A Quantitative Investigation of CO₂ Sequestration by Mineral Carbonation

Muneer Mohammad, Student Member, IEEE Mehrdad Ehsani, Fellow, IEEE

Abstract—Anthropogenic activities have led to a substantial increase in carbon dioxide (CO₂), a greenhouse gas (GHG), contributing to heightened concerns of global warming. In the last decade alone CO₂ emissions increased by 2.0 ppm/yr. globally. In the year 2009, United States and China contributed up to 43.4% of global CO₂ emissions. CO₂ capture and sequestration have been recognized as promising solutions to mitigate CO₂ emissions from fossil fuel based power plants. Typical techniques for carbon capture include post-combustion capture, pre-combustion capture and oxy-combustion capture, which are under active research generally. Mineral carbonation has been investigated as a suitable technique for long term storage of CO₂. Sequestration is a highly energy intensive process and the additional energy is typically supplied by the power plant itself. This leads to a reduction in net amount of CO₂ captured because of extra CO₂ emitted. This paper presents a quantitative analysis of the energy consumption during sequestration process for a typical 1GW pulverized coal and a 1GW natural gas based power plant. Furthermore, it has been established that the present day sequestration methods and procedures are not viable to achieve the goal of carbon sequestration.

Index Terms—Mineral Carbonation, CO₂ Sequestration, Calcium Silicates

I. INTRODUCTION

Among the shocking warnings of severe weather alarms and globally rising temperatures, politicians, scientists, engineers, and others are searching for ways to reduce the rising threat of climate change. Currently, fossil fuels are the main source satisfying the global primary energy demand, and will remain or the rest of 21st century [1]. Approximately 85% of the world’s energy needs are supplied by fossil fuels because of their low cost, existing reliable technology for energy production, and availability. As it is shown in Fig. 1, approximately 70% of United States’ electricity needs are met by coal and natural gas power plants [2]. Presently, renewable energy power plants based on solar and wind are too sporadic to satisfy major electricity needs and transmission and infrastructure issues hinder expansion of their share in the market. Nuclear plants deliver base-load electricity, but the future of nuclear energy is plagued by several techno-economic and social issues. This leaves natural gas and coal as the two resources that could play substantial roles in the near-term addition of electrical generating capacity. The ignition of fossil fuels produces carbon dioxide (CO₂), which is the major greenhouse gas (GHG); many climatologists believe that emission of this GHG into the atmosphere is the major cause of the climate change.

Fig. 1. 2007 U.S. Electric Power Industry Net Generation

Fig. 2. Net CO₂ emission from burning fossil fuels

Fig. 2 depicts the global CO₂ emissions from burning fossil fuels during the last century. In the last 50 years alone the CO₂ emissions have risen by 300%. One of the methods for mitigating potential global climate change due to anthropogenic emissions of CO₂ into atmosphere is to capture CO₂ from burning fossil fuels, and to store it in oceanic or geologic reservoirs [1, 3, 4]. This is not the only solution, but the development of carbon capture and sequestration technology, which has accelerated significantly in the last decade, might play a vital role in addressing this issue. Carbon sequestration is a critical technology for decreasing greenhouse gas GHG) emissions from fossil fuel power plants. Capture of approximately 90% of emissions has significant progressive impacts on the technology, plant performance, and project economics. However, it also presents challenges for the first movers who implement the technology [1, 5].

All CO₂ sequestration methods consist of two steps. In the first step, the carbon dioxide is captured and separated from the flue gas or the fuel. The CO₂, having been isolated, is then...
stored in a reservoir [1, 5-7]. Active research is being undertaken in both these areas. Some of these technologies are at an early stage of development. Separation of CO₂ from the captured flue gas is required to avoid storage of huge volumes of N₂. The separation is typically established using absorption with monoethanolamine followed by stripping with steam. Absorption technology is energy-intensive and usually accounts for two-thirds to three-quarters of the total sequestration costs.

