	0.001084	-0.00032	-0.00016
Terrestrial ecotoxicity	kg 1,4-DCB	-107.3595	0	47.46684	59.32708	1.013937	13.91404	-143.291	-85.7908
Freshwater ecotoxicity	kg 1,4-DCB	-128.9915	0	0.147304	0.29286	0.016303	0.56225	-0.9045	-129.106
Marine ecotoxicity	kg 1,4-DCB	-184.5163	0	0.258918	0.445394	0.022689	0.760568	-1.32187	-184.682
Human carcinogenic toxicity	kg 1,4-DCB	-1996.642	0	0.324434	0.473592	0.129335	0.868296	-2.46746	**-1995.97**

Human non-carcinogenic toxicity	kg 1,4-DCB	-389.482	0	4.306786	8.383451	0.362445	12.92448	-30.8763	**-384.583**
Land use	m2a crop eq	-3.413478	0	0.341335	2.515687	0.013224	0.560195	-1.0037	-5.84022
Mineral resource scarcity	kg Cu eq	-12.65659	0	0.009561	0.03526	0.004181	0.020977	-12.6935	-0.0331
Fossil resource scarcity	kg oil eq	21.56164	0	10.60484	21.30322	0.100329	3.741064	-3.49168	-10.6961
Water consumption	m3	1.12482	0	0.044765	0.280503	1.106619	0.238113	-0.07846	-0.46672

Soil stabilization Endpoint

Impact category	Unit	Total	Bauxite residue, remediation and utilization (IR)| Soil Stabilizer (Gravel replacement)	Ground granulated blast furnace slag (GLO)| market for	APOS, U	Quicklime, milled, packed (RER)| market for quicklime, milled, packed	APOS, U	Electricity, medium voltage (RER)| market group for	APOS, U	Gravel, crushed (RoW)| production	APOS, U	Redmud from bauxite digestion (GLO)| market for	APOS, U	Fly ash and scrubber sludge {Europe without Switzerland}| treatment of fly ash and scrubber sludge, hazardous waste incineration	APOS, U
Global warming, Human health	DALY	-0.000621	0	4.05E-06	2.12E-05	7.84E-06	-9.83E-06	-1.51E-05	-0.00063
Stratospheric ozone depletion	DALY	-1.41E-07	0	1.02E-09	1.16E-09	2.44E-09	-2.30E-09	-5.65E-09	-1.37E-07
Ionizing radiation	DALY	-1.97E-08	0	1.47E-09	3.79E-08	3.80E-08	-8.06E-09	-4.53E-09	-5.04E-08
Ozone formation, Human health	DALY	-9.08E-07	0	1.09E-08	1.23E-08	1.51E-08	-3.35E-08	-9.92E-08	-8.13E-07
Fine particulate matter formation	DALY	-0.000651	0	6.17E-06	3.89E-06	8.72E-06	-1.51E-05	-2.23E-05	-0.00063
Human carcinogenic toxicity	DALY	-0.006795	0	1.51E-06	1.57E-07	1.71E-06	-2.61E-06	-0.00661	-0.00018
Human non-carcinogenic toxicity	DALY	-0.00015	0	3.45E-06	1.91E-07	1.75E-06	-1.90E-06	-8.76E-05	-6.56E-05
Water consumption, Human health	DALY	-2.98E-06	0	7.07E-08	1.51E-08	1.41E-07	-7.71E-07	-9.95E-07	-1.44E-06
Global warming, Terrestrial ecosystems	species.yr	-1.88E-06	0	1.22E-08	6.38E-08	2.36E-08	-2.97E-08	-4.54E-08	-1.90E-06
Global warming, Freshwater ecosystems	species.yr	-5.12E-11	0	3.34E-13	1.74E-12	6.46E-13	-8.10E-13	-1.24E-12	-5.19E-11
Ozone formation, Terrestrial ecosystems	species.yr	-1.32E-07	0	1.63E-09	1.79E-09	2.15E-09	-4.82E-09	-1.44E-08	-1.19E-07
Terrestrial acidification	species.yr	-7.2E-07	0	4.52E-09	3.65E-09	7.76E-09	-9.33E-09	-1.75E-08	-7.09E-07
Freshwater eutrophication	species.yr	-4.76E-07	0	2.17E-09	2.10E-10	5.95E-09	-3.33E-09	-3.20E-07	-1.61E-07
Marine eutrophication	species.yr	-2.89E-11	0	4.62E-13	6.19E-14	1.09E-12	-5.38E-13	-2.77E-13	-2.97E-11
Terrestrial ecotoxicity	species.yr	-8.71E-09	0	3.90E-10	6.77E-11	9.40E-11	-2.59E-10	-9.77E-10	-8.02E-09
Freshwater ecotoxicity	species.yr	-9.75E-08	0	5.01E-10	2.03E-11	2.31E-10	-2.07E-10	-8.97E-08	-8.33E-09
Marine ecotoxicity	species.yr	-2.1E-08	0	1.02E-10	4.68E-12	4.73E-11	-4.41E-11	-1.94E-08	-1.73E-09
Land use	species.yr	-1.48E-07	0	9.61E-10	2.23E-09	2.94E-09	-4.09E-09	-5.17E-08	-9.80E-08
Water consumption, Terrestrial ecosystem	species.yr	-1.84E-08	0	4.99E-10	1.08E-10	7.15E-10	-4.70E-09	-6.06E-09	-8.94E-09
Water consumption, Aquatic ecosystems	species.yr	-1.27E-12	0	2.54E-14	4.88E-15	3.12E-14	-2.28E-13	-2.78E-13	-8.29E-13
Mineral resource scarcity	USD2013	-0.037992	0	0.04847	0.000813	0.002871	-0.0121	-0.00763	-0.07042
Fossil resource scarcity	USD2013	-28.18351	0	0.201796	0.941744	0.346086	-0.63415	-4.56785	-24.4711

