A Review of the Existing and Prospective Methods for the Reuse of CO_2 Collected with Carbon Capture Technology

by

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Abstract

Climate change, which is linked with fossil fuel combustion related Carbon Dioxide (CO_2) emissions, is one of the major environmental problems that our society will be facing in the coming decades. Carbon capture and sequestration (CCS) methods coupled with CO_2 reuse is a way to mitigate CO_2 emissions. This research has two concurrent goals. First, the researcher will review current companies reusing CO_2 collected via carbon capture technology to see how the CO_2 reuse company landscape has changed since The Global CCS Institute's 2011 report. The second portion of this report is the community engagement phase. The goal of this research is to assess a sample of subjects both on their current knowledge of carbon capture, sequestration (CCS) and reuse, and on their capacity to increase their understanding of this topic after viewing a short presentation.

Table of Contents

Introduction

The ultimate goal of carbon capture and sequestration (CCS) and reuse is the reduction of anthropogenically-produced CO_2 emissions, which has been shown to be a major contributor towards climate change (NASA, 2016b). More specifically, carbon capture technology is being developed and utilized to capture CO_2 from fossil fuel combustion power generating units and other similarly powered industrial facilities before it reaches the atmosphere. Carbon capture technology can reduce the amount of CO_2 that is released into the atmosphere from power plants by up to 90% (Forbes et al, 2008). This is important because climate change, which is linked with fossil fuel combustion related CO_2 emissions, is one of the major environmental problems that our society will be contending with in the coming decades (NASA, 2016c). Carbon capture and sequestration methods coupled with applications for CO_2 reuse is a way to mitigate CO_2 emissions, perhaps serving reduce the effects of climate change for future generations.

The average atmospheric CO_2 reached 400 ppm in the spring of 2015 (Figure 1) (NASA, 2016a). Scientists are projecting that CO_2 levels will continue to increase given the energy, food, and other societal needs for an expected growing population, contributing to increasing average global temperature as well as extreme weather events including floods, hurricanes, droughts and wildfires (NASA, 2016c).

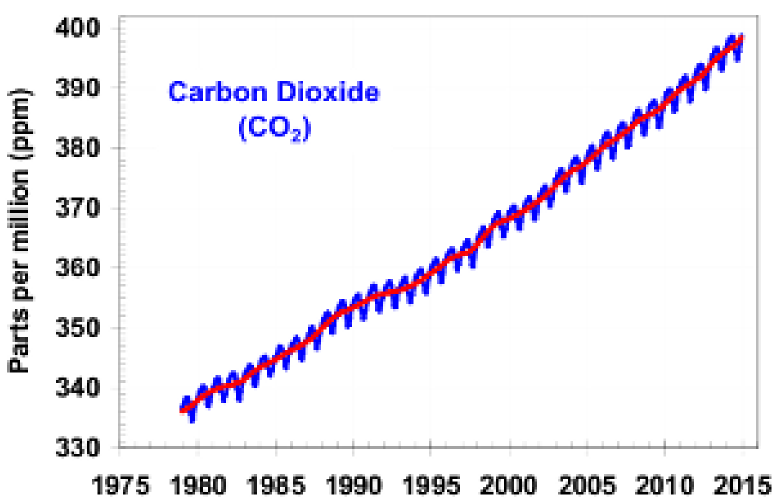

Figure 1. Global average of CO_2 concentration since 1979 (U.S. Department of Commerce, 2015).

In the United States, power-generating units contributed 37% of the CO_2 emissions and 31% of the overall greenhouse gas emissions in 2013 (Figure 2) (U.S. Environmental Protection Agency, 2016a, 2016b). Although other types of power generation facilities exist, including nuclear, hydropower and renewable technologies, coal-fired power plants are the biggest anthropogenic emission source. As of 2012, there were 572 coal-fired power plants in the U.S. (Union of Concerned Scientists, 2015), and more than 2,300 (7,000 individual units) globally (IEA Clean Coal Centre, 2012). In addition, half of the new power plants in the U.S. in 2013 were from natural gas (US Energy Information Administration, 2014). They are meant to replace older/existing coal-fired units and are intended to produce less CO_2 emissions than coal per energy unit but nevertheless are still producing CO_2.

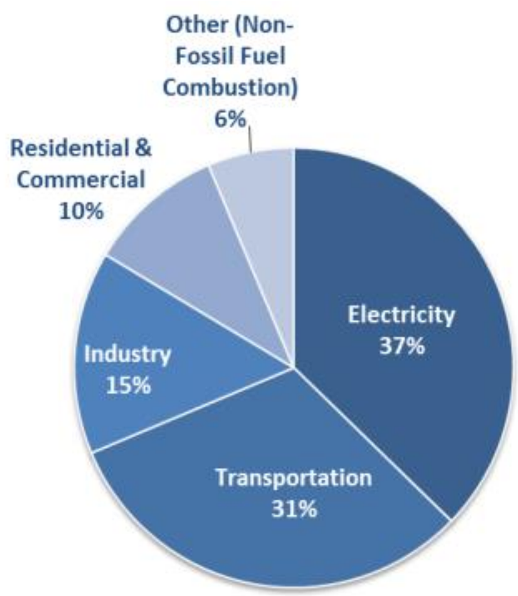

Figure 2. Summary of CO_2 emissions by sector (Environmental Protection Agency, 2016a).

