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Original Research Article

Multi-Criteria Decision Analysis of the Environmental and Economic Parameters for Mineral Carbonation of Steel Slags as a Carbon Capture, Utilization and Storage Material

P. Watjanatepin[*1], *L. Steinwidder*[2], *A. de Schutter*[3], *N. Miladinović*[3], *T. Van Duyse*[1,4], *L. Eelen*[1], *G. Granata*[1,3], *S. Vicca*[2], *T. Van Gerven*[3], *K. Van Acker*[1,5,6]

[1]Sustainable Materials Processing and Recycling (SeMPeR), Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44, 3001 Leuven, Belgium
e-mail: ponnapat.watjanatepin@kuleuven.be, tom.vanduyse@kuleuven.be, lola.eelen@kuleuven.be, karel.vanacker@kuleuven.be

[2]Biobased Sustainability Engineering (SUSTAIN), Department of Bioscience Engineering, University of Antwerp, Antwerp, Belgium
e-mail: laura.steinwidder@uantwerpen.be, sara.vicca@uantwerpen.be

[3]Process Engineering for Sustainable Systems (ProcESS), Department of Chemical Engineering, KU Leuven, Leuven, Belgium
e-mail: anthony.deschutter@kuleuven.be, nina.miladinovic@kuleuven.be, giuseppe.granata@kuleuven.be, tom.vangerven@kuleuven.be

[4]Environmental Economics (EnvEcon), Department of Engineering Management, University of Antwerp, Antwerp, Belgium
e-mail: tom.vanduyse@kuleuven.be

[5]Center for Economics and Corporate Sustainability (CEDON), KU Leuven, Warmoesberg 26, BE-1000 Brussels, Belgium
e-mail: karel.vanacker@kuleuven.be

[6] FlandersMake@KU Leuven, Leuven, Belgium
e-mail: karel.vanacker@kuleuven.be

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ABSTRACT

Mineral carbonation, where steel slags react with carbon dioxide from flue gases to form stable carbonates and silicates, offers a potential carbon capture, utilization, and storage pathway with agricultural applications. However, it is essential to assess the environmental and economic impacts to determine its industrial feasibility. The trade-offs between the environmental and economic impacts would provide the most optimal scenario for further upscaling and adoption of mineral carbonation of steel slags as a carbon capture, utilization and storage technology. This study quantifies the environmental and economic impacts of steel slag mineral carbonation, using life cycle assessment and life cycle costing respectively, and identifies optimal trade-offs using multi-criteria decision analysis. Basic oxygen slags with treatment 2 was identified as the optimal condition, based on the weighting of equal environmental and economic importance, for further optimization and scaling of the mineral carbonation process. In conclusion, these

* Corresponding author

findings contribute to advancing steel slag mineral carbonation and enhancing the sustainability of the steel manufacturing value chain.

KEYWORDS

Multi-criteria decision analysis, Life cycle assessment, Life cycle costing, Mineral carbonation, Steel slags.

INTRODUCTION

Currently, society across the world has increasing demands for raw materials in order to support the population growth and sustain the economic and societal activities. Hence, iron and steel are among the highly consumed primary raw materials in order to support this demand. However, the manufacturing of steel and iron is also one of the most concentrated anthropogenic carbon point sources in terms of its emission [1]. Moreover, approximately 10-20% of steel slags per crude steel mass are also generated in the steel production value chain especially for the steel manufacturing value chain with basic oxygen and electric arc furnaces [2].

Interestingly, these carbon dioxide and steel slag waste streams can be used to produce stable silicates and carbonates via mineral carbonation [2, 3]. Essentially, the mineral carbonation process involves a chemical reaction of water and carbon dioxide on the surface of the alkaline source (in this case, the steel slags) to create silicates and carbonate layers on the carbonated slag surfaces. The mineral carbonation process can also keep the carbon dioxide sequestered in a stable manner for millennia [3]. Therefore, the process of mineral carbonation of steel slags can be designated as a carbon capture and storage technology. The carbonated slags can be applied in a wide range of sectors such as construction and agriculture. With the 'utilization' aspect of the steel slags demonstrated mineral carbonation of slags becomes a carbon capture, utilization and storage technology (CCUS) [4]. Interestingly for the process of mineral carbonation as a CCUS, the carbon dioxide used does not necessarily have to be of a high level of purity. Therefore, flue gases with different carbon dioxide concentrations resulting from the steel manufacturing process could be used in the process. Hence, the mineral carbonation of steel slags is a potential pathway to valorise both waste streams of the steel industry which includes the slags and flue gases in order to generate values from these wastes.

Nonetheless, in order for the CCUS technologies to be viable, net negative carbon performance is essential. In other words, as CCUS technologies are often energy-intensive, the carbon emissions that result from the carbon capture and storage process should be less than the carbon dioxide that is captured and stably sequestered. In order to quantify this, life cycle assessment (LCA) is used [5]. LCA provides a quantitative environmental performance of a system with different environmental impact categories [5, 6]. However, it is essential to also analyse impact categories other than the global warming potential (GWP) in order to provide a comprehensive understanding of the CCUS system.

Another important aspect to consider for the adoption of CCUS technologies is that they must be economically viable to be implemented in the value chain. If the CCUS technology does not provide economic value, it might be more interesting for a company to decide to just pay for the allowances to release the carbon emissions into the atmosphere [7]. Therefore, as a rule of thumb, the cost of operating the CCUS to remove carbon dioxide should be cheaper than the price of the carbon credits in the emission trading scheme. To evaluate this, life cycle costing (LCC) can be used to calculate the net present value (NPV) of the CCUS system [8]. The NPV refers to the net amount of cash after considering the difference between the revenues and the costs over a chosen period of time. The higher the NPV signifies a more economically viable system.

One of the most complex challenges in the field of sustainability assessment is how to integrate both the LCA and the LCC together in order to evaluate the best trade-off of the system under assessment. The reasoning behind this necessity is that the relationship between the environmental benefits and the economic performance of a CCUS system is often inversely proportionate, meaning that to have higher carbon capture and sequestration, more investment is required [9]. Therefore, the use of an integrated LCA-LCC assessment can provide the best trade-off scenario of the CCUS system to help the steel manufacturing industry in making a decision on adopting the mineral carbonation technology. The Global CO_2 Initiative published guidelines in 2021 for assessing both the environmental and economic impacts of carbon capture, utilization, and storage technologies [9, 10]. However, there is currently no published study on the integrated environmental and economic performance of mineral carbonation of steel slags for agricultural applications. Most existing studies focus solely on the environmental impact assessment or the economic evaluation of mineral carbonation of steel slags. **Table 1** and **Table 2** provided an overview of the literature landscape on the LCA and LCC studies related to mineral carbonation of steel slags where applicable respectively. **Table 1** summarized the overview of the LCA studies addressing the environmental impacts of mineral carbonation of steel slags. The review paper of Ragipani [3] summarized the different valorisation pathways of steel slags mineral carbonation, however, the applications described are in the construction or chemical applications. The studies of Di Maria [14, 15] investigated the environmental impact assessment via LCA of carbonated stainless steel slags for concrete blocks substitute in place of ordinary Portland cement (OPC) for the construction industry. Similarly, the study of Huang investigated the environmental impacts of blast furnace slags mineral carbonation for the replacement of the OPC in concrete blocks for the construction industry [16] The study of Shao [17] also investigated the environmental impacts of steel slags mineral carbonation for the production of construction materials.The study of the authors [11] quantified the environmental impacts of steel slags mineral carbonation in agricultural applications. Nonetheless, only the environmental aspects were considered, and not yet the economic impacts. The LCA study of Lefebvre [12] focused on the environmental impact assessment of the use of carbonated basalt rocks in agriculture. Therefore, only two LCA studies investigated the environmental impacts of mineral carbonation in agriculture, but only one study actually focused on the steel slags as the alkaline source for mineral carbonation in agriculture [11]. **Table 2** summarized the overview of the LCC studies addressing the economic impacts of mineral carbonation. In terms of the economic assessment, none of the existing studies investigated the economic impacts of steel slags mineral carbonation in agriculture. The study of Zendehboudi investigated the economic impacts of the ex-situ mineral carbonation of saline aquifers for CCS applications [7] while the study of Pasquier [13] focused on the techno-economic assessments for the mining waste. The study of Lee [18] investigated the economic feasibility of an additional steel slags mineral carbonation unit at a power plant. Therefore, the novelty of this study lies in its holistic assessment of both the environmental and economic impacts of carbonated steel slags for agricultural applications, as well as in integrating both perspectives to identify optimal trade-off scenarios which can be select for further improvements and optimization of steel slag mineral carbonation process. With respect to the MCDA, there are also no published studies at the time of the preparation of this manuscript that investigated the multi-criteria trade-off of mineral carbonation of steel slags in agricultural applications. Only two MCDA study by Falsafi [17] exists related to mineral carbonation of steel slags for identifying different valorisation pathways in the construction industry together with the study by Strunge [20] which also employed MCDA to determine the optimal trade-off points between the environmental, economic and social impacts of carbonated steel slags in the cement sector. Therefore, as previously stated, no MCDA studies exist yet to address the topic of steel slags mineral carbonation in the agricultural industry. The proposed assessment could be repeated to make such a decision on other CCUS technology developments as well.

Table 1: Literature Overview of LCA Studies on the Mineral Carbonation of Steel Slags

Literature Review on LCA Studies of Mineral Carbonation of Steel Slags		
Title and Reference	**Carbonated Material and Application**	**Main Findings**
A review on steel slag valorisation via mineral carbonation [3]	Steel slags (Construction application)	This review examines ex situ mineral carbonation methods, encompassing both direct and indirect approaches, for the production of weathered aggregates suitable for construction and value-added chemicals such as precipitated calcium carbonate. We provide a detailed analysis of slag characteristics and their implications for dissolution and carbonation mechanisms. Current research efforts are primarily aimed at overcoming the slow carbonation kinetics observed under atmospheric conditions.
Life cycle assessment to evaluate the environmental performance of new construction material from stainless steel slag [15]	Stainless steel slags (SSS) (Construction application)	The analysis shows that producing SSS-blocks through alkali activation and carbonation can reduce certain environmental impacts compared to OPC concrete. However, the LCA identifies the production of alkali activators as a primary limitation, and the use of electricity and pure CO2 streams during carbonation negatively impacts the overall environmental performance.
Environmental assessment of CO2 mineralisation for sustainable construction Materials [14]	Stainless steel slags (SSS) (Construction application)	The LCA results show that carbonated blocks have lower environmental impacts in most categories, with a negative carbon footprint as a key finding. However, energy consumption remains the primary environmental hotspot. To further reduce impacts, improving energy efficiency in the mineral carbonation process and establishing a CO2 valorization network are recommended.
Life-cycle assessment of emerging CO2 mineral carbonation-cured concrete blocks [16]	Blast furnace slags (Construction application)	Using blast furnace slag instead of ordinary Portland cement in concrete block production could reduce GWP by up to 30% and CED by up to 28%, depending on the scenario.
Preliminary Environmental Assessment of Carbonated Slags as a Carbon Capture, Utilization, and Storage Materials (CCUS) [11]	Basic oxygen furnace slags and argon oxygen decarburization slags (Agriculture applications)	This study explored an environmentally friendly industrial waste valorization pathway by conducting a life cycle assessment (LCA) of carbonated steel slags, using the ReCiPe 2016 midpoint methodology to calculate environmental impacts.

Assessing the carbon balance of soil carbonation and enhanced weathering [12]	Basalt rocks (Agriculture applications)	The study compares CO2 emissions from enhanced weathering and carbonation processes, finding that they release approximately 75 and 135 kg of CO2 equivalent per tonne of CO2 removed, respectively, with transportation identified as the key factor reducing their effectiveness.
Life cycle assessment of upcycling waste slag via CO2 pre-treatment: Comparative study of carbonation routes [17]	Yellow phosphorus slags (YPS) and basic oxygen furnace slags (BOFS)	The LCA results indicate that aqueous carbonation reduces carbon emissions (11.3% and 214.0%) and human carcinogenic toxicity (2.4% and 0.2%) compared to dry carbonation for YPS and BOFS, but increases mineral resource scarcity and water consumption.