CO₂ capture and isolation from power plants can be achieved via three prevalent technologies:

1. Flue gas separation: This method is based on chemical absorption. In a power plant employing this technology, the flue gas is passed through a solvent in a packed absorber column, wherein CO₂ is absorbed by the solvent on account of some chemical bond formation. The solvent then passes into a regenerator unit, where CO₂ is extracted from it and may be put into commercial uses or stored in reservoirs. Although solvent based extraction of CO₂ involves additional cost, this technology can be fitted onto the existing power plants easily. This technique is a prime example of post combustion CO₂ capture [4].

2. Pre-combustion carbon capture: This method involves capturing CO₂ before fuel is burnt in the plants. As the captured CO₂ has a higher concentration than the previous method, these separation methods turn out to be more efficient. Physical solvents which extract CO₂ via absorption are more suited since CO₂ is obtained at high pressures when syngas exits shifting converters. Other techniques such as polymer-based membranes and chemical looping combustion are in research stages. Pre-combustion carbon capture is more suited for integrated coal gasification combined cycle power plants (IGCC) wherein coal undergoes gasification to form syngas (CO + Hydrogen). Hydrogen is utilized as the main fuel while CO can be further converted to CO₂ easily to complete carbon capture. Cost is a major drawback as IGCC plants produce power at a higher cost than conventional pulverized coal powered plants. Also, this process could be used in industrial settings which involve production of syngas from coal.

3. Oxycombustion: This involves combustion of fossil fuel in an atmosphere enriched with oxygen. Again, the intent is to obtain a higher concentration of CO₂ in the byproduct of combustion. The higher concentration of CO₂ in the flue gas mixture makes separation process less energy intensive. In this method, pure oxygen is usually obtained via an air separation unit which consumes about 15% of a power plant’s generated power. It may also prove to be a cost hindrance since cryogenic systems are required for oxygen separation.

Once CO₂ has been captured it needs to be stored. Various techniques exist for CO₂ storage. Mineral Carbonation seems to be a promising technique for CO₂ storage [1, 5, 7]. This technique involves reacting CO₂ with reactive calcium or magnesium ores (silicates/oxides) and obtaining calcium/magnesium carbonates, thereby storing CO₂ in these compounds. The carbonates could be further used in the industry or stored as landfills. The main motivation for the mineralization technique is that since carbonates have lower energy levels than CO₂, carbon dioxide to carbonates conversion is an exothermic reaction, which does not need energy inputs theoretically. However, for better kinetics, energy is provided. This storage methodology is a permanent solution against geological/ocean bed sequestration, which could lead to CO₂ leakage [3,7, 8].

Possible feedstock for mineral CO₂ sequestration include primary Ca/Mg-silicates, such as wollastonite (CaSiO₃) [9] and olivine (Mg₂SiO₄) and industrial residues, such as steel slag [10] and waste cement [11]. The proposed procedure of the entire CO₂ sequestration based on the mineral carbonation includes capture of flue gas, compression, transportation, mining, and grinding is presented in Fig. 2. The carbonation reaction is usually very slow; enhancement of this process in mineral carbonation is possible by grinding the feedstock, elevating the temperature and CO₂ pressure. However this will consume energy and decrease the net amount of CO₂ sequestered because of the additional CO₂ emissions caused. But the mineral carbonation reaction generates usable heat which can be utilized for producing part of the energy requirements. Therefore energy and efficiency analysis play an important role which is the main goal of this paper.

As mentioned earlier, the major cost of the carbon sequestration is the energy requirement; therefore in this paper energy analysis will be covered. Because the purpose of carbon capture sequestration is to decrease the amount of CO₂ emitted into the air, the energy used in the process itself
shouldn’t cause an extra CO₂ emission. Therefore a trade-off between the sequestration and the energy requirement for this process should be done. So we need to minimize the emitted CO₂ by preventing increase in generation capacity of the fossil fuel power plant for the purpose of sequestration. This paper discusses a scenario disturbing picture wherein the amount of CO₂ produced during sequestration is comparable to the CO₂ generated from the power plant. Furthermore, the energy consumed during carbon capture will be discussed in detail. This energy either needs to be provided externally or can be apportioned from the existing power plant.