Carbon capture is a technology that is not being used extensively. Currently, there are only 15 large-scale CCS projects in operation, 7 under construction, 9 in advanced planning, and 12 in early planning (Global CCS Institute, 2015). Carbon capture can either be implemented on new power plants, or retrofitted onto existing power plants; however, retrofitting existing power plants with carbon capture technology is often cost-prohibitive (Forbes et al, 2008).

In carbon capture, CO_2 is first captured from a power plant or other industrial facility. Then, it is piped to a location where it can be sequestered deep underground, reused as CO_2, or converted to other chemical forms for reuse. There are several methods for capturing the CO_2, including pre-combustion capture, post-combustion capture and oxyfuel combustion (Figure 3).

An additional aspect of carbon capture is the pipeline transport of CO_2 to sequestration sites. It can be sequestered long-term in sites such as depleted or semi-depleted oil wells. Additionally it can be injected into geological formations or sequestered in underground saltwater formations in either terrestrial or aquatic environments. (Carbon Capture & Storage Association, 2015; Forbes et al, 2008).

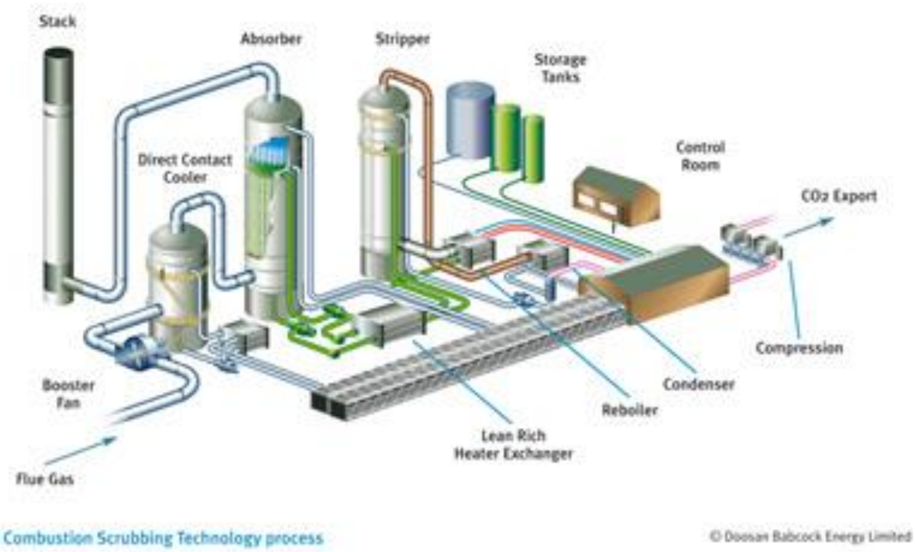

Figure 3. Post-Combustion Technology (Carbon Capture & Storage Association, 2016).

The words reuse and utilization will be used interchangeably in this report. There are several ways in which CO_2 can be reused. One major use for captured CO_2 that is being practiced in several locations is Enhanced Oil Recovery (EOR). In EOR, CO_2 is injected into an oil reservoir, which helps improve the oil flow rate. The injected CO_2 remains underground permanently. Another use is CO_2-based geothermal power that utilizes supercritical CO_2 to extract geothermal heat in circumstances where the heat doesn't easily reach the surface. There are several additional potential uses for captured CO_2 that are being explored and/or currently being utilized (DNV, 2011).

The following section will discuss the two primary purposes of this paper.

a. Study of Companies Utilizing CO_2

The Global CCS Institute published "Accelerating the uptake of CCS: industrial use of captured carbon dioxide" in 2011, a comprehensive report of the state of carbon capture reuse (Global CCS Institute, 2011). This report will henceforth be referred to as The Global CCS Institute's 2011 report. One weakness of the report is that it gave a comparable amount of discussion to both very actively-pursued and not as actively-pursued methods of CO_2 reuse. Some methods of reuse, such as algae biomass, have had many companies pursuing the technology since 2011, but others, for instance enhanced coal bed methane, have had very few companies pursuing the technology. Still others such as urea yield boosting might have current research investigations being conducted by governments or private companies in countries such as India or China, but this information is not readily available. **The first primary purpose of this project is to investigate companies endeavoring in CO_2 reuse. This research will focus on the current status of companies highlighted in The Global CCS Institute's 2011 report. Additional companies will be investigated, both in the major reuse categories outlined in the 2011 report, and in lesser-known categories of CO_2-reuse.**

In investigating these companies, the research will attempt to answer the following questions:

- How successful is each of the companies being reviewed?
- Which categories of research are being pursued by many companies, vs. the categories being pursued by very few companies?
- What is each company doing that separates it from other companies?
- What are "up and coming" methods of CO_2 reuse currently being pursued in laboratories that might be pursued more by companies in the future?
- In general, does it appear as if carbon capture coupled with reuse is picking up speed, staying the same, or becoming less commonplace?