Table 2: Literature Review on LCC Studies of Mineral Carbonation

Literature Review on LCC Studies of Mineral Carbonation		
Title and Reference	**Carbonated Material and Application**	**Main Findings**
Practical and Economic Aspects of the Ex-Situ Process: Implications for CO2 Sequestration [7]	Steel slags (Carbon capture and storage applications)	The risk of CO2 leakage and slow CO2 dissolution in brine pose significant technical challenges for large-scale CO2 sequestration in saline aquifers. This study presents the technical and economic feasibility of ESDA compared to standard carbon capture and storage (CCS) technologies, addressing factors such as CO2 displacement, geochemical reactions, leakage, pressure build-up, well spacing, and dissolution efficiency.
Technical & economic evaluation of a mineral carbonation process using southern Québec mining wastes for CO2 sequestration of raw flue gas with by-product recovery [13]	Mining wastes (Mining application)	The global process cost is estimated at $144/tCO2 ($146/tCO2 avoided). With revenues of $644/tCO2 from by-product sales and carbon credits, the process achieves a profitable balance and a payback period of 1.4 years, making it economically advantageous.
Economic Evaluation of Carbon Capture and Utilization Applying the Technology of Mineral Carbonation at Coal-Fired Power Plant [19]	Steel slags (Power plant/power generation)	This study reveals that the Levelized Cost of Energy (LCOE) and the cost of CO2 avoided for a 400 tCO2/day capacity carbon capture and utilization (CCU) plant utilizing mineral carbonation technology are 26 USD/MWh and 64 USD/tCO2, respectively. These values indicate a relatively low LCOE and CO2 avoided cost compared to other carbon capture and storage (CCS) and CCU technologies.

To answer this need, the multi-criteria decision analysis (MCDA) can be used to quantitatively calculate the priority scores of different process scenarios in order to rank the most optimized scenario of the system under study [10]. Analytical Hierarchy Process (AHP) approach is a type of multi-criteria decision analysis that is widely used across different applications today. The AHP approach involves the conversion of assessment criteria into overall weighted scores [10]. Unlike the other outranking MCDA approaches, the AHP approach compares the assessed criteria against each other, leading to a consistent comparison of relative importance in a pairwise comparison matrix. The matrix is then used to calculate the final weighted score that can be used to rank the most optimized scenario of the system. The AHP method is widely used due to its ease of use, but still able to have a consistent and systemic comparison of all studied parameters. The AHP method has been used in different cases and sectors to identify the optimal trade-off points between different indicators of interest. For example, the study of Widiante [22] employed AHP as an MCDA to determine optimal employee placement for human resources, the study of Hou [23] used AHP to assess 38 indices for the determination of the ideal geological storage for carbon, capture and storage technologies and the study of Roy [24] performed the AHP to identify ideal medical tourism sites based on different cities. The two MCDA studies [19, 20] previously mentioned on the mineral carbonation of steel slags both also utilized the AHP approach. The main rationale for using the AHP method is summarized in the review study of Rachman [25] as a structured method for a systematic analysis that integrates subjective judgements (or preferences) via pairwise comparisons. The AHP method can also investigate the interactions or contributions between different the criteria which is an additional benefit when compared to other ranking methodologies. In this way, the AHP method can increase the transparency in the interpretation of the ranking of the results [26].

The objective of this study is to identify an optimal scenario (or scenarios) based on the trade-off between the environmental and economic performances of steel slag mineral carbonation as a CCUS scenario by using a simulated industrial case study in agriculture. Specifically, the aim is to (1) quantify the selected environmental and economic impacts of the mineral carbonation scenarios in a steel manufacturing plant, and (2) employ the AHP approach in order to identify and choose the most optimized scenario of steel slags mineral carbonation using the quantified environmental and economic performances based on the empirical data available from the research project as well as based on different projected scenarios. The obtained results can contribute to the decision-making process of mineral carbonation technology adopters to integrate mineral carbonation of steel slags as a CCUS in their steel manufacturing value chain. This could influence future processes and value chain design and optimization towards a more sustainable steel manufacturing process.

METHODS

In this section, the different mineral carbonation cases are described. These cases are later used as inputs for the environmental and economic assessments. The results from these assessments serve as the criteria for identifying and selecting the most optimal carbonation conditions, considering both environmental and economic perspectives equally. The second section provides a methodological description of the life cycle assessment and life cycle costing calculations. Finally, the last section outlines the methodological approach for the multi-criteria decision analysis (MCDA), specifically the analytical hierarchy process. This description includes the assumptions and scope of the MCDA approach, aimed at identifying the optimal carbonation conditions for further investigation, process optimization, and future scaling to an industrial-level setup.

Mineral Carbonation Case Description

This study employs the experimental data performed on a lab-scale mineral carbonation of steel slags at the University of Leuven, Belgium. The study subsequently projected the lab-scale mass and energy consumption as well as the yields to an industrial-scale pilot plant (TRL 6) scenario based on the upscaling frameworks with a power law learning curve which incorporates the process efficiency and the economy-of-scale [18, 19, 20]. The projected industrial scenarios have a capacity equivalent to the industrial wet mineral carbonation installation in the study of Lee et al. [19]. The study assumes a mineral carbonation capacity of 61.8 tons per day, producing 22557 tons per year of carbonated steel slags.

There are 5 mineral carbonation cases in total which act as the baseline scenarios. These 5 mineral carbonation scenarios can be sub-categorized into 3 mineral carbonation of basic oxygen furnace (BOF) steel slags scenarios and 2 mineral carbonation of argon oxygen decarburization (AOD) steel slags scenarios with varying degrees of carbonation. The main difference between each scenario is, therefore, the carbonation degree which reflects how long the mineral carbonation took place for each case. BOF T1 case refers to the mineral carbonation of BOF steel slags at 2 bar for 3 hours. BOF T2 case refers to the mineral carbonation of BOF steel slags at 4 bar for 2 hours. The BOF T3 case refers to the mineral carbonation of BOF steel slags at 4 bars for 91 hours. The AOD T1 case refers to the mineral carbonation of AOD steel slags at 4 bar for 3 hours. Finally, the AOD T2 case refers to the mineral carbonation of AOD steel slags at 4 bar for 33 hours. The different absolute residence times are due to the differences in the composition of the slags which resulted in different carbonation duration needed to reach the maximal carbonation levels which are identified and reported in previous studies of the authors [11, 21]. Within this study, the carbonated slag products are assumed to be sold as either a replacement for basalt rock powder or the liming agent. In the baseline scenarios, it was assumed that 50% of the produced carbonated slags are sold as basalt rock powder replacements and the remaining 50% are sold as liming agent replacements.

This study also expands the baseline scenarios into multiple scenarios to account for the different possibilities in the carbonation process in terms of the technological/environmental aspect and the economic aspect. The first group of expanded scenarios includes the variations in the proportion of what the carbonated slag products can be sold as. The motivation behind adding this scenario analysis is that the use of basalt rock powder as the source of macronutrients in agriculture at present is limited to mostly organic farmers. This means that it would be difficult to achieve a high sales volume for the basalt rock powder. Therefore, the study also tries to project what should be the lowest proportion of the carbonated slag products to be sold as basalt rock powder possible in order to still achieve economic viability. This is defined as having an internal rate of return (IRR) of at least 7%. This leads to one exception of case BOF T3 where the baseline NPV has an IRR lower than 7%. Hence, instead of excluding BOF T3, the minimal amount of carbonated slags percentage to be sold as basalt rock powder substitute was determined to at least satisfy a 7% IRR. This calculation resulted in a percentage of 65% carbonated slags sold as basalt rock powder substitute and 35% as liming agent substitute.

Other expansions of the baseline scenarios include (1) the inclusion of the drying process to dry the carbonated slag products at the end, (2) the change of the electricity grid mix of Belgium to an average EU-27 + Switzerland mix, and finally, (3) the inclusion of both the drying process and the change of the electricity grid mix of Belgium to the EU-27 + Switzerland mix. The motivation for these scenarios is that at the moment of publication, it is still unclear whether mineral carbonation of steel slags would require a drying process or not. On the one hand, it is possible to use the carbonated slags directly from the reactor onto the fields for agricultural applications. On the other hand, wet carbonated slag products are heavier than dried products, which may prove to be problematic when considering the transportation of these products. The study of Lefebvre et al. (2018) [12] have identified that the transportation of carbonated rocks is the hotspot of the climate change impacts for the full life cycle of carbonation of rocks with more than 50% of the total climate change impacts depending on the transportation radii. Therefore, this study takes into account both possibilities with (expanded scenarios) and without the drying process (baseline). The motivation for having scenarios with a different electricity mix is twofold: firstly, to explore the possible impacts of what would happen if the mineral carbonation process is not used in Belgium, but elsewhere in Europe, and secondly, to investigate what would happen if the electricity mix has less share of renewable energy but cheaper. Finally, the motivation for the inclusion of the third scenario expansion is to complete the assessment with a complete list of scenarios that have both the drying process and a different energy mix.

In total, this study uses 25 scenarios, with 5 baseline scenarios, 5 scenarios with differing proportions of the products sold, 5 scenarios with the drying process with Belgian electricity mix, 5 scenarios with the whole value chain with the EU-27 + Switzerland mix, and 5 scenarios with the drying and the whole value chain with the EU-27 + Switzerland mix.

Life Cycle Assessment and Life Cycle Costing

The upscaled mass and energy balances of the mineral carbonation process are subsequently used for the life cycle assessment (LCA) and the life cycle costing (LCC). The upscaled inventory for the LCA calculation is shown below in Table 1. The LCA models used in this study were created with Activity Browser with the Ecoinvent 3.8 database. The LCA is performed in accordance with the ISO 14044 standard [5]and aligned with the ILCD handbook for life cycle assessment [6]. The environmental impacts of all 25 scenarios are then calculated using the Environmental Footprint 3.0 (EF 3.0) methodology. The functional unit is 1 kg of steel slag mineral carbonation at plant capacity. The system boundary is illustrated below in Figure 1. The system boundary of both the LCA and LCC are within the red box which includes the slag and water mixing reactor, the mineral carbonation reactor and the membrane separation unit for the CO_2. The system boundary in green are the basis for the scenario analyses which included the drying steps as post-treatments. As the mineral carbonation of steel slags is considered a CCUS technology, the guidelines on the LCA and TEA from the Global CO_2 Initiative [9] are used as a reference. Both the LCA and the LCC have the same system boundary on an annual time scale. Within this study, the global warming potential (GWP), freshwater ecotoxicity (FET), human toxicity, cancer (HTC), and ionizing radiation (IR) are reported. The reasoning for these impact categories is that (1) as it is an investigation on the CCUS, the GWP must be net negative to ensure that the technology actually removes carbon dioxide even with all the mass and energy consumption it requires to operate the CCUS, (2) FET, HTC and IR are chosen because upon reviewing the EF 3.0 normalized results of all environmental impact categories, these impacts have the highest top 3 scores. The normalization of the EF 3.0 approach was performed in order to see the number of impacts an average citizen in the world would generate if the mineral carbonation of steel slags was employed. This means that the use of mineral carbonation has potentially high emissions to these impact categories. The results of the selected environmental impacts of all 25 scenarios are then reported in Table 3. For the LCC, the discounted cash flow model was used for the calculation under the same system boundary as the LCA. The LCC employed a project lifetime of 15 years with a discount rate of 7% per year. The annual revenues and costs included in the LCC calculation are displayed in Table 2: Annual Life Cycle Costing Inventory of Steel Slags Mineral Carbonation for Baseline Cases. The maintenance costs are included as 10% of the revenues per annum and the drying costs are included according to the electricity price for the heating of 1 kg of steel slags either in Belgium or the average EU-27 + Switzerland price depending on the scenarios. Grinding costs are included in the price of the slags. This project is assumed to be constructed in Flanders, Belgium. Therefore, the costs related to labour,

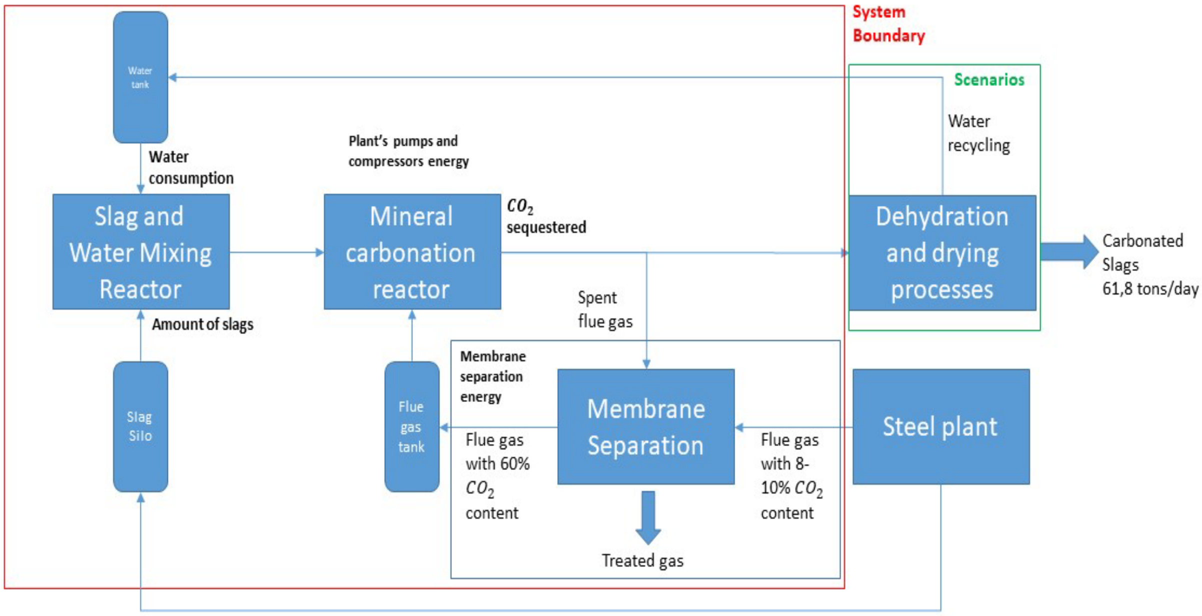


Figure 1: System Boundary of the LCA and LCC

maintenance, energy, materials, possible income from the EU ETS scheme, and avoided landfill costs are based on Belgian data. The infrastructure costs for capital expenditure (CAPEX) are based on the study of Lee et al. [19] as the mineral carbonation plant setup and capacity are similar as indicated. The net present value (NPV) of all 25 cases is then calculated and reported in Table 3. As the scope of this study is on the MCDA, for a detailed life cycle assessment and life cycle costing of the mineral carbonation of steel slags with process hotspots, readers are encouraged to also check other assessed cases in published and accepted works by the authors in Watjanatepin et al. (2023) [11] and Watjanatepin et al. (2024) [21] respectively.

