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Techno-economic and environmental evaluation of CO_2 mineralization technology based on bench-scale experiments

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ABSTRACT

This work presents a techno-economic & environmental analysis of a CO_2 mineralization process, intended to examine its potential for CO_2 reduction and economic feasibility. The CO_2 mineralization technology of this study is composed of the CO_2 carbonation process and the brine electrolysis process, producing various chemical compounds such as sodium bicarbonate, hydrogen, and chlorine. Notably, the CO_2 mineralization process is able to utilize flue gas with a low concentration of CO_2 that has not been subjected to CO_2 capture processes. For the technical feasibility analysis of the CO_2 mineralization process examined in the study, performance evaluation is conducted for a bench-scale CO_2 mineralization test unit (2 kg/day CO_2 utilization capacity), yielding sodium bicarbonate of over 97% purity. It is also estimated that the CO_2 utilization process of this study produces 0.65 tons of CO_2 emissions per ton of sodium bicarbonate produced, which indicates a 2.09 ton CO_2 reduction compared to the conventional processes which produce 2.74 tons of CO_2 emissions for the same amount of sodium bicarbonate production. With these results as a basis, an economic evaluation is conducted for a commercial-scale CO_2 utilization plant (sodium bicarbonate production capacity: approximately 5000 tons/year) which utilizes CO_2 in flue gas produced from thermal power plants. The evaluation supports the economic feasibility of the process with a benefit/cost ratio (B/C ratio) of 1.12 and internal rate of return (IRR) of 10.4%.

1. Introduction

CO_2 utilization aims to use the anthropogenic CO_2 produced from processes such as the combustion of fossil fuels as feedstock or working fluid in industrial chemicals and fuel production. There are a variety of applications of CO_2 utilization, which can be divided into three categories: resource recovery, non-consumptive uses, and consumptive uses [1]. Resource recovery includes process of recovery of conventional and unconventional hydrocarbon resources such as oil (enhanced oil recovery, EOR), gas (enhanced gas recovery, EGR) and methane (enhanced coalbed methane, ECBM). This has shown promise as an economical method to reduce the costs of Carbon Capture & Storage (CCS) technology. Currently, the Boundary Dam CCS project of Canada (in operation since 2014 [2]) and the Petra Nova power plant of USA (in operation since 2016 [3]) each captures over 1 million tons of CO_2 per year, which are utilized for EOR projects. Non-consumptive CO_2-use applications have an indirect CO_2 reduction benefit(not directly consumed) in the form of production of fresh water or various minerals [1]. This application also includes the production of fuel and chemicals, and use of CO_2 as a working fluid and for desalination process. Lastly, consumptive CO_2-use applications include the formation of minerals, or long-lived compounds leading to net-carbon sequestration [1].

CO_2 utilization is intended to be a measure of reducing CO_2 emission in a cost-effective manner, particularly in a nation where onshore/offshore site required for CO_2 storage or resource recovery is scarce. It has been estimated that the maximum potential of CO_2 reduction by CO_2 utilization to chemicals and liquid fuel would be around 200 $MtCO_2/yr$ and 2 $GtCO_2/yr$, respectively [4]. Given the economic incentive coupled with CO_2 reduction potential, various research efforts are underway for the development of CO_2 utilization technologies.

This study focuses on mineralization as means of CO_2 utilization. Examples of companies that are operating commercial-scale projects of CO_2 mineralization include Skyonic Corporation and Calera Corporation in the US, and Twence in the Netherlands. The Skymine project of Skyonic has been supported by the US Department of Energy since 2010, for developing a technology to chemically react flue gas with caustic soda obtained from the electrolysis of brine to produce chemicals such as sodium bicarbonate ($NaHCO_3$). In San Antonio, TX, a

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plant utilizing CO_2 emitted from a cement factory to produce sodium bicarbonate, hydrogen chloride(HCl), bleach(NaOCl) and chlorine(Cl_2), has been in operation since October 2014. The plant is capable of utilizing approximately 75,000 tons of CO_2 per year to produce 140,000 tons of sodium bicarbonate per year [5]. Calera uses an electrochemical process named "Alkalinity Based on Low Energy (ABLE)" to react calcium and magnesium cations obtained from caustic soda and sea water with CO_2 in flue gas to produce calcium carbonate and magnesium carbonate, respectively. Presently, a pilot plant has been constructed and is in operation in California, where CO_2 from the Dynegy Moss Landing Power Plant (generation capacity: 1.5 GW) is utilized to produce supplementary cement materials (5 tons/day) [6]. Twence, from the Netherlands, has developed a plant capable of utilizing CO_2 and sodium carbonate produced by waste-to-energy plants to produce sodium bicarbonate, which in turn is utilized to remove SOx/HCl in flue gas. The plant is capable of utilizing approximately 2000 tons of CO_2 per year to produce 8000 tons of sodium bicarbonate per year.

