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LIFE-CYCLE IMPACT ASSESSMENT OF FOSSIL POWER PLANTS WITH AND WITHOUT CO_2 CAPTURE EVALUATING THE POSSIBILITY OF CO_2 UTILIZATION

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Abstract

The CO_2 emission is more than 36 billion tons per year in global scale. As carbon dioxide emission raises global temperature by trapping solar energy in the atmosphere, research is ongoing to facilitate the capture of CO_2 with high efficiency. While CO_2 footprint of Bangladesh is relatively low, with upcoming coal-based power plants (>17000 MW) in the next decade, fossil CO_2 emission will increase significantly. To understand the underlying benefit of CO_2 capture process, cradle-to-gate life cycle impact assessment (LCIA) of the power plants using fossil sources (e.g. natural gas, coal) can provide an in-depth insight. This paper aims to conduct life cycle impact assessment on natural gas and coal (sub critical and supercritical) fired power plants with and without CO_2 capture facility for comparison of overall impact on the environment. An open source software titled OpenLCA was used to carry out LCIA and study different impact parameters (i.e. green-house gas emission, toxicity and ozone layer depletion). It was found that the CO_2 emission from super-critical pulverized coal (SCPC) and sub-critical pulverized coal (Sub-PC) fired power plants could be brought down by more than 80% using CO_2 capture facility. Along with capture, it is equally important to ensure proper sinks for this captured CO_2. As Bangladesh has no dedicated geological reservoir for CO_2 storage, potential sink for captured CO_2 could be immediate utilization after capture. This paper also presents preliminary results on utilizing CO_2 through mineralization during preparation of alternative admixture and construction materials. Due to the ever-growing real-estate sector of Bangladesh, there is great potential in capturing and utilizing CO_2 through construction activities.

Keywords: CO_2 capture; CO_2 utilization; Life cycle impact assessment; CO_2 mineralization

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1. Introduction

Carbon dioxide emission occurs because of burning fossil fuels like coal, natural gas and as a result of certain chemical reactions. After the industrial revolution, there has been a rapid rise in global emissions over the past few centuries, especially in recent decades. It has reached over 407.4 ppm now [1]. The World Resources Institute (WRI) published a report on the share of different sectors in total global emissions: Energy (66.5%), Agriculture (13.8%), Land use change (12.2%), Industrial processes (4.3%) and Waste (3.2%) [2]. In Bangladesh, CO_2 emissions per capita was 0.56 metric tons in 2018 which increased from 0.19 metric tons in 1999 [3]. The annual rate was maximum in 2001(15.42%) which decreased to 6.64% in 2018 [4]. So, CO_2 capture and separation technologies including solvent, sorbent and membrane have gained much attention in the recent decades. Carbon dioxide can be captured either before or after combustion. The principle of “pre-combustion” is the capture of CO_2 from the reformed synthesis gas. Separation of CO_2 from flue gas stream after combustion is called - “post-combustion” capture [5]. Moreover, extensive research has been conducted to develop clean technologies to lower CO_2 emission using alternatives like solar, wind, nuclear and hydrogen based power generation [6]. However, there are existing fossil-based power plants which supply a major share of world power demand [7]. For CO_2 emission from different types of power plants like Natural Gas Combined Cycle (NGCC), super-critical pulverized coal (SCPC) and sub-critical pulverized coal (Sub-PC) fired power plants, it is important to assess the resulting environmental impacts. In order to evaluate these environmental impacts, we used Life cycle impact assessment to compare among the power plants with and without CO_2 capture.

Now, the question arises, what should be done with this captured CO_2. This has become a major concern as captured CO_2 should be re-utilized for a long term so that it will not be emitted to the environment soon. The CO_2 captured at power plants can be potentially used as a raw material for chemical industry. IEA developed a model which indicates that the CO_2 levels should not be more than 15 gigatons annually to limit the increase of temperature within

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2°C by 2050 [8]. CO_2 can be stored underground and can be converted into many useful compounds. CO_2 capture technologies may contribute to reduce 20% of global emissions by 2050 and 55% by the end of this century [9]. CO_2 has already its established market as blanketing agent, fire extinguisher, drying ice, refrigerating fluid, aerosol propellant, respiratory stimulant after addition to medical O_2, in beverage industries, extracting agent in supercritical extraction of caffeine, flavor and flagrances, etc. The reaction of CO_2 with many purified silicon oxide-based minerals such as olivine, serpentine, wollastonite or similar solid residuals from waste incineration, can produce calcium or magnesium carbonates usable as building materials. A possible technology for CO_2 reduction to the atmosphere is carbonation. In this paper, industrial residues are presented as a possible feedstock for CO_2 sequestration. Experiments to observe effects of variations of the reaction rate, time and water content on CO_2 capture by fly ash, have also been conducted in this study.