Table 3: Daily Life Cycle Inventory of Steel Slags Mineral Carbonation for Baseline Cases

Inputs (Units)	Life Cycle Inventory				
	BOF T1	BOF T2	BOF T3	AOD T1	AOD T2
Ground basic oxygen furnace (BOF) or argon-oxygen decarburization (AOD) slags (tons)	61.8	61.8	61.8	61.8	61.8

Carbon dioxide sequestered (tons)	1.54	3.16	10.01	3.52	6.39
Distilled water (tons)	24.72	24.72	24.72	24.72	24.72
Energy for membrane separation (MWh)	0.53	1.01	3.50	1.22	2.22
Plant energy (MWh)	0.74	1.52	4.83	1.67	3.07
Outputs (Units)	Life Cycle Inventory				
	BOF T1	BOF T2	BOF T3	AOD T1	AOD T2
Carbonated steel slags	61.8	61.8	61.8	61.8	61.8

Table 4: Annual Life Cycle Costing Inventory of Steel Slags Mineral Carbonation for Baseline Cases

Inputs (Units)	Life Cycle Inventory					
	BOF T1	BOF T2	BOF T3	AOD T1	AOD T2	Reference
Ground basic oxygen furnace (BOF) or argon-oxygen decarburization (AOD) slags (M€)	0.33	0.33	0.33	0.33	0.33	[22]
Distilled water (M€)	0.04	0.04	0.04	0.04	0.04	[23]
Costs for membrane separation (M€)	0.02	0.03	0.09	0.03	0.06	[24]
Plant energy (M€)	0.16	0.33	1.03	0.36	0.66	[24]
Labour costs (M€/3 persons)	0.14	0.14	0.14	0.14	0.14	[25]
Maintenance costs at 5% of the annual turnover (M€)	0.09	0.09	0.09	0.09	0.09	[26]

Infrastructure costs – CAPEX (M€)	8.32	8.32	8.32	8.32	8.32	[19]
Outputs (Units)	Life Cycle Inventory					
	BOF T1	BOF T2	BOF T3	AOD T1	AOD T2	
Carbonated steel slags in which:						
50% of the slags are sold as basalt rock powder substitute (M€)	1.13	1.13	1.13	1.13	1.13	[22]
50% of the slags are sold as liming agent substitutes (M€)	0.67	0.67	0.67	0.67	0.67	[27]
Possible EU ETS income from avoided carbon emissions (M€)	0.049	0.16	0.51	0.19	0.40	[28]
Possible avoided slags landfill costs in Flanders (M€)	0.013	0.013	0.013	0.013	0.013	[29]

Multi-Criteria Decision Analysis

To perform the MCDA, the AHP approach is used. The AHP approach followed within this study was in line with the multi-attributional decision-making guidelines of the Global CO_2 Initiative for the environmental and economic assessment of CCUS [10]. The objective of this MCDA is "What is the preference order of the mineral carbonation of steel slag scenarios?". By answering this question, it will be possible to identify the optimal tradeoff between the environmental and economic performance amongst all steel slags mineral carbonation scenarios. And subsequently, a decision could be made on which scenarios to choose and further investigate for process improvements and upscaling. The AHP approach first calculated the pairwise matrix of all the scenario attributes. Firstly, the main criteria are weighted. In this study, the two main criteria are (1) environmental performance and (2) economic performance. Both are given equal weight to designate equal importance for both the environmental and economic impacts at 0.5 and 0.5. The main motivation for assigning equal weighting for both the environmental and economic criteria is twofold. Firstly, in order to justify the definition of CCUS of mineral carbonation, the GWP must be net negative or at least neutral. Therefore, the environmental impact must be well quantified. Secondly, the economic performance is equally important since the CCUS technology is neither impactful nor useful if the costs to operate such a CCUS technology is too high. In that case, alternative options of the technology or even paying for the emission allowances might be cheaper than investing in an expensive technology that is not economically viable. This explains the motivation behind this weighting. This equal weighting was also used in the guidelines document of the Global CO_2 Initiative [10] where at 50% allocation are weighted for both the environmental and economic impacts as a baseline guidance for CCUS technology assessments. Similarly, the MCDA study of Falsafi [17] also used equal weighting (0.5-0.5) for the allocation between environmental and economic impacts. Subsequently, the study then defines the 5 attributes to be optimized which are GWP, FET, HTC, IR, and NPV with a discount rate of 7%. The NPV is a sub-criteria under the economic performance while the rest of the attributes are sub-criteria to the environmental performance. To assign the weight to the environmental performance sub-criteria, the normalized EF 3.0 results of the environmental impacts of mineral carbonation are consulted based on previous studies [11, 21] which found that the most impactful environmental category when deploying mineral carbonation is IR, FET and HTC in descending order. With this information in combination with the definition of a CCUS that must have a net negative GWP and economic impacts, the global priority weight is then assigned as 0.325 for the GWP, 0.05 for the FET, 0.025 for the HTC, 0.1 for the IR, and 0.5 for the NPV based on the AHP pairwise matrix calculation. The pairwise matrix calculation for the determination of the aforementioned weighting values assigned are tabulated in **Supplementary Material – Table 1**. The global priority weight is also given in Figure 2. To calculate the local priority vector, 5 pairwise matrix calculations are performed for each attribute. Each matrix consists of a 25 by 25 matrix to account for all the 25 scenarios. Each attribute has an order of preference quantitatively defined in order to have an objective analysis. The calculation of the pairwise matrices entail the comparison of each of the raw environmental and economic assessment results from the LCA and LCC (in Table 3) respectively to determine the performance of each indicator and each scenario. Subsequently, the local priority vector is then calculated based on the normalization of each attribute's pairwise matrix for all 25 scenarios. All 5 normalized pairwise matrices for all attributes are displayed in the Supplementary Materials – particularly **Supplementary Material – Table 2** to **Supplementary Material – Table 6**. Finally, to calculate the global priority score for each attribute for each scenario, the global priority weights are then multiplied by the local priority vectors. The final preference scores are then the summation of all global priority scores of each attribute (GWP, FET, HTC, IR and NPV) for each of the 25 scenarios. The final preference score results are tabulated in Supplementary Material – Table 7 Based on the final preference scores, it is then possible to rank the scenarios from highest to lowest scores and indicate the optimal scenario. This ranking is illustrated in Figure 3. In addition to this, the contribution analysis of all 25 scenarios is also performed to interpret which attributes contribute most to each score for each scenario. This contribution analysis is displayed in Figure 4.

RESULTS AND DISCUSSION

This section is divided into two main parts. The first section presents the environmental impacts from the LCA and the economic assessment from the LCC according to the methodology described in the previous section. The main insights are also discussed in this section. The second section presents the results from the AHP as an MCDA approach to identify the optimal mineral carbonation of steel slags condition for further process optimization and scale-up.

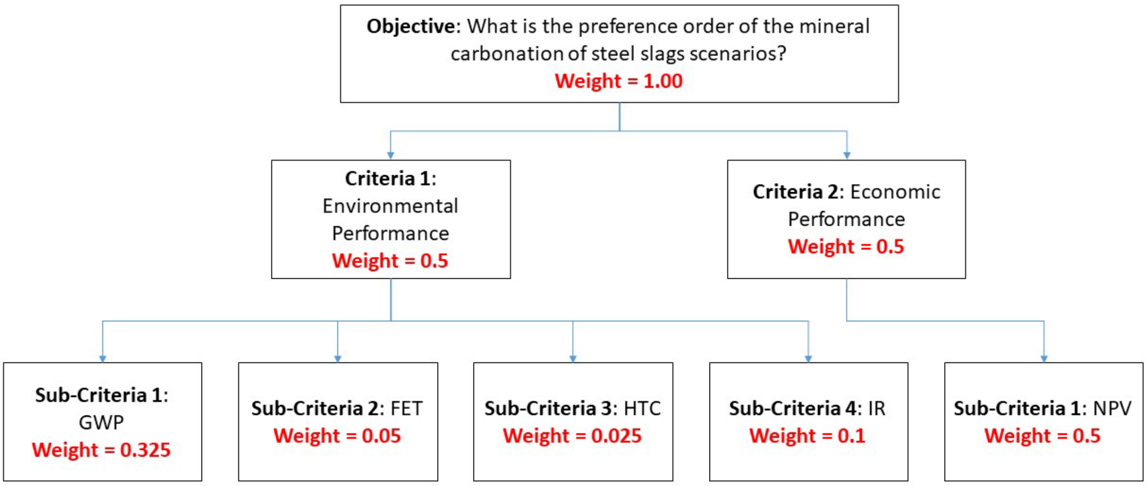
Life Cycle Assessment and Life Cycle Costing

Table 3 below summarizes the results of the LCA and the LCC for selected parameters,

Figure 2: Global priority weight for the MCDA

namely the GWP, FET, HTC and IR for the environmental impacts and the NPV for the economic performance for all 25 scenarios of mineral carbonation. The results of these parameters are used as a criterion in the MCDA.

In essence, the environmental impacts for the baseline cases showed that the BOF T3 case is the most net negative case of the mineral carbonation of steel slags. This is because in a wet carbonation process, the longer the carbonation time in the reactor, the higher the amount of carbon dioxide that is sequestered on the surface of the steel slags, resulting in a larger net



negative impact. This trend is observed for both the BOF and AOD slags mineral carbonation where the more net negative results are observed the longer the mineral carbonation takes place. When it comes to the other impacts, particularly the FET and HTC, there is a further decrease in both impact categories with the longer duration of the carbonation due to the fact that more carbon dioxide is being absorbed into the slags, thus requiring fewer treatments of the emissions due to the avoided impacts of reusing the emitted gases in a different application. In terms of the IR, the trend is reversed, meaning that the shorter the mineral carbonation duration, the lower the IR results become. This is due to the fact that the shorter the mineral carbonation duration, the lower the energy is consumed in the process, hence, lowering the IR impacts.

With respect to the NPV, the results depend on the optimal tradeoff between the costs related to the consumption of the materials and energy and the revenues generated from the carbonated slags in agriculture. The results showed that the highest NPV case is BOF T2 and AOD T1 respectively. Based on the previously published and accepted study of Watjanatepin et al. (2023) [11] and Watjanatepin et al. (2024) [21] the hotspot in the LCC is the energy costs of the mineral carbonation. Therefore, this explains why the longer duration of mineral carbonation resulted in less NPV. A scenario analysis was also performed on the LCC to investigate the lowest percentage of the carbonated slag products to be sold as basalt rock powder to still achieve the internal rate of return (IRR) of 7%. The motivation behind this is that in reality, it might be quite difficult to reach a high proportion of revenues from selling the carbonated slags as basalt rock powder since the market for basalt rock powder is quite limited to organic farming.

Comparison of drying and no-drying scenarios revealed a negative environmental impact of drying. This was expected since an additional step has been added to the value chain of the mineral carbonation of steel slags. Similarly, the NPV was also lower when the drying step was added. As a future study aspect, the drying step will become particularly important as it is related to the potential environmental impact savings from the reduced mass of the slags to be transported during the use phase of the carbonated slags. This is because dried carbonated slags would weigh less and therefore result in lower environmental impacts from the transportation to the site of application. The LCA study by Lefebvre et al. (2018) on the mineral carbonation of rocks in agriculture have indicated the transportation step as the hotspot in climate change, with transportation accounting for up to 50% of the total life cycle impacts for the GWP depending on the transportation radii [12]. At the present moment in this study, the use phase has not been assessed yet but the impact measurement campaigns are ongoing. The environmental impacts are also higher when the average EU-27 + Switzerland mix is used instead of the Belgian electricity mix. This could be explained by the higher shares of renewable energy in the Belgian electricity mix than the average EU-27 + Switzerland mix. However, the NPV is higher for the cases with the average EU-27 + Switzerland mix because the electricity prices are lower than the prices in the Belgian market. Therefore, this is also one potential tradeoff aspect that can be further explored: higher electricity prices would result in lower NPV but potentially lower environmental impacts in this scenario. This also means that the location of where the mineral carbonation technology is to be adopted within the steel manufacturing value chain could directly influence the environmental and economic impacts. Another interesting aspect of the BOF T3 scenario is that the IRR is dependent on the discount rate that was used for the calculation of the LCC. Up to this point in the research project, the discount rate of 3%, 7% (baseline used and reported in this study) and 15% has been calculated. The trend observed is that only the discount rate of 3% would make the BOF T3 scenario economically viable, but a discount rate of 3% often means that this has to be a public project that is subsidized by authorities. Nonetheless, this would result in the highest carbon sequestration and be the best case environmentally. The influence of the discount rates on the IRR of the best environmental scenario could be worth investigating further as a point of future studies.