Soil stabilization Midpoint

Impact category	Unit	Total	Bauxite residue, remediation and utilization (IR)	Soil Stabilizer (Gravel replacement)	Ground granulated blast furnace slag (GLO)| market for	APOS, U	Quicklime, milled, packed (RER)| market for quicklime, milled, packed	APOS, U	Electricity, medium voltage (RER)| market group for	APOS, U	Gravel, crushed (RoW)| production	APOS, U	Redmud from bauxite digestion (GLO)| market for	APOS, U	Fly ash and scrubber sludge {Europe without Switzerland}| treatment of fly ash and scrubber sludge, hazardous waste incineration	APOS, U
Global warming	kg CO2 eq	-663.948	0	4.361028	22.80141	8.44559	-10.594	-16.23	-678.32
Stratospheric ozone depletion	kg CFC11 eq	-0.000262	0	1.92E-06	2.19E-06	4.59E-06	-4.33E-06	-1.07E-05	-0.00026
Ionizing radiation	kBq Co-60 eq	-2.196768	0	0.173847	0.446075	4.481794	-0.94994	-0.53398	-5.9357
Ozone formation, Human health	kg NOx eq	-0.972013	0	0.011958	0.013491	0.016566	-0.03676	-0.109	-0.89363
Fine particulate matter formation	kg PM2.5 eq	-1.029334	0	0.009826	0.0062	0.01388	-0.02401	-0.03542	-1.0074
Ozone formation, Terrestrial ecosystems	kg NOx eq	-0.999335	0	0.012641	0.013861	0.016705	-0.03733	-0.11144	-0.91976
Terrestrial acidification	kg SO2 eq	-3.378187	0	0.021309	0.017219	0.036579	-0.044	-0.08246	-3.34354
Freshwater eutrophication	kg P eq	-0.710887	0	0.00324	0.000313	0.008888	-0.00497	-0.4784	-0.24039
Marine eutrophication	kg N eq	-0.016984	0	0.000272	3.64E-05	0.000642	-0.00032	-0.00016	-0.01749
Terrestrial ecotoxicity	kg 1,4-DCB	-662.6061	0	34.17935	5.932708	8.24191	-22.7168	-85.6287	-703.839
Freshwater ecotoxicity	kg 1,4-DCB	-140.0333	0	0.724437	0.029286	0.333046	-0.29904	-128.862	-12.0264
Marine ecotoxicity	kg 1,4-DCB	-199.6583	0	0.966548	0.044539	0.450519	-0.41964	-184.333	-16.5065
Human carcinogenic toxicity	kg 1,4-DCB	-2046.717	0	0.455244	0.047359	0.514331	-0.78519	-1992.2	-54.8528
Human non-carcinogenic toxicity	kg 1,4-DCB	-653.1713	0	15.10484	0.838345	7.655751	-8.31586	-383.856	-287.446
Land use	m2a crop eq	-16.2214	0	0.108385	0.251569	0.331829	-0.46079	-5.82918	-11.0438
Mineral resource scarcity	kg Cu eq	-0.15608	0	0.20987	0.003526	0.012426	-0.05238	-0.03304	-0.30526
Fossil resource scarcity	kg oil eq	-138.5418	0	0.904763	2.130322	2.216001	-2.66585	-10.6759	-132.482
Water consumption	m3	-1.445839	0	0.090749	0.02805	0.141045	-0.37217	-0.46584	-0.8857

