# Economic and Sustainability Evaluations of Carbon Capture and Transformation Technologies

## Honors Capstone Final Report

Honors Student: Katherine Giammalvo; Capstone Advisor: Rohini Bala Chandran

**ABSTRACT**
Carbon dioxide is a major contributor to global warming, and there is an environmental benefit to capturing carbon dioxide from the atmosphere, oceans, or other sources. There is also economic value in refining or converting carbon dioxide into an economically valuable substance, such as carbon-based fuels. One barrier to the widespread implementation of existing technologies is that it is difficult to develop an economically viable system where the economic benefit of the product outweighs the costs of the capture/refinement processes. Additionally, many of these technologies require substantial inputs of energy and other resources including water and scarce materials (e.g., precious metal catalysts for chemical transformations) in order to function. There is a lack of knowledge on the comparative effectiveness of technologies that draw from on different sources of carbon dioxide capture, for example, air versus oceanic capture of $CO_2$. This project establishes a holistic comparison of existing technologies with respect to the concentration of $CO_2$ in the source stream, performance of capture and conversion technologies, operating costs and resource use. Information on costs and energy use for existing technologies were collected from data reported in the scientific literature. $CO_2$ capture methods considered include: (a) thermochemical direct air capture, (b) amine scrubbing, and (c) electrochemical technologies. For the products I evaluate the value of making: (a) a pure stream of $CO_2$; (b) methanol; and (c) thermoplastic polymers. Thermodynamic and data-driven analysis is performed to establish and identify combinations of sources, technologies, and products which are the most effective while being economically viable and sustainable. These learnings will provide guidance to shape ongoing research in electrochemical technologies, and to improve the future design of carbon capture and transformation technologies. This analysis showed that all carbon capture methods of producing these value-added products were less energy intensive than production by traditional methods. Additionally, all of the processes were economically profitable and amine scrubbing was found to be the least expensive and least energy intensive carbon capture method.

**INTRODUCTION**
Climate change threatens many aspects of human life on earth by: impacting water availability, increasing occurrences of floods and droughts, causing extinction of plant and animal species, raising sea levels, and reducing food production and security (1). The impacts of climate change compound as the change in global temperature increases. For example, a 1.5°C increase in global temperature from pre-industrial levels corresponds to an additional 4% of the world population in 2000 being exposed to new or aggravated water scarcity (1). However, a 2°C increase doubles that number to nearly 8% (1). This trend of increasing impact from increasing temperature is true of almost every aspect of climate change effects. Therefore, there is a global incentive to limit the total temperature increase in order to maintain a livable biosphere.

The Paris Agreement is a legally binding international treaty outlined by the United Nations Framework Convention on Climate Change (UNFCCC) and adopted by 196 parties in 2015 (2).

This agreement aims to keep global temperature increase in this century well below 2°C above pre-industrial levels, and preferably below 1.5°C above pre-industrial levels. However, the United Nations *Emissions Gap Report* of 2021 projects a global temperature rise of 2.7°C by the end of the century (3). One potential contribution to keep global temperature rise below 1.5°C is carbon dioxide capture (4). These technologies involve removing carbon dioxide from the atmosphere or environment in order to reduce the concentration of $CO_2$ contributing to global warming. Furthermore, if global temperatures overshoot 1.5°C as projected (1), carbon capture technologies will be required to return atmospheric carbon concentrations to pre-1.5°C levels (4).

The present work discusses the sustainability and economic implications of various $CO_2$ sequestration and transformation technologies. Specifically, I outline the energy demands of each technology as well as the potential profits associated with capturing and transforming $CO_2$ into various value-added products. My aim is to quantify economic incentives associated with these processes, in order to encourage the implementation of these technologies on a large scale. This information will give a point of reference for researchers developing new carbon capture and transformation technologies to determine how their method compares to those currently on the market. The scope of this work is limited to four methods of carbon capture from three sources, and five types of end products (including pure $CO_2$). These capture technologies were selected as they are the most commonly used capture methods for each source, and the products were chosen to represent a broad selection of the various types of carbon products that can exist, including minerals, fuels, and polymers. The specific technologies and products included in this analysis are outlined in Figure 1 below