2. Materials and Methods

2.1. Life cycle impact assessment (LCIA) strategy

The goal of the study is to estimate the life cycle environmental impacts of electricity generation from different plants such as NGCC, SCPC and Sub-PC to produce 3600MJ of electricity. The scope of the study is from cradle to gate, comprising extraction, processing, and transportation of the fuels, their combustion to generate electricity in power plants and plant construction and decommissioning at the end of their lifetime. To perform the analyses, a widely accepted open source LCA software, OpenLCA, was used. LCA usually requires manipulating a large set of data and assumptions, and the use of specific software tools can facilitate this process. OpenLCA has been carrying out these tasks reliably over the years. Further details on the usefulness of OpenLCA can be found in a publication by Ciroth [10].

2.2. Database

For conducting the analysis in OpenLCA software NETL CO_2 capture database was used. The National Energy Technology Laboratory's (NETL) Carbon Capture and Storage (CCS) Database, includes information on active, proposed, and terminated CCS projects worldwide. As of April 2018, this rigorous database contained 305 total CCS projects worldwide, with 299 sites identified. The 299 site-located projects include 76 capture, 76 storages, and 147 for capture and storage in more than 30 countries across 6 continents [11].

2.3. Impact Assessment Method

CML (baseline) [v4.4, January 2015] was used as impact assessment method for conducting the analysis.

2.4. LCIA study

For the same amount of energy production (3600 MJ), 5 impact category (selected based on a comprehensive set of environmental issues related to product system) graphs were plotted to compare the processes [12]. These parameters are important for deciding whether a fossil power plant is environmentally acceptable with or, without CO_2 capture facility.

3. Experimental

CO_2 capture by fly ash via carbonation reaction was evaluated where reaction time, water content and flow rate of carbon dioxide were varied as key parameters. Figure 1 represents the experimental setup where two glass reactors were used; one contained the sample and other was filled up with silica gel to absorb water vapor. Fly ash was collected from Barapukuria Coal Power Plant. Water and fly ash were mixed while varying the water content (70%, 80% and 90%) as well as run time (30 minutes and 45 minutes). CO_2 was supplied from CO_2 cylinder to the glass reactor containing the sample. The increase in the weight of the reactor after reaction time was measured. The weight difference indicated the extent of reaction that took place to form carbonates**.**

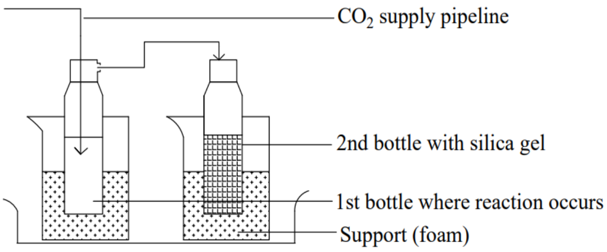

Figure 1: Schematic of the set-up for CO_2 carbonation

4. Results and Discussions

4.1. LCIA Study

4.1.1. Climate Change

Global Warming Potential is the impact category that represents effect of the processes on climate change. As expected, the Global Warming Potential is found to be less for plants with capture facility for all three types of processes considered. For SCPC power plant without capture, it is 4.4 times higher (as can be seen from Figure 2, the value is (8.87/2.29) than the value for same plant with capture. And for Sub-PC without capture it is 3.83 times higher than with capture power plant. So, CO_2 capture facility is expected to render a process environmentally beneficial considering climate change.