In conclusion, the GWP results showed that all the mineral carbonation treatments can serve according to the definition of a CCUS where there is a net negative GWP after the treatment due to the carbon sequestration that outweighs the energy and mass consumed during the carbonation process. Similarly, the FET and HTC results also decrease along with the increased amount of sequestered carbon dioxide due to the avoided impacts of the emission treatments. Inversely for the IR, the IR impacts actually decrease, if there is less sequestration due to the shorter mineral carbonation duration. Finally, the NPV results displayed a reflective optimal point where a tradeoff has to be established between the costs related to the mineral carbonation process (and in particular, the energy costs) with the revenues generated from the carbonated slags products, carbon avoidance revenues according to the European Emission Trading Scheme (EU-ETS) and the avoided landfilling costs of the slags.

Table 5: Selected environmental and economic impacts as inputs for the MCDA

Scenario Attributes from the LCA and LCC Results	**Attributes**				
	LCA				**LCC**
Scenarios	GWP [kg CO_2 eq.]	FET [comparative toxic unit for ecosystems (CTUe)]	HTC [comparative toxic unit for human (CTUh)]	IR [human exposure efficiency relative to u235]	NPV [€]
Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	-0.05	0.56	8.26E-12	0.01	1.75E+07
Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	-0.10	0.41	5.99E-12	0.01	1.85E+07
Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	-0.32	0.24	3.55E-12	0.04	1.23E+07
Baseline: AODT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	-0.11	0.42	6.14E-12	0.01	1.82E+07
Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	-0.20	0.31	4.49E-12	0.03	1.56E+07

BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	-0.05	0.56	8.26E-12	0.01	1.33E+07
BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	-0.10	0.41	5.99E-12	0.01	1.34E+07
BOFT3 (65% Basalt Rock Powder to 35% Liming Agent Produciton Volume)	-0.32	0.24	3.55E-12	0.04	8.46E+06
AODT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	-0.11	0.42	6.14E-12	0.01	1.31E+07
AODT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	-0.20	0.31	4.49E-12	0.03	1.05E+07
BOF T1 with drying	-0.03	0.72	1.06E-11	0.03	1.72E+07
BOF T2 with drying	-0.07	0.53	7.73E-12	0.04	1.83E+07
BOF T3 with drying	-0.29	0.36	5.23E-12	0.08	1.20E+07
AOD T1 with drying	-0.09	0.54	7.89E-12	0.04	1.79E+07
AOD T2 with drying	-0.17	0.43	6.27E-12	0.06	1.53E+07
BOF T1 EU-27 + Switzerland	-0.04	0.64	9.46E-12	0.01	1.79E+07
BOF T2 EU-27 + Switzerland	-0.09	0.48	7.07E-12	0.01	1.95E+07
BOF T3 EU-27 + Switzerland	-0.30	0.33	4.82E-12	0.04	1.53E+07
AOD T1 EU-27 + Switzerland	-0.08	0.49	7.25E-12	0.02	1.93E+07
AOD T2 EU-27 + Switzerland	-0.18	0.38	5.63E-12	0.03	1.75E+07
BOF T1 EU-27 + Switzerland with drying	-0.03	0.85	1.25E-11	0.03	4.64E+06
BOF T2 EU-27 + Switzerland with drying	-0.06	0.64	9.42E-12	0.04	5.19E+06
BOF T3 EU-27 + Switzerland with drying	-0.26	0.51	7.54E-12	0.80	2.02E+06
AOD T1 EU-27 + Switzerland with drying	-0.08	0.66	9.65E-12	0.46	5.03E+06
AOD T2 EU-27 + Switzerland with drying	-0.15	0.57	8.33E-12	0.07	3.71E+06

Multi-Criteria Decision Analysis

The results from the MCDA are illustrated below in Figure 3. It should be noted that the EU-28 mix shown in the figure refers to the average EU 27 + Switzerland energy mix. The figure shows the final total preference scores for each of the 25 scenarios assessed in order to ascertain and rank the performance of the scenarios based on the 5 criteria: GWP, FET, HTC, IR and NPV. As a recap, the aim of this paper, besides assessing the environmental and economic performance of the different scenarios presented in the previous section, is to identify optimal scenario(s) based on the empirical data of steel slags mineral carbonation and on projected scenarios. Across all projected scenarios, the case of BOF T2 with the average EU-27 + Switzerland mix ranked the highest (Figure 3), followed by AOD T1 with the average EU-27 + Switzerland mix, BOF T3 with the 65% of carbonated slags product sold as basalt rock powder, baseline BOF T2 and baseline BOF T3 respectively.

With respect to the empirical cases, if a scenario has to be chosen to be implemented based on only the five baseline cases that has been performed experimentally, then the BOF T2 scenario would be recommended based on this finding. The results also show that the total preference scores decreased when the drying step was added. This is due to the fact that the drying step contributed negatively to increase the environmental impacts and to decrease the overall NPV for the economic performance. It is also generally observed that the cases with the use of the average EU-27 + Switzerland mix resulted in higher total preference scores than the baseline cases because of the higher NPV as a consequence of the lower electricity prices than the average Belgian market mix prices. It is also very interesting to indicate that one limitation of the AHP approach (but also in general for any MCDA) is that the result can vary and is very much dependent on the weighting chosen by the practitioner. In this particular study, an equal 50:50 weight was given to both the environmental and economic criteria. However, the ranking could change completely if this weight ratio is modified which will consequently give a different priority to certain criteria. Therefore, it is advised as a future work possibility to investigate further by conducting a sensitivity analysis on the MCDA study in order to investigate the impacts of the weighting choices on the final preference weighting score. Regardless of this, the current study already gives a preliminary indication of the optimal scenario to be employed in an industrial steel manufacturing value chain to steer towards a circular economy. BOF T2 with the average EU-27 + Switzerland mix seems to be the most optimal scenario when both the environmental and economic performance are taken into account. This may indicate that there has to be support from the Belgian authorities to give subsidies to industries wanting to adopt mineral carbonation as a CCUS in order to have a better performing BOF T2 (or other baseline scenario of interest) to increase the economic performance. This also refers to supportive actions such as lowering the prices of electricity or increasing the revenue streams like the avoided landfilling costs (local authority) or EU-ETS allowance price (European authority) to augment the economic viability.

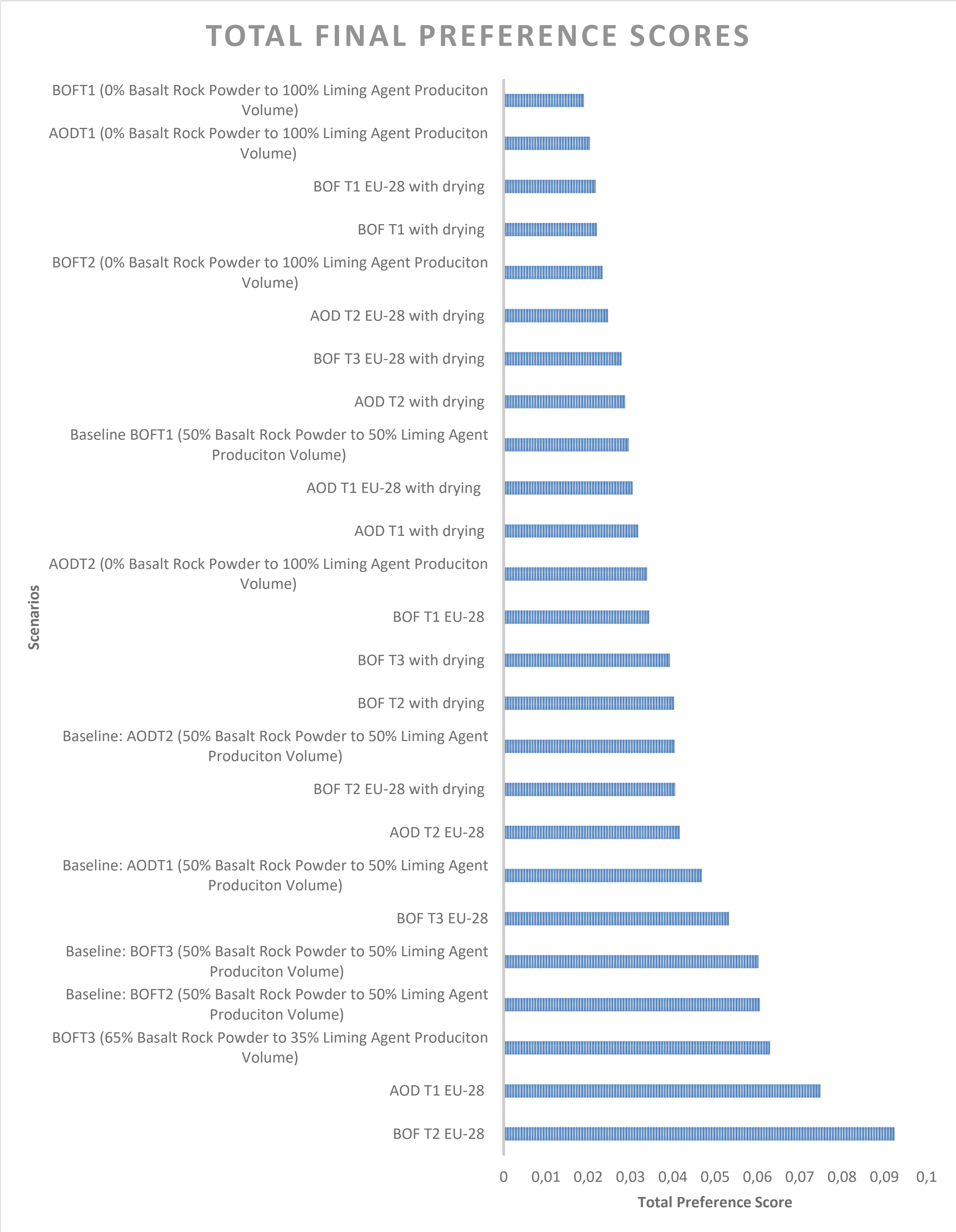


Figure 3: Total final preference scores from the MCDA

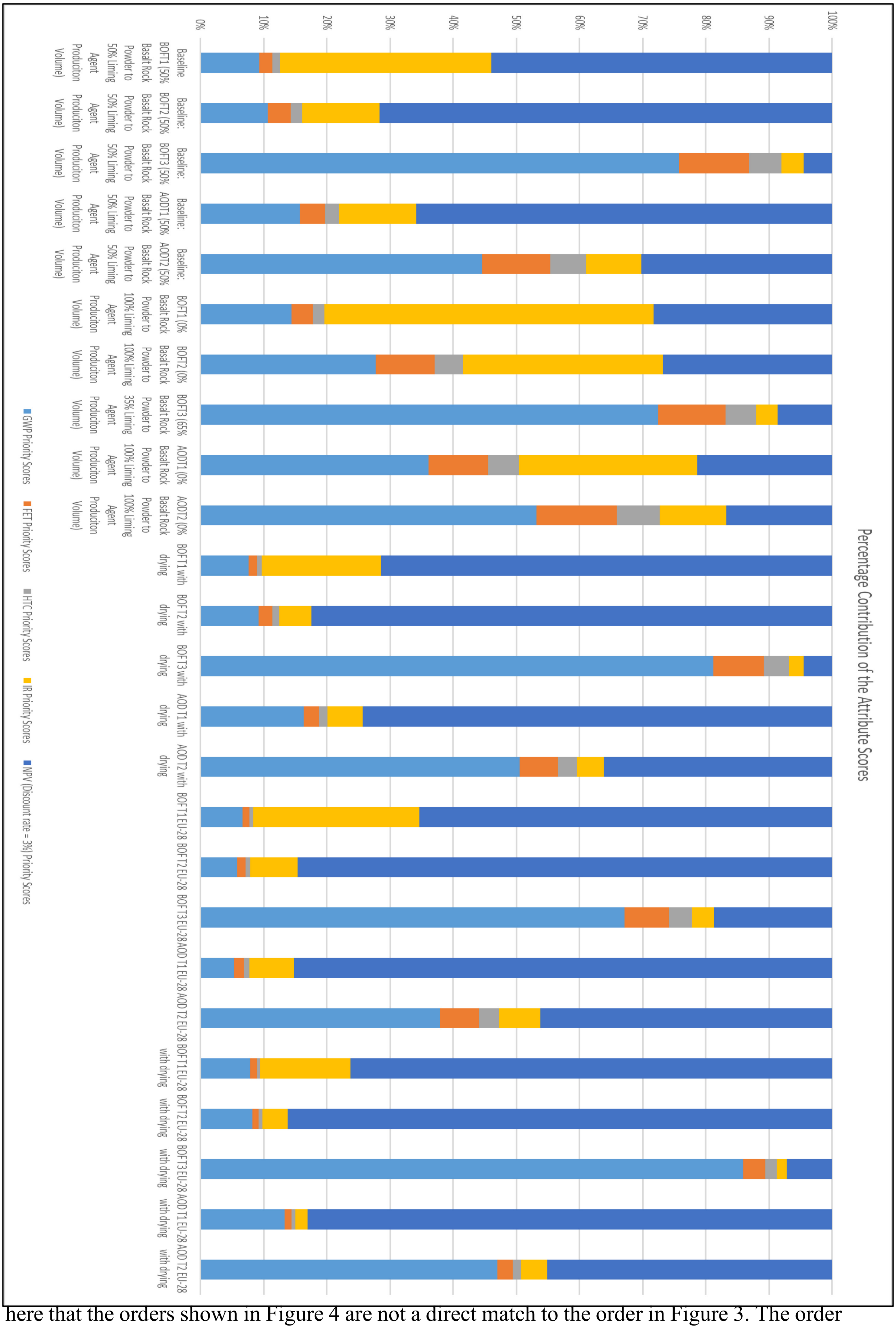


Figure 4: Percentage contribution of each attribute score for each carbonation scenario