CO_2 reuse is often a form of storage, and the CO_2 may or may not be permanently stored within the process of being reused. This process of storage within reuse will be referred to in this report as reuse with storage and not as sequestration to distinguish it from the permanent sequestration methods discussed previously. CO_2 reuse can be broken down into two broad categories: long-term vs. short-term methods of CO_2 storage. A long-term storage method has the intent of permanently storing CO_2. For instance, in enhanced oil recovery (EOR), the CO_2 that is used is permanently storing underground. However, in the making of polymers or fuels, the CO_2 is only stored for the lifetime of the product. Table 1 identifies the methods explored in this review that fall within the two categories. Note that even if a method is short-term, it may displace the additional CO_2 that would have been released if an equal or similar product had been made from raw materials, for instance in the case with algae cultivation being used to make fuels.

Table 1. Short-term and long-term methods used for CO_2 reuse and storage. (Global CCS Institute, 2011).

Short-Term	Long-Term
Algae Biomass Cultivation*	Enhanced Oil Recovery (EOR)
Polymer Processing	Enhanced Coal Bed Methane Recovery (ECBM)
Liquid Fuels	Enhanced Geothermal Systems (EGS)
Formic Acid Production	Bauxite Residue Carbonation
Urea-Yield Boosting	Mineral Carbonization/Concrete Curing
	Enhanced Uranium Leaching

*In the CCS 2011 report it is noted that algae utilization could be a semi-permanent method of CO_2 storage, but for the purposes of this review it is categorized as short-term.

b. Community Engagement

The second primary purpose of this project is to assess both the current degree of individual knowledge, and their capacity to increase their knowledge of CO_2 utilization. If numerous companies are going to pursue carbon capture and CO_2 reuse, it will require community understanding. If individuals don't understand CO_2 reuse then they might not be enticed to select products created through CO_2 reuse processes, and/or accept the integration of CCS projects into their neighborhoods (Ziegler, 2010).

In order to understand the importance of CCS and reuse, an individual must initially have a basic understanding of CO_2 and how it relates to climate change.

To assess the capability of community members to learn basic concepts on CO_2, climate change, and carbon capture, sequestration and reuse, a 12-minute test lecture was presented to the Raleigh Talkmasters Toastmasters club in Raleigh on 4-14-16 at 7:15 a.m. (Figure 25-26). The Toastmasters members, referred to henceforth as Test Group 1, were given a pre- and post-presentation questionnaire along with demographic questions on their age, educational level and gender. Additionally, a second test group, Test Group 2, was requested from social media – individuals volunteered to view a more detailed presentation, and fill out an identical pre- and post-questionnaire. The presentations and an assessment of the results are included in Appendix A.

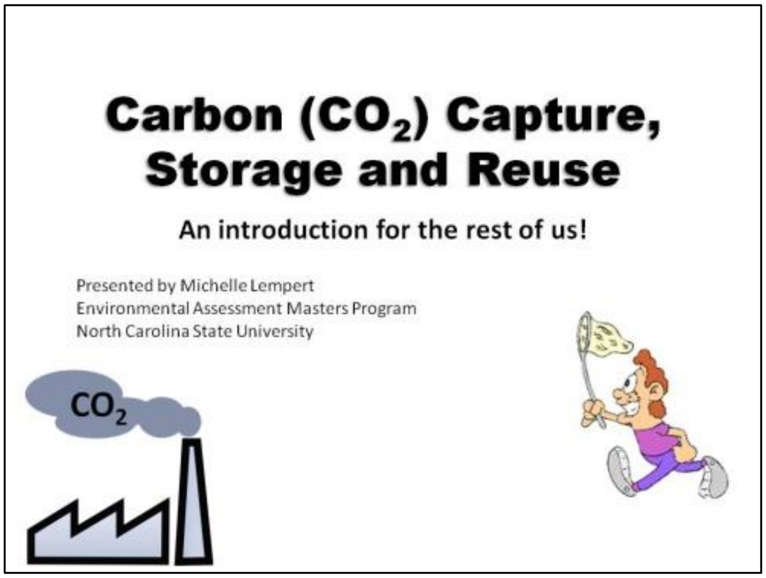

Figure 4. Page 1 of the PowerPoint Presentation presented to Toastmasters on 4/14/2016 and viewed by a second independent test group. The remainder of the presentation is available in Appendix A.

Methods

The approach for this review was to begin with The Global CCS Institute's 2011 report, investigate the companies discussed in that report, and see what's changed since 2011. This involved an exploration of several companies and their methodology for reusing captured CO_2. Initially this involved wide-breadth searches, with a focus on companies that were listed in the Global CCS Institute's 2011 report, but not limited to that publication.