II. LITERATURE REVIEW

Carbon capture and carbon storage techniques have been under active research for about two decades now. Reducing CO₂ emissions by sequestering CO₂ from fossil fuel based power plants and storing it in the oceans was proposed by Marchetti in as early as 1977 [12]. Academic interest in this field took flight in the 1980s and 1990s [13-19] leading to International Conference on Carbon Dioxide Removal (ICCDR-1) in 1992 where researchers from all around the world met and discussed ideas on CO₂ capture and storage. The conference opened up active research in this field tremendously. Around 1991, International Energy Agency (IEA) established a mandate to research and develop techniques for capture and storage of CO₂ and help enhance international awareness on climate change [20]. Japan has been at the forefront in this field and has established an international organization for CO₂ fixation and utilization RITE (Research Institute of Innovative Technology for the Earth), which actively focuses on developing innovative environmental technologies for CO₂ sequestration.

Popular techniques for capturing CO₂ from power plants include post combustion CO₂ capture from flue gas, which involves isolating CO₂ after the fuel is burnt. Pre-combustion isolation of CO₂ is the process of converting fuel to syngas and extracting CO₂ via the water gas shift process. Oxycombustion involves fuel combustion in a highly oxygen enriched environment and CO₂ is captured from flue gases after fuel combustion [4,5].

Once CO₂ has been captured and isolated, it is stored in carbon sinks. Ocean sequestration technique involves speeding up the natural process of CO₂ absorption in the oceans [21-24]. A large amount of CO₂ can be theoretically sequestered in the oceans. However this technology has a lot of environmental concerns [25] primarily with increasing acidification of the oceans. Another viable option for storage is storing CO₂ in geological formations such as deep saline formations, coal beds, and depleted oil and gas reservoirs. Geological storage is being researched as it presents a cost effective storage alternative for large amounts of CO₂ storage. Especially, deep saline aquifers have very high potential storage capacities for CO₂ because they are wide spread and available [22]. In contrast to oil and gas reservoirs, they do not require special structural trap geometries [26]. However, uncertainties in long term storage integrity and cost of the storage techniques still pose a stumbling block to this process. Human activities such as drilling, geological fractures, and structural leaks all contribute to the increased risk of CO₂ leakage.

Carbon dioxide storage by mineral carbonation is an alternative to storage in oceans or reservoirs [27]. It offers some significant advantages over CO₂ storage in geological reservoirs and oceans. Mineral carbonation provides a permanent CO₂ storage solution by conversion of CO₂ [28] into carbonates since chemical sequestration reaction produces thermodynamically stable products. It eliminates potential hazards of CO₂ leakage encountered with storage in geological formations or acidification of oceans [29-31]. An inherent benefit of carbonation process is that the carbonation reaction is an exothermic reaction, which theoretically implies no energy input for the chemical reaction [32]. However, naturally occurring reactions are slow, and different techniques to speed up the kinetics in efficient ways have been researched into. Carbonation processes with olivine and serpentine ores have been studied in detail [33]. Mineral carbonation requires abundant quantities of Ca or Mg silicate ores. The advantage that this process offers is the wide spread availability of minerals [27] such as Wollastonite (CaSiO₃) or Olivine (Mg,2SiO₄).

Huijen et.al [9] provide a method to carry out energy efficient CO₂ carbonation by aqueous mineralization of wollastonite ore [9]. The energy analysis has been carried further in this paper. The energy utilized for a 1000 MW pulverized coal based power plant adopting CO₂ sequestration will be determined. A similar analysis has been carried out for a 1000 MW natural gas based power plant incorporating CO₂ sequestration to isolate and sink CO₂.

III. CASE STUDY

A 1000 MW pulverized coal (PC) power plant and a 1000 MW natural gas powered plant have been considered to compute the CO₂ emissions.

There are three current technologies for pulverized coal plant. The ultra-supercritical pulverized coal plant has been known to have the highest efficiency. The efficiencies of these power plants are commonly estimated to be around 44% and typical natural gas power plants have efficiencies around 55%.

The calorific value of Bituminous coal is known to be in the range of 17 MJ/kg to 23.5 MJ/kg while the higher-grade anthracite coal has a higher calorific value of 32 MJ/kg to 35 MJ/kg. Bituminous coal (calorific value 20 MJ/kg) has been used as fuel for PC, given the relative abundance of bituminous coal as compared to anthracite. Also, calorific value of methane (natural gas) has been selected to be 55 MJ/kg. With the above specifications for pulverized coal plant and natural gas based power plant, the daily requirement of fuel (bituminous coal/natural gas) has been computed for the respective plants.

