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Economic and market analysis of CO_2 utilization technologies – focus on CO_2 derived from North Dakota lignite

J.D. Laumb[a]*, J.P. Kay[a], M.J. Holmes[a], R.M. Cowan[a], A. Azenkeng[a], L.V. Heebink[a], S.K. Hanson[b], M.D. Jensen[a], P.A. Letvin[a], L.J. Raymond[a]

[a]*Energy & Environmental Research Center, University of North Dakota, 15 North 23rd Street, Stop 9018, Grand Forks, North Dakota 58202-9018, USA*
[b]*Research, Innovation, & Outreach, University of Minnesota, 399 McNeal Hall, 1985 Buford Avenue, St. Paul, MN 55108*

Abstract

Based on information obtained about the technical aspects of the technologies, several challenges are expected to be faced by any potential CO_2 utilization technologies intended for North Dakota lignite plants. The weather, alkaline content of lignite fly ash, and space limitations in the immediate vicinity of existing power plants are challenging hurdles to overcome. Currently, no CO_2 utilization option is ready for implementation or integration with North Dakota power plants. Mineralization technologies suffer from the lack of a well-defined product and insufficient alkalinity in lignite fly ash. Algae and microalgae technologies are not economically feasible and will have weather-related challenges.

Keywords: CO_2 utilization; CO_2 reuse

1. Introduction

Because of the abundant supply of coal resources such as lignite in North Dakota and some of the Midwestern states, the United States will rely on the use of fossil fuels for its energy needs for many years to come, thus sustaining or increasing the level of CO_2 emissions. Since lignite produces more CO_2 per unit of energy compared to the other ranks of coal, it will be the fuel most impacted by any move to force CO_2 emission reductions from power plants. Given that the primary use for North Dakota lignite is minemouth electrical power plants, any CO_2 regulations will potentially have more impact on the North

* Corresponding author. Tel.: +1-701-777-5114; fax: +1-701-777-5181.
E-mail address: jlaumb@undeerc.org.

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Dakota power industry and economy. To lessen the impact on the state, it is important to begin exploring ways of addressing the CO_2 emission issue in a sustainable manner. To this end, approaches that focus on CO_2 capture and reuse are attractive, particularly in areas where geologic storage may not be an optimal solution. Also, finding a potential use for the captured CO_2 might generate additional revenue to help offset some of the costs associated with CO_2 capture and, hence, act as an incentive for capturing CO_2 from lignite-fired power plants.

The primary purpose of this Energy & Environmental Research Center (EERC) study was to assess existing and emerging technologies for the beneficial use of CO_2 captured from North Dakota lignite-fired power plants. In the context of this study, the best technology is defined as one that not only utilizes CO_2 efficiently and cost-effectively but also results in or produces the most marketable product. By specific recommendation of the North Dakota Industrial Commission's (NDIC's) Lignite Research Council, technologies related to enhanced oil recovery (EOR), enhanced coalbed methane (ECBM), and enhanced gas recovery (EGR) were not considered in the investigation. All other areas that show both near- and long-term promise were considered in the study.

2. Methods

While carbon capture, utilization, and storage (CCUS) technologies are developing rapidly worldwide and possess the potential to offer a significant contribution to CO_2 mitigation, there is interest in also exploring the possibility of CO_2 utilization in other end uses, such as in building material production, fuels, and chemicals. Several broad technology areas are being developed to facilitate the beneficial use of captured CO_2 from large point sources, such as coal power plants. These technologies encompass various applications, including EOR, ECBM recovery, CO_2 conversion to chemical feedstocks and fuels, biological conversion (photosynthesis) processes, and CO_2 mineralization for the production of materials. EOR is one of the largest uses of CO_2 captured from anthropogenic point sources, especially in the last few decades when there has been a greater desire to rely more on locally produced oil. During times of high natural gas prices in the United States, some of the CO_2 has been directed to ECBM recovery to boost production. In the last several years, more attention is being directed to other technologies such as algae growth, electrofuels, and chemicals as a means of providing a beneficial use for the captured CO_2, which could offset some of the high costs associated with CCUS technologies. An overview of these technologies is presented in Figure 1.