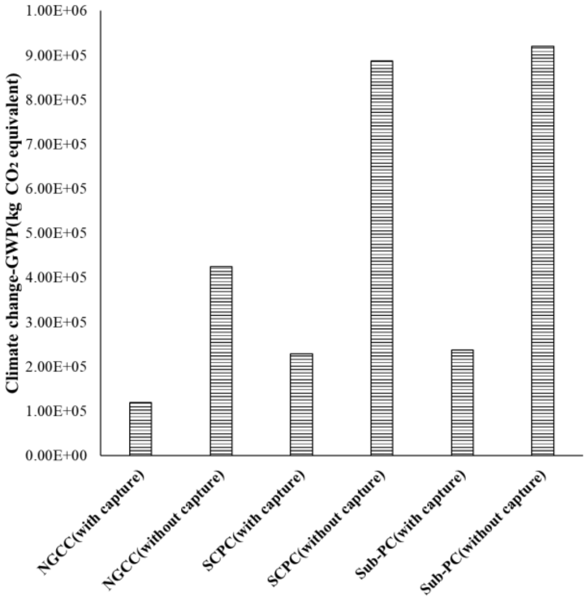

Figure 2: Climate change potential-GWP (kg CO_2 eq.) of different power plants (using OpenLCA software and NETL database)

4.1.2. Ozone Layer Depletion

This impact category represents the contribution to the destruction of ozone layer due to the emissions from the respective processes. Based on the results shown in Figure 3, power plant using natural gas as fuel was found to leave the least impact on ozone layer depletion. For SCPC and Sub-PC along with a capture plant Ozone Layer Depletion (kg Trichloroflurocarbon eq (kg CFC-11 eq) (Chlorofloro Carbon) is 1.35 times and 13.33 times higher than the respective without capture plants. So, benefit in this impact category cannot be expected from the addition of CO_2 capture facility.

4.1.3. Photochemical Oxidation

The large majority of this impact is due to the emissions of propane (20.6%), ethane (17.65%), methane, butane (16.52%), nitrogen dioxide (12.9%) etc. at the NGCC power plant whereas at SCPC, NOx (-232.48kg Ethylene eq from LCA) are the main contributor of the Photochemical Oxidation. From Figure 4 it is clear that for NGCC power plant without capture the value of photochemical oxidation is lesser than the same power plant with capture, and for Sub-PC with capture the value is the least among all the compared power plants. The negative impacts of SCPC without capture and Sub-PC imply environmental savings in this impact category.

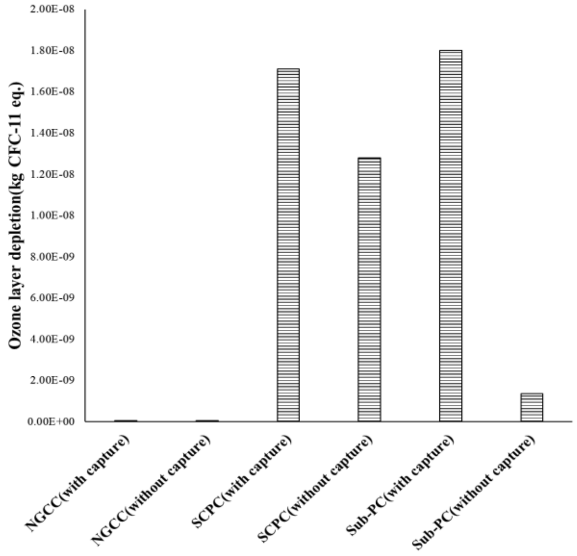

Figure 3: Ozone layer depletion potential (kg CFC-11 eq.) of different power plants (using OpenLCA software and NETL database)

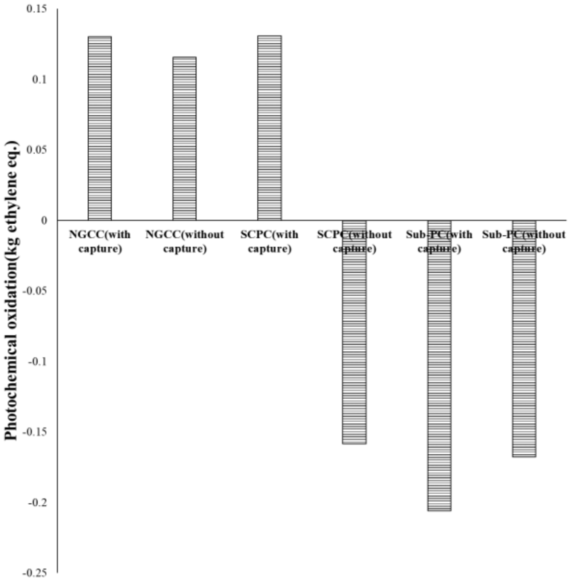

Figure 4: Photochemical oxidation potential (kg ethylene eq.) of different power plants (using OpenLCA software and NETL database)