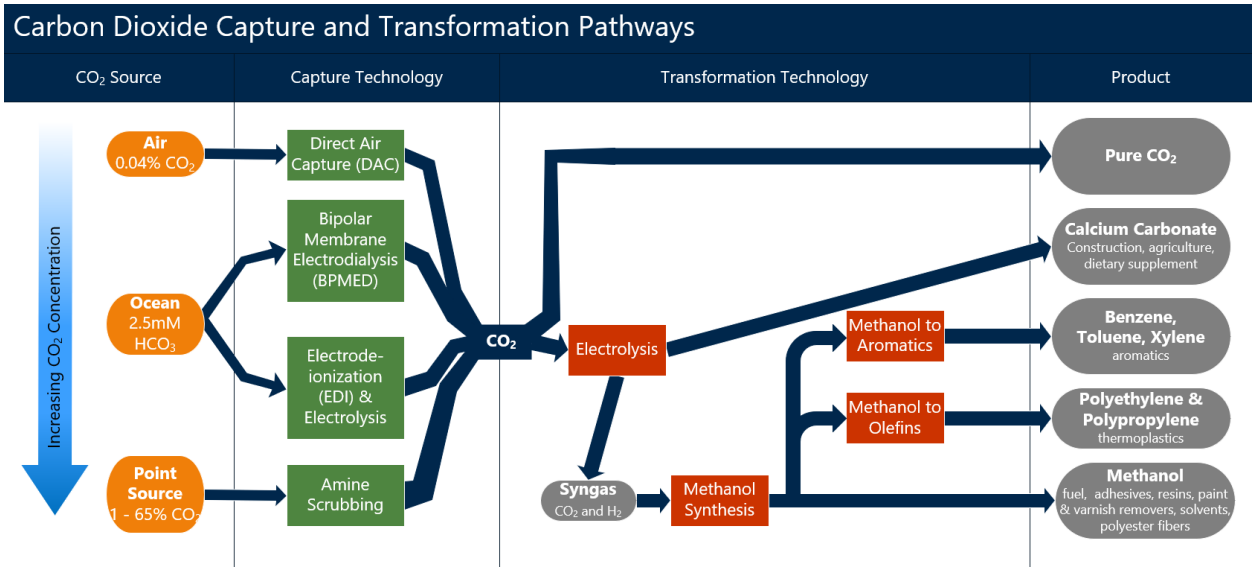


**Figure 1.** A process flow diagram of the carbon dioxide capture and transformation processes included in this analysis. Potential uses of the final products are also listed. The carbon dioxide sources are listed on the right in order of increasing carbon dioxide concentration.

## BACKGROUND

This section summarizes the methods included in this project and outlined in Figure 1, as well as some prominent non-profitable methods of carbon capture which are not included in this analysis.

### Overview of Carbon Capture Technologies

Four carbon capture technologies were included in this work, each of which draws carbon dioxide from one of three distinct sources. The first source is air, which contains 0.04% $CO_2$. The second is the ocean, which contains carbon in the form of $HCO_3$ at a concentration of approximately 2.5 mM. The third is point sources, which are emissions from industrial processes, and vary in concentration from 1-65% $CO_2$.

**Direct Air Capture.** The primary method currently used to capture carbon dioxide from the air is direct air capture (DAC). There are two thoroughly researched methods of DAC which are (a) high temperature aqueous solution DAC and (b) low temperature solid sorbent DAC (5). High temperature DAC uses a combination of two fluid loops where each loop passes through a causticiser, causing the carbon to be transformed into $Na_2CO_3$ (or $K_2CO_3$), then to $CaCO_3$, and finally be removed from the flow in the form of pure $CO_2$. The primary energy requirement from this method is that the causticiser must be heated to ~900°C to facilitate this reaction (5). Low temperature DAC occurs in a single chamber containing solid $CO_2$ sorbent. Air flows through this chamber and the $CO_2$ is absorbed, then the chamber is heated, releasing the captured $CO_2$ from the sorbent and allowing it to be collected (5). This process also requires significant energy input in order to heat the sorbent. Additionally, there are chemical and sorbent materials costs associated with both of these processes. Diagrams of each process are shown below in Figure 2. In this project, low temperature DAC is used for the analysis, as it has a lower cost requirement per metric ton of $CO_2$ captured.

