materials proceedings

MDPI

Proceeding Paper

Potential Benefits from Carbon Capture Utilisation and Methanol Production in Magnesite Processing Line †

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† Presented at the 2nd International Conference on Raw Materials and Circular Economy "RawMat2023", Athens, Greece, 28 August–2 September 2023.

Abstract: Magnesite ($MgCO_3$) is a carbonate mineral, which is calcinated and further processed to generate magnesia (MgO) refractory materials and other products. $MgCO_3$ products are mainly used in the iron and steel industries, in cement manufacture as a refractory material, and as raw materials in the chemical industry, in agriculture, etc. The MgO refractory industry is linked with carbon dioxide (CO_2) emissions released not only from the fuel combustion in the production process of $MgCO_3$, but also from its decomposition. Even though the exact amount of CO_2 eq. depends on the specific product, there is the urge to minimise the CO_2 emitted from MgO_3 processing. Carbon capture and utilisation (CCU) technology has gained ground in recent years in this industry. The incorporation of CCU systems for the processing of fuel gases has been investigated as a means to contribute further to the decarbonisation of the extractive industries. The CO_2 captured through this process can be converted into a value-added chemical or liquid fuel. This study aims to overview the impact of the application of CCU technologies in $MgCO_3$ processing lines and the conversion of the captured CO_2 to methanol (MeOH). In this regard, the strengths (S), the weaknesses (W), the opportunities (O), and the threats (T) of the proposed concept will be discussed in a SWOT analysis coupled with the environmental and techno-economic aspects.

Keywords: magnesite; magnesia; carbon capture and utilisation; methanol (MeOH); SWOT analysis

Citation: Peppas, A.; Skenderas, D.; Politi, C.; Sparis, D. Potential Benefits from Carbon Capture Utilisation and Methanol Production in Magnesite Processing Line. *Mater. Proc.* **2023**, *15*, 29. https://doi.org/10.3390/materproc2023015029

Academic Editors: Antonios Peppas, Christos Roumpos, Charalampos Vasilatos and Anthimos Xenidis

Published: 3 November 2023

1. Introduction

Magnesite is a magnesium-rich carbonate mineral with a chemical composition of $MgCO_3$ that is a principal source of magnesium and is typically mined through open-pit operations [1]. Theoretically, $MgCO_3$ contains 52.4% CO_2 and 47.6% MgO, but these percentages vary in nature because they include different amounts of impurities [2]. Raw magnesite may be used for surface coatings, landscaping, ceramics, and as a fire retardant [3]. However, mostly it is further processed for the production of dead burned magnesia (magnesium oxide—MgO) or caustic calcined magnesia. The products generated depend on the different heat treatments applied [4]. Dead burned magnesia is widely used for refractory bricks which are stable at high temperatures and are used to line furnaces in the steel industry, non-ferrous metal processing units, and cement kilns. Indicatively, 57% of the magnesia produced is used in the steel-making sector [5]. Caustic calcined magnesia is used principally as a supplement in agribusiness (e.g., for fertiliser production), for fillers in paints, paper, and plastics, and numerous other applications [5]. However, the magnesia production process results in the generation of important emissions. About 70% of these emissions are derived from processes (carbonate decomposition) and thermal energy consumption [5].

The chemical reactions among the raw materials and their thermal decomposition during the production process result in the process emissions. These emissions, which are related to the nature and the stoichiometry of the ore processed, are unavoidable [5]. In this regard, to lessen their environmental impact and reduce CO_2 emissions, the sector has focused on improving the productivity and the energy efficiency of the plants. Even though there an important reduction in energy consumption of up to 50% has been seen since 1980, process emissions remain an unsolved issue. A sustainable solution to deal with this problem is carbon capture utilisation (CCU). With CCU, the process CO_2 emitted can be captured as a high-purity CO_2 stream or with the flue gases, from an indirect calcination step or thermal treatment process, respectively [5].

Through magnesite processing, CO_2 emissions are generated. China, which is the main magnesia producer and exporter, covers up to 71% of the world's magnesia demand. Russia, Turkey, and Brazil together account for 11% [6]. The remaining part is covered mostly by the other main producers, such as Austria, Slovakia, Spain, Australia, Greece, North Korea, and India [5]. The trends in overall magnesia production closely reflect those of the Chinese outputs. In this view, the carbon footprint of magnesia considering the Chinese production ranges from 1.440 to 4.804 CO_2 eq./kg MgO. The less heat is required for a product, the smaller its carbon footprint [7].

CCU has been identified as a technology that will play a crucial role in addressing decarbonisation [8]. CCU refers to a process that captures CO_2 emissions from industrial or power generation sources and converts or utilises the CO_2 to produce marketable products, such as chemicals, fuels, biological processes, and polymers. [9].

This study opts to overview the effect of CCU technology applications in the $MgCO_3$ processing line and the production of methanol (MeOH) from the CO_2 captured. This will be implemented in the framework of a SWOT analysis focusing on the environmental and techno-economic aspects of the system discussed. SWOT analysis is a framework for identifying and analysing the strengths (S), weaknesses (W), opportunities (O), and threats (T) of a system or project to evaluate its viability [10].