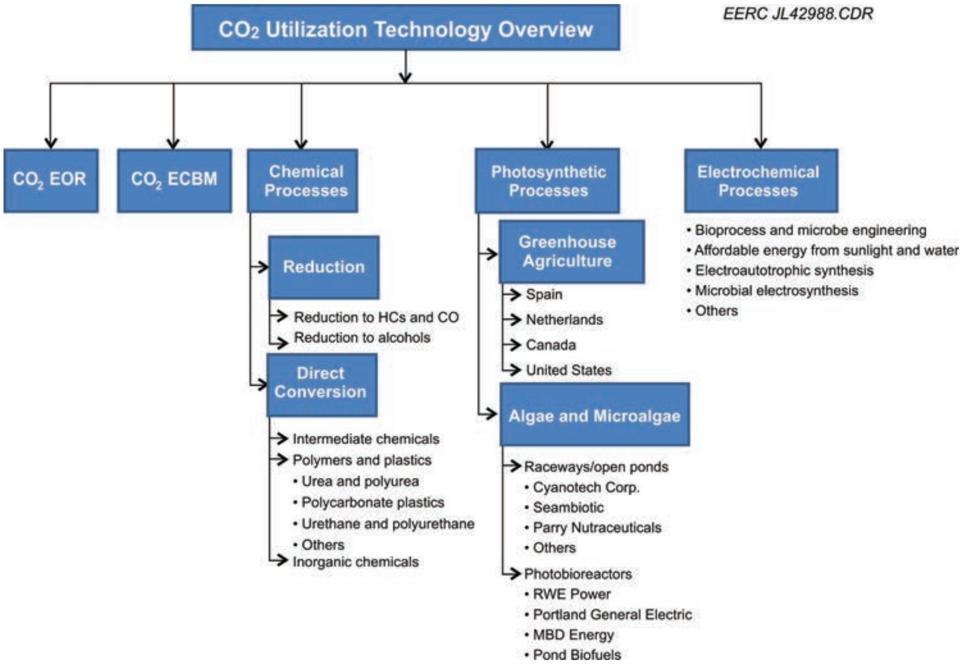

Fig. 1. An overview of CO_2 utilization technologies

Currently, the major areas of CO_2 utilization technologies include CO_2 EOR, CO_2 ECBM, CO_2 EGR, mineralization, chemical conversion processes, biological (photosynthetic) processes, and electrochemical processes. However, the specific goals of this project did not include further research into EOR, ECBM, or EGR. Thus, the remaining areas that were the focus of this study are mineralization, chemical conversion processes, biological processes, and electrochemical processes. The technologies in these areas that are under development were evaluated for their suitability to use CO_2 captured from North Dakota lignite-fired power plants. The criteria used for evaluating these technologies include the following:

- Technological feasibility
- Lignite-specific challenges/CO_2 purity requirements
- Regional and climatic challenges
- Source of CO_2
- Amount of CO_2 used
- Potential market for products
- Initial process economics
- Integration with the North Dakota fleet of plants
- Maturity and commercialization prospects

Since there are several options within each main technology area mentioned above, only the top few options, particularly those that have advanced to at least the pilot-scale demonstration stage, are evaluated in detail based on the criteria listed above. These are grouped under the main technology area. Because there is no one technology option that clearly meets all of the criteria set above, it is not possible to declare any option as the best available technology option for enabling the beneficial use of CO_2 captured from North Dakota lignite-fired power plants. Every option has its merits and demerits, depending on its stage of development and/or the principal concept of the technology. The technologies identified as the most promising based on these criteria then underwent a more comprehensive market analysis and economic evaluation.

3. Results and discussion

CO_2 utilization technologies were divided into the following six categories:

- The direct use of CO_2, such as in carbonated beverages, as a dry cleaning solvent, or for energy recovery processes like EOR or ECBM production.
- The mineralization of CO_2 by reacting it with metal oxides or metal hydroxides to form metal carbonates or metal bicarbonates that may be used in construction materials.
- Use as a feedstock in the manufacture of chemicals, including chemical products or precursor chemicals that require chemical reduction of the carbon to a less oxidized form.
- Use as a feedstock in the manufacture of chemicals, including chemical products of precursor chemicals like urea or bicarbonate that do not require chemical reduction of the carbon.
- Photosynthesis-based technologies that reduce the carbon in CO_2 to organic carbon for use as food, fuel, or a chemical feedstock.
- Novel technologies based on the direct use of engineered microorganisms, electricity, and/or the direct use of sunlight for the production of fuels and/or chemical precursors.