Hybrid high performance binder Endpoint (GREECE)

Impact category	Unit	Total	Bauxite residue, remediation and utilization (GR)	High Performance Binder - Hybrid, air quenching, Rotary Kiln, lean concrete substituted, truck transport	Charcoal (GLO)| production	APOS, U	Silica sand (GLO)| market for	APOS, U	Limestone, crushed, for mill (RoW)| market for limestone, crushed, for mill	APOS, U	Natural gas, high pressure {Europe without Switzerland}| market group for	APOS, U	Tap water (RER)| market group for	APOS, U	Sodium hydroxide, without water, in 50% solution state (GLO)| market for	APOS, U	Plasticiser, for concrete, based on sulfonated melamine formaldehyde (GLO)| market for	APOS, U	Ground granulated blast furnace slag (GLO)| market for	APOS, U	Cement, Portland {Europe without Switzerland}| market for	APOS, U	Sand (GLO)| market for	APOS, U	Gravel, round (RoW)| market for gravel, round	APOS, U	Electricity, medium voltage (RER)| market group for	APOS, U	Redmud from bauxite digestion (GLO)| market for	APOS, U	Lean concrete (RoW)| production, with cement CEM II/B	APOS, U
Global warming, Human health	DALY	7.48E-04	2.46E-04	3.81E-05	1.08E-05	1.30E-06	1.64E-05	2.26E-07	3.78E-05	1.49E-05	1.88E-05	2.28E-04	5.30E-05	7.04E-05	2.73E-05	-1.51E-05	-8.10E-04
Stratospheric ozone depletion	DALY	9.73E-08	0.00E+00	1.76E-09	1.99E-09	1.98E-09	1.20E-08	6.21E-11	2.32E-08	3.52E-09	4.72E-09	1.22E-08	1.42E-08	1.88E-08	8.47E-09	-5.65E-09	-8.45E-08
Ionizing radiation	DALY	3.08E-07	0.00E+00	2.28E-09	2.09E-09	2.96E-10	1.61E-09	6.64E-10	4.02E-08	8.05E-09	6.83E-09	6.90E-08	2.19E-08	2.77E-08	1.32E-07	-4.53E-09	-1.61E-07
Ozone formation, Human health	DALY	1.37E-06	0.00E+00	5.01E-08	4.25E-08	2.29E-08	3.52E-08	5.27E-10	9.37E-08	3.70E-08	5.04E-08	3.72E-07	3.08E-07	4.07E-07	5.24E-08	-9.92E-08	-1.97E-06
Fine particulate matter formation	DALY	4.24E-04	0.00E+00	1.49E-05	1.51E-05	6.18E-06	9.19E-06	2.72E-07	5.89E-05	1.98E-05	2.86E-05	8.65E-05	7.58E-05	1.01E-04	3.03E-05	-2.23E-05	-5.57E-04
Human carcinogenic toxicity	DALY	-6.56E-03	0.00E+00	6.26E-07	1.14E-06	1.72E-07	9.39E-07	2.60E-07	6.53E-06	1.75E-06	7.00E-06	7.95E-06	8.54E-06	1.13E-05	5.94E-06	-6.61E-03	-6.11E-05
Human non-carcinogenic toxicity	DALY	-1.53E-05	0.00E+00	7.75E-07	1.59E-06	1.20E-07	4.27E-07	5.01E-08	9.36E-06	3.05E-06	1.60E-05	1.03E-05	1.06E-05	1.40E-05	6.07E-06	-8.76E-05	-8.59E-05
Water consumption, Human health	DALY	4.17E-05	0.00E+00	1.09E-06	8.57E-07	9.07E-08	9.58E-09	1.48E-06	2.02E-06	6.63E-07	3.28E-07	1.06E-06	1.46E-05	2.00E-05	4.89E-07	-9.95E-07	-4.34E-05