here that the orders shown in Figure 4 are not a direct match to the order in Figure 3. The order of Figure 4 is based on the five groups of sub-scenarios ranging from BOF T1 to AOD T2. It should also be noted that the EU-28 mix shown in the figure refers to the average EU 27 + Switzerland energy mix. Regardless, this does not influence the results. The contribution analysis can be interpreted in groups of 5 scenarios since the trends are repeated amongst the 5 treatment types – BOF T1-T3 and AOD T1-T2. For BOF T1, T2 and AOD T1, the total preference score composition shows that the NPV is actually the highest contributor to the final score. Among these three cases, it is very interesting to observe that the IR scores and the GWP scores are inversely proportional, as explained in the paragraphs above. As a recap, the longer the mineral carbonation, the more carbon is sequestered onto the slags, resulting in higher GWP scores, but the longer carbonation duration results in higher energy consumption which consequently lowers the IR score. This trend is exactly observed between BOF T1, T2 and AOD T1 in this figure. When it comes to BOF T3 and AOD T2, a similar trend is observed where the total preference score of both cases is dominated by the GWP scores due to the high carbon sequestration of the two cases. And since the IR score is inversely proportional, it is clearly seen that the IR score contribution is fairly minimal for both BOF T3 and AOD T2. Moreover, since these two cases have lower absolute NPV scores than BOF T1, T2 and AOD T1, the contribution by NPV is also lower.

As stated above, the main limitation of an MCDA study relates to the weighting since the final ranking score as well as the contribution of the scores will vary according to the weight given to the environmental and economic criteria [10]. To address this uncertainty, it is possible, and advisable as a future study, to perform a sensitivity analysis by varying the weighting of the criteria in order to investigate the impacts of the choice of practitioner. Aligning with the recommendations in the studies of McCord [10] and Falsafi [17], other allocation of the weightings would be interesting to further investigate in order to visualize the impacts on the final MCDA results if other weightings are used (for instance, 0.3 to 0.7 or 0.4 to 0.6 or other ratios). In addition to this, it is also recommended to perform a sensitivity analysis on the NPVs by varying the discount rate. The motivation behind this suggestion is that the contribution of the NPV score is the highest in many carbonation cases, and therefore, this warrants further investigation into what would impact on the total score if the NPV also changes [24]. Alternatively, it might also be of interest to perform a survey with steel-making industries to assess the weight that they would give to decide on the adoption of mineral carbonation as a CCUS. Finally, it would also be of interest to add more sub-criteria to the assessment, for instance, the inclusion of all impact categories of EF 3.0 or other economic parameters. As this study is a part of an ongoing research project, the effects of the carbonation level on the slags in agriculture is still being investigated. Once these impacts have been quantified, it would certainly be interesting to include scenario analyses based on these findings. Additionally, the investigation on whether an extended or a shorter duration of mineral carbonation process should be performed could also be investigated further. Another interesting aspect that is worth further investigation is how would the LCA results change if the investment is directed towards a different CCUS technology? It could be very interesting to perform a consequential LCA to quantify the impacts related to the change in the demand or on the investment of the current system under investigation. Nonetheless, even with the current results, it can be hypothesized that if the IRR of mineral carbonation is lower, economic performance is would also be lower. Therefore, the cases become less preferred, especially if the weighting is given more on the economic performance and not at 50:50. If the IRR is lower, the case should at least ensure that it can have better environmental performance (for instance, capture a lot of CO_2) to at least overtake the spot with a better preference score. Thus, the relationship between the IRR and the environmental impacts is certainly an attractive future prospects to explore deeper.However, despite this limitation, the current results obtained are already a very useful preliminary indication for technology developers to ascertain the optimal scenario and the direction of development. Furthermore, the results are also very relevant for technology adopters since this indicates which scenario could fit into the value chain best [25]. Based on the MCDA results presented in this study, the authors are now using these results to plot the Pareto front and to subsequently, calculate the optimal carbonation duration for the process optimization which will become the topic of a future publication. To this end, the MCDA results do indicate a ranking of possible environmentally sustainable and economically viable scenario pathways to valorize both waste streams of the steel manufacturing value chains, namely the steel slags and the waste carbon dioxide in the flue gases.

CONCLUSION

In conclusion, this study aims to rank the performance of mineral carbonation scenarios based on environmental and economic criteria by using MCDA, particularly with the Analytical Hierarchical Process approach. The study used upscaled experimental data of different mineral carbonation scenarios to calculate the preliminary environmental and economic impacts which are subsequently used for the MCDA. The results demonstrated the possibility of mineral carbonation of steel slags as a CCUS in a steel manufacturing value chain while simultaneously valorising both waste streams of the value chain, specifically the steel slags and the carbon dioxide in the flue gases. The results indicated that the BOF T2 with an average EU-27 + Switzerland mix has the highest preference score, and similarly, the BOF T2 case has the highest preference score for the baseline case. This means that this carbonation condition would be the most optimized under the criteria assessed. The breakdown analysis showed that the NPV score is the dominating contributor which could vary according to the weighting chosen by the practitioner. The results of this study provide a preliminary indication of the optimal condition of steel slag mineral carbonation for further development and adoption which could potentially lead one step closer towards a sustainable steel manufacturing value chain.

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APPENDIX

Table of Content

3. Supplementary Material – Table 3: Freshwater ecotoxicity potential normalized pairwise matrix
4. Supplementary Material – Table 4: Human toxicity potential normalized pairwise matrix
5. Supplementary Material – Table 5: Ionising radiation potential normalized pairwise matrix
6. Supplementary Material – Table 6: Net present value normalized pairwise matrix
7. Supplementary Material – Table 7: Calculation of the total preference score from the matrix multiplication of the attribute priority score with the scenario-specific priority score

Supplementary Material – Table 1: Global priority pairwise matrix for the calculation of the weighting of the different indicators

Global priority vector	Global priority vector = Criteria vector * priority vector

	Sub-Criteria	Criteria vector	Priority vector	Global priority vector
Environmental	GWP	0.5	0.65	0.325
	FET	0.5	0.1	0.05
	HTC	0.5	0.05	0.025
	IR	0.5	0.2	0.1
Economical	NPV	0.5	1	0.5

Supplementary Material – Table 2: Global warming potential normalized pairwise matrix

Global warming normalized matrix																											
Scenarios	Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: AODT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOFT3 (65% Basalt Rock Powder to 35% Liming Agent Produciton Volume)	AODT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	AODT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOF T1 with drying	BOF T2 with drying	BOF T3 with drying	AOD T1 with drying	AOD T2 with drying	BOF T1 EU-28	BOF T2 EU-28	BOF T3 EU-28	AOD T1 EU-28	AOD T2 EU-28	BOF T1 EU-28 with drying	BOF T2 EU-28 with drying	BOF T3 EU-28 with drying	AOD T1 EU-28 with drying	AOD T2 EU-28 with drying	Normalized total	Priority vector
Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.009	0.005	0.021	0.003	0.004	0.009	0.005	0.021	0.003	0.004	0.023	0.003	0.008	0.004	0.003	0.026	0.004	0.011	0.004	0.003	0.023	0.003	0.005	0.003	0.004	0.212	0.008
Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.026	0.014	0.021	0.005	0.004	0.026	0.015	0.021	0.005	0.004	0.038	0.030	0.011	0.035	0.004	0.044	0.035	0.014	0.032	0.005	0.038	0.028	0.007	0.031	0.007	0.500	0.020
Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.078	0.123	0.192	0.133	0.217	0.078	0.136	0.192	0.133	0.217	0.068	0.089	0.231	0.105	0.152	0.079	0.105	0.293	0.096	0.162	0.068	0.085	0.247	0.094	0.142	3.519	0.140
Baseline: AODT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.043	0.041	0.021	0.015	0.004	0.043	0.045	0.021	0.015	0.006	0.038	0.030	0.011	0.035	0.003	-0.001	0.035	0.014	0.032	0.003	0.038	0.028	0.007	0.031	0.007	0.567	0.023
Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.061	0.068	0.027	0.074	0.031	0.061	0.076	0.027	0.074	0.031	0.053	0.069	0.015	0.082	0.065	0.062	0.082	0.020	0.075	0.070	0.053	0.066	0.016	0.073	0.061	1.391	0.055
BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.009	0.005	0.021	0.003	0.004	0.009	0.005	0.021	0.003	0.004	0.023	0.003	0.008	0.004	0.003	0.026	0.004	0.011	0.004	0.003	0.023	0.003	0.005	0.003	0.004	0.212	0.008
BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.026	0.014	0.021	0.005	0.004	0.026	0.015	0.021	0.005	0.004	0.038	0.030	0.011	0.035	0.004	0.044	0.035	0.014	0.032	0.005	0.038	0.028	0.007	0.031	0.007	0.500	0.020
BOFT3 (65% Basalt Rock Powder to 35% Liming Agent Produciton Volume)	0.078	0.123	0.192	0.133	0.217	0.078	0.136	0.192	0.133	0.217	0.068	0.089	0.231	0.105	0.152	0.079	0.105	0.293	0.096	0.162	0.068	0.085	0.247	0.094	0.142	3.519	0.140
AODT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.043	0.041	0.021	0.015	0.004	0.043	0.045	0.021	0.015	0.006	0.038	0.030	0.011	0.035	0.003	-0.001	0.035	0.014	0.032	0.003	0.038	0.028	0.007	0.031	0.007	0.567	0.023
AODT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.061	0.068	0.027	0.074	0.031	0.061	0.076	0.027	0.074	0.031	0.053	0.069	0.015	0.082	0.065	0.062	0.082	0.020	0.075	0.070	0.053	0.066	0.016	0.073	0.061	1.391	0.055
BOF T1 with drying	0.003	0.003	0.021	0.003	0.004	0.003	0.003	0.021	0.003	0.004	0.008	0.003	0.008	0.002	0.003	0.003	0.002	0.011	0.004	0.003	0.000	0.003	0.005	0.003	0.003	0.131	0.005
BOF T2 with drying	0.026	0.005	0.021	0.005	0.004	0.026	0.005	0.021	0.005	0.004	0.023	0.010	0.008	0.004	0.004	0.026	0.004	0.011	0.004	0.003	0.023	0.028	0.007	0.003	0.004	0.285	0.011
BOF T3 with drying	0.078	0.096	0.063	0.103	0.155	0.078	0.106	0.063	0.103	0.155	0.068	0.089	0.077	0.082	0.152	0.079	0.082	0.032	0.096	0.162	0.068	0.085	0.148	0.094	0.142	2.460	0.098
AOD T1 with drying	0.026	0.005	0.021	0.005	0.004	0.026	0.005	0.021	0.005	0.004	0.038	0.030	0.011	0.012	0.004	0.026	0.000	0.011	0.032	0.005	0.038	0.028	0.007	0.031	0.004	0.399	0.016
AOD T2 with drying	0.061	0.068	0.027	0.074	0.010	0.061	0.076	0.027	0.074	0.010	0.053	0.050	0.011	0.058	0.022	0.062	0.058	0.014	0.053	0.008	0.053	0.066	0.010	0.052	0.061	1.118	0.045
BOF T1 EU-28	0.003	0.003	0.021	0.003	0.004	0.003	0.003	0.021	0.003	0.004	0.023	0.003	0.008	0.004	0.003	0.009	0.002	0.011	0.004	0.003	0.023	0.003	0.005	0.003	0.003	0.176	0.007
BOF T2 EU-28	0.026	0.005	0.021	0.005	0.004	0.026	0.005	0.021	0.005	0.004	0.038	0.030	0.011	0.000	0.004	0.044	0.012	0.011	0.032	0.005	0.038	0.028	0.007	0.031	0.004	0.417	0.017
BOF T3 EU-28	0.078	0.096	0.063	0.103	0.155	0.078	0.136	0.063	0.103	0.155	0.068	0.089	0.231	0.105	0.152	0.079	0.105	0.098	0.096	0.162	0.068	0.085	0.148	0.094	0.142	2.757	0.110
AOD T1 EU-28	0.026	0.005	0.021	0.005	0.004	0.026	0.005	0.021	0.005	0.004	0.023	0.030	0.008	0.004	0.004	0.026	0.004	0.011	0.011	0.005	0.023	0.028	0.007	0.000	0.004	0.310	0.012
AOD T2 EU-28	0.061	0.068	0.027	0.074	0.010	0.061	0.076	0.027	0.074	0.010	0.053	0.069	0.011	0.058	0.065	0.062	0.058	0.014	0.053	0.023	0.053	0.066	0.010	0.073	0.061	1.218	0.049
BOF T1 EU-28 with drying	0.003	0.003	0.021	0.003	0.004	0.003	0.003	0.021	0.003	0.004	0.002	0.003	0.008	0.002	0.003	0.003	0.002	0.011	0.004	0.003	0.008	0.003	0.005	0.003	0.003	0.132	0.005
BOF T2 EU-28 with drying	0.026	0.005	0.021	0.005	0.004	0.026	0.005	0.021	0.005	0.004	0.023	0.003	0.008	0.004	0.003	0.026	0.004	0.011	0.004	0.003	0.023	0.009	0.007	0.003	0.004	0.258	0.010
BOF T3 EU-28 with drying	0.078	0.096	0.038	0.103	0.093	0.078	0.106	0.038	0.103	0.093	0.068	0.069	0.025	0.082	0.109	-0.002	0.082	0.032	0.075	0.116	0.068	0.066	0.049	0.073	0.101	1.843	0.073
AOD T1 EU-28 with drying	0.026	0.005	0.021	0.005	0.004	0.026	0.005	0.021	0.005	0.004	0.023	0.030	0.008	0.004	0.004	0.026	0.004	0.011	0.004	0.003	0.023	0.028	0.007	0.010	0.004	0.312	0.012
AOD T2 EU-28 with drying	0.043	0.041	0.027	0.044	0.010	0.043	0.045	0.027	0.044	0.010	0.053	0.050	0.011	0.058	0.007	0.062	0.058	0.014	0.053	0.008	0.053	0.047	0.010	0.052	0.020	0.893	0.036
Total	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	25	1