Search Terms

For each reuse category, the search terms aligned with the specific area of research. Searches were in lib.ncsu.edu and on the web using Google as a primary search engine using the following search terms:

Algae; CO_2-based polymers; polymer processing; enhanced oil recovery; sodium bicarbonate or baking soda or $NaHCO_3$; hydrochloric acid or HCl; bleach or NaOCl; formic acid or CH_2O_2; methanol or CH_3OH; dimethyl-ether or C_2H_6O; synthetic gas or syngas; urea-yield boosting; carbonation of bauxite residue; aluminum; coal bed methane recovery; calcium carbonate; concrete curing; enhanced geothermal systems; geothermal; enhanced uranium leaching; uranium; innovative. All terms were searched with or without (depending on the efficacy) the following terms or a combination of these terms: *CO_2; carbon dioxide; reuse; carbon capture; CCS.*

When reviewing CO_2 reuse company websites, initially the home page, technologies pages, news, press and products pages were studied. This was followed by a web search on the company if the website was not thorough and informative. Additional articles would often be cited.

Initially, one week of research was allotted for each CO_2 reuse category. In practice, for some reuse categories such as algae, many more companies were found, so those categories required more time for research than other categories such as bauxite residue. Additional time was spent gaining basic knowledge in each category. For basic knowledge, journals, government websites and educational institution websites were initially sought out, in that order, followed by additional sources such as news articles and general websites for filling in gaps.

Innovative methods of CO_2 reuse were researched toward the end of the study period, and this was mostly on lib.ncsu.edu, focusing on journal articles from 2014-2016, and then expanding to 2011-2016. The Global CCS Institute's 2011 report was found to be pretty thorough in its discussion of CO_2 reuse methods, and fewer additional methods of reuse were found than was expected.

Criteria for inclusion/exclusion

References: About half of the initial references were included in the final report. If a source was read for the researcher's general knowledge but not specifically cited, then it was not included in the paper.

Reuse Companies: If there was sufficient information on a company, and it related specifically to the reuse category being discussed, then it was included in this report. There are additional companies that could have been investigated, but time was a limiting factor.

Methods of Reuse: There were many existing uses of CO_2 listed in a table in The Global CCS Institute's 2011 report that were not directly included in this current report. This list includes but is not limited to: beverage carbonation, wine making, food preservation, coffee decaffeination, pharmaceutical processes, pulp and paper processing, water treatment, inerting, steel manufacture, metal working, supercritical CO_2 as a solvent, electronics, pneumatics, welding, refrigerant gas and fire suppression technology. Many of these are considered to be mature technologies. However, potential future research could review if and how these mature categories of CO_2 utilization are using waste CO_2 from power, steel and cement plant facilities.

Laboratories/University Studies: The Global CCS Institute's 2011 report also included several laboratories and universities in Appendix L, "Emerging Technologies – Demonstration Projects and R&D studies." These laboratories/universities were not included in this current review because they were assumed by the researcher to be short-term demonstration projects, versus companies, which are generally pursuing technologies for a longer time period. However, journal articles/laboratory studies were included in this current report for purposes of detailing specific processes, for instance in the case of liquid fuels where multiple research studies are cited regarding finding of a catalyst that will assist in the conversion of CO_2 to CO, to be made into fuels.

Source types

Primary sources of information: Peer-reviewed journal articles were considered to be primary sources of technical and scientific information. Websites for companies specializing in a reuse category were considered to be a primary source for the purposes of informing the associated attributes summarized this report. Additionally, government websites and educational institution websites were considered to be primary sources.

Secondary sources of information: News articles about the companies and processes were considered to be secondary sources, and primarily relied on when primary source information could not be uncovered. General websites (websites consulted for informational purposes that didn't have a school or government affiliation) were also considered to be secondary sources.

Specific Information about Reuse Companies

The following is a list of basic information that was searched for when looking at CO_2 reuse company websites:

1. What is their general reuse category (for example Polymers, Algae, Urea, etc.)
2. What does the company website state is their source of CO_2? A number of companies were included that are not using waste CO_2 in their processes. For example, some companies are using atmospheric CO_2 and others using methane (CH_4). Still other companies are not using CO_2 at all, but were included for comparison/explanatory purposes. For example, a sample of companies producing bioplastics that are not using

CO_2 but are applicable to this review were included because their processes helps to explain one of the main usage categories.

3. Do they offer a short-term or long-term method of CO_2 storage (Table 1)?
4. What does the company website state are their processes? Does the website discuss any trademarks and/or patents? What are they doing that separates them from other companies? Further, does the company website state that they currently have test/pilot projects, or fully operational facilities and/or processes?
5. What kind of products do they create, and what are they useful for?
6. Does the website state any recent sources of income? What is the latest company news? Are any notable celebrities representing the company? (For instance, Carbon Engineering is financed partially by Bill Gates.) Based on their website, do they appear to be a successful company? It was noted if it appeared a company was going out of business or had gone out of business.

