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Proceeding Paper

Preliminary Environmental Assessment of Carbonated Slags as a Carbon Capture, Utilization, and Storage Materials (CCUS) †

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Abstract: The steel manufacturing industry is one of the most concentrated anthropogenic carbon-emitting point sources that is still expected to increase further each year. Moreover, steel slags are also generated at a rate of 10–20% of the total crude steel production. The possibility to valorize both the flue gases and steel slags through mineral carbonation has garnered the spotlight in recent research on waste valorization and sustainable steel production practices. Mineral carbonation of steel slags leads to the stable adsorption of carbon dioxide onto the surface of the steel slags. Nonetheless, it is essential to assess whether the environmental benefits resulting from the mineral carbonation process would outweigh the environmental burdens associated with the transformation and carbonation processes. To this end, this study aims to illustrate the potential environmentally friendly industrial waste valorization pathway by performing life cycle assessment (LCA) to obtain the environmental impacts of carbonated steel slags. The environmental impacts are calculated by the ReCiPe 2016 midpoint methodology. Furthermore, contribution analysis for the carbonated slag production is provided. This study also illustrates a comparison of steel slag carbonation with pure carbon and flue gases by means of scenario analysis. The results of this study should provide insights into the possibility of employing mineral carbonation on industrial wastes in the metallurgical sector as well as highlight the possible areas of improvement for prospective scale-ups. To this end, the results of this study could contribute to the improvement of the environmental sustainability of the steel manufacturing sector.

Keywords: life cycle assessment; carbonated slags; carbon capture; utilization and storage

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1. Introduction

The metallurgical industry, particularly the iron and steel manufacturing sector, is one of the most concentrated anthropogenic emission point sources in the world [1]. However, due to the urbanization of cities, globalization, and the increase in the world population, the demand for iron and steel will continue to increase over the upcoming decades [2]. Nonetheless, the production of these components has resulted in intense environmental impacts from the steel and iron industry such as carbon emissions. In addition to this, steel slags are also generated at a rate of 10–20% of the total mass of crude steel production [3]. Even if the valorization percentage of the steel slags is as high as 80 to 90% in Europe, the USA, and Japan, these regions are not the regions where the majority of the steel is being produced. In other developing regions, where most of the world's steel production occurs, the valorization of the steel slag is at best at about 30% [4,5]. Hence, research is warranted into the different valorization pathways of steel slags. Given the two mentioned streams, carbon emissions and steel slags, there is a need to reduce or valorize the streams in order to ensure sustainable production of the metallurgical industry.

In this context, mineral carbonation or enhanced weathering of the steel slags can fulfil the role of valorizing the two streams simultaneously [6]. Mineral carbonation of the steel slags entails the formation of carbonate layers on the steel slags from the carbon dioxide that reacts with the slags [3]. Mineral carbonation can be considered as a carbon capture, utilization, and storage (CCUS) technology as the process involves the capture and absorption of carbon dioxide, which could be from flue gases, onto the surface of an alkaline source [7]. Studies have also shown that the carbon dioxide that has been captured is sequestered for millennia and longer [4,8]. However, in order to be classified as a carbon-neutral technology as per the definition of IPCC, it is important that the net carbon emission is at 0 or below, meaning that the environmental impacts from the carbonation process must be less than the amount of carbon captured and sequestered. Therefore, assessment of the environmental impact is essential in order to quantify the net carbon emissions. In view of this need, life cycle assessment (LCA) is a method standardized by the ISO to evaluate and assess the environmental footprint of a product or a service [9]. LCA can provide the net carbon emission in the impact category of the global warming potential (GWP); however, other environmental impact categories can also be calculated and are recommended to be consulted in order to have a comprehensive overview of the environmental impacts of the system under study [9].

The aim of this paper is to present a preliminary environmental impact assessment of lab-scale carbonated slags in the context of a CCUS in an agricultural application as a replacement for basalt. The preliminary environmental impacts can also illustrate the potential of a net-negative waste valorization pathway for the steel slags and waste carbon dioxide by means of mineral carbonation. A scenario analysis is also performed to investigate a simulated case of using flue gases to compare with the use of pure carbon dioxide.