Impact category	Unit															
Global warming, Terrestrial ecosystems	species.yr	2.26E-06	7.42E-07	1.15E-07	3.26E-08	3.91E-09	4.96E-08	6.81E-10	1.14E-07	4.50E-08	5.66E-08	6.89E-07	1.60E-07	2.12E-07	8.22E-08	-4.54E-08	-2.44E-06
Global warming, Freshwater ecosystems	species.yr	6.17E-11	2.03E-11	3.14E-12	8.91E-13	1.07E-13	1.35E-12	1.86E-14	3.12E-12	1.23E-12	1.55E-12	1.88E-11	4.37E-12	5.80E-12	2.25E-12	-1.24E-12	-6.67E-11
Ozone formation, Terrestrial ecosystems	species.yr	2.00E-07	0.00E+00	9.36E-09	6.12E-09	3.31E-09	5.31E-09	7.64E-11	1.34E-08	5.56E-09	7.56E-09	5.33E-08	4.44E-08	5.87E-08	7.49E-09	-1.44E-08	-2.82E-07
Terrestrial acidification	species.yr	3.27E-07	0.00E+00	6.16E-09	1.31E-08	3.39E-09	9.17E-09	2.12E-10	3.34E-08	1.50E-08	2.09E-08	8.24E-08	5.73E-08	7.60E-08	2.70E-08	-1.75E-08	-4.27E-07
Freshwater eutrophication	species.yr	-2.27E-07	0.00E+00	1.27E-09	1.94E-09	1.40E-10	4.74E-10	1.23E-10	1.58E-08	3.75E-09	1.01E-08	1.88E-08	8.57E-09	1.14E-08	2.07E-08	-3.20E-07	-9.06E-08
Marine eutrophication	species.yr	1.75E-11	0.00E+00	3.29E-13	3.18E-13	3.81E-14	8.21E-14	2.44E-14	3.70E-12	6.74E-13	2.14E-12	3.28E-12	1.45E-12	1.92E-12	3.79E-12	-2.77E-13	-1.51E-11
Terrestrial ecotoxicity	species.yr	1.67E-08	0.00E+00	2.57E-10	5.48E-10	2.38E-11	5.20E-11	7.01E-12	1.38E-09	5.07E-10	1.81E-09	2.14E-09	4.58E-09	6.05E-09	3.27E-10	-9.77E-10	-2.34E-08
Freshwater ecotoxicity	species.yr	-8.18E-08	0.00E+00	7.76E-11	1.43E-10	1.21E-11	4.27E-11	6.85E-12	9.92E-10	2.93E-10	2.32E-10	1.02E-09	9.59E-10	1.27E-09	8.02E-10	-8.97E-08	-8.10E-09
Marine ecotoxicity	species.yr	-1.77E-08	0.00E+00	1.73E-11	3.25E-11	2.68E-12	3.07E-11	1.45E-12	2.11E-10	6.36E-11	4.71E-10	2.22E-10	2.21E-10	2.93E-10	1.65E-10	-1.94E-08	-1.79E-09
Land use	species.yr	5.21E-07	0.00E+00	4.60E-07	4.67E-09	4.07E-10	3.24E-10	7.11E-11	7.50E-09	1.91E-09	4.45E-09	1.53E-08	2.94E-08	3.88E-08	1.02E-08	-5.17E-08	-1.36E-07
Water consumption, Terrestrial ecosystem	species.yr	2.54E-07	0.00E+00	6.65E-09	5.23E-09	5.52E-10	1.08E-11	9.02E-09	1.23E-08	4.04E-09	2.31E-09	6.24E-09	8.91E-08	1.22E-07	2.49E-09	-6.06E-09	-2.65E-07
Water consumption, Aquatic ecosystems	species.yr	1.16E-11	0.00E+00	3.09E-13	2.45E-13	2.59E-14	1.95E-15	4.04E-13	6.33E-13	1.97E-13	1.18E-13	2.85E-13	4.02E-12	5.49E-12	1.09E-13	-2.78E-13	-1.23E-11
Mineral resource scarcity	USD2013	6.83E-01	0.00E+00	2.02E-03	3.92E-03	9.31E-04	5.75E-03	5.83E-04	2.71E-02	9.05E-03	2.25E-01	3.09E-01	4.25E-02	5.60E-02	9.98E-03	-7.63E-03	-1.03E+00
Fossil resource scarcity	USD2013	4.23E+01	0.00E+00	6.32E-01	8.52E-01	1.60E-01	1.60E+01	1.19E-02	2.09E+00	2.87E+00	9.35E-01	6.41E+00	6.78E+00	8.96E+00	1.20E+00	-4.57E+00	-3.96E+01

Hybrid high performance binder Midpoint (GREECE)