General Information about Reuse Companies

The following are additional questions the researcher was seeking to answer:

- Which reuse categories are being pursued by the most companies, vs. the categories being pursued by the least companies?
- In general, does it appear as if carbon capture coupled with reuse is picking up speed, staying the same, or becoming less commonplace?

The results are discussed in the body of this paper, and summarized in the chart in Appendix B. The researcher attempted to include the most current and accurate data on companies, however the confirmation of current and accurate information from websites and print media was a limiting factor.

Body

This section includes a discussion that focuses on companies employing each of the short-term and long-term methods of carbon reuse (Table 1), with a final section discussing additional uses for captured CO_2. A chart of the companies referred to in the text is in Appendix B.

Short-Term CO_2 Reuse/Storage Methodologies

Algal Biomass

Introduction on Algal Biomass

Algae can utilize CO_2 in the photosynthetic process to create biomass that can be used for the creation/development of many marketable products including foods, biofuels and cosmetics. Waste CO_2 from power, steel and cement plant facilities can be utilized in the production of algal biomass. Approximately 1.8 tonnes of CO_2 can be consumed for each tonne of algae biomass created. (Global CCS Institute, 2011).

There are multiple avenues in which CO_2 can be provided to algae for enhancing growth of their biomass, including flue gas from power, steel and cement plants; supercritical CO_2 from power, steel and cement plants; and CO_2 absorbed directly from the atmosphere. Different strains of algae prefer different sources of CO_2. There are around 100,000 different strains of algae (U.S. Department of Energy, 2012). Research is being conducted by several companies and laboratories to determine and/or bioengineer preferential strains. Some traits of preferential strains include growing well using CO_2 from industrial flue gas, and growing well in dense mass culture (Bhola et al., 2014; Benemann et al., 2003).

Bhola et al. (2014) considers contributions from several research studies (Calvin, 1989; Iverson, 2006; and Ho et al. 2011) when discussing the process of algal photosynthesis. Algal photosynthesis involves a light and a dark phase. During the light phase of photosynthesis, sunlight and water enter the organism to create sugar and O_2. ATP and NADPH are formed. During the dark phase, also known as the Calvin cycle, CO_2 is converted to sugar with the aid of the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO). The algal biomass results from this dark phase (Figure 5) (Bhola et al., 2014).

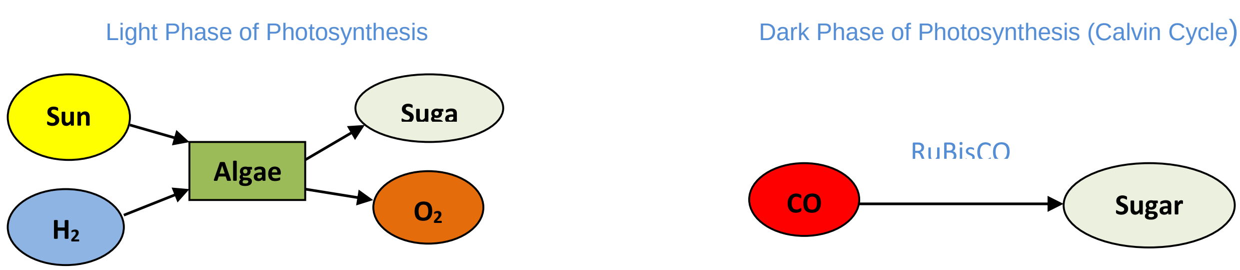

Figure 5. The dark and light phase of photosynthesis.

Algal biomass can be cultivated using a few different methods, including the open pond system and the photo bioreactor (PBR) system (Figure 6). Additional used systems include a fermenter, and a vertical growth/closed loop production system. The algal biomass can double in mass in as quickly as 24-hours, and unlike other plants that are used in the creation of biofuels (sugarcane, corn, sorghum, etc) which can only be harvested one or two times per year, algae can grow and be harvested all year round.

Figure 6.

a. Algal Open Pond System (eXtension, 2014).

b. Closed System Photobioreactor (ClimateTechWiki, 2016).

Companies Utilizing Algae Biomass

An extraordinary amount of research has been done on creating useful products out of algal oil. Several companies are in various stages of research and development, testing, or current use of algal oils. For instance, Cellana is using algae to create omega-3 oils, animal feed and biofuel feedstocks (Cellana, 2015a). Algae Systems (2011) was testing using it for jet fuel, diesel and gasoline, and fertilizer. They have gone out of business but they hope to reopen. LanzaTech has a suite of products fabricated from algae biomass: Ethanol, acetic acid, I-Propanol, acetone, lactic acid, 2,3 BDO, n-Butanol, MEK, succinic acid, Isoprene (LanzaTech, 2016a). HY-TEK Bio's algae biomass is being used for: omega-3s, soaps, soy milk thickeners, lubricants, carbs, and proteins for food supplements (HY-TEK Bio LLC, 2014a). TerraVia's algal biomass is being made into products including the cosmetic brand Algenist, VeganEgg, and an alternative to palm oil (Figure 7) (TerraVia, 2014).