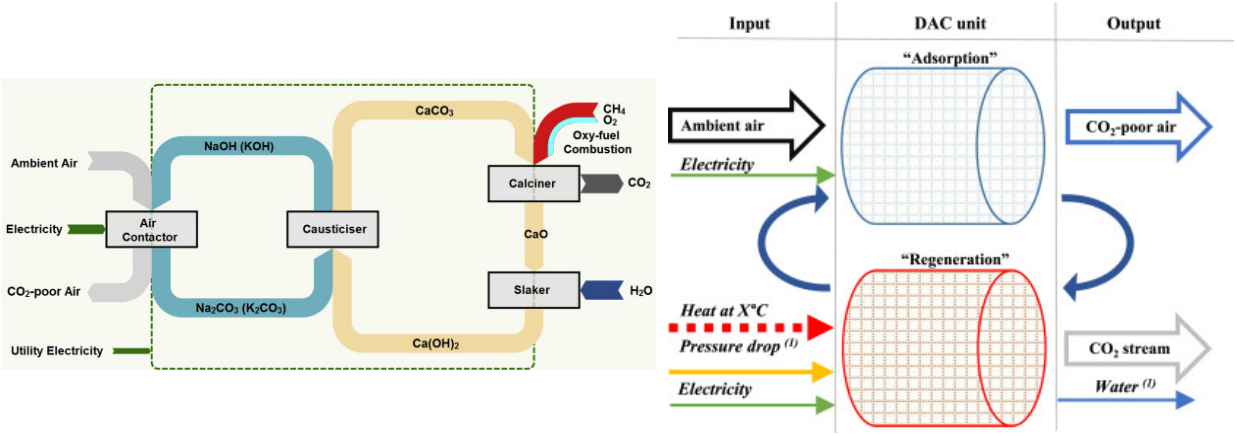


**Figure 2.** Process diagrams of (left) High Temperature Aqueous Solution DAC and (right) Low Temperature Solid Sorbent DAC methods. (5)

**Bipolar Membrane Electrodialysis.** BPMED is a method used to capture carbon from ocean water, which consists of creating an electric field across a membrane in order to generate a pH difference on either side of the membrane. $CO_2$ is first captured by the sorbent, then a pH gradient is generated to acidify the sorbent and release the captured $CO_2$ (6). Figure 3a shows a general diagram of a BPMED structure, while Figure 3b outlines the reactions taking place for a carbon capture BPMED, specifically.

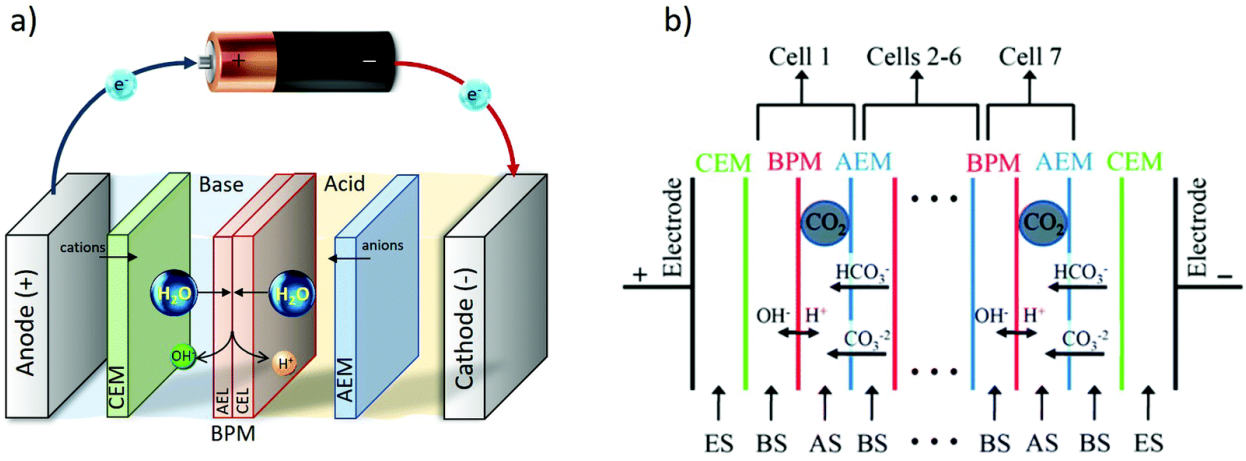


**Figure 3.** (a) a diagram of the general structure of a BMPED system, showing the anion and cation exchange layers in the membrane (AEL, CEL) and the anion and cation exchange membranes (AEM, CEM). (b) a diagram of the reactions taking place in a BPMED system specifically designed for carbon capture including (ES) electrode solution = KOH, (AS) acid solution of $KH_2PO_4 + H_3PO_4$, (BS) base solution of six different mixtures of $KHCO_3$, $K_2CO_3$ and KOH (6)

**Electrode Ionization and Electrolysis.** This is a relatively new method which combines electrode ionization and electrolysis into a single system designed to capture carbon from ocean water. This system passes seawater between a cation exchange membrane and anion exchange membrane, in order to facilitate a sequence of chemical reactions which extract $CO_2$ from the seawater (7). A diagram of this in Figure 4, including chemical formulas for the relevant reactions.