4.1.4. Human Toxicity

Human toxicity includes impacts of all chemicals (mainly particulate matters in case of this study) on human and is represented as equivalent of 1,4-dichlorobenzene. It is shown in the Figure 5. Human toxicity is the least for NGCC plants (benzene being the major contributor to the total Human Toxicity (51%), Thalium (30%)) NOx (14%) and rest others) and for SCPC (Thalium (50%), Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin (8%) and rest other particulates. For Sub-PC plants with a capture plant the value is slightly higher. Human toxicity potential is slightly less for NGCC without capture plant than in presence of capture plant. However, in case of SCPC and Sub-PC plants the CO_2 capture facility significantly reduces the human toxicity potential.

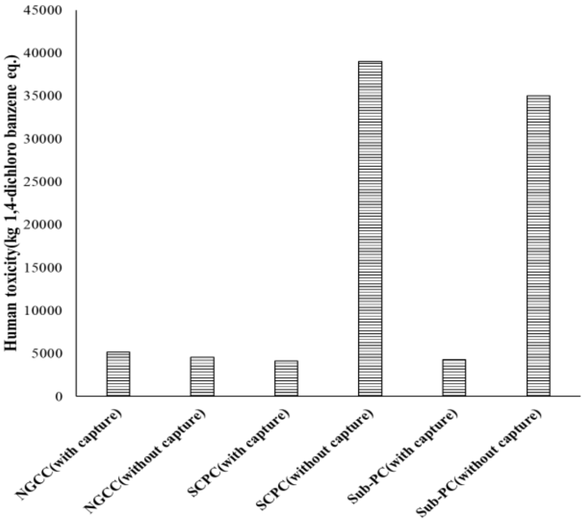

Figure 5: Human toxicity potential (kg 1,4-dichoro benzene eq.) of different power plants (using OpenLCA software and NETL database)

4.1.5. Eutrophication Potential

Eutrophication value implies the enrichment of the environment with nutrients. From the LCA analysis the eutrophication potential was found to be the least for NGCC power plants as can be seen from Figure 6. The eutrophication potential was found to slightly increase with the addition of CO_2 capture facility as can be seen from Figure 6.

4.1.6. Acidification Potential

Acidification occurs due to emissions of oxides of sulfur and nitrogen. The combustion of fossil fuels at power stations and industrial plants contribute to emission of acidifying compounds. For example, SO_2 emitted from plants absorb water from atmosphere to form sulfurous acid. CO_2 released from various sources dissolves into the rivers and oceans which increases the concentration of hydrogen ion lowering the pH [13]. The source of this impact can be divided into three sections: gas extraction, combustion for electricity generation and gas distribution [14]. It can be seen from Figure 7 that Sub-PC without capture has the highest acidification potential in terms of SO_2 equivalents, which is 2.6 times higher than emission from NGCC without capture power plant. This is partially due to the fact that power plants with capture require advanced flue gas cleaning with desulphurization.

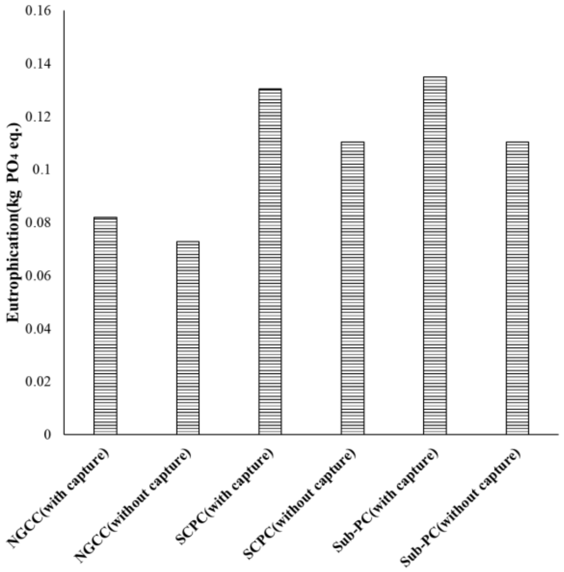

Figure 6: Eutrophication Potential (kg PO_4 eq.) of different power plants (using OpenLCA software and NETL database)

Although addition of CO_2 capture facility causes slight increase of acidification potential in case of NGCC, in all other cases it significantly reduces the acidification potential.