Figure 7. Products made from TerraVia's algal biomass

The cost of producing a gallon of algal biofuel has gone from $240 to $7.50 per gallon, and current research is attempting to reach a yield cost of under $3.00 per gallon, and eventually targeting down to $2.00 per gallon (Biofuels Digest, 2014). In using plants as biofuel (for instance corn, sorghum and sugarcane), it would take land three times the size of the U.S. to provide enough fuel for the U.S. auto fleet (Biello, 2011). Using algae biomass as an alternative, the United States petroleum needs could be fueled using land approximately the size of Maryland, or 0.49% the size of the continental US *(*Chanakya et al, 2012).

If the process of algae biomass utilization is coupled with a wastewater treatment facility, then it can serve as a positive feedback loop where the algae uses the wastewater for obtaining nutrients, while at the same time as a co-benefit, treating and cleaning the wastewater. Algae Systems (2011) was testing doing this but they have shut down operations, but they hope to raise money to reopen (UTV44, 2015). MicroBio Engineering discusses this on their website as well, but their current status on this project is unknown (MicroBio Engineering, 2016).

Several corporations have patents on either their specific strains of non-native or bioengineered algae, and/or their processes for processing and/or utilizing algae. For instance, Cellana has patented the ReNew™ and Alduo™ technology (Cellana, 2015a). T2 has patented the

LipiTrigger™ growth enhancer (T2energy, 2016). Bioprocess Algae has proprietary Grower Harvester™ bioreactors (Bioprocess Algae, 2016), and Algenol has the Direct to Ethanol ® process (Algenol, 2011). Heliae has the PhycoTerra™ fertilizer (Heliae, 2015). Muradel has the proprietary Green2Black™ technology (Muradel, 2015), and MicroBio Engineering has developed the RNEW® process (Figure 8) (MicroBio Engineering, 2016).

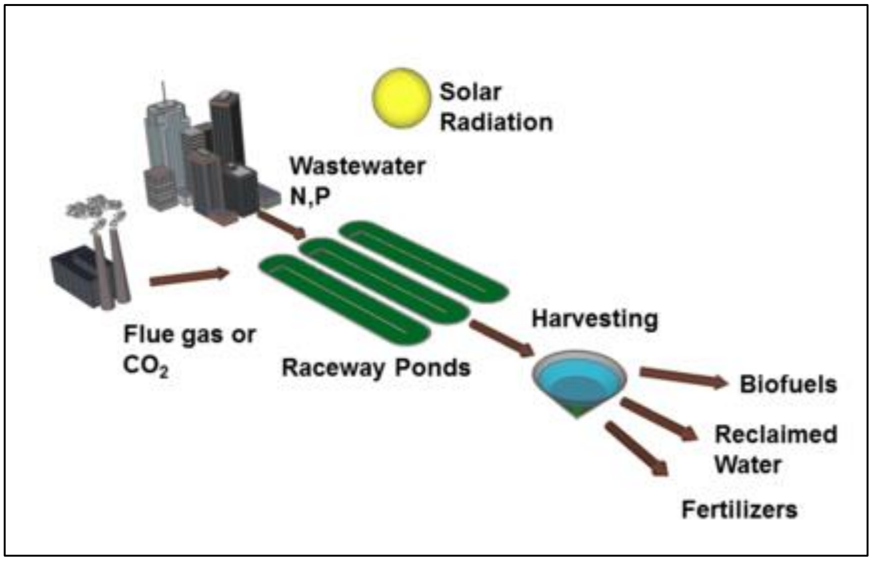

Figure 8. RNEW™ Process (MicroBio Engineering, 2016).

Several companies have pilot or test projects for algae biomass production. For instance, Cellana has the Kona Demonstration Facility (KDF) in Hawaii (Cellana, 2015a). Other companies have entered into joint ventures and partnerships, including TerraVia (fka Solazyme) partnering with Bunge, an agribusiness/food company (TerraVia, 2015b); Heliae partnering with Sincere Corporation in Japan to create the company Alvita (Heliae Development, LLC, 2015b); and the joint venture of Muradel with Murdoch University, University of Adelaide and SQC Pty Ltd. (Aban Infrastructure Private Limited, 2014). Neste Oil has made an agreement with Renewable Algal Energy, LLC to buy their crude algae oil for feedstock for biodiesel (Renewable Algal Energy 2014). At one point, Algenol had a plan to partner with Dow Chemical Company (Morsella, 2011). ExxonMobil and Chevron were at least at one point investing in algal biofuels (Blank, 2009). Monsanto purchased the algal development company Agradis in 2013. However, the research was unable to find out if this venture went anywhere – there is not a current site for Agradis (Monsanto, 2013). Monsanto also partnered with Sapphire Energy and supplied them funding to study algae genes (Sapphire, 2011b). However, this article that was last viewed on 3/12/2016 was not available on the web on 4/1/2016, and it looks like this collaboration may have ended. It is unclear if Sapphire Energy is still an active company (Sapphire, 2011a, 2011b).