2. Materials and Methods

2.1. Description of the LCA Methodology and Scenario Analysis

The LCA methodology is a four-step assessment that is used to quantify the environmental impacts of a system under study. In the first step, the goal and scope definition must be defined in order to set up the objective of the LCA as well as the system boundary under study. Here, the functional unit as well as the reference flow quantity must also be defined so that the subsequent step can be prepared accordingly. In the second step, the life cycle inventory is constructed based on the empirical or literature data in such a way that the mass and energy balance related to the system under study are aligned with the reference flow defined in the first step. Subsequently, the third step, life cycle impact assessment, translate the mass and energy quantities from the life cycle inventory to equivalent environmental impacts with the use of characterization factors. In the final step, the obtained results are interpreted and assessed based on the objective of the LCA study, and if needed, the LCA can be reiterated.

Within the scope of this paper, the wet carbonation of argon–oxygen decarburization (AOD) steel slags on a lab scale is assessed. The scope of the study is from cradle to gate, which includes the production of the carbonated slags and the use of the obtained slags in comparison to the application of basalt. The functional unit of this LCA study is the production and use of 0.5 kg of carbonated AOD slags. The life cycle inventory is then constructed based on the empirical and literature data according to this reference flow. The steel slags are treated as a by-product and are allocated based on economic allocation where the price of the stainless steel is 2200 EUR/ton and the price of the AOD slags is at 27 EUR/ton. The ReCiPe 2016 midpoint impact assessment is the methodology used to calculate the environmental impacts. In this study, the GaBi software is used to calculate the environmental impacts with the use of Ecoinvent 3.8 and ThinkSteps databases. The impacts related to the processes of basalt production are calculated based on the process activities available on Ecoinvent 3.8 for "Market for basalt". The activity took into account the environmental impacts related to the extraction of raw materials and the post-processing of the product. Within this study, the carbonated slags are used for the cultivation of maize at 5 ton/ha while the avoided impacts of the basalt are calculated based on the application rate of 50 ton/ha. The contribution analysis is also performed in order to interpret the calculated environmental impacts. In order to demonstrate the importance of valorizing the waste carbon stream, a scenario analysis is performed with a simulated case where the flue gas with a carbon dioxide content of 20 v/v% is used under the assumption of the same experimental conditions and carbon sequestration potential as the case of pure carbon dioxide, but with supplemental energy to compensate for the longer reaction duration. The amount of carbon sequestered is experimentally measured by thermogravimetric analysis (TGA) and is taken into account in the LCA.

2.2. Description of the Carbonated Slag Production System

The lab-scale scenario that will be used for the preliminary environmental assessment is the wet carbonation of the argon–oxygen decarburization (AOD) steel slags. The AOD slags were obtained from Aperam, Belgium and were grinded to a size of 2 mm. The grinding energy was assumed to be at 0.0763 kWh per kg of grinded steel slags. The grinded AOD slags were then manually sieved to exclude the slags with sizes greater than 2 mm. As a consequence, one kg of AOD slags resulted in 0.502 kg after sieving. The sieved AOD slags of 0.502 were then fed into the carbonation reactor along with 0.14 kg of distilled water and 0.0835 kg of pure carbon dioxide. An assumption was also made that on a lab-scale, the leftover carbon dioxide, if any, can be reused in the next carbonation process. A water bath was used to heat the carbonation reactor to maintain a constant temperature of 30 Celsius during the reaction for the duration of 3 h. This resulted in an energy consumption of 0.0903 kWh. The final product was 0.5 kg of carbonated steel slags with 0.04 kg of carbon dioxide sequestered. In the scenario analysis where a flue gas with a carbon dioxide content of 20 v/v% was simulated, additional energy of 0.00968 kWh was supplemented to the carbonation step based on the ideal gas law calculation with the assumption of maintaining the same stoichiometric available carbon dioxide ratio as in the case of pure carbon dioxide. The life cycle inventory is shown below in Table 1.

Table 1. Life cycle inventory of the AOD slag carbonation.