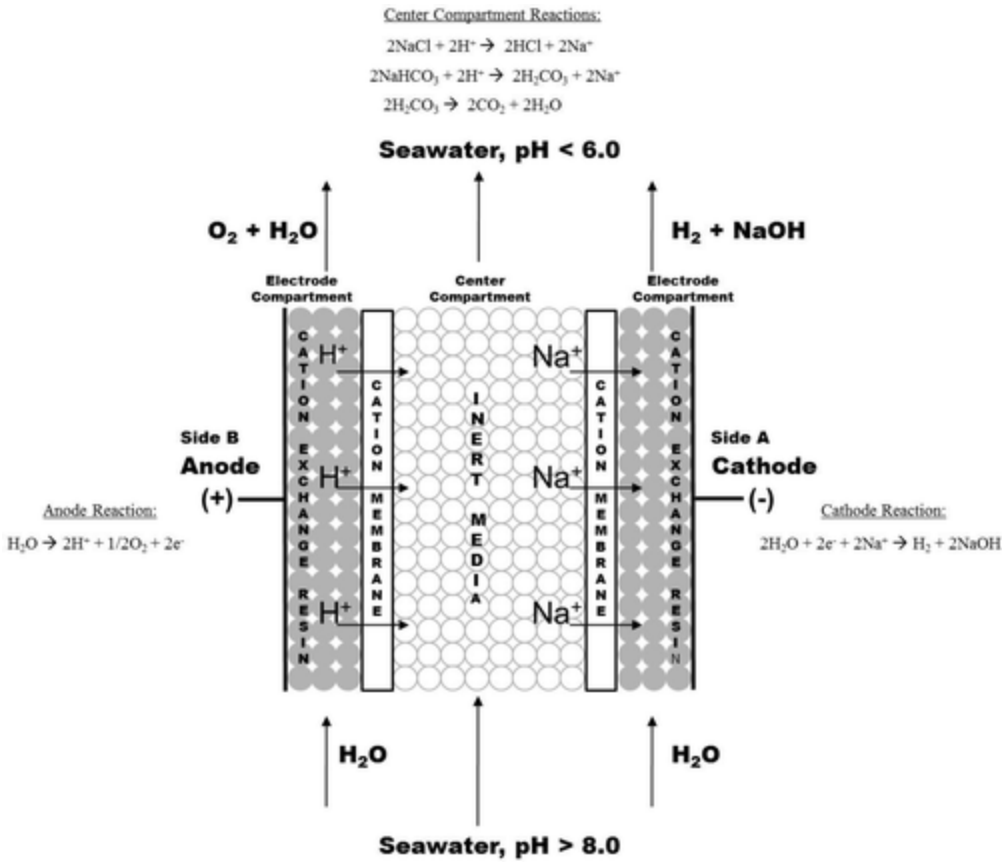


**Figure 4.** A diagram of carbon dioxide capture from seawater using a combined electrode ionization and electrolysis method. Formulas for the relevant chemical reactions are included for each section of the chamber. (7)

**Amine Scrubbing.** Carbon dioxide from point source flue gases is almost always captured using amine scrubbing methods. This technology can use various aqueous amine solutions, but this paper considers amine scrubbing using monoethanolamine (MEA), which absorbs $CO_2$ by reacting with carbamate. Pure $CO_2$ is then released when the MEA is heated. This method can capture up to 90% of the $CO_2$ in the flume (8). A diagram of the MEA amine scrubbing method is shown in Figure 5.