These numbers are later used to perform a molar analysis and the amount of daily carbon dioxide emissions from both the plants has been computed.
In the next step, energy efficiency of mineral carbonation process has been calculated. The calcium mineral (wollastonite) is ground to a suitable size and is mixed with water to obtain an appropriate water to mineral (W:M) ratio. The slurry is then sent to a pressurized reactor, which is maintained at a particular pressure, and heated to a temperature which is 20°C less than reactor temperature. Meanwhile, pressurized CO₂ obtained from flue gases is let into the reactor chamber. The mineral carbonation process is summarized in Fig. 4.

The carbonation process is influenced chiefly by parameters such as pressure of CO₂ (p), temperature and size of mineral particle. The operating values of reactor pressure, water to mineral ratio (W:M), temperature and size of crushed mineral are chosen from an earlier study [11] wherein these process conditions are proven to guarantee maximum energetic efficiency for CO₂ sequestration process. The values for the optimum set of conditions are 20 bar (p_CO₂), temperature 200°C (T), size d < 38 μm, and W:M ratio 5 kg/kg which provide 75% carbon capture efficiency to the sequestration process.

The case study assumes sequestration to be performed in the power plant itself as against being located in a far off location. Hence, cost of transportation of CO₂ has not been considered.

The CO₂ generated is then processed through a capture plant to convert the Calcium mineral, Wollastonite to a carbonate. This process is described by the equation below:

\[ C + O_2 \rightarrow CO_2 \]  \hspace{1cm} (1)

\[ CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2 \]  \hspace{1cm} (2)

The Gibbs free energy and enthalpy change for the reaction are −44 kJ/mol and −87 kJ/mol. Coal contains elements other than carbon such as Sulfur, Nitrogen etc. These elements are oxidized to form the corresponding oxides and along with carbon dioxide form flue gases. No energy penalty is attributed to separation of carbon dioxide from the flue gases.

**A. Assumptions**

The performed calculations are based on assumptions in [11], the carbonation process can be affected by several parameters such as pressure of CO₂, pressure of water vapor, size of the feedstock particles, liquid to solid ratio and temperature of reaction. All these parameters play a very crucial role in determining the energy required. The important steps involved in the carbonation process are mentioned below:

a) Feedstock grinding and crushing
b) CO₂ compression and pumping
c) Slurry L:S ratio
d) Carbonate formation

**IV. ENERGY ANALYSIS**

The energy required for aqueous mineralization of carbon-dioxide can be divided into two categories: Electrical and Heat. The electrical energy is used to perform tasks such as crushing, pumping, compressing etc. The heat energy is used to increase the temperature of the slurry to achieve optimum reaction temperatures [11]. As mentioned previously these energies are very sensitive to several parameters. A particular configuration and the energy requirements for that particular set of conditions are evaluated.

The exothermic nature of the carbonation reaction mentioned in (2) can be used to reduce the energy requirements of the carbonation process. The heat energy can be partially converted into electrical energy through steam engine; this has to do with Carnot Efficiency. Carnot’s theorem states that no engine operating between two heat reservoirs can be more efficient than a Carnot engine. The Carnot efficiency is stated below:

\[ \text{Carnot Efficiency} = 1 - \frac{T_c}{T_h} \]  \hspace{1cm} (3)

Factors such as droplet formation reduce this to numbers much below the Carnot Efficiency. A preliminary analysis of literature confirms that this number is around 50% [34]. This number has been used in the calculations for estimating energy recovered.

As mentioned previously the energy requirements can be calculated as a sum total of electrical and heat energy. For the conditions mentioned in Section III the electrical energy required to capture the amount of CO₂ emitted is calculated. The assumptions made in previous section are mentioned here for the sake of completion. Coal plant efficiency is assumed to
be 44% and that of a natural gas plant is 55%. The calculations are performed for a 1000 MW fossil fuel powered plant (coal and natural gas). In case of pulverized coal power plant, the total weight of coal used per day is approximately 9815 metric tons. Assuming the percentage of carbon by weight is 60%, the total carbon combusted is 5889 metric tons. Using molar analysis it can be concluded that 21600 metric tons of CO\textsubscript{2} is produced each day.