Input	Amount	Unit
Grinded AOD slags	1	kg
BE: electricity grid mix	0.0903	kWh
Tap water	0.140	Kg
Carbon dioxide	0.0835	kg
Output	**Amount**	**Unit**
Carbonated AOD slags	0.5	kg

3. Results and Discussion

The environmental impacts of the carbonated AOD slags in comparison to the application of basalt in agriculture are summarized in Table 2. The environmental impacts associated with the scenario of AOD slag carbonation with flue gases (20 v/v% carbon dioxide) are also included. The results indicated that the wet carbonation of the steel slags as a substitute for basalt and lime is a net-negative technology, particularly when assessing the GWP. Despite the potential to have avoided impacts in different impact categories, it is important to also consider the other impact categories such as freshwater and marine ecotoxicity, human toxicity (cancer), and ionizing radiation since the environmental impacts for these categories are burdensome to the environment. The scenario analysis results also indicated that when flue gas is used instead of pure carbon dioxide, the absolute values of the different environmental impacts can become even lower. This can be explained by the fact that the energy requirements for longer carbonation are essentially lower than the energy requirements for the capture, purification, compression, and transportation of the carbon dioxide in the case of using pure carbon dioxide. The LCA results suggested the potential for slag carbonation and the potential use in agriculture as a meaningful CCUS since the technology satisfies the definition of net-negative carbon removal technology given by the IPCC, where the net carbon emission in the case of this study is negative at −0.043 and −0.059 kg eq. respectively.

Table 2. Midpoint environmental impacts of the AOD slag carbonation.

Midpoint Environmental Impact Categories	Carbonation of AOD Slags	Carbonation of AOD Slags with Flue Gases
Climate change, default, incl. biogenic carbon (kg CO_2 eq.)	-4.33×10^{-2}	-5.94×10^{-2}
Fine particulate matter formation (kg PM2.5 eq.)	-2.16×10^{-4}	-2.29×10^{-4}
Fossil depletion (kg oil eq.)	-2.89×10^{-2}	-3.84×10^{-2}
Freshwater consumption (m^3)	-1.81×10^{-3}	-1.91×10^{-3}
Freshwater ecotoxicity (kg 1.4 DB eq.)	2.30×10^{-3}	1.83×10^{-3}
Freshwater eutrophication (kg P eq.)	-4.51×10^{-6}	-6.89×10^{-6}
Human toxicity, cancer (kg 1.4-DB eq.)	2.14×10^{-1}	2.13×10^{-1}
Human toxicity, non-cancer (kg 1.4-DB eq.)	-2.83×10^{-2}	-3.72×10^{-2}
Ionizing radiation (kBq Co-60 eq. to air)	3.98×10^{-2}	2.85×10^{-2}
Land use (annual crop eq.·y)	-2.94×10^{-2}	-3.00×10^{-2}
Marine ecotoxicity (kg 1.4-DB eq.)	3.00×10^{-3}	2.37×10^{-3}
Marine Eutrophication (kg N eq.)	-1.05×10^{-7}	-5.63×10^{-7}
Metal depletion (kg Cu eq.)	-2.45×10^{-4}	-2.75×10^{-4}
Photochemical ozone formation, ecosystems (kg NOx eq.)	-6.20×10^{-4}	-6.70×10^{-4}
Photochemical ozone formation, human health (kg NOx eq.)	-6.08×10^{-4}	-6.57×10^{-4}
Stratospheric ozone depletion (kg CFC-11 eq.)	-4.66×10^{-8}	-5.51×10^{-8}
Terrestrial acidification (kg SO_2 eq.)	-4.15×10^{-4}	-4.49×10^{-4}
Terrestrial ecotoxicity (kg 1.4-DB eq.)	-3.60×10^{-1}	-4.46×10^{-1}

The GWP contribution analysis of the AOD slags production and use as a substitute for basalt in agriculture is performed and presented in Figure 1 below. The results from the scenario analysis with the flue gas of 20 v/v% carbon dioxide are also presented. The contribution analysis for both cases indicates that the most impactful step in the production of the carbonated slags is the electricity consumed during the carbonation. In view of this, future experiments will focus on performing the carbonation process without the use of heating since the carbonation process can be exothermic and could provide sufficient heating [4]. In this way, the GWP impacts related to the electricity consumed during the carbonation could potentially be reduced, which in turn will reduce the overall GWP further. Contribution analysis also indicates the technological importance of the utilization of the carbonated slags since the biggest share of GWP avoided impacts resulting from basalt production and usage. To this end, carbonated slags, with the ability to valorize both the carbon emission stream and the steel slags stream, have been demonstrated to be a net-negative CCUS that warrants further research in process optimization and scale-up by taking these findings into account [10]. Furthermore, given these findings, it would be of great interest to test the applications in the agricultural field setting as well as to assess the in-situ climate mitigation effect to provide more insights into these results.