Impact category	Unit	Min	Max	Bauxite residue, remediation and utilization (GR) | High Performance Binder - Hybrid, air quenching, Rotary Kiln, lean concrete substituted, truck transport	Charcoal {GLO}| production | APOS, U	Silica sand {GLO}| market for | APOS, U	Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill | APOS, U	Natural gas, high pressure {Europe without Switzerland}| market group for | APOS, U	Tap water {RER}| market group for | APOS, U	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | APOS, U	Plasticiser, for concrete, based on sulfonated melamine formaldehyde {GLO}| market for | APOS, U	Ground granulated blast furnace slag {GLO}| market for | APOS, U	Cement, Portland {Europe without Switzerland}| market for | APOS, U	Sand {GLO}| market for | APOS, U	Gravel, round {RoW}| market for gravel, round | APOS, U	Electricity, medium voltage {RER}| market group for | APOS, U	Redmud from bauxite digestion {GLO}| market for | APOS, U	Concrete minimum	Concrete maximum	Lean concrete {RoW}| production, with cement CEM II/B | APOS, U
Global warming	kg CO2 eq	-66.43258	-1750.55	265	41.00958	11.65322	1.397448	17.6955	0.243183	40.7347	16.07157	20.2061	245.9717	57.1163	75.84392	29.36467	-16.23	-872.5104748	-1684.12	-872.51
Stratospheric ozone depletion	kg CFC11 eq	0.000183	-0.00032	0	3.31E-06	3.74E-06	3.72E-06	2.26E-05	1.17E-07	4.38E-05	6.63E-06	8.88E-06	2.30E-05	2.69E-05	3.55E-05	1.60E-05	-1.07E-05	-0.000159332	-0.00035	-0.00016
Ionizing radiation	kBq Co-60 eq	36.32329	-22.4971	0	0.268987	0.246011	0.034917	0.189354	0.078217	4.733158	0.948323	0.80549	8.132387	2.576887	3.260686	15.58285	-0.53398	-18.93820958	-39.8821	-18.9382
Ozone formation, Human health	kg NOx eq	1.508725	-4.89539	0	0.055059	0.04671	0.025197	0.038658	0.000579	0.102977	0.040626	0.055404	0.409014	0.338395	0.447506	0.057599	-0.109	-2.159284453	-4.24483	-2.15928
Fine particulate matter formation	kg PM2.5 eq	0.67477	-1.98646	0	0.02364	0.024107	0.009827	0.014636	0.000433	0.09366	0.031559	0.045529	0.137663	0.120571	0.160302	0.04826	-0.03542	-0.886680894	-1.77455	-0.88668
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.552751	-4.95562	0	0.072564	0.047411	0.025644	0.041155	0.000592	0.104002	0.043138	0.058571	0.413351	0.344334	0.455348	0.058083	-0.11144	-2.189870801	-4.3185	-2.18987
Terrestrial acidification	kg SO2 eq	1.540579	-4.37691	0	0.029038	0.061821	0.015977	0.043238	0.000998	0.157601	0.070891	0.098734	0.388739	0.270338	0.358476	0.127184	-0.08246	-2.015690087	-3.9018	-2.01569
Freshwater eutrophication	kg P eq	-0.339409	-0.80854	0	0.001901	0.002901	0.00021	0.000708	0.000184	0.023559	0.005603	0.01501	0.028134	0.012797	0.017084	0.030903	-0.4784	-0.135310871	-0.33382	-0.13531
Marine eutrophication	kg N eq	0.010277	-0.02095	0	0.000193	0.000187	2.24E-05	4.83E-05	1.44E-05	0.002176	0.000397	0.001258	0.001928	0.000851	0.001131	0.002234	-0.00016	-0.008872408	-0.02236	-0.00887
Terrestrial ecotoxicity	kg 1,4-DCB	1464.367	-6360.82	0	22.57189	48.06725	2.084456	4.554073	0.614815	120.7928	44.40967	158.3643	187.6259	401.8631	530.3907	28.65649	-85.6287	-2048.610249	-5776.58	-2048.61
Freshwater ecotoxicity	kg 1,4-DCB	-117.3907	-164.42	0	0.112092	0.206838	0.017541	0.061603	0.009885	1.432999	0.422763	3.356557	1.472875	1.385791	1.83411	1.157975	-128.862	-11.69918993	-35.3302	-11.6992
Marine ecotoxicity	kg 1,4-DCB	-167.8602	-236.439	0	0.164345	0.30903	0.0255	0.292825	0.013758	2.010544	0.605531	4.478341	2.112522	2.106525	2.787372	1.566419	-184.333	-17.07425135	-51.5044	-17.0743
Human carcinogenic toxicity	kg 1,4-DCB	-1976.488	-2078.36	0	0.188516	0.343514	0.051755	0.282926	0.078424	1.966981	0.525624	2.109296	2.394875	2.571882	3.407554	1.788288	-1992.2	-18.39315122	-83.4805	-18.3932
Human non-carcinogenic toxicity	kg 1,4-DCB	-67.171	-1596.92	0	3.396668	6.982564	0.525403	1.872165	0.219773	41.03162	13.35353	69.98578	45.13461	46.30444	61.25992	26.61846	-383.856	-376.546949	-1153.2	-376.547
Land use	m2a crop eq	58.78316	-18.1466	0	51.87207	0.526475	0.045812	0.036536	0.008018	0.845755	0.214782	0.502185	1.728018	3.311756	4.367193	1.153743	-5.82918	-15.37788229	-61.5519	-15.3779
Mineral resource scarcity	kg Cu eq	2.955612	-11.9948	0	0.00877	0.017319	0.00405	0.024926	0.002535	0.117431	0.039274	0.972397	1.332234	0.183935	0.242578	0.043203	-0.03304	-4.443368101	-10.5071	-4.44337
Fossil resource scarcity	kg oil eq	132.5536	-242.521	0	1.966116	2.903566	0.404039	44.68274	0.060836	10.27624	8.30153	4.192069	21.22075	17.8506	23.66614	7.704863	-10.6759	-123.0712848	-252.003	-123.071
Water consumption	m3	20.05158	-23.6022	0	0.502696	0.410169	0.0419	0.011909	0.671014	1.031319	0.323155	0.420469	0.627596	6.894315	9.092475	0.490403	-0.46584	-20.47152378	-23.1823	-20.5889