In July of 2015, The U.S. Department of Energy awarded a total of $18 Million to several companies for the development of bioproducts and biofuels from algal biomass. Companies that received awards included the Colorado School of Mines, Duke University, Arizona State University, and the University of California. Research topics included increasing biomass yield from algae, the development of new products from algal oil, and utilization of flue gas from a nearby power plant for increasing algal yield (U.S. Department of Energy, 2015).

Additional sources of capital for algal development for companies, and research institutions include entering and winning contests, receiving grants and awards, joint ventures with larger corporations, and investment by state and federal governments. Some companies are traded on the public exchange, for instance TerraVia (fka Solazyme), which is publicly traded on the NASDAQ exchange as SZYM, but most appear to be privately-owned (TerraVia, 2014.).

Carbon Capture Corporation is an algae reuse company that was reported on in The Global CCS Institute's 2011 report, but appears to not be operational anymore. It is uncertain if the company BioFields is operational, but the website was entirely in Spanish and no translated version of the website could be found. Honeywell UOP and MBD were additional companies listed in the CCS 2011 report but the processes couldn't be found specifically on their websites. A2BE Carbon Capture was also included, but the website for this company contains no information except for a home page.

Summary of Algal Biomass Utilization

The study of algae biomass utilization has much potential. Coupling algae biomass with the utilization of CO_2 from a dedicated flue gas or supercritical CO_2 source will be a way to reuse the CO_2, though not necessarily permanently removing it from the atmosphere. Using CO_2 in the process of algae cultivation is different from other uses of CO_2 reuse in that it may result in either semi-permanent or non-permanent storage of CO_2. However, if biofuels replace fossil fuels, then it will prevent the introduction of anthropogenic combustion-related CO_2 into the atmosphere. Partnerships between CO_2-producing industries and algae producers are critical for the continued development of this category of research.

Polymer Processing

Introduction on Polymer Processing

A polymer is a moldable pellet also known as plastic that can be molded into many different products including packaging and clothing. Traditional fossil fuel forms of plastic include primarily: polyethylene terephthalate (PET), high density polyethylene (HDPE), polyvinyl chloride (PVC), low density polyethylene (LDPE), polypropylene (PP) and polystyrene (PS) (Earth 911, 2016; Eartheasy.com, 2012; Environmental Protection Agency, 2010).

Bioplastics are different in from traditional fossil fuel plastics in that they have some purported environmental benefit. Some bioplastics are bio-based (sourced from plants, algae, etc), some are biodegradable, and some are both. For instance, polyactide (PLA) is derived from corn or sugar cane or other sources of plants. “Drop-in” bioplastics are at least partially bio-based, but not biodegradable. There are fossil-fuel based plastics that are biodegradable. This means that the CO_2 will potentially make it back into the atmosphere. Polybutyrate or PBAT is an example, which is great for garbage bags – it biodegrades rapidly (Australian Academy of Science, 2015; Innovative Industry, 2010; Bioplastics Council, 2010).

The process of incorporating CO_2 into plastic has been shown to be more carbon friendly than traditional plastics: Polyethercarbonate polyols with 20% CO_2 by weight have been shown to reduce GHG emissions by 11–19%, and save fossil resources by 13–16% (Assen, 2014).

Companies Creating CO_2-Based Polymers

Novomer is one of the few companies using CO_2 to make polymers. Their product, Converge®, is about 50% CO_2. Converge® and uses CO_2 as raw material to produce polyols for polyurethane applications. It is being used for coatings, adhesives, sealant sand elastomers, and flexible and rigid foams. They produce foam that can be used in Enhanced Oil Recovery (EOR) (Novomer, 2015).

Novomer’s process sequesters the CO_2 for the lifetime of the product. They also make another product that combines Carbon monoxide (CO) with ethylene oxide to create a chemical intermediate that can be transformed to acrylic acid, acrylate esters, succinic anhydride and 1,4-butanediol. This product is used to make diapers, paints, coatings, plastics, and textiles. It can also produce polypropiolactone, which is biodegradable and can be used as a packaging material. They also make thermoplastics (Figure 9) (Novomer, 2015).

Figure 9. Novomer's thermoplastics (U.S. Department of Energy, 2013b).

Another company that is researching using CO_2 to make plastic is Bayer. They are researching making polyols utilizing CO_2 that is collected from a power plant in Germany (Plastic News, 2013; Bayer, 2015a; Bayer, 2015b).

Liquid Light has signed an agreement with the Coca Cola Company to make mono-ethylene glycol (MEG) from waste CO_2 using low-energy catalytic electrochemistry. MEG is one of the ingredients in Coca-Cola's plant-based PET bottle (Bioplastics Magazine, 2015).