Direct-use technologies include the use of CO_2 for EOR, for ECBM production, as a solvent or refrigerant, or in foods and beverages. These technologies are well known, have been extensively documented elsewhere, and were not a focus area of this project. However, it should be noted that the supply of CO_2 for EOR and ECBM projects could represent a good near-term opportunity for North Dakota lignite users.

3.1. Mineralization

Mineralization to form products from CO_2 is a relatively new concept. It is the formation of a carbonate or bicarbonate solid from CO_2; thus, the CO_2 becomes a part of the solid product. CO_2 captured from any source can be used as a feedstock for mineralization reactions. The process also requires a source for the alkalinity required by the reaction; lignite fly ash could potentially provide this alkalinity. The most advanced of the mineralization technologies is still only at a pilot scale of development, and the products that will be generated by the various technologies, should they become commercial, are more likely to fill niche markets than be widely employed. Nationwide, 19 mineralization technology developers were identified. Most of the companies working in the area of CO_2 mineralization have provided lists of potential products but have not provided a clear path to making and marketing those products. The market will dictate the type and quantity of products that are made. The entry-level product for most mineralization companies will likely be aggregate that can be used for roads and/or as a component of concrete. Although the concept shows promise, it does not appear to offer an economically viable opportunity for the lignite industry in the near term because 1) aggregate made from mineralization of CO_2 is estimated to cost roughly double the current rate for gravel aggregate because of the value of the materials required to supply the metal cations and alkalinity for the mineralization and 2) lignite fly ash is more valuable as a raw material used for solidification of waste pits in the western North Dakota oil fields than as a source of alkalinity for mineralization reactions.

3.2. Chemical production (reductive and nonreductive)

CO_2 can be used in the production of chemicals and fuels. Many approaches are being developed to utilize CO_2 captured from various sources to produce useful fuels and chemical feedstocks and in the direct conversion of CO_2 to chemical products such as polycarbonate plastics or urea. The potential for these technologies to use CO_2 from coal-fired power plants is limited because 1) substantial energy input is needed to convert the carbon in CO_2 from its fully oxidized state into a reduced state where it can serve as a fuel and 2) the industries using CO_2 as a feedstock in chemical production also perform upstream processes that produce CO_2 either directly (typically at high temperature and pressure) or when they consume fuel in order to provide energy for the overall process.

The status of CO_2 reduction to fuels is currently limited to research and development studies, mostly in academic laboratories. When a fuel is made from CO_2, energy is used to reduce the carbon from a fully oxidized state to a more reduced state. The amount of energy required for this reduction process is greater than the amount of energy that can be obtained either from the process or from use of the newly produced fuel. A CO_2-to-fuel process only makes sense where the product formed is of very high value, the fuel is used as a storage product made from an intermittent energy supply source (e.g., wind, solar), and/or the fuel produced is useful in ways that the original source fuel was not (e.g., production of a transportation fuel from coal-derived CO_2).

When CO_2 is directly converted into chemicals, it is reacted with another feedstock that had to be produced in an upstream process. The quantity of CO_2 produced in this upstream process, along with the CO_2 produced from energy generation associated with this upstream process, will exceed the CO_2 demand of the step that uses CO_2. Therefore, most companies performing these processes will not use externally supplied CO_2. Additionally, most of the CO_2 use processes, or the upstream processes used to generate the reactive intermediates, require reaction conditions such as high pressure and/or high temperature, with fossil fuel combustion typically used to provide the heat and power necessary to meet these needs. In fact, more CO_2 is produced during polycarbonate plastic or urea production than is used to make the products. Some of the largest postcombustion CO_2 facilities operating in the world are located at urea plants where CO_2 is captured from natural gas combustion flue gas in order to supply some of the CO_2 used for converting ammonia to urea.