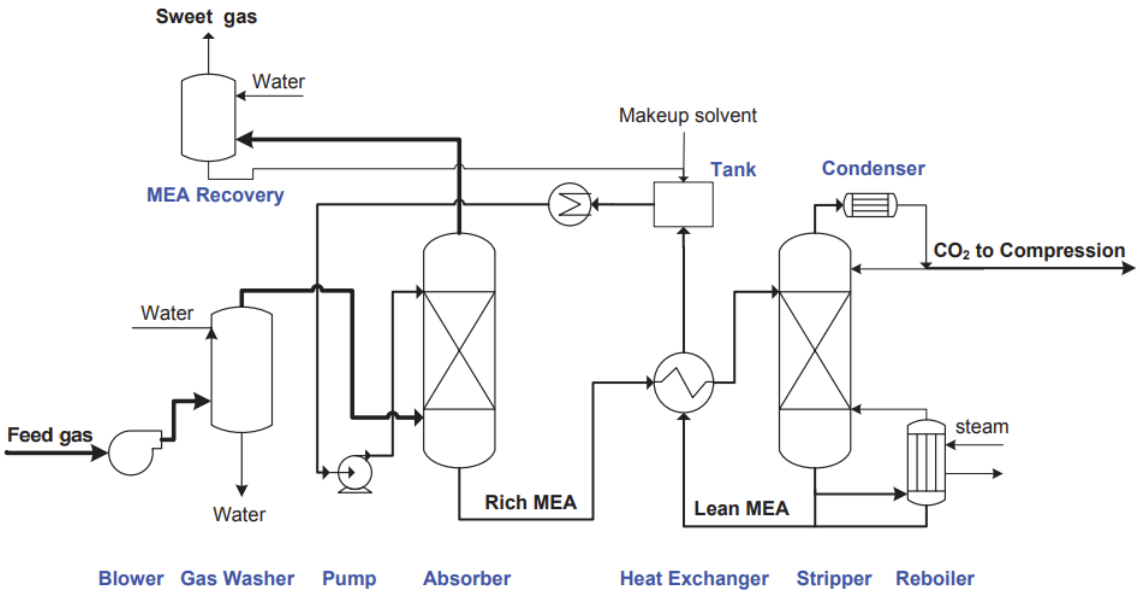


**Figure 5.** Example of an Amine Scrubbing process, which uses MEA as the aqueous sorbent (9)

**Overview of Transformation Technologies**

Four transformation technologies are included in this analysis, some of which are utilized in series in order to create four different value-added products from carbon dioxide. A diagram of these processes is shown in Figure 1. The technical principles of these processes are described below.

**Electrolysis.** Electrolysis is a process which decomposes a chemical into its component parts by passing an electric current through the solution. In this case, the electrolysis performed separates hydrogen and oxygen from water, such that the hydrogen can be added to captured $CO_2$ to create syngas.

**Methanol Synthesis.** This process intakes a combination of hydrogen and $CO_2$ to create methane, which can then be sold as a value-added product on its own or developed into another product using subsequent processes. Methanol synthesis works by reduction of $CO_2$ and hydrogen over a copper or zinc catalyst at 250°C and 80 bar.

**Methanol to Olefins.** This process also takes in methanol and synthesizes ethylene or propylene over zeolite catalysts at 495°C. There is only one commercial MTO plant currently in operation, which is in China and has an estimated lifetime of 50 years.

**Methanol to Aromatics.** This process takes in methanol and uses a process similar to the MTO method to form aromatic compounds (including benzene, toluene, and xylene) using a modified, more acidic catalyst, at temperatures around 400°C.

**Non-Profitable Capture Methods**

While not included in this analysis, it is important to note that many non-profitable carbon capture methods also exist and that some are very well established. These methods seek only to remove carbon from the environment and store it for the long term, without creating any value-added product. While these methods are very effective for carbon capture, they do not include the economic incentives associated with the processes included in this analysis. A few such methods include (10):

- Afforestation and Reforestation - planting new trees or replanting trees in depleted areas, which then absorb carbon dioxide through the naturally occurring process of photosynthesis
- Soil Carbon Sequestration - changing land management practices or land use in order to to increase the rate of $CO_2$ capture in soil
- Enhanced Weathering - simulating the natural process of weathering rocks at an increased speed, while also releasing cations in order to rapidly speed up the natural process of $CO_2$ capture which occurs from the weathering of rocks
- Ocean Fertilization - adding nutrients to an ocean in order to increase the growth rates of algae and other organisms, which absorb $CO_2$ through photosynthesis and eventually create long term storage of $CO_2$ in deep oceanic layers
- Ocean Alkalinity Enhancement - spreading pulverized silicate or carbonate minerals on the ocean surface to enhance weathering reactions which consume atmospheric $CO_2$ (11)

**METHODS**

The following section outlines the functional units and independent calculations used to compare the carbon capture and transformation processes described above in terms of both energy requirements and costs.

**Normalization**

All values throughout this work have been normalized to units of cost or energy per metric ton of $CO_2$. This is commonly referred to as the functional unit of the life cycle assessment, and is used to create valuable comparisons between processes.

**Thermodynamic Minimums**

As a point of comparison for each capture method, the thermodynamic minimum energy input required to separate carbon dioxide from the source and compress it to common storage pressures was found. The thermodynamic minimum of separation was found using the equation below:

$$W_{min,\,s} = \frac{R_u T_0 \Sigma_i y_i ln(y_i)}{M_m} \tag{12}$$

where $W_{min,\,s}$ is the minimum energy of separation per unit mass of the mixture, $R_u$ is the universal gas constant, $T_0$ is the temperature of the environment, $y_i$ is the mole fraction of $CO_2$ in

the mixture and $M_m$ is the molar mass of the mixture. This equation is derived from the thermodynamic principle of enthalpy, and from the change in enthalpy between the mixed and separated states of the fluid. The temperature of the reaction was assumed to occur at $T_0$ = 273 K.