The emission factor (α) is defined as the amount of CO\textsubscript{2} emitted per kWh of energy produced. In case of pulverized coal power plant this turns out to be 0.9 kg of CO\textsubscript{2}/kWh. A similar analysis for a natural gas powered power plant leads to the following numbers: volume of natural gas used daily: 4430\times10^3 m^3/day, weight of CO\textsubscript{2} produced 7857 metric tons per day, and emission factor of the plant is 0.33 kg of CO\textsubscript{2}/kWh.

Using numbers mentioned in [11] and above the amount of energy required to reduce the CO\textsubscript{2} emissions is computed. The energy for grinding of feedstock is estimated to be around 253 kWh/ton of CO\textsubscript{2} captured while the energy required for compression and pumping of CO\textsubscript{2} is around 150 kWh/ton of CO\textsubscript{2} [11]. The total electrical energy required is equal to 403 kWh/ton of CO\textsubscript{2}. Heat energy is required to bring the slurry to the optimum reaction temperature (200 °C). The energy required for this stage is 799 kWh/ton of CO\textsubscript{2}. In addition to these, we can also extract heat from the exothermic reaction of carbon dioxide with calcium silicate. This reaction supplies 752 kWh/ton of CO\textsubscript{2} captured. Using these numbers and previous calculations the total energy required is calculated to be 25.96\times10^6 kWh/day. This amounts to a 1.08 GW power plant. A part of this energy can be obtained by the conversion of reaction heat energy into electricity using steam turbine. The amount of electrical energy generated is limited by the steam turbine efficiency. Under such conditions, the electrical energy recovered is 8.12\times10^6 kWh. In other words this is equivalent to a 340 MW plant.

A similar analysis for a natural gas plant mentioned previously results in numbers that are substantially smaller due to the reduced emissions of a natural gas plant. Hence the expectation is reduced energy requirements. The gross total energy required per day is 400 MWh whereas the total energy recovered is 124 MWh, leading to net energy requirement of 276 MW.

The numbers presented in the above section are dependent on many factors, one of them being the emission factor. This directly controls that amount of energy required and recovered. The emission factor (α) can go as low as 0.3 kg/kWh for natural gas plants and can be as high as 0.9 kg/kWh for certain coal powered plants. A sensitivity analysis performed using α as the variable and a graph is plotted for the variation of total power required, Fig. 5.

![Fig. 5. Total energy required for varying emission factor](image)

Table 1. Summary of power Requirements for carbon capture for natural gas and coal power plants

| Parameters                              | Pulverized coal plant | Natural gas plant |
|-----------------------------------------|-----------------------|-------------------|
| Net Fuel consumption per day            | 9815 metric tons      | 4430 \times 10^6 lit |
| Emissions of CO\textsubscript{2} per day| 21600 metric tons     | 7900 metric tons  |
| Gross power needed for sequestration    | 1080 MW               | 400 MW            |
| Total power recovered from the reactor  | 340 MW                | 124 MW            |
| Net sequestration power requirement     | 740 MW                | 276 MW            |
| Sequestration power requirement         | 74%                    | 27.60%            |

V. CONCLUSION AND FUTURE WORK

Table 1 indicates that power requirements for carbon capture are a large portion of energy of the power plant for which the capture plant is designed. Results for pulverized coal power plant indicate a power plant that is 42.5% larger is required to capture the CO\textsubscript{2} while providing 1000 MW to the end users. The same numbers for natural gas present a slightly less pessimistic outlook. A natural gas power plant needs to be 21.6% larger to supply 1000 MW of electrical output.

As mentioned in equation (2) carbonation reaction is a naturally occurring spontaneous, exothermic reaction. Yet the sequestration process in energy intensive. This is largely due to the slow nature of the reaction. To speed up the kinetics and make the reaction feasible on an industrial scale presents a very good opportunity for research.