3.3. Photosynthesis-based technologies

Photosynthesis-based processes using externally sourced CO_2 include algae production and greenhouse agriculture. In order for these technologies to provide a favorable CO_2 demand, the energy input for CO_2 reduction to organic carbon needs to be primarily from sunlight rather than from electric lights unless the electricity is derived from a zero-carbon source (i.e., wind, solar, nuclear). Greenhouse agriculture and algae systems can use low-concentration CO_2 streams. In algae production, CO_2 must be supplied both as a source of carbon for growth of the algae and to control the pH of the growth media. In greenhouse agriculture, CO_2 serves as the carbon source for plant growth and can increase plant growth rates. CO_2 supply to greenhouses is particularly important in colder climates where increasing air exchange to supply CO_2 from the outside air would result in excessive heating costs.

The microalgae production industry is a small and well-developed industry that has a proven ability to make money. The industry purchases externally sourced CO_2, but the size of its markets is small relative to the amount of CO_2 that is potentially available from power plants. Less than 18,150 tonnes/yr (20,000 tons/yr) of algae is produced worldwide, primarily for use as nutritional supplements [1]. There has been a recent explosion of algae start-up companies (some estimate more than 200 since 2005) that are trying to break into potential algae product markets that promise to be much larger than the nutritional supplement market but require much less expensive algae. These larger markets include the production of biofuels, animal feeds, and fish meal replacements. Since these products have a relatively low value, production costs must be substantially reduced from current commercial production costs. Production of these lower-value products cannot be performed in an economically viable manner even under the most favorable conditions.

Algae and microalgae technologies are not economically feasible for North Dakota. The successful algae-producing companies are located in environments that favor the manufacture of their products (i.e., moderate temperatures and sunlight are available without extra cost). Their high-value nutrient supplement products are dry, shelf-stable and, therefore, relatively inexpensive to transport, making them readily available to the local population even without local producers. Irrespective of location, algae and microalgae products that could utilize a substantial amount of CO_2 (e.g., fuels and feed) are currently more expensive to produce than their potential market value.

Greenhouse agriculture, or controlled-environment agriculture, involves growing plants in a greenhouse. High-technology greenhouses are supplied with CO_2, heat and humidity control, and supplemental light as required to ensure high productivity. The common products from this type of agriculture include flowers, specialty fruits, and vegetables. North Dakota power plants may potentially benefit from the development of greenhouse agriculture operations in the state. These facilities can use both CO_2 and low-grade heat from the power plants and will also be customers for electricity used in supplemental lighting. The total demand for CO_2 is unlikely to be high, but the market and economic indicators investigated appear to indicate that a profitable venture could be developed based on this CO_2 use technology.

3.4. Novel technologies

Twelve novel CO_2 utilization technologies were evaluated. These are primarily conceptual and laboratory-scale proof-of-concept processes of the type being supported by the U.S. Department of Energy's ARPA-E (Advanced Research Projects Agency-Energy) Program. They include processes that involve the electrochemical conversion of CO_2 to fuels and/or other chemicals, bioelectrochemical systems such as reverse microbial fuel cells that combine microbial processes and electrochemistry to produce chemicals, the use of microorganisms that convert H_2 and CO_2 to desirable chemicals, and other processes that use sunlight to power chemical synthesis reactions. All of the novel CO_2 utilization technologies are at a very early stage of development and are not close to moving out of the laboratory. In addition, these processes require the input of energy to convert CO_2 into a useful product. The hope is that some of these concepts will, at the very least, contribute to the development of useful technologies that can be commercially relevant sometime in the future, perhaps within the next 25 years. A great deal of work and the investment of substantial time and money will be required if that is to happen.

3.5. Market analysis

The CO_2 mineralization technologies do not yet have well-defined products. The market will dictate the type and quantity of products that are made, but the entry-level product for most mineralization companies will likely be aggregate that can be used for roads and/or as a component of concrete. There is a substantial need for aggregate in North Dakota, particularly in the Devils Lake Basin and in the Bakken–Three Forks shale oil development area. The cost of gravel is roughly one-half of the developer-estimated cost of aggregate formed by mineralization, indicating that product improvements are needed for this technology to compete economically. Another use for mineralization products might be as solidifying agents for drilling waste pits formed during oil field operations. The fly ash is currently more valuable for this use than as an alkalinity source for a mineralization process.