Supplementary Material – Table 3: Freshwater ecotoxicity potential normalized pairwise matrix

Freshwater ecotoxicity normalized matrix																											
Scenarios	Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: AODT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOFT3 (65% Basalt Rock Powder to 35% Liming Agent Produciton Volume)	AODT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	AODT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOF T1 with drying	BOF T2 with drying	BOF T3 with drying	AOD T1 with drying	AOD T2 with drying	BOF T1 EU-28	BOF T2 EU-28	BOF T3 EU-28	AOD T1 EU-28	AOD T2 EU-28	BOF T1 EU-28 with drying	BOF T2 EU-28 with drying	BOF T3 EU-28 with drying	AOD T1 EU-28 with drying	AOD T2 EU-28 with drying	Normalized total	Priority vector
Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.008	0.004	0.022	0.003	0.007	0.000	0.004	0.027	0.003	0.008	0.038	0.003	0.004	0.003	0.002	0.031	0.002	0.005	0.002	0.004	0.045	0.032	0.003	0.030	0.024	0.314	0.013
Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.059	0.025	0.028	0.059	0.013	0.060	0.000	0.035	0.060	0.014	0.048	0.069	0.012	0.063	0.054	0.056	0.065	0.010	0.059	0.009	0.045	0.057	0.073	0.054	0.057	1.084	0.044
Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.076	0.176	0.200	0.137	0.330	0.077	0.181	0.000	0.139	0.353	0.048	0.088	0.258	0.081	0.125	0.056	0.116	0.249	0.107	0.192	0.045	0.057	0.094	0.054	0.073	3.313	0.134
Baseline: AODT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.059	0.008	0.028	0.020	0.009	0.060	0.009	0.035	0.000	0.010	0.048	0.069	0.007	0.063	0.054	0.056	0.065	0.010	0.059	0.009	0.045	0.057	0.052	0.054	0.057	0.943	0.038
Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.076	0.126	0.040	0.137	0.066	0.077	0.129	0.050	0.139	0.000	0.048	0.088	0.110	0.081	0.125	0.056	0.090	0.149	0.083	0.137	0.045	0.057	0.094	0.054	0.073	2.133	0.086
BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.008	0.004	0.022	0.003	0.007	0.000	0.004	0.027	0.003	0.008	0.038	0.003	0.004	0.003	0.002	0.031	0.002	0.005	0.002	0.004	0.045	0.032	0.003	0.030	0.024	0.314	0.013
BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.059	0.025	0.028	0.059	0.013	0.060	0.000	0.035	0.060	0.014	0.048	0.069	0.012	0.063	0.054	0.056	0.065	0.010	0.059	0.009	0.045	0.057	0.073	0.054	0.057	1.084	0.044
BOFT3 (65% Basalt Rock Powder to 35% Liming Agent Produciton Volume)	0.076	0.176	0.200	0.137	0.330	0.077	0.181	0.000	0.139	0.353	0.048	0.088	0.258	0.081	0.125	0.056	0.116	0.249	0.107	0.192	0.045	0.057	0.094	0.054	0.073	3.313	0.134
AODT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.059	0.008	0.028	0.020	0.009	0.060	0.009	0.035	0.000	0.010	0.048	0.069	0.007	0.063	0.054	0.056	0.065	0.010	0.059	0.009	0.045	0.057	0.052	0.054	0.057	0.943	0.038
AODT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.076	0.126	0.040	0.137	0.066	0.077	0.129	0.050	0.139	0.000	0.048	0.088	0.110	0.081	0.125	0.056	0.090	0.149	0.083	0.137	0.045	0.057	0.094	0.054	0.073	2.133	0.086
BOF T1 with drying	0.001	0.003	0.022	0.002	0.007	0.001	0.003	0.027	0.002	0.008	0.005	0.001	0.004	0.001	0.002	0.001	0.001	0.005	0.001	0.003	0.035	0.001	0.001	0.001	0.001	0.143	0.006
BOF T2 with drying	0.025	0.004	0.022	0.003	0.007	0.026	0.004	0.027	0.003	0.008	0.038	0.010	0.005	0.027	0.004	0.044	0.004	0.007	0.004	0.004	0.045	0.044	0.003	0.042	0.024	0.433	0.018
BOF T3 with drying	0.076	0.075	0.028	0.098	0.022	0.077	0.077	0.035	0.100	0.023	0.048	0.069	0.037	0.063	0.089	0.056	0.090	0.016	0.083	0.082	0.045	0.057	0.073	0.054	0.073	1.549	0.063
AOD T1 with drying	0.025	0.004	0.022	0.003	0.007	0.026	0.004	0.027	0.003	0.008	0.038	0.003	0.005	0.009	0.002	0.044	0.003	0.005	0.004	0.004	0.045	0.032	0.003	0.042	0.024	0.392	0.016
AOD T2 with drying	0.059	0.008	0.028	0.006	0.009	0.060	0.009	0.035	0.007	0.010	0.048	0.049	0.007	0.063	0.018	0.056	0.039	0.010	0.059	0.009	0.045	0.057	0.052	0.054	0.057	0.855	0.035
BOF T1 EU-28	0.002	0.003	0.022	0.002	0.007	0.002	0.003	0.027	0.002	0.008	0.027	0.001	0.004	0.001	0.002	0.006	0.002	0.005	0.002	0.003	0.035	0.002	0.001	0.018	0.002	0.189	0.008
BOF T2 EU-28	0.042	0.005	0.022	0.004	0.009	0.043	0.005	0.027	0.004	0.010	0.048	0.029	0.005	0.045	0.006	0.044	0.013	0.007	0.036	0.005	0.045	0.044	0.031	0.042	0.041	0.614	0.025
BOF T3 EU-28	0.076	0.126	0.040	0.098	0.022	0.077	0.129	0.050	0.100	0.023	0.048	0.069	0.110	0.081	0.089	0.056	0.090	0.050	0.083	0.137	0.045	0.057	0.073	0.054	0.073	1.858	0.075
AOD T1 EU-28	0.042	0.005	0.022	0.004	0.009	0.043	0.005	0.027	0.004	0.010	0.048	0.029	0.005	0.027	0.004	0.044	0.004	0.007	0.012	0.004	0.045	0.044	0.031	0.042	0.041	0.559	0.023
AOD T2 EU-28	0.059	0.075	0.028	0.059	0.013	0.060	0.077	0.035	0.060	0.014	0.048	0.069	0.012	0.063	0.054	0.056	0.065	0.010	0.083	0.027	0.045	0.057	0.073	0.054	0.057	1.254	0.051
BOF T1 EU-28 with drying	0.001	0.003	0.022	0.002	0.007	0.001	0.003	0.027	0.002	0.008	0.001	0.001	0.004	0.001	0.002	0.001	0.001	0.005	0.001	0.003	0.005	0.001	0.001	0.001	0.002	0.108	0.004
BOF T2 EU-28 with drying	0.002	0.003	0.022	0.002	0.007	0.002	0.003	0.027	0.002	0.008	0.027	0.001	0.004	0.002	0.002	0.000	0.002	0.005	0.002	0.003	0.045	0.006	0.001	0.018	0.002	0.198	0.008
BOF T3 EU-28 with drying	0.025	0.004	0.022	0.004	0.007	0.026	0.004	0.027	0.004	0.008	0.048	0.029	0.005	0.027	0.004	0.044	0.004	0.007	0.004	0.004	0.045	0.044	0.010	0.042	0.024	0.473	0.019
AOD T1 EU-28 with drying	0.002	0.003	0.022	0.002	0.007	0.002	0.003	0.027	0.002	0.008	0.027	0.001	0.004	0.001	0.002	0.002	0.002	0.005	0.002	0.003	0.035	0.002	0.002	0.006	0.002	0.174	0.007
AOD T2 EU-28 with drying	0.001	0.004	0.022	0.003	0.007	0.003	0.004	0.027	0.003	0.008	0.038	0.003	0.004	0.003	0.002	0.031	0.003	0.005	0.002	0.004	0.045	0.032	0.003	0.030	0.008	0.295	0.012
Total	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	25	1

Supplementary Material – Table 4: Human toxicity potential normalized pairwise matrix