Furthermore, the thermodynamic minimum energy required to pressurize the $CO_2$ to the common storage pressure $P_f$ = 12.22 atm is given by:

$$W_{min,\,p} = nR_u T_0 ln\left[\frac{P_0}{P_f}\right] = nR_u T_0 ln\left[\frac{V_0}{V_f}\right] \quad (12)$$

where $W_{min,\,p}$ is the minimum energy of pressurization for n moles of $CO_2$ to go from an initial pressure $P_0$ to final pressure $P_f$ (or from initial volume $V_0$ to final volume $V_f$). The pressure variation of this formula was used for the air and point source capture methods, while the volume variation was used for the oceanic capture methods. This calculation assumes that the temperature of the $CO_2$ does not change between capture and storage.

## DISCUSSION

This section summarizes the energy demands and costs associated with each process, and includes graphical comparisons of these technologies.

### Energy Considerations

The energy requirements of each process were found from literature, and normalized such that all energy inputs were in units of GJ/ton C. For those technologies which require both electrical energy and thermal energy input, an efficiency of 100% was assumed for transformation from electrical to thermal energy. For those which include a range of energy requirements depending on the specific implementation, an average energy between the maximum and minimum values was considered. High temperature DAC, low temperature DAC, amine scrubbing, BPMED, and EDI/electrolysis have energy requirements of 8.6 GJ/(ton C), 7.2 GJ/(ton C), 3.2 GJ/(ton C), 7.4 GJ/(ton C), and 63.0 GJ/(ton C), respectively (K6, K12). The energy demands for BPMED and EDI/electrolysis include only the energy required for the electrochemical step, not that associated with any other components such as pumps. The energy demands for these processes are compared in Figure 6, along with their associated thermodynamic minimums, as calculated from the equations given previously.

The energy associated with EDI/electrolysis is the highest, likely because this is the newest technology which has not yet been optimized. Additionally, the process with the lowest energy demand is amine scrubbing. Because amine scrubbing removes carbon dioxide from point sources, which are the most concentrated sources of $CO_2$ available, the thermodynamic minimum energy required for this process is also extremely low.

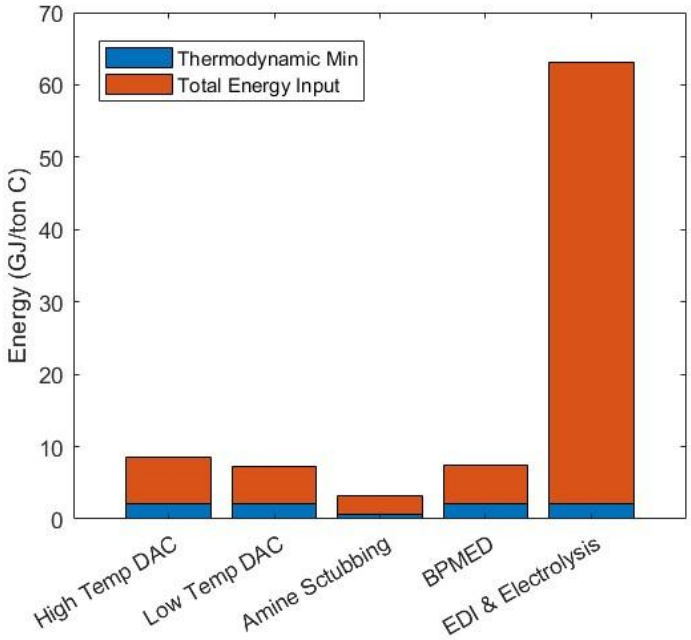


**Figure 6.** Energy required for each individual technology, both capture and transformation (GJ/ton C). Thermodynamic minimum energy requirements are shown for capture technologies only.

Methanol synthesis requires 6.9 GJ/ton C to create methanol from pure $CO_2$. The processes to transform methanol into polyethylene, polypropylene, benzene, toluene, and xylene require 2.12 GJ/ton C, 2.12 GJ/ton C, 1.97 GJ/ton C, 1.99 GJ/ton C, and 2.01 GJ/ton C, respectively (5). The electrolysis process required to create calcium carbonate from $CO_2$ requires 10.79 GJ/ton C. Figure 7 shows on the left a plot of the total input energy required for complete processes from the $CO_2$ source to the value-added product. The required energy input is different depending on the method of $CO_2$ capture, and the lowest energy input capture methods were selected for each source. The plot on the right of Figure 7 compares the energy input of the carbon capture and transformation processes to the energy required for traditional manufacturing methods (for non-fuels) or to the potential energy contained in the product as represented by the higher heating value (for fuels) (12). This plot gives an indication of the energy saved by creating the value-added products using the $CO_2$ capture methods.