Greenhouse agriculture appears to be the most promising technology for which products are obvious and can be assessed for potential markets. Based on the market analysis conducted as part of this study, it is known that greenhouse agriculture can produce much higher yields of some vegetable crops than traditional agriculture. The market price for greenhouse tomatoes is quite high, and there is also a high demand in the United States, which imports nearly 1.2 million tonnes (1.3 million tons) of tomatoes annually [2]. The capital and operating expenses for such an enterprise could be large and the amount of daylight during the winter in North Dakota could pose a seasonal production issue. However, people and companies are interested in buying locally sourced vegetables such as tomatoes, peppers, and cucumbers because they are fresher and transportation costs are lower (it should be noted that the added expense associated with greenhouse agriculture probably eliminates the cost advantage to the individual consumer). Large grocery chains and food service companies that are headquartered in or near the region have expressed interest in the availability of produce from this type of regional source. Finally, there are few greenhouse agriculture enterprises in the region around western North Dakota, so the competition would be minimal.

3.6. Economics – greenhouse agriculture

Product value that can be derived from the greenhouse depends on how productive the operation is and the price of the product. Table 1 shows average productivities for two of the major greenhouse agriculture areas: Almeria, Spain, and the Netherlands. As seen in Table 1, the greenhouses in the Netherlands are much more productive. This is a function of the intensity and sophistication of the greenhouse operations. Figure 2 shows the U.S. producer price for tomatoes from 1991 through 2007 reported for all farm operations. For a producer price of \$8/kg for tomatoes and a productivity of 42 kg/m^2/year, the potential production cost would be \$336/m^2/year. If this production is performed using liquid CO_2 priced at \$110/tonne and the supply of CO_2 costs \$2.41/m^2/year, then the CO_2 cost represents only 0.7% of the producer cost, providing a good price for the CO_2 supply.

In light of the above analysis, North Dakota power plants will potentially benefit from any greenhouse agriculture operations in the state. In most cases, these greenhouses have been subsidiary companies owned by the power plants themselves so as to facilitate integration with the current plants and to derive additional synergistic benefits such as a supply of low-grade heat for maintaining the temperature in the greenhouses in the winter or a supply of power to cool the greenhouses in the hot summer months. Also, collocation removes extra transportation requirements and associated costs, which makes the operation even more economically feasible. Based on 2003 estimates, the United States imports a total of about 280,000 tonnes of greenhouse-grown tomatoes annually [3]. In 2009, the U.S. imported a total of 1.2 million tonnes (1.3 million tons) of tomatoes (not all of which were greenhouse-grown) [2]. This high demand, coupled with very good prices, could mean a significant revenue source for North Dakota power plants.

4. Conclusions

Based on information obtained about the technical aspects of the technologies, the following key challenges are expected to be faced by any potential CO_2 utilization technologies intended for North Dakota lignite power utilities:

- The weather will be a serious challenge to algae and microalgae technologies in North Dakota. Raceway or open-pond technologies will be particularly impacted because of freezing of the water in the ponds during winter months. Photobioreactors (PBRs) will also be affected, although to a lesser extent. The only remedy is to use heated systems, but additional heating will drive up the cost even more.
- The alkaline content of lignite fly ash is lower than the desired levels for mineralization processes; external sources of alkalinity may be needed to make this a feasible option.
- Flue gas contaminants are a potential threat to the highly sensitive catalyst systems currently being developed for use in most chemical conversion processes.
- Land space limitations in the immediate vicinity of existing power plants may limit the application of some technology options such as greenhouse agriculture or algae cultivation. PBR algae systems may not have excessive space demands, but the technology is currently too expensive to be a practical option.