The heat recovered from the reactor is used to supply a fraction of the gross power required for sequestration. The energy efficiency of heat to electricity conversion has been considered to be 50% which is the typical case for steam turbines. This intermediate stage presents an attractive opportunity to optimize carbon sequestration energy efficiency. If the reuse of this heat is made more efficient, the net sequestration energy requirement will also reduce.

The purpose of Carbon capture method discussed in this paper is to reduce the amount of CO\textsubscript{2} emitted into the atmosphere by power plants. This places tight restrictions on the energy requirements of the process. In principle the mineral carbonation stage needs to be made more energy efficient. Only if such a solution is combined with a highly efficient steam turbine, the implementation discussed here can
be treated as a viable solution. Under such circumstances renewable energy sources such as solar, wind, biomass can be considered for meeting the energy needs.

REFERENCES

[1] W. J. J. Huijgen, R. N. J. Comans, and G.-J. Witkamp, "Cost evaluation of CO2 sequestration by aqueous mineral carbonation," *Energy Conversion and Management*, vol. 48, pp. 1923-1935, 2007.

[2] K. van Alphen, P. M. Noothout, M. P. Hekkert, and W. C. Turkenburg, "Evaluating the development of carbon capture and storage technologies in the United States," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 971-980, 2010.

[3] T. Xu, J. A. Apps, and K. Pruess, "Mineral sequestration of carbon dioxide in a sandstone–shale system," *Chemical Geology*, vol. 217, pp. 295-318, 2005.

[4] J. D. Figueroa, T. Fout, S. Plasyinski, H. McBride, and R. D. Srivastava, "Advances in CO2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program," *International Journal of Greenhouse Gas Control*, vol. 2, pp. 9-20, 2008.

[5] C. Fu and T. Gundersen, "Carbon Capture and Storage in the Power Industry: Challenges and Opportunities," *Energy Procedia*, vol. 16, Part C, pp. 1806-1812, 2012.

[6] S. Yixin, Z. Xudong, and S. Monkman, "A New CO2 Sequestration Process via Concrete Products Production," in *IEEE EIC Climate Change Technology Conference*, 2006, pp. 1-6.

[7] G. Montes-Hernandez, R. Perez-Lopez, F. Renurd, J. M. Nieto, and L. Charlet, "Mineral sequestration of CO2 by aqueous carbonation of coal combustion fly-ash," *Journal of Hazardous Materials*, vol. 161, pp. 1347-1354, 2009.

[8] M. M. Maroto-Valer, D. J. Fauth, M. E. Kuchta, Y. Zhang, and J. M. Andresen, "Activation of magnesium rich minerals as carbonation feedstock materials for CO2 sequestration," *Fuel Processing Technology*, vol. 86, pp. 1627-1645, 2005.

[9] W. J. J. Huijgen, G.-J. Witkamp, and R. N. J. Comans, "Mechanisms of aqueous wollastonite carbonation as a possible CO2 sequestration process," *Chemical Engineering Science*, vol. 61, pp. 4242-4251, 2006.

[10] W. J. J. Huijgen and R. N. J. Comans, "Mineral CO2 Sequestration by Steel Slag Carbonation," *Environmental Science & Technology*, vol. 39, pp. 9676-9682, 2005.

[11] W. J. J. Huijgen, R. N. J. Comans, G. J. Witkamp, and G. J. Ruigij, "Energy Consumption and Net CO2 Sequestration of Aqueous Mineral Carbonation," *Industrial & Engineering Chemistry Research*, vol. 45, pp. 9184-9194, 2006.

[12] C. Marchetti, "On Geoengineering and the CO2 Problem," *Climatic Change*, vol. 1, pp. 59-68, 1977.

[13] J. A. Oude Lohuis, "Carbon dioxide disposal and sustainable development in the Netherlands," *Energy Conversion and Management*, vol. 34, pp. 815-821, 1993.

[14] S. Holloway, "An overview of the underground disposal of carbon dioxide," *Energy Conversion and Management*, vol. 38, Supplement, pp. S193-S198, 1997.