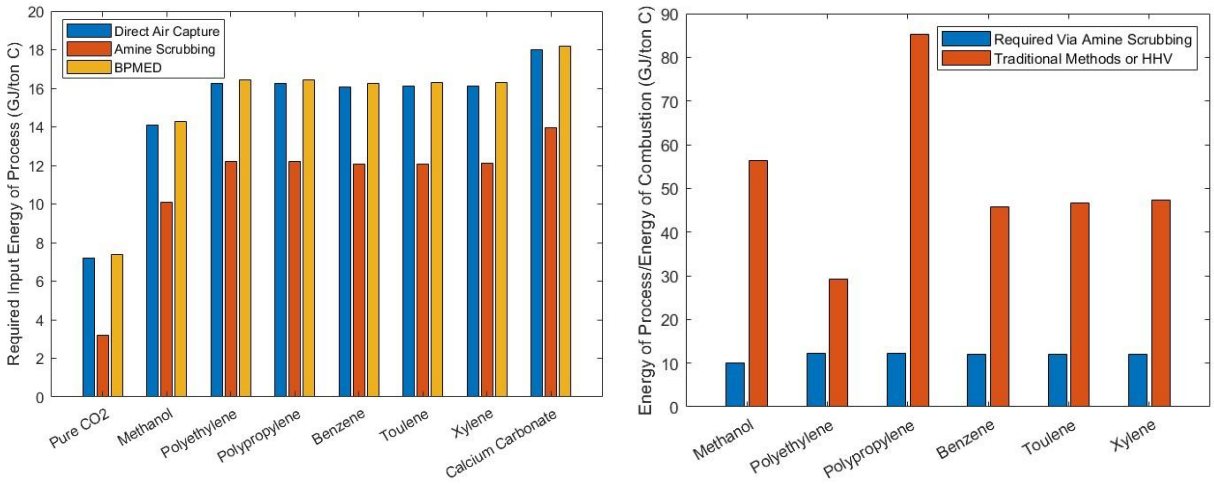


**Figure 7.** (left) Energy required to produce each value-added product (in GJ/ton C) corresponding to different carbon capture methods. (right) The energy required to produce products via carbon capture using amine scrubbing compared with either the energy contained in the products (HHV) for fuels, or the energy from alternative production methods for non-fuels.

**Cost Considerations**

The costs of amine scrubbing and electrolysis to form calcium carbonate are $5.46 /ton C and $145 /ton C, respectively. The other transformation technologies are all electrochemical processes, for which estimations of the total operating costs at large scale are unavailable. This is because no large scale $CO_2$ electrolysis processes are currently in operation and publishing their associated operating costs. Because electricity would likely be the largest continuous operating cost for these systems, and the design of the systems would be similar to large scale hydrogen fuel cells for energy production, the costs of these systems were calculated using the capital costs associated with hydrogen fuel cell energy production (13), and the operating costs were assumed to be the cost of energy (5) with a constant pricing rate of $0.175/kWh. The systems were assumed to have a lifespan of 5 years, which allowed the capital expenditure costs to be normalized into $/ton C.

The revenue and market sizes associated with each type of product were published by the Independent Commodity Intelligence Services in the ICIS Chemical Business Journal (14-19). This publication has not released reports on the pricing of $CO_2$ or $CaCO_3$, so these values were taken from costs to purchase bulk quantities of these products online.

**Summative Results**

Deciding on a method of carbon capture and transformation likely involves comparisons of more than one of the metrics included in this analysis. To serve this purpose, Table 1 summarizes the findings of earlier sections, with all values normalized per ton of carbon captured. For these

summarized results, the method of carbon capture used is amine scrubbing, since this method is both the least expensive and the least energy intensive.

**Table 1.** A summary of the results from the energy considerations and cost considerations, as well as an output of the market size available for each product. Note that these values assume amine scrubbing as the method of carbon capture.

| Product | Process Cost ($/ton C) | Revenue ($/ton C) | Profit ($/ton C) | Energy Input (GJ/ton C) | Market Size (ton C/yr) |
|---|---|---|---|---|---|
| Pure CO2 | 5.46 | 10506.79 | 10501.33 | 3.18 | |
| Methanol | 521.66 | 4705.96 | 4184.30 | 6.91 | 10.35 |
| Polyethylene | 680.44 | 1338.97 | 658.54 | 2.13 | 26.37 |
| Polypropylene | 680.46 | 1107.36 | 426.90 | 2.13 | 40.69 |
| Benzene | 669.04 | 735.01 | 65.97 | 1.97 | 240.28 |
| Toluene | 670.68 | 725.00 | 54.32 | 1.99 | 295.78 |
| Xylene | 671.89 | 730.90 | 59.01 | 2.01 | 274.99 |
| Calcium Carbonate | 5.46 | 11944.45 | 11939.00 | 13.97 | |

Some of these results are also summarized in Figure 8, which allows for a more visual comparison between products produced from methanol using the carbon dioxide capture methods. Again, the capture method is assumed to be amine scrubbing. This type of visualization is useful as it allows a quick comparison between potential profits, energy requirements, and market size. More than one of these metrics would likely weigh into the decision of which value-added product to make, especially if that product is intended to be sold on the market. For example, benzene and toluene have lower energy input requirements and a greater market size (which is advantageous), but would sell for a lower price per ton of carbon captured.