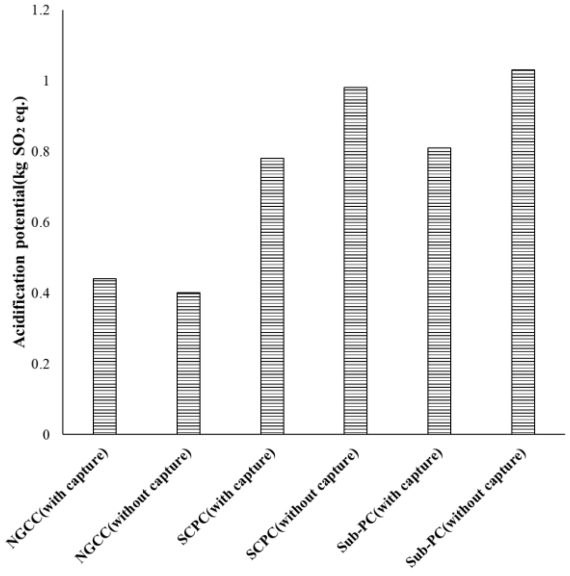

Figure 7: Acidification potential (kg SO_2 eq.) of different power plants (using OpenLCA software and NETL database)

4.1.7. Particulate Matter Formation Potential

The pollutants which contribute to Particulate Matter (PM) related impacts are total suspended particles, PM_{10}, $PM_{10-2.5}$, $PM_{2.5}$ and secondary PM formed from SO_2, NO_x and NH_3. Particulate Matter Formation Potential (PMFP) is expressed as kg $PM_{2.5}$ equivalents. The increase in PM emission can lead to cardiopulmonary diseases and lung cancer. From Figure 8, Sub-PC and SCPC plants without capture released the highest amount of particulate matter. If capture facility is considered with Sub-PC and SCPC, PM formation can be decreased significantly. NGCC plants were found to have the least impacts in this category.

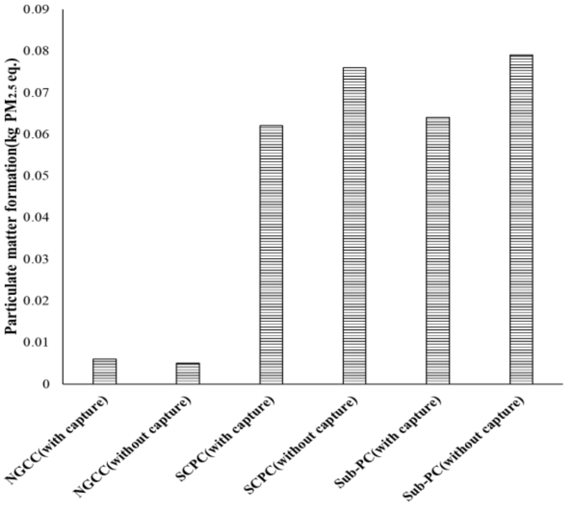

Figure 8: Particulate Matter Formation Potential (kg $PM_{2.5}$ eq.) of different power plant (using OpenLCA software and NETL database)

4.2. Normalized Results

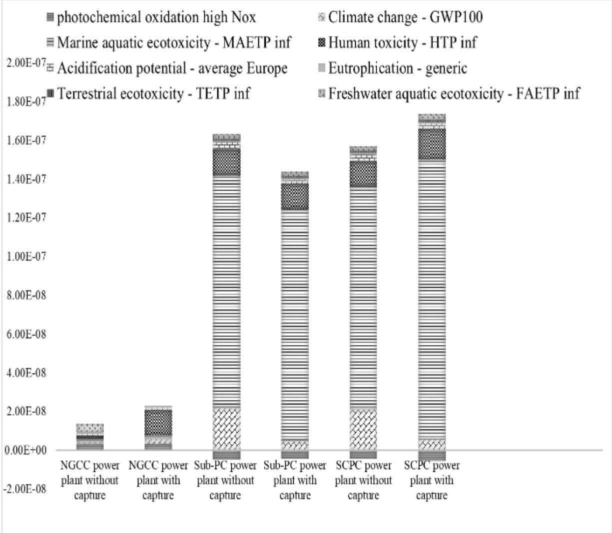

Figure 9: Normalized results (using OpenLCA software and NETL database)

From the normalized graph (Figure 9), the relative contribution from the impact categories can be observed. The major contributor was marine aquatic ecotoxicity. Though climate change and terrestrial ecotoxicity were equally responsible for the environmental pollution, it could be said that climate change had slightly larger impact than the terrestrial ecotoxicity. SCPC power plant with CO_2 capture caused the highest combined impact than any other scenarios. While CO_2 capture decreases the climate change impact but increases the marine aquatic ecotoxicity in the long run.