2. Magnesite Processing Line

The typical magnesite processing line includes several stages, including the beneficiation and the extraction processes. The beneficiation processes include techniques regarding the enrichment and size reduction of the ore for further processing. After beneficiation, the metallurgical extraction process follows. Typically, the magnesite is subject to calcination in a kiln or rotary furnace. Calcination involves heating magnesite. Depending on the heat treatment applied, different products can be generated. At a temperature of 700 °C, the CO_2 included in the $MgCO_3$ begins to escape.

$$MgCO_3 \rightarrow MgO + CO_2$$

In a temperature range from 700 °C to 1000 °C, caustic calcined magnesia is obtained. A further temperature increase in the range of 1500 °C to 2300 °C results in the generation of dead burned magnesia [2]. The quality and special characteristics of the magnesite ore processed affect the treatment temperatures applied and the characteristics of the products, resulting in important CO_2 emissions. A typical composition of flue gases from a magnesite processing line is shown in Table 1.

Table 1. Magnesite processing line flue gas composition (% mass) [11,12].

Compounds	Composition Range (%)
CO_2	13.5–17.5
H_2O	5.0–11.0
N_2	67.0–75.0
O_2	0.0–10.5

The specific composition of the flue gases is defined by the quality of the ore and the energy fuel used. The CO_2 refers to that coming from fuel consumption and the process emissions. The final CO_2 mix is mostly defined by the fuel mix used, as the process CO_2 emitted is relatively stable [12]. Even though the implementation of new, more efficient technologies and the use of green energy sources will significantly affect the magnesia industry emissions, a solution needs to deal with the process emissions arising from the carbonate decomposition.

3. Carbon Capture Utilisation in the Magnesite Processing Line

Environmental and climate targets require the industry to transition to more efficient technologies that will impact less on the environment to reach net zero emissions globally. CCU has gained momentum in recent years as it seems to play a strategic role in global decarbonisation, especially in heavy industries such as mining and metallurgy [8,13].

CCU includes technologies for capturing CO_2 emissions from different stages of an industrial process and generating useful marketable products. The capture and utilisation stages are distinguished. For the capturing of CO_2, the main methods are (i) post-combustion, in which CO_2 is derived from the flue gases emitted from the process line where it is applied; (ii) pre-combustion, which is a more intrusive method as it involves converting the fuel into a gas mixture consisting of hydrogen and CO_2 before it is burnt; and (iii) oxyfuel combustion, which involves burning fuel with almost pure oxygen to produce CO_2 and steam, capturing the CO_2 released [14].

The efficiency of the CCU technology applied is connected to the ability and the efficiency of capturing the CO_2 from flue gases. This concentration is a key factor for the selection of the proper CO_2 capture technology as well [15]. The higher the concentration of CO_2 in the flue gases, the easier it is to capture it [16]. Typically, flue gases from industrial processes such as power plants or cement factories have CO_2 concentrations ranging from 5% to 10% [17–19]. In this light, the concentration of flue gases in a magnesite processing line, as indicated in Table 1. (13.5% to 17.5%), makes the application of CCU technologies even more efficient. The cost efficiency of carbon capture increases with higher CO_2 concentration. Indicatively, the cost efficiency of 13% flue gas CO_2 concentration compared to 5% flue gas CO_2 concentration is 22% and 33% higher for full capture (90%) and partial capture (67%), respectively [20].

Regarding the utilisation of CO_2, five main utilisation paths are followed: chemical conversion, direct chemical utilisation, mineral carbonisation, enhanced oil recovery, and biological conversion [21]. This technology allows for the utilisation of CO_2 to generate valuable products such as methanol, urea, carbamates, and fine chemicals. Of these products, methanol production from the hydrogenation of CO_2 feedstocks is gaining more ground. Methanol is a biodegradable product that can be used as an alternative fuel and has other implications in the pharmaceutical sector, for acetic acid or plastic production, etc. [22,23]. In particular, CCU methanol production is considered to lower the CO_2 footprint compared to conventional methanol [24].

Regarding the magnesite processing line, CCU can be applied. Specifically, CO_2 can be captured from the indirect $MgCO_3$ calcination stage, or cumulatively with the CO_2 emissions of the other stages (the flue gases), using the post-combustion capturing method. The CO_2 captured can be used for methanol production as an alternative fuel that will feed back the process [3] or as a product to be exported that may contribute credits and economic value to the company. Combining the use of green energy with CCU methanol production will result in more environmentally friendly methanol production with a lower carbon footprint than traditional methanol [24].