Human toxicity - cancer normalized matrix																											
Scenarios	Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: AODT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOFT3 (65% Basalt Rock Powder to 35% Liming Agent Produciton Volume)	ADDT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	ADDT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOF T1 with drying	BOF T2 with drying	BOF T3 with drying	AOD T1 with drying	AOD T2 with drying	BOF T1 EU-28	BOF T2 EU-28	BOF T3 EU-28	AOD T1 EU-28	AOD T2 EU-28	BOF T1 EU-28 with drying	BOF T2 EU-28 with drying	BOF T3 EU-28 with drying	AOD T1 EU-28 with drying	AOD T2 EU-28 with drying	Normalized total	Priority vector
Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.011	0.006	0.023	0.005	0.012	0.011	0.006	0.023	0.005	0.012	0.033	0.004	0.006	0.004	0.004	0.039	0.003	0.007	0.003	0.006	0.037	0.039	0.004	0.037	0.003	0.344	0.014
Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.053	0.028	0.033	0.009	0.017	0.053	0.028	0.033	0.008	0.017	0.046	0.062	0.014	0.059	0.065	0.054	0.081	0.010	0.081	0.011	0.048	0.055	0.064	0.052	0.052	1.034	0.042
Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.074	0.138	0.167	0.137	0.256	0.074	0.138	0.167	0.128	0.256	0.059	0.087	0.209	0.082	0.109	0.054	0.113	0.242	0.000	0.162	0.048	0.055	0.090	0.066	0.073	2.985	0.120
Baseline: AODT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.053	0.009	0.033	0.027	0.017	0.053	0.009	0.033	0.026	0.017	0.046	0.062	0.014	0.059	0.065	0.054	0.049	0.010	0.081	0.011	0.048	0.055	0.064	0.052	0.052	1.000	0.040
Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.074	0.138	0.055	0.137	0.085	0.074	0.138	0.055	0.128	0.085	0.059	0.087	0.125	0.082	0.109	0.054	0.081	0.145	0.081	0.162	0.048	0.055	0.090	0.052	0.073	2.274	0.092
BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.011	0.006	0.023	0.005	0.012	0.011	0.006	0.023	0.005	0.012	0.033	0.004	0.006	0.004	0.004	0.039	0.003	0.007	0.003	0.006	0.037	0.039	0.004	0.037	0.003	0.344	0.014
BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.053	0.028	0.033	0.009	0.017	0.053	0.028	0.033	0.008	0.017	0.046	0.062	0.014	0.059	0.065	0.054	0.081	0.010	0.081	0.011	0.048	0.055	0.064	0.052	0.052	1.034	0.042
BOFT3 (65% Basalt Rock Powder to 35% Liming Agent Produciton Volume)	0.074	0.138	0.167	0.137	0.256	0.074	0.138	0.167	0.128	0.256	0.059	0.087	0.209	0.082	0.109	0.054	0.113	0.242	0.000	0.162	0.048	0.055	0.090	0.066	0.073	2.985	0.120
AODT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.053	0.009	0.033	0.027	0.017	0.053	0.009	0.033	0.026	0.017	0.046	0.062	0.014	0.059	0.065	0.054	0.049	0.010	0.081	0.011	0.048	0.055	0.064	0.052	0.052	1.000	0.040
AODT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.074	0.138	0.055	0.137	0.085	0.074	0.138	0.055	0.128	0.085	0.059	0.087	0.125	0.082	0.109	0.054	0.081	0.145	0.081	0.162	0.048	0.055	0.090	0.052	0.073	2.274	0.092
BOF T1 with drying	0.002	0.004	0.018	0.004	0.009	0.002	0.004	0.018	0.004	0.009	0.007	0.002	0.006	0.002	0.003	0.002	0.002	0.007	0.002	0.005	0.027	0.002	0.002	0.002	0.002	0.147	0.006
BOF T2 with drying	0.032	0.006	0.023	0.005	0.012	0.032	0.006	0.023	0.005	0.012	0.033	0.012	0.008	0.035	0.004	0.039	0.005	0.010	0.005	0.006	0.037	0.039	0.004	0.037	0.031	0.464	0.019
BOF T3 with drying	0.074	0.083	0.033	0.082	0.028	0.074	0.083	0.033	0.077	0.028	0.046	0.062	0.042	0.059	0.109	0.054	0.081	0.016	0.081	0.097	0.048	0.055	0.064	0.052	0.073	1.535	0.062
AOD T1 with drying	0.032	0.006	0.023	0.005	0.012	0.032	0.006	0.023	0.005	0.012	0.033	0.004	0.008	0.012	0.004	0.039	0.005	0.007	0.005	0.006	0.037	0.039	0.004	0.037	0.031	0.429	0.017
AOD T2 with drying	0.053	0.009	0.033	0.009	0.017	0.053	0.009	0.033	0.008	0.017	0.046	0.062	0.008	0.059	0.022	0.054	0.049	0.010	0.049	0.011	0.048	0.055	0.064	0.052	0.052	0.883	0.036
BOF T1 EU-28	0.002	0.004	0.023	0.004	0.012	0.002	0.004	0.023	0.004	0.012	0.033	0.002	0.006	0.002	0.003	0.008	0.003	0.007	0.003	0.005	0.027	0.003	0.003	0.022	0.002	0.218	0.009
BOF T2 EU-28	0.053	0.006	0.023	0.009	0.017	0.053	0.006	0.023	0.008	0.017	0.046	0.037	0.008	0.035	0.007	0.039	0.016	0.010	0.049	0.006	0.037	0.039	0.039	0.037	0.052	0.674	0.027
BOF T3 EU-28	0.074	0.138	0.033	0.137	0.028	0.074	0.138	0.033	0.128	0.028	0.046	0.062	0.125	0.082	0.109	0.054	0.081	0.048	0.081	0.097	0.048	0.055	0.064	0.052	0.073	1.891	0.076
AOD T1 EU-28	0.053	0.006	0.023	0.005	0.017	0.053	0.006	0.023	0.005	0.017	0.046	0.037	0.008	0.035	0.007	0.039	0.005	0.010	0.016	0.006	0.037	0.039	0.039	0.037	0.052	0.623	0.025
AOD T2 EU-28	0.053	0.083	0.033	0.082	0.017	0.053	0.083	0.033	0.077	0.017	0.046	0.062	0.014	0.059	0.065	0.054	0.081	0.016	0.081	0.032	0.048	0.055	0.064	0.052	0.052	1.314	0.053
BOF T1 EU-28 with drying	0.001	0.003	0.018	0.003	0.009	0.001	0.003	0.018	0.003	0.009	0.001	0.002	0.005	0.002	0.002	0.002	0.002	0.005	0.002	0.004	0.005	0.001	0.002	0.001	0.001	0.108	0.004
BOF T2 EU-28 with drying	0.002	0.004	0.023	0.004	0.012	0.002	0.004	0.023	0.004	0.012	0.033	0.002	0.006	0.002	0.003	0.023	0.003	0.007	0.003	0.005	0.037	0.008	0.003	0.022	0.002	0.250	0.010
BOF T3 EU-28 with drying	0.032	0.006	0.023	0.005	0.012	0.032	0.006	0.023	0.005	0.012	0.046	0.037	0.008	0.035	0.004	0.039	0.005	0.010	0.005	0.006	0.037	0.039	0.013	0.037	0.031	0.510	0.021
AOD T1 EU-28 with drying	0.002	0.004	0.018	0.004	0.012	0.002	0.004	0.018	0.004	0.012	0.020	0.002	0.006	0.002	0.003	0.003	0.003	0.007	0.003	0.005	0.027	0.003	0.003	0.007	0.002	0.175	0.007
AOD T2 EU-28 with drying	0.004	0.006	0.023	0.005	0.012	0.004	0.006	0.023	0.005	0.012	0.033	0.004	0.006	0.004	0.004	0.039	0.003	0.007	0.003	0.006	0.037	0.039	0.004	0.037	0.010	0.337	0.014
Total	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	25	1

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Supplementary Material – Table 5: Ionising radiation potential normalized pairwise matrix

Ionising radiation normalized matrix																										
Scenarios	Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: ADOT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOFT3 (65% Basalt Rock Powder to 35% Liming Agent Produciton Volume)	AODT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	AODT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOF T1 with drying	BOF T2 with drying	BOF T3 with drying	AOD T1 with drying	AOD T2 with drying	BOF T1 EU-28	BOF T2 EU-28	BOF T3 EU-28	AOD T1 EU-28	AOD T2 EU-28	BOF T1 EU-28 with drying	BOF T2 EU-28 with drying	BOF T3 EU-28 with drying	AOD T1 EU-28 with drying	AOD T2 EU-28 with drying	Normalized total	Priority vector
Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.140	0.198	0.071	0.129	0.095	0.000	0.212	0.072	0.134	0.093	0.106	0.065	0.053	0.058	0.063	0.254	0.151	0.063	0.107	0.083	0.087	0.058	0.041	0.043	0.057	2.433	0.099
Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.046	0.066	0.071	0.129	0.095	0.054	0.000	0.072	0.134	0.093	0.106	0.065	0.053	0.058	0.063	0.028	0.151	0.063	0.107	0.083	0.087	0.058	0.041	0.043	0.057	1.824	0.074
Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.028	0.013	0.014	0.009	0.004	0.033	0.014	0.000	0.009	0.004	0.004	0.039	0.038	0.035	0.045	0.017	0.010	0.038	0.007	0.005	0.006	0.035	0.041	0.043	0.041	0.531	0.022
Baseline: AODT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.046	0.022	0.071	0.043	0.095	0.054	0.023	0.072	0.000	0.093	0.106	0.065	0.038	0.058	0.045	0.028	0.017	0.063	0.107	0.083	0.087	0.058	0.041	0.043	0.057	1.415	0.057
Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.028	0.013	0.071	0.009	0.019	0.033	0.014	0.072	0.009	0.000	0.007	0.065	0.053	0.058	0.045	0.017	0.010	0.063	0.007	0.050	0.052	0.058	0.041	0.043	0.041	0.878	0.036
BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.140	0.198	0.071	0.129	0.095	0.000	0.212	0.072	0.134	0.093	0.106	0.065	0.053	0.058	0.063	0.254	0.151	0.063	0.107	0.083	0.087	0.058	0.041	0.043	0.057	2.433	0.099
BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.046	0.066	0.071	0.129	0.095	0.054	0.000	0.072	0.134	0.093	0.106	0.065	0.053	0.058	0.063	0.028	0.151	0.063	0.107	0.083	0.087	0.058	0.041	0.043	0.057	1.824	0.074
BOFT3 (65% Basalt Rock Powder to 35% Liming Agent Produciton Volume)	0.028	0.013	0.014	0.009	0.004	0.033	0.014	0.000	0.009	0.004	0.004	0.039	0.038	0.035	0.045	0.017	0.010	0.038	0.007	0.005	0.006	0.035	0.041	0.043	0.041	0.531	0.022
AODT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.046	0.022	0.071	0.043	0.095	0.054	0.023	0.072	0.000	0.093	0.106	0.065	0.038	0.058	0.045	0.028	0.017	0.063	0.107	0.083	0.087	0.058	0.041	0.043	0.057	1.415	0.057
AODT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.028	0.013	0.071	0.009	0.019	0.033	0.014	0.072	0.009	0.000	0.007	0.065	0.053	0.058	0.045	0.017	0.010	0.063	0.007	0.050	0.052	0.058	0.041	0.043	0.041	0.878	0.036
BOF T1 with drying	0.028	0.013	0.071	0.009	0.057	0.033	0.014	0.072	0.009	0.093	0.021	0.065	0.053	0.058	0.045	0.017	0.010	0.063	0.012	0.050	0.052	0.058	0.041	0.043	0.041	1.028	0.042
BOF T2 with drying	0.028	0.013	0.005	0.009	0.004	0.033	0.014	0.005	0.009	0.004	0.004	0.013	0.038	0.035	0.045	0.017	0.010	0.038	0.007	0.005	0.003	0.035	0.041	0.043	0.041	0.498	0.020
BOF T3 with drying	0.020	0.009	0.003	0.006	0.003	0.023	0.010	0.003	0.006	0.003	0.003	0.003	0.008	0.002	0.002	0.012	0.007	0.003	0.005	0.003	0.003	0.002	0.041	0.043	0.003	0.225	0.009
AOD T1 with drying	0.028	0.013	0.005	0.009	0.004	0.033	0.014	0.005	0.009	0.004	0.004	0.004	0.038	0.012	0.045	0.017	0.010	0.004	0.007	0.003	0.003	0.035	0.041	0.043	0.041	0.430	0.017
AOD T2 with drying	0.020	0.009	0.003	0.009	0.004	0.023	0.010	0.003	0.009	0.004	0.004	0.003	0.038	0.002	0.009	0.012	0.010	0.003	0.007	0.003	0.003	0.002	0.041	0.043	0.024	0.298	0.012
BOF T1 EU-28	0.046	0.198	0.071	0.129	0.095	0.054	0.212	0.072	0.134	0.093	0.106	0.065	0.053	0.058	0.063	0.085	0.151	0.063	0.107	0.083	0.087	0.058	0.041	0.043	0.057	2.224	0.090
BOF T2 EU-28	0.046	0.022	0.071	0.129	0.095	0.054	0.023	0.072	0.134	0.093	0.106	0.065	0.053	0.058	0.045	0.028	0.050	0.063	0.107	0.083	0.087	0.058	0.041	0.043	0.057	1.684	0.068
BOF T3 EU-28	0.028	0.013	0.005	0.009	0.004	0.033	0.014	0.005	0.009	0.004	0.004	0.004	0.038	0.035	0.045	0.017	0.010	0.013	0.007	0.005	0.003	0.035	0.041	0.043	0.041	0.464	0.019
AOD T1 EU-28	0.046	0.022	0.071	0.014	0.095	0.054	0.023	0.072	0.015	0.093	0.063	0.065	0.053	0.058	0.045	0.028	0.017	0.063	0.036	0.083	0.087	0.058	0.041	0.043	0.057	1.302	0.053
AOD T2 EU-28	0.028	0.013	0.043	0.009	0.006	0.033	0.014	0.043	0.009	0.006	0.007	0.039	0.038	0.058	0.045	0.017	0.010	0.038	0.007	0.017	0.006	0.058	0.041	0.043	0.041	0.668	0.027
BOF T1 EU-28 with drying	0.028	0.013	0.043	0.009	0.006	0.033	0.014	0.043	0.009	0.006	0.007	0.065	0.038	0.058	0.045	0.017	0.010	0.063	0.007	0.050	0.017	0.058	0.041	0.043	0.041	0.764	0.031
BOF T2 EU-28 with drying	0.028	0.013	0.005	0.009	0.004	0.033	0.014	0.005	0.009	0.004	0.004	0.004	0.038	0.004	0.045	0.017	0.010	0.004	0.007	0.003	0.003	0.012	0.041	0.043	0.041	0.400	0.016
BOF T3 EU-28 with drying	0.015	0.007	0.002	0.005	0.002	0.018	0.008	0.002	0.005	0.002	0.002	0.001	0.001	0.001	0.001	0.009	0.006	0.001	0.004	0.002	0.002	0.001	0.005	0.001	0.001	0.103	0.004
AOD T1 EU-28 with drying	0.015	0.007	0.002	0.005	0.002	0.018	0.008	0.002	0.009	0.002	0.002	0.001	0.001	0.001	0.001	0.009	0.006	0.001	0.004	0.002	0.002	0.001	0.041	0.005	0.001	0.148	0.006
AOD T2 EU-28 with drying	0.020	0.009	0.003	0.006	0.004	0.023	0.010	0.003	0.006	0.004	0.004	0.003	0.023	0.002	0.003	0.012	0.007	0.003	0.005	0.003	0.003	0.002	0.041	0.043	0.008	0.250	0.010
Total	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	25	1