4.3. CO_2 Utilization

Based on the LCIA, it was evident that solvent based CO_2 capture had significant impact on the environment if considered carefully (Figure 9). Therefore, it is necessary to find alternative benign methods for CO_2 capture and utilization to mitigate the climate change impact (without elevating other impacts). In this study, we conducted experiments on residual material from a coal-based power plant (fly ash) for assessing its CO_2 capture potential. Based on the collected data, a bar graph was plotted to observe the results. Based on the data, the highest value of weight gain indicated that maximum amount of CO_2 was captured at a particular condition. The maximum weight gain (as can be seen from Figure 10), was found to be 0.6 g/g of coal fly ash at a flow rate 4L/min and 30 minutes time. The weight gain is an indirect measure of CO_2 capture through the formation of carbonates depending on the components of fly ash [15]. The results from this study showed that it could be a promising method compared to conventional CO_2 capture technique. Also, the product from mineralization can be further used as a mineral admixture for concrete or, at cement industry. The limiting factors for this process could be the high energy consumption and costs may due to the exothermic nature of the CO_2 mineralization reaction [16].

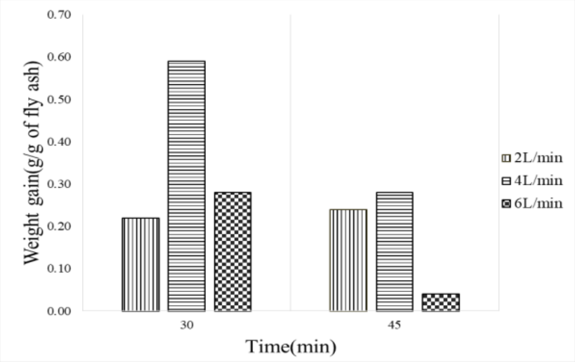

Figure 10: Performance of CO_2 mineralization

Even with the limitations, the benefit of this method lies in the availability of the solid residues from solid fuel-based power plants and construction sites. This method can serve multiple purposes at once – a) CO_2 capture, b) sequestration and c) utilization.

The final product could be utilized in construction industry and this re-use is beneficial to both economy and environment. The carbonation of solid residues also reduces the leaching of harmful elements which is a positive environmental impact [16].

Conclusion

From the LCIA study, NGCC plant was found to perform better in most impact categories (except photochemical oxidation) compared to other plants with or, without CO_2 capture. It should be noted that in some cases, plants with CO_2 capture may leave a higher degree of environmental impacts. For instance, the plants with capture cause more ozone layer depletion than the corresponding plants without capture plant. However, CO_2 capture facility improved performance of Sub-PC and SCPC plants in the impact categories like climate change, human toxicity, acidification potential, and particulate matter formation potential. It was found from a normalized impact assessment that the inclusion of CO_2 capture would decrease the climate change impact while it would increase the aquatic toxicity over its life cycle. Careful consideration must be made to understand the overall impact of this process. As the increasing concentration of CO_2 leading to global warming obligates the CO_2 capture technologies to be implemented on a large scale, an alternative method of capture, sequestration and utilization of CO_2 was explored through carbonization of CO_2 in fly ash from power plants. The results from the experiments showed up to 0.6 g of weight increase in the fly ash through CO_2 purging. Further research is ongoing to determine the life cycle impact analysis of the CO_2 mineralization process.

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List of Abbreviations

LCIA	Life Cycle Impact Assessment
SCPC	Super-Critical Pulverized Coal
Sub-PC	Sub-critical Pulverized Coal
NGCC	Natural Gas Combined Cycle
WRI	World Resources Institute.
NETL	The National Energy Technology Laboratory’s
CCS	Carbon Capture and Storage Database
PM	Particulate Matter
PMFP	Particulate Matter Formation Potential

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