4. SWOT Analysis

SWOT analysis is a theoretical framework used to qualitatively evaluate the "strengths", "weaknesses", "opportunities", and "threats" in any field that requires strategic planning [25]. Strengths and weaknesses refer to internal characteristics, while opportunities and threats refer to external ones. The opportunities and threats affect the systems, and hence they can only react to and not influence them [26]. Strengths and weaknesses include attributes, characteristics, and factors that provide competitive advantages or weaken the position of a system in the marketplace. Along the same line, opportunities and threats include favourable or unfavourable situations and factors that can provide or deprive a system of new sources or competitive advantages, respectively. In this framework, a SWOT analysis is performed to evaluate the potential of incorporating the CCU technology in the magnesite processing line and for methanol production.

Strengths: The utilisation of CCU in the magnesite processing companies which generate an important carbon footprint would assist the reduction of CO_2 emissions, addressing the decarbonisation challenge of process emissions [27]. The high concentration of CO_2 in flue gases contributes to the efficiency and effectiveness of the carbon capture process on the magnesite processing line. In this way, the environmental performance of the company would improve and comply with the restrictions and environmental laws, avoiding any financial fines and gaining credits. Except for being able to reduce the CO_2 emitted, this process leads to the generation of added-value products. Whether these products are used internally (as fuels for processing) or are outputted in the marketplace, they may benefit companies economically.

Weaknesses: The adoption of new technologies in complex industries is challenging. The efficiency of these technologies and the synergy of the existing technologies with the new ones may need time, affecting the processing line and productivity of the company. Except for the technical aspect, the implementation of CCU technology is capital-intensive to deploy and energy-intensive to operate. The cost of CO_2 capture is mainly related to the conditions of the gas stream (temperature, flow rate, CO_2 concentration, etc.), the technologies used, and the electricity and fuel prices. The fluctuations in the flue gas stream characteristics and the energy prices makes it a risky investment for companies [8,28,29]. The safety issues generated are not to be ignored as well. Even though CCU is considered safe, new regulations need to be applied to ensure and protect human health, the environment, and the uninterrupted operation of the company.

Opportunities: Even though CCU technology is under development, some trends support the implementation of CCU technologies. The target regulations toward global decarbonisation are becoming stricter, demanding respective actions from industry. The International Energy Agency estimates that CCU could reduce CO_2 emissions by up to 10% by 2050 [30]. In this line, governments are providing funding, boosting the industrial involvement in funded projects, and trying to set the corresponding framework, driving progress towards net zero ambitions [28]. For instance, the United States announced favourable CCUS tax credit changes in the 2022 Inflation Reduction Act; the European Union launched the Net Zero Industry Act in March 2023, proposing an annual CO_2 injection target and improved permitting procedures for CCUS; the United Kingdom announced GBP 20 billion in its Spring Budget 2023 for the early deployment of CCUS projects; and Indonesia finalised its legal and regulatory framework for CCUS in March 2023 [31]. Regarding methanol production, the environmental feasibility of producing CO_2-captured methanol, especially if combined with the use of green energy consumption to decrease the carbon footprint, is expected to impact methanol market requirements [24].

Threats: CCU technologies have already been applied in the industry; however, it remains a technology under development. The evolution and the upgrades that may follow in this field may affect the competitiveness of a company utilising CCU technologies at this stage. The correlation of this technology with energy makes its cost-effectiveness susceptible to political and geopolitical instabilities that affect the energy price [29]. Furthermore, even if governments' regulations support the transition to technologies that will contribute to industry and global decarbonisation, most countries in the world have not issued specific policies, laws, standard systems, or technical specifications targeting CCU [32]. As for methanol, price and market regulations are unstable. This may lead to economic limitations [28].

5. Discussion

The products generated from magnesite processing, and especially magnesia, are of great importance for varying industries. The nature of magnesite, combined with the processing it is required to undergo, generates an important amount of CO_2 emissions. With the aim of global decarbonisation, the industry is attempting to face this challenge with more efficient processing technologies and the use of green energies. The need to further lower the emissions created by the demand for addressing the process emissions problem is also present. A promising solution to deal with this challenge is the utilisation of CCU technologies for capturing the generated CO_2 and converting it into valuable products. For this to turn into a feasible and efficient solution for the magnesia industry, technical, environmental, and economic obstacles require further development and evaluation.

6. Conclusions

This study evaluated the potential of incorporating CCU technology in a magnesite processing line to deal with CO_2 emissions and methanol production. According to the literature review, this solution may lead to an important reduction of the carbon footprint of magnesite extraction processing. In this scope, reasons that may promote or risk the suggested concept were identified through a SWOT analysis. Considering the points mentioned, even if this is a promising solution with regard to the environmental conditions, target and regulation, cooperation of industry and government is required regarding the technical and economic terms.

Author Contributions: Conceptualisation, A.P., C.P. and D.S. (Dimitris Sparis); methodology, A.P., C.P. and D.S. (Doris Skenderas); validation, A.P. and C.P.; investigation, D.S. (Doris Skenderas); writing—original draft preparation, D.S. (Doris Skenderas); writing—review and editing, C.P. and D.S. (Dimitris Sparis); supervision, A.P. and C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data sources used are cited.

Conflicts of Interest: The authors declare no conflict of interest.

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