Hybrid high performance binder Midpoint (ROMANIA)

Impact category	Unit	Min	Max	Bauxite residue, remediation and utilization (RO) | High Performance Binder - Hybrid, air quenching, Rotary Kiln, lean concrete substituted, truck transport	Charcoal {GLO}| production | APOS, U	Silica sand {GLO}| market for | APOS, U	Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill | APOS, U	Natural gas, high pressure {Europe without Switzerland}| market group for | APOS, U	Tap water {RER}| market group for | APOS, U	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | APOS, U	Plasticiser, for concrete, based on sulfonated melamine formaldehyde {GLO}| market for | APOS, U	Ground granulated blast furnace slag {GLO}| market for | APOS, U	Cement, Portland {Europe without Switzerland}| market for | APOS, U	Sand {GLO}| market for | APOS, U	Gravel, round {RoW}| market for gravel, round | APOS, U	Electricity, medium voltage {RER}| market group for | APOS, U	Redmud from bauxite digestion {GLO}| market for | APOS, U	Concrete minimum	Concrete maximum
Global warming	kg CO2 eq	-75.55908	-1497.61	203	41.00958	4.120721	0.926437	18.05501	0.20563	34.38285	13.61998	17.08069	207.9257	48.22651	64.04091	24.81704	-16.23	-736.7401428	-1422.05
Stratospheric ozone depletion	kg CFC11 eq	0.000155	-0.00027	0	3.31E-06	1.32E-06	2.47E-06	2.30E-05	9.89E-08	3.69E-05	5.62E-06	7.51E-06	1.94E-05	2.27E-05	3.00E-05	1.35E-05	-1.07E-05	-0.000134539	-0.00029
Ionizing radiation	kBq Co-60 eq	30.5573	-19.1101	0	0.268987	0.086993	0.023148	0.193201	0.066139	3.995107	0.803664	0.6809	6.874499	2.175811	2.753251	13.16958	-0.53398	-15.99125699	-33.6761
Ozone formation, Human health	kg NOx eq	1.245415	-4.16216	0	0.055059	0.016517	0.016704	0.039444	0.00049	0.08692	0.034429	0.046834	0.345749	0.285726	0.377864	0.048679	-0.109	-1.823280731	-3.5843
Fine particulate matter formation	kg PM2.5 eq	0.557165	-1.68996	0	0.02364	0.008525	0.006515	0.014934	0.000366	0.079056	0.026745	0.038486	0.11637	0.101805	0.135355	0.040786	-0.03542	-0.74870552	-1.49841
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.284963	-4.21065	0	0.072564	0.016765	0.017001	0.041991	0.000501	0.087785	0.036558	0.049512	0.349416	0.290741	0.384486	0.049088	-0.11144	-1.849107574	-3.6465
Terrestrial acidification	kg SO2 eq	1.267609	-3.72907	0	0.029038	0.021861	0.010592	0.044116	0.000844	0.133026	0.060077	0.083462	0.32861	0.228262	0.302689	0.107487	-0.08246	-1.702030916	-3.29465
Freshwater eutrophication	kg P eq	-0.362007	-0.75813	0	0.001901	0.001026	0.000139	0.000722	0.000155	0.019886	0.004748	0.012688	0.023783	0.010806	0.014425	0.026117	-0.4784	-0.114255305	-0.28187
Marine eutrophication	kg N eq	0.008601	-0.01777	0	0.000193	6.61E-05	1.49E-05	4.93E-05	1.21E-05	0.001837	0.000336	0.001064	0.00163	0.000718	0.000955	0.001888	-0.00016	-0.007491783	-0.01888
Terrestrial ecotoxicity	kg 1,4-DCB	1203.939	-5403.58	0	22.57189	16.99717	1.381889	4.646594	0.519873	101.9573	37.63532	133.8691	158.6047	339.3157	447.8501	24.21854	-85.6287	-1729.82841	-4877.69
Freshwater ecotoxicity	kg 1,4-DCB	-119.246	-158.957	0	0.112092	0.073141	0.011629	0.062854	0.008359	1.209549	0.358273	2.837377	1.245056	1.170101	1.548682	0.978642	-128.862	-9.878692701	-29.8325
Marine ecotoxicity	kg 1,4-DCB	-170.4943	-228.402	0	0.164345	0.109277	0.016905	0.298774	0.011633	1.697036	0.513161	3.785648	1.785765	1.778658	2.353595	1.323832	-184.333	-14.41734712	-43.4898
Human carcinogenic toxicity	kg 1,4-DCB	-1979.025	-2065.05	0	0.188516	0.121471	0.034311	0.288674	0.066313	1.660265	0.445444	1.783038	2.024445	2.171585	2.877262	1.511341	-1992.2	-15.53101452	-70.4902
Human non-carcinogenic toxicity	kg 1,4-DCB	-118.9617	-1410.66	0	3.396668	2.46912	0.348315	1.9102	0.185835	34.63347	11.31655	59.16064	38.15336	39.09745	51.7265	22.49613	-383.856	-317.9529198	-973.75
Land use	m2a crop eq	56.54355	-8.41523	0	51.87207	0.186168	0.030371	0.037278	0.00678	0.713874	0.182019	0.424509	1.460734	2.796302	3.68756	0.975066	-5.82918	-12.98494806	-51.9738
Mineral resource scarcity	kg Cu eq	2.489323	-10.1347	0	0.00877	0.006124	0.002685	0.025432	0.002144	0.09912	0.033283	0.82199	1.126169	0.155307	0.204828	0.036512	-0.03304	-3.751940801	-8.87207
Fossil resource scarcity	kg oil eq	116.9849	-199.724	0	1.966116	1.026736	0.267857	45.59051	0.051441	8.673844	7.035195	3.543655	17.9384	15.07226	19.98316	6.511632	-10.6759	-103.9203065	-212.789
Water consumption	m3	16.73274	-20.1281	0	0.502696	0.145041	0.027777	0.012151	0.567394	0.870503	0.27386	0.355433	0.530522	5.821258	7.677483	0.414456	-0.46584	-17.28597397	-19.5749