Supplementary Material – Table 6: Net present value normalized pairwise matrix

NPV (5%) normalized matrix

Scenarios	Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: AODT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOFT3 (12.5% Basalt Rock Powder to 87.5% Liming Agent Produciton Volume)	AODT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	AODT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	BOF T1 with drying	BOF T2 with drying	BOF T3 with drying	AOD T1 with drying	AOD T2 with drying	BOF T1 EU-28	BOF T2 EU-28	BOF T3 EU-28	AOD T1 EU-28	AOD T2 EU-28	BOF T1 EU-28 with drying	BOF T2 EU-28 with drying	BOF T3 EU-28 with drying	AOD T1 EU-28 with drying	AOD T2 EU-28 with drying	Normalized total	Priority vector
Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.027	0.018	0.073	0.016	0.093	0.063	0.067	0.054	0.060	0.061	0.074	0.016	0.067	0.014	0.089	0.013	0.039	0.085	0.026	0.011	0.052	0.054	0.046	0.053	0.051	1.222	0.049
Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.133	0.091	0.073	0.144	0.093	0.089	0.094	0.070	0.084	0.061	0.124	0.144	0.067	0.127	0.089	0.114	0.064	0.085	0.042	0.161	0.052	0.054	0.046	0.053	0.051	2.206	0.088
Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.004	0.013	0.010	0.007	0.004	0.004	0.003	0.039	0.004	0.044	0.005	0.007	0.029	0.006	0.004	0.005	0.027	0.003	0.018	0.005	0.041	0.042	0.046	0.041	0.039	0.449	0.018
Baseline: AODT1 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.080	0.030	0.073	0.048	0.093	0.063	0.067	0.054	0.084	0.061	0.124	0.144	0.067	0.127	0.089	0.114	0.039	0.085	0.026	0.097	0.052	0.054	0.046	0.053	0.051	1.822	0.073
Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Produciton Volume)	0.005	0.018	0.052	0.010	0.019	0.063	0.067	0.054	0.060	0.061	0.005	0.010	0.048	0.008	0.053	0.008	0.039	0.051	0.026	0.006	0.052	0.054	0.046	0.053	0.051	0.920	0.037
BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.005	0.013	0.031	0.010	0.004	0.013	0.004	0.039	0.036	0.044	0.005	0.010	0.048	0.008	0.004	0.008	0.027	0.003	0.018	0.006	0.041	0.042	0.046	0.041	0.039	0.545	0.022
BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.005	0.013	0.052	0.010	0.004	0.038	0.013	0.039	0.036	0.044	0.005	0.010	0.048	0.008	0.004	0.008	0.027	0.003	0.018	0.006	0.041	0.042	0.046	0.041	0.039	0.600	0.024
BOFT3 (12.5% Basalt Rock Powder to 87.5% Liming Agent Produciton Volume)	0.004	0.010	0.002	0.007	0.003	0.003	0.003	0.008	0.002	0.002	0.003	0.007	0.001	0.006	0.002	0.005	0.021	0.002	0.014	0.005	0.029	0.030	0.036	0.030	0.028	0.263	0.011
AODT1 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.005	0.013	0.031	0.007	0.004	0.004	0.004	0.039	0.012	0.044	0.005	0.007	0.048	0.008	0.004	0.008	0.027	0.003	0.018	0.006	0.041	0.042	0.046	0.041	0.039	0.507	0.020
AODT2 (0% Basalt Rock Powder to 100% Liming Agent Produciton Volume)	0.004	0.013	0.002	0.007	0.003	0.003	0.003	0.039	0.002	0.009	0.003	0.007	0.002	0.006	0.004	0.005	0.027	0.003	0.018	0.005	0.041	0.042	0.036	0.041	0.039	0.363	0.015
BOF T1 with drying	0.009	0.018	0.052	0.010	0.093	0.063	0.067	0.054	0.060	0.061	0.025	0.010	0.067	0.014	0.089	0.013	0.039	0.085	0.026	0.011	0.052	0.054	0.046	0.053	0.051	1.121	0.045
BOF T2 with drying	0.080	0.030	0.073	0.144	0.093	0.089	0.067	0.054	0.084	0.061	0.124	0.048	0.067	0.127	0.089	0.114	0.039	0.085	0.026	0.097	0.052	0.054	0.046	0.053	0.051	1.847	0.074
BOF T3 with drying	0.004	0.013	0.003	0.007	0.004	0.003	0.003	0.039	0.002	0.044	0.003	0.007	0.010	0.006	0.004	0.005	0.027	0.003	0.018	0.005	0.041	0.042	0.036	0.041	0.039	0.408	0.016
AOD T1 with drying	0.080	0.030	0.073	0.016	0.093	0.063	0.067	0.054	0.060	0.061	0.074	0.016	0.067	0.042	0.089	0.114	0.039	0.085	0.026	0.097	0.052	0.054	0.046	0.053	0.051	1.503	0.060
AOD T2 with drying	0.005	0.018	0.052	0.010	0.006	0.063	0.067	0.054	0.060	0.044	0.005	0.010	0.048	0.008	0.018	0.008	0.039	0.051	0.026	0.006	0.052	0.054	0.046	0.053	0.051	0.854	0.034
BOF T1 EU-28	0.080	0.030	0.073	0.016	0.093	0.063	0.067	0.054	0.060	0.061	0.074	0.016	0.067	0.014	0.089	0.038	0.039	0.085	0.026	0.097	0.052	0.054	0.046	0.053	0.051	1.398	0.056
BOF T2 EU-28	0.133	0.272	0.073	0.241	0.093	0.089	0.094	0.070	0.084	0.061	0.124	0.241	0.067	0.212	0.089	0.190	0.194	0.085	0.383	0.161	0.052	0.054	0.046	0.053	0.051	3.212	0.128
BOF T3 EU-28	0.005	0.018	0.052	0.010	0.006	0.063	0.067	0.054	0.060	0.044	0.005	0.010	0.048	0.008	0.006	0.008	0.039	0.017	0.026	0.006	0.052	0.054	0.046	0.053	0.051	0.808	0.032
AOD T1 EU-28	0.133	0.272	0.073	0.241	0.093	0.089	0.094	0.070	0.084	0.061	0.124	0.241	0.067	0.212	0.089	0.190	0.064	0.085	0.128	0.161	0.052	0.054	0.046	0.053	0.051	2.827	0.113
AOD T2 EU-28	0.186	0.018	0.073	0.016	0.093	0.063	0.067	0.054	0.060	0.061	0.074	0.016	0.067	0.014	0.089	0.013	0.039	0.085	0.026	0.032	0.052	0.054	0.046	0.053	0.051	1.403	0.056
BOF T1 EU-28 with drying	0.003	0.010	0.001	0.005	0.002	0.002	0.002	0.002	0.002	0.001	0.003	0.005	0.001	0.005	0.002	0.004	0.021	0.002	0.014	0.004	0.006	0.002	0.026	0.002	0.017	0.143	0.006
BOF T2 EU-28 with drying	0.003	0.010	0.001	0.005	0.002	0.002	0.002	0.002	0.002	0.001	0.003	0.005	0.001	0.005	0.002	0.004	0.021	0.002	0.014	0.004	0.017	0.006	0.026	0.018	0.028	0.186	0.007
BOF T3 EU-28 with drying	0.003	0.010	0.001	0.005	0.002	0.001	0.001	0.001	0.001	0.001	0.003	0.005	0.001	0.005	0.002	0.004	0.021	0.002	0.014	0.004	0.001	0.001	0.005	0.001	0.001	0.099	0.004
AOD T1 EU-28 with drying	0.003	0.010	0.001	0.005	0.002	0.002	0.002	0.002	0.002	0.001	0.003	0.005	0.001	0.005	0.002	0.004	0.021	0.002	0.014	0.004	0.017	0.002	0.026	0.006	0.028	0.170	0.007
AOD T2 EU-28 with drying	0.003	0.010	0.001	0.005	0.002	0.002	0.002	0.002	0.002	0.001	0.003	0.005	0.001	0.005	0.002	0.004	0.021	0.002	0.014	0.004	0.002	0.001	0.026	0.001	0.006	0.126	0.005
Total	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	25	1

Supplementary Material – Table 7: Calculation of the total preference score from the matrix multiplication of the attribute priority score with the scenario-specific priority score

Final Preference Priority Score	Baseline BOFT1 (50% Basalt Rock Powder to 50% Liming Agent Producito n Volume)	Baseline: BOFT2 (50% Basalt Rock Powder to 50% Liming Agent Producito n Volume)	Baseline: BOFT3 (50% Basalt Rock Powder to 50% Liming Agent Producito n Volume)	Baseline: AODT1 (50% Basalt Rock Powder to 50% Liming Agent Producito n Volume)	Baseline: AODT2 (50% Basalt Rock Powder to 50% Liming Agent Producito n Volume)	BOFT1 (0% Basalt Rock Powder to 100% Liming Agent Producito n Volume)	BOFT2 (0% Basalt Rock Powder to 100% Liming Agent Producito n Volume)	BOFT3 (65% Basalt Rock Powder to 35% Liming Agent Producito n Volume)	AODT1 (0% Basalt Rock Powder to 100% Liming Agent Producito n Volume)	AODT2 (0% Basalt Rock Powder to 100% Liming Agent Producito n Volume)	BOF T1 with drying	BOF T2 with drying
GWP Priority Scores	0.002742	0.00648	0.045583	0.007343	0.018025	0.002742	0.00648	0.045583	0.007343	0.018025	0.001692	0.003692
FET Priority Scores	0.000637	0.002198	0.006715	0.001912	0.004324	0.000637	0.002198	0.006715	0.001912	0.004324	0.000289	0.000878
HTC Priority Scores	0.000346	0.001041	0.003005	0.001007	0.002289	0.000346	0.001041	0.003005	0.001007	0.002289	0.000148	0.000467
IR Priority Scores	0.009871	0.007398	0.002155	0.005739	0.003562	0.009871	0.007398	0.002155	0.005739	0.003562	0.00417	0.002021
NPV (Discount rate = 3%) Priority Scores	0.015913	0.043363	0.002704	0.030769	0.012182	0.005352	0.006266	0.005421	0.004339	0.005685	0.015722	0.033184
Total	0.02951	0.060479	0.060161	0.04677	0.040382	0.018948	0.023382	0.062879	0.02034	0.033885	0.022022	0.040242

Final Preference Priority Score	BOF T3 with drying	AOD T1 with drying	AOD T2 with drying	BOF T1 EU-28	BOF T2 EU-28	BOF T3 EU-28	AOD T1 EU-28	AOD T2 EU-28	BOF T1 EU-28 with drying	BOF T2 EU-28 with drying	BOF T3 EU-28 with drying	AOD T1 EU-28 with drying	AOD T2 EU-28 with drying
GWP Priority Scores	0.031873	0.005173	0.01449	0.002279	0.005401	0.035714	0.004014	0.015784	0.001716	0.003344	0.023875	0.00404	0.011568
FET Priority Scores	0.003139	0.000794	0.001734	0.000384	0.001244	0.003765	0.001134	0.002542	0.000218	0.000401	0.000959	0.000352	0.000597
HTC Priority Scores	0.001546	0.000432	0.000889	0.00022	0.000678	0.001904	0.000628	0.001323	0.000109	0.000251	0.000514	0.000176	0.000339
IR Priority Scores	0.000913	0.001746	0.00121	0.009022	0.006832	0.001883	0.005283	0.00271	0.003099	0.001621	0.000419	0.000602	0.001016
NPV (Discount rate = 3%) Priority Scores	0.00178	0.023586	0.010365	0.022422	0.078181	0.009936	0.06379	0.019236	0.016554	0.034879	0.002012	0.025265	0.011091
Total	0.039251	0.031731	0.028689	0.034327	0.092337	0.053203	0.074848	0.041595	0.021696	0.040497	0.027778	0.030436	0.024611