[15] W. D. Gunter, E. H. Perkins, and T. J. McCann, "Aquifer disposal of CO2-rich gases: Reaction design for added capacity," *Energy Conversion and Management*, vol. 34, pp. 941-948, 1993.

[16] S. Bachu, W. D. Gunter, and E. H. Perkins, "Aquifer disposal of CO2: Hydrodynamic and mineral trapping," *Energy Conversion and Management*, vol. 35, pp. 269-279, 1994.

[17] V. RAMANATHAN, "The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment," *Science*, vol. 240, pp. 293-299, 1988.

[18] H. E. Dunsmore, "A geological perspective on global warming and the possibility of carbon dioxide removal as calcium carbonate mineral," *Energy Conversion and Management*, vol. 33, pp. 565-572, 1992.

[19] W. S. Broecker, T. Takahashi, H. J. Simpson, and T.-H. Peng, "Fate of Fossil Fuel Carbon Dioxide and the Global Carbon Budget," *Science*, vol. 206, pp. 409-418, 1979.

[20] I. C. Webster, "IEA Greenhouse Gas Programme: Continued international collaboration," *Energy Conversion and Management*, vol. 36, pp. 865-868, 1995.

[21] E. E. Adams, D. S. Golomb, and H. J. Herzog, "Ocean disposal of CO2 at intermediate depths," *Energy Conversion and Management*, vol. 36, pp. 447-452, 1998.

[22] P. D. Bergman and E. M. Winter, "Disposal of carbon dioxide in aquifers in the U.S.,” *Energy Conversion and Management*, vol. 36, pp. 523-526, 1995.

[23] C. R. Liro, E. E. Adams, and H. J. Herzog, "Modeling the release of CO2 in the deep ocean," *Energy Conversion and Management*, vol. 33, pp. 667-676, 1992.

[24] H. Herzog, K. Caldeira, and E. Adams, "Carbon Sequestration Via Direct Injection," in *Encyclopedia of Ocean Sciences*, H. S. Editor-in-Chief: John, Ed., ed Oxford: Academic Press, 2001, pp. 408-414.

[25] M. I. Hoffert, Y.-C. Wey, A. J. Callegari, and W. S. Broecker, "Atmospheric response to deep-sea injections of fossil-fuel carbon dioxide," *Climatic Change*, vol. 2, pp. 53-68, 1979.

[26] P. D. Bergman, E. M. Winter, and Z.-Y. Chen, "Disposal of power plant CO2 in depleted oil and gas reservoirs in Texas," *Energy Conversion and Management*, vol. 38, Supplement, pp. S211-S216, 1997.

[27] K. S. Lackner, C. H. Wendt, D. P. Butt, E. L. Joyce Jr, and D. H. Sharp, "Carbon dioxide disposal in carbonate minerals," *Energy*, vol. 20, pp. 1153-1170, 1995.

[28] W. K. O'Connor, D. C. Dahlin, D. N. Nilsen, R. P. Walters, and P. C. Turner, "Carbon Dioxide Sequestration By Direct Mineral Carbonation With Carbonic Acid," presented at the International Conference on Coal Utilization and Fuel Systems, Clearwater, FL, 2000.

[29] H. J. Herzog, E. M. Drake, and E. E. Adams, "CO2 Capture, Reuse and Storage Technologies for Mitigating Global Climate Change - A White Paper," 1997.

[30] S. J. Gerdemann, D. C. Dahlin, W. K. O'Connor, and L. R. Penner, "Carbon dioxide sequestration by mineral carbonation, 2003.

[31] W. J. J. Huijgen and R. N. J. Comans, "Carbonation of Steel Slag for CO2 Sequestration: Leaching of Products and Reaction Mechanisms," *Environmental Science & Technology*, vol. 40, pp. 2790-2796, 2006.

[32] W. K. O'Connor, D. C. Dahlin, D. N. Nilsen, G. E. Rush, R. P. Walters, and P. C. Turner, "Carbon Dioxide Sequestration By Direct Mineral Carbonation: Results from Recent Studies and Current Status, 2001.

[33] Y. Aksu, (2011). Turbines Info. Available: [http://www.turbinesinfo.com/steam-turbine-efficiency/](http://www.turbinesinfo.com/steam-turbine-efficiency/).