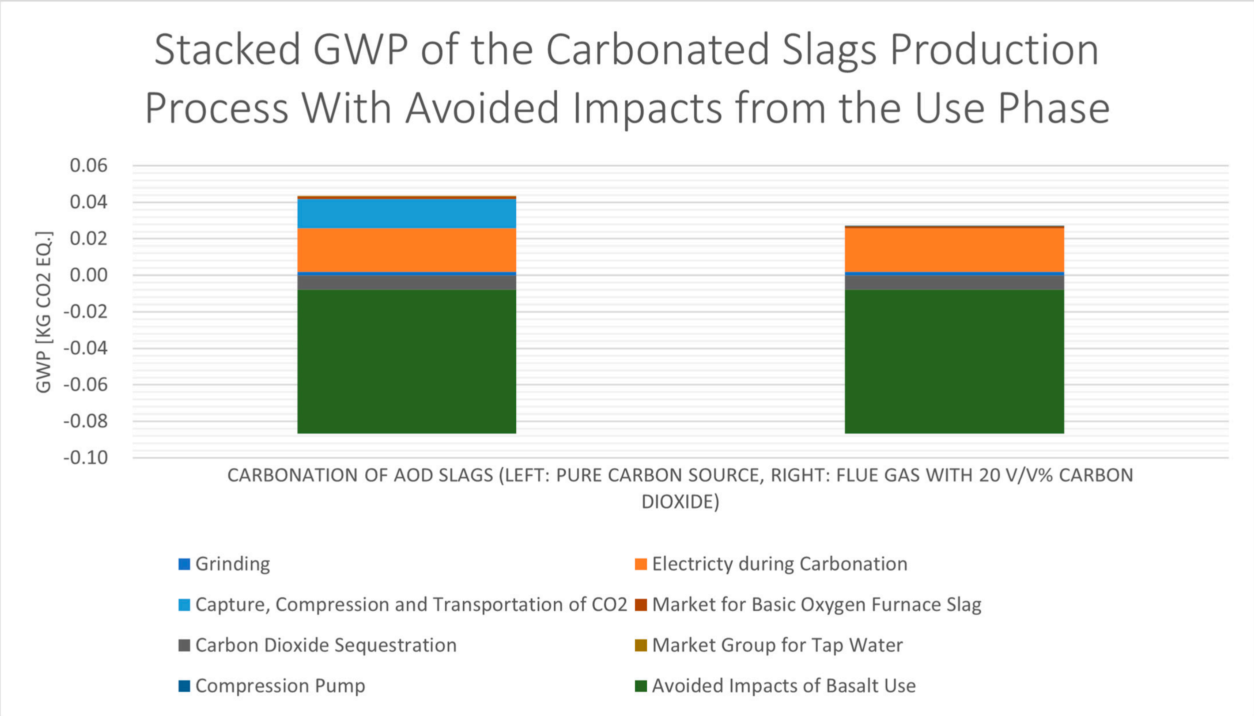

Figure 1. Contribution analysis of the AOD slag carbonation.

4. Conclusions

In conclusion, this study aims to perform a preliminary environmental impact assessment on lab-scale carbonation of AOD slags in order to illustrate the potential of steel slag carbonation as an effective CCUS. The results obtained presented a net-negative carbon emission for the AOD slags carbonation which satisfied the criteria of a carbon-neutral technology CCUS by the IPCC. In addition to this, the scenario analysis with the simulated flue gas carbonation also highlighted the importance of valorizing all potential waste streams to achieve lower environmental impact results. The results of this study provide insights into the possibility to employ mineral carbonation on industrial wastes in the metallurgical sector. The reduction in electricity consumption during carbonation and the technological fulfilment of the function of carbonated steel slags are also important aspects to focus the research and scale-up on. The results presented in this study highlight the potential of steel slag carbonation to contribute to the improvement of the current environmental sustainability of the steel manufacturing sector.

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