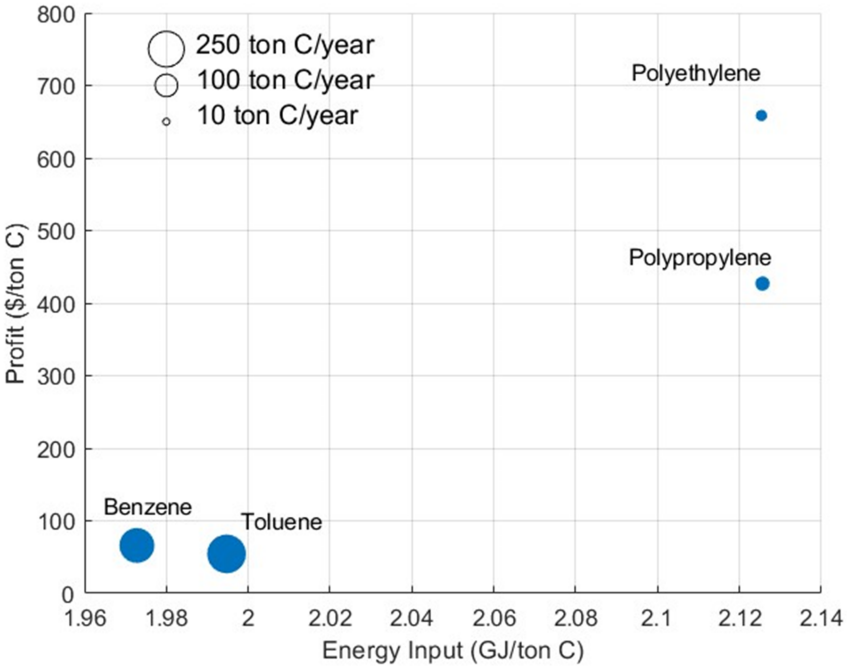


**Figure 8.** A graph summarizing the data for benzene, toluene, polypropylene, and polyethylene. This graph includes energy input and costs on the x- and y- axis, and market size corresponding to the size of the bubbles. These calculations assume amine scrubbing as the capture method.

## CONCLUSIONS

Among the capture technologies explored in the present work, amine scrubbing is currently the least expensive and least energy intensive due to the greater concentration of $CO_2$ in point sources than in the atmosphere. Additionally, of the potential value-added products considered in this paper, methanol was the most economically feasible, with the highest potential profit per ton of carbon captured ($4,184 /ton C captured). Of the four products which required further processing after creating methanol, benzene had the lowest energy requirement per ton of carbon captured (1.98 GJ/ton C). Finally, of all products considered, toluene had the largest potential market size per ton of carbon captured (295.8 tons C/year) and polypropylene offered the greatest energy savings when derived from captured carbon as compared to traditional manufacturing methods.

These various metrics allow for comparisons between potential $CO_2$ capture and transformation technologies, and create a point of reference for those developing new technologies. Emerging technologies should aim to be better than the existing technologies in one or more of the metrics listed above, in order to improve carbon capture methods overall. Furthermore, the knowledge that all of these products can be developed at a profit using carbon capture methods is a

particularly valuable incentive for companies to adopt these technologies as part of their development.

## FUTURE WORK

There are several areas which merit further exploration, to expand and complete the present work. The most immediate such area involves expanding this analysis to include a larger array of carbon-based value-added products. While this work is fairly comprehensive with respect to the carbon capture technologies included, it analyzes only a very limited subset of the carbon transformation technologies and value-added products. The most logical and valuable next step is to continue to collect data for other value-added products and to include them in this analysis, such that a more comprehensive comparison is available.

Beyond this, some beneficial related work would be to determine which potential processes would be valuable for certain industries; for example, applications which use a lot of methanol and release a lot of carbon dioxide at point sources could benefit from capturing that carbon via amine scrubbing and transforming it into methanol for use in their own production processes.

Finally, it would also be useful to understand environmental implications beyond energy demand associated with each technology. For example, comparing eutrophication, global warming index, water use, and other metrics would allow a more comprehensive comparison of carbon capture and transformation technologies.

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