Table 1. Vegetable yield in greenhouses, annual productivity, kg/m^2 [4]

Crop	Almeria, Spain	The Netherlands
Tomatoes	10 12	42
Peppers	6 7	26
Cucumbers	8 9	58
Snap beans	5	32

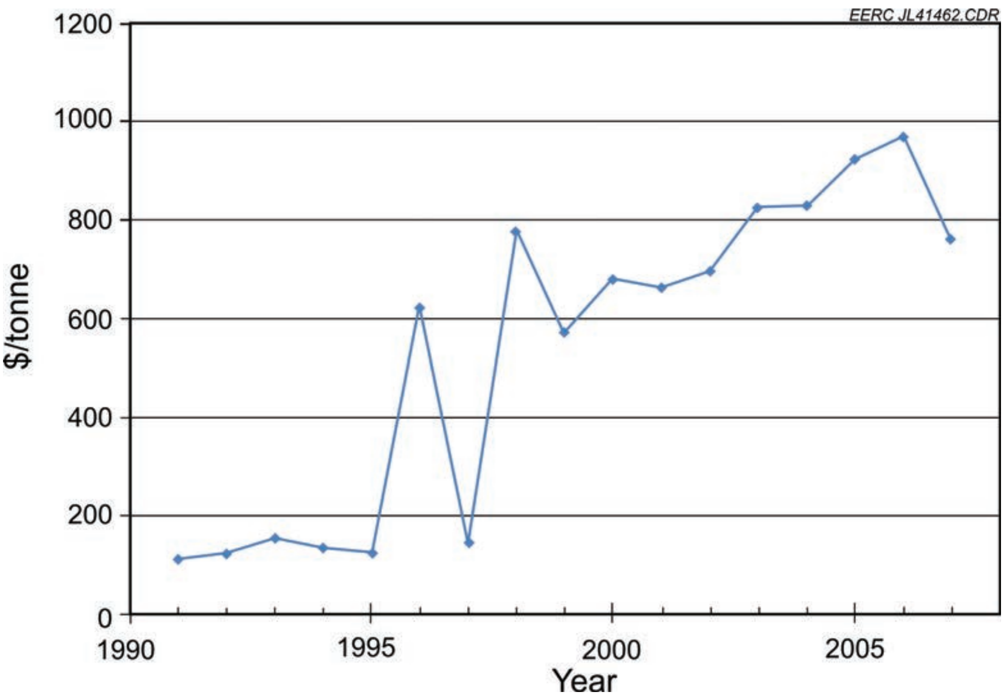

Fig. 2. U.S. producer price for tomatoes [5]

Currently, no CO_2 utilization option is ready for implementation or integration with North Dakota power plants. Mineralization technologies suffer from the lack of a well-defined product and insufficient alkalinity in lignite fly ash to make any significant reduction in the produced CO_2. Algae and microalgae technologies are not economically feasible and will have serious weather-related challenges as well. Algae oil productivity is also currently very limited; in order to sustain the demand of any algae-derived biofuel products such as biodiesel, research and development are still warranted. However, the most promising option appears to be greenhouse agriculture, which has a readily available market and is carried out in closed environments where temperatures can be easily controlled relatively cheaply by using waste heat from power plants.

Based on the market analysis conducted as part of this study, it is known that greenhouse agriculture can produce larger yields of some vegetable crops than traditional agriculture. The market price for greenhouse tomatoes is quite high, and there is also a high demand in the United States, which imports nearly 1.2 million tonnes of tomatoes annually [2]. The capital and operating expenses for such an enterprise could be large, and the amount of daylight during the winter in North Dakota could pose a seasonal production issue. However, people and companies are interested in buying locally sourced vegetables such as tomatoes, peppers, and cucumbers because they are fresher and transportation costs are lower (although the added expense associated with greenhouse agriculture probably eliminates the cost advantage to the individual consumer). Large grocery chains and food service companies that are headquartered in or near the region have expressed interest in the availability of produce from this type of regional source. Finally, there are few greenhouse agriculture enterprises in the region around western North Dakota, so the competition would be minimal.

A preliminary economic feasibility analysis indicates that none of the currently available technologies would be feasible for North Dakota power plants. However, greenhouse agriculture appears to be a promising option, and there seems to be a demand for the products both locally and across the United States. A more detailed economic study based on an actual greenhouse in operation would be needed to determine the exact profitability of greenhouse farming in North Dakota. Algae technologies, although seemingly very appealing, are still expensive to operate; more importantly, the product yield is still too low to meet demand.

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