Lesser processes table

What has and hasn't been aggregated into one process category for hybrid high performance binder figures

Significant	Lesser
Concrete	Water
BR	Silica sand
cement	Plasticiser
Gravel	Limestone
Direct emissions	GGBFS
Methane	Sodium hydroxide
Charcoal	

Inorganic binder (GREECE) Endpoint

Impact category	Unit	Total	Bauxite residue, remediation and utilization (GR) | High Performance Binder - Inorganic Polymer, air quenching, Rotary Kiln	Charcoal {GLO}| production | APOS, U	Silica sand {GLO}| market for | APOS, U	Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill | APOS, U	Natural gas, high pressure {Europe without Switzerland}| market group for | APOS, U	Sodium silicate, without water, in 48% solution state {RER}| market for sodium silicate, without water, in 48% solution state | APOS, U	Sand {GLO}| market for | APOS, U	Gravel, round {RoW}| market for gravel, round | APOS, U	Electricity, medium voltage {RER}| market group for | APOS, U	Redmud from bauxite digestion {GLO}| market for | APOS, U	Lean concrete {RoW}| production, with cement CEM II/B | APOS, U
Global warming, Human health	DALY	0.000158	0.000246	3.81E-05	1.08E-05	9.01E-07	1.64E-05	0.00027	3.39E-05	4.50E-05	2.73E-05	-1.51E-05	-0.00052
Stratospheric ozone depletion	DALY	1.19E-07	0	1.76E-09	1.99E-09	1.37E-09	1.20E-08	1.32E-07	9.12E-09	1.21E-08	8.47E-09	-5.65E-09	-5.39E-08
Ionizing radiation	DALY	3.20E-07	0	2.28E-09	2.09E-09	2.06E-10	1.61E-09	2.57E-07	1.40E-08	1.77E-08	1.32E-07	-4.53E-09	-1.02E-07
Ozone formation, Human health	DALY	-4.25E-08	0	5.01E-08	4.25E-08	1.59E-08	3.52E-08	6.55E-07	1.97E-07	2.61E-07	5.24E-08	-9.92E-08	-1.25E-06
Fine particulate matter formation	DALY	0.000188	0	1.49E-05	1.51E-05	4.29E-06	9.19E-06	0.000378	4.85E-05	6.45E-05	3.03E-05	-2.23E-05	-0.00036
Human carcinogenic toxicity	DALY	-0.006581	0	6.26E-07	1.14E-06	1.19E-07	9.39E-07	5.02E-05	5.46E-06	7.24E-06	5.94E-06	-0.00661	-3.89E-05
Human non-carcinogenic toxicity	DALY	-2.19E-05	0	7.75E-07	1.59E-06	8.32E-08	4.27E-07	9.58E-05	6.76E-06	8.94E-06	6.07E-06	-8.76E-05	-5.48E-05
Water consumption, Human health	DALY	7.82E-06	0	1.09E-06	8.57E-07	6.30E-08	9.58E-09	1.19E-05	9.35E-06	1.28E-05	4.89E-07	-9.95E-07	-2.77E-05