Regarding the potential CO_2 reduction of CO_2 mineralization technology, life cycle analysis (LCA) studies on various CO_2 utilization technologies conducted by the Global CCS Institute suggest that CO_2 mineralization has the potential to give greater amounts of CO_2 reduction compared to other CO_2 utilization technologies [7]. On the other hand, even though several commercial-scale CO_2 utilization plants are operating, detailed studies on the economic feasibility and CO_2 reduction evaluation are limited [8–10]. In order for CO_2 mineralization technology to be accepted as a meaningful means of reducing CO_2, more comprehensive life cycle analysis (LCA) and techno-economic assessment (TEA) are needed, in addition to concrete strategies for entering the market.

Motivated by the current state, this study proposes a reliable technological means for CO_2 mineralization to $NaHCO_3$ through technological developments including reactor design and bench-scale tests, and a detailed analysis of a scaled-up plant based on process simulation. Evidence is provided for the technical feasibility of the CO_2 mineralization plant, achieved through effective process configuration. The economic feasibility and potential CO_2 reduction of commercial-scale plants are assessed through comprehensive TEA and LCA of the scaled-up plant.

2. Methodology

2.1. Framework overview

The techno-economic evaluation of this study involves a technical feasibility analysis, CO_2 reduction estimation, and an economic analysis of the commercial scale CO_2 utilization plant. For this purpose, an optimal plant capacity should be identified based on a market analysis of the products produced from CO_2 utilization, as well as an economic feasibility analysis and a life cycle analysis (LCA) for the calculation of net CO_2 emission (or reduction) by the conventional processes and the CO_2 utilization process. Various methodologies have been proposed for such collective analyses [11–13]. And this study used the methodology proposed by Kosan et al. for the techno-economic analysis of the CO_2 utilization technology [13].

Key performance data based on a bench-scale CO_2 utilization process are used for the technical feasibility analysis of this work. The capacity and overall process scheme of commercial CO_2 utilization plants is determined based on market research of the target products. The mass and energy balance is subsequently obtained through process simulation, which is the basis for economic feasibility analysis and the calculation of equipment sizing, as well as capital and O&M costs.

2.2. Key performance indicators

Feasibility of the CO_2 utilization process is evaluated based on the aforementioned mass and energy balance, using the technological, economic, and environmental metrics described below.

2.2.1. Technological metrics

The CO_2 utilization process of this paper comprises a carbonation process that reacts CO_2 in flue gas to produce sodium bicarbonate, and a brine electrolysis process to produce caustic soda, which is a key feedstock of the carbonation reaction. Considering such characteristics of the process, the key technological metrics used for the technical evaluation of the entire CO_2 utilization process are the CO_2 conversion rate and the electric power consumption for the brine electrolysis (refer to Appendix A for details).

CO_2 conversion rate (CO_{2conv}) refers to the proportion of CO_2 that is converted in the CO_2 carbonation process to produce the sodium bicarbonate, the final product. CO_{2conv} is a key metric for the performance evaluation of the CO_2 carbonation process. In the case of the brine electrolysis process, the durability of the membrane electrode assembly and the electric power consumption ($E_{consump\,BE}$) of brine electrolysis are key performance data. The electric power consumption of the brine electrolysis process is particularly important as this factor accounts for the greatest proportion of the O&M costs for the brine electrolysis process, greatly affecting the economics of the plant [14]. In addition to this, electric power consumption determines the amount of indirect CO_2 emissions from the power consumption, and thus is a key metric in the CO_2 reduction feasibility analysis.

2.2.2. Economic metrics

For the economic feasibility analysis, the key metrics are B/C ratio (Benefit/Cost ratio), NPV (Net Present Value) and IRR (Internal Rate of Return) (refer to Appendix A). B/C ratio is the ratio of the benefits of a project relative to its cost, and is frequently used in economic feasibility analyses. NPV is the total of the present values of all cash flow minus the present values of all capital investment, and IRR is the rate of return that sets the net present value of all cash flows from the investment equal to zero [15]. By definition, a project is economically feasible if B/C ratio $>$ 1.0, NPV $>$ 0, or IRR is greater than the capital opportunity costs.

2.2.3. Environmental metrics

The CO_2 reduction feasibility analysis of the CO_2 utilization process is conducted through comparison with the CO_2 emission data of the conventional processes when producing the same amount of product (refer to Appendix A). CO_2 emissions include both direct and indirect emissions in the process boundaries. For the CO_2 reduction feasibility evaluation, the mass and energy balance obtained from process simulation of the bench-scale performance evaluation is used for the calculation of net CO_2 emission reduction. The equation for this calculation can be found in Appendix A. In the case of the conventional processes to produce the same amount of product, CO_2 emission data per ton of product proposed in various literatures is used, as it is difficult to obtain detailed design and operation data to perform an accurate analysis. In addition, a sensitivity analysis is performed to evaluate the effects of various factors such as financial parameters (discount rate, carbon credit etc.) and market factors (product price, electricity cost etc.).

3. Process development & evaluation

As mentioned in Section 2, the techno-economic and environmental feasibility of the CO_2 utilization plant is analyzed using the framework proposed by Kosan et al. [13]. The CO_2 utilization process developed in this study is based on the carbonation and brine electrolysis process, and is designed to replace the conventional processes for sodium bicarbonate production (e.g., the Solvay process). The process is capable of producing sodium bicarbonate using CO_2 from flue gas, as well as simultaneously producing chlorine and hydrogen through the brine