Global warming, Terrestrial ecosystems	species.yr	4.76E-07	7.42E-07	1.15E-07	3.26E-08	2.72E-09	4.96E-08	8.16E-07	1.02E-07	1.36E-07	8.22E-08	-4.54E-08	-1.56E-06
Global warming, Freshwater ecosystems	species.yr	1.30E-11	2.03E-11	3.14E-12	8.91E-13	7.42E-14	1.35E-12	2.23E-11	2.79E-12	3.71E-12	2.25E-12	-1.24E-12	-4.25E-11
Ozone formation, Terrestrial ecosystems	species.yr	-3.72E-09	0	9.36E-09	6.12E-09	2.30E-09	5.31E-09	9.41E-08	2.84E-08	3.76E-08	7.49E-09	-1.44E-08	-1.80E-07
Terrestrial acidification	species.yr	9.28E-08	0	6.16E-09	1.31E-08	2.35E-09	9.17E-09	2.40E-07	3.67E-08	4.86E-08	2.70E-08	-1.75E-08	-2.72E-07
Freshwater eutrophication	species.yr	-2.31E-07	0	1.27E-09	1.94E-09	9.75E-11	4.74E-10	1.10E-07	5.48E-09	7.32E-09	2.07E-08	-3.20E-07	-5.78E-08
Marine eutrophication	species.yr	2.00E-11	0	3.29E-13	3.18E-13	2.64E-14	8.21E-14	2.32E-11	9.25E-13	1.23E-12	3.79E-12	-2.77E-13	-9.61E-12
Terrestrial ecotoxicity	species.yr	8.67E-09	0	2.57E-10	5.48E-10	1.65E-11	5.20E-11	1.65E-08	2.93E-09	3.87E-09	3.27E-10	-9.77E-10	-1.49E-08
Freshwater ecotoxicity	species.yr	-8.28E-08	0	7.76E-11	1.43E-10	8.43E-12	4.27E-11	9.62E-09	6.14E-10	8.12E-10	8.02E-10	-8.97E-08	-5.16E-09
Marine ecotoxicity	species.yr	-1.79E-08	0	1.73E-11	3.25E-11	1.86E-12	3.07E-11	2.08E-09	1.42E-10	1.87E-10	1.65E-10	-1.94E-08	-1.14E-09
Land use	species.yr	4.51E-07	0	4.60E-07	4.67E-09	2.82E-10	3.24E-10	7.11E-08	1.88E-08	2.48E-08	1.02E-08	-5.17E-08	-8.70E-08
Water consumption, Terrestrial ecosystem	species.yr	4.69E-08	0	6.65E-09	5.23E-09	3.83E-10	1.08E-11	7.23E-08	5.70E-08	7.78E-08	2.49E-09	-6.06E-09	-1.69E-07
Water consumption, Aquatic ecosystems	species.yr	2.33E-12	0	3.09E-13	2.45E-13	1.80E-14	1.95E-15	3.68E-12	2.57E-12	3.52E-12	1.09E-13	-2.78E-13	-7.85E-12
Mineral resource scarcity	USD2013	-0.255909	0	0.002021	0.003924	0.000647	0.005751	0.321953	0.027174	0.035849	0.009982	-0.00763	-0.65558
Fossil resource scarcity	USD2013	18.12363	0	0.631877	0.851612	0.111242	15.98807	19.05555	4.336139	5.733994	1.203316	-4.56785	-25.2203