Additional Companies Creating Biopolymers

Little evidence could be found on additional CO_2-based polymers being trademarked by other companies. Forms of bioplastics that don't utilize CO_2 are more common. For instance, Newlight Technologies and Calysta Energy are using CH_4 in the production of polymer materials (Newlight Technologies, 2016a; Calysta Inc., 2016a). Braskem in Brazil is using ethanol from sugar cane to create polymers (Braskem, 2016), and NatureWorks is creating a polymer from corn sugar (Natureworks LLC, 2016a). BASF uses EcoFlex, which is compostable; and EcoVio, which is both compostable and bio-based (BASF, 2016). Corbion has the trademark Puralact®, which is made from lactides and PLA resins. Additionally, Succinity is a joint venture between BASF and Corbion for producing Succinity®, a biobased succinic acid. This is produced using microorganisms and atmospheric CO_2, and is used in life sciences, biodegradable polymers, polyurethanes, plasticizers, industrial solvents and coatings (Succinity GmbH, 2016).

Summary on Polymer Processing

In summary, several companies are currently making polymers from sugar cane and corn and other crops. This process stores atmospheric CO_2 and lowers the amount of CO_2 that would have been released by making plastics with fossil fuels. However, industrial waste stream CO_2-based plastics are only being pursued by a few companies. Unless this category of research takes off and is pursued by several new companies, it is likely that crop-based bioplastics are going to continue to be the norm in the bioplastics arena.

Formic Acid

Introduction on Formic Acid

Formic acid (CH_2O_2) is a chemical that naturally occurs in ants and other stinging life forms and plants. It is used for de-icing runways, as an animal feed preservative, and as a coolant during petroleum extraction. It's also been promoted as an environmentally-friendly industrial cleaner, a medical treatment, and a coagulant in rubber production. In the future, formic acid might have additional uses such as powering cell phones fuel cells, and acting as a hydrogen (H_2) carrier, releasing H_2 for hydrogen fuel.

Company Development

Formic acid is heavily produced and utilized throughout the world. Much of the world's production occurs in Europe, and BASF is the world's largest producer of it (BASF, 2012). Kemira Oyj also produced a large amount of formic acid, though in 2013 they sold their formic acid business to Taminco Corporation in Allentown, PA (Kemira, 2013).

A small number of companies are studying or working with the creation of formic acid from CO_2. For instance, Mantra Energy is promoting the generation of it from CO_2 for its use in agriculture, in textile production, leather tanning, pharmaceuticals, oil well drilling, and de-icing. Mantra trademarked the Electro-Reduction of CO_2 (ERC). Mantra has developed a pilot plant that converts CO_2 from a cement plant in Richmond, BC into formic acid and salts. As of February, 2016, they have successfully demonstrated the operation of Electro-Reduction of CO_2 for greater than 2,500 hours (Figure 10) (Mantra Energy, 2014, 2016).

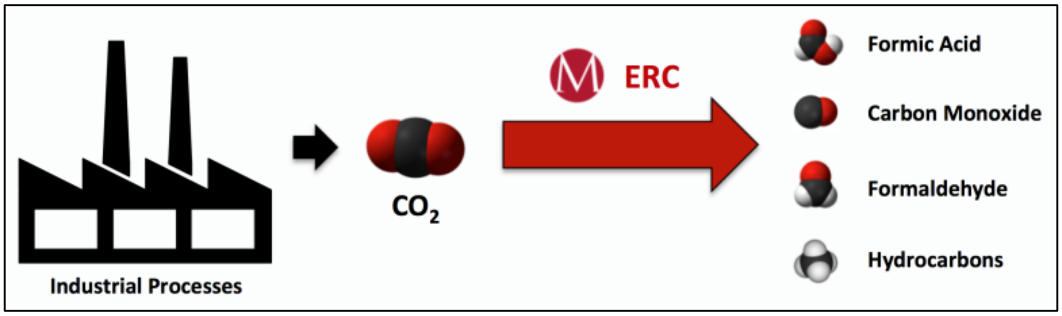

Figure 10. Image of Electro-Reduction of CO_2 from http://mantraenergy.com/mantra-energy/technology/erc-technology/ (Mantra Energy, 2014).

Formic acid can be produced as by-product of acetic acid (a component of vinegar) production. It can also be made by combining methanol (CH_3OH) and CO in the presence of sodium methoxide (CH_3NaO).

Additionally, CO_2 can be combined with H_2 to create formic acid. However, it's a difficult process due to the thermodynamic stability of CO_2 (Moret et al., 2014). Another potential method of creating CH_2O_2 from CO_2 is the biological CO_2 fixation powered by sugars. In 2013, Gate Fuels Inc. in Blacksburg, VA, received seed funding of $150,000 by U.S. Department of Energy for pursuit of this method (SBIR-STTR, 2013).

In addition, the start-up Liquid Light, Inc. has partnered with Public Service Electric and Gas (PSE&G) and Princeton researchers to convert CO_2 and water into formic acid in an electrochemical cell. This process will use solar power for its energy (Quick, 2014; White et al., 2014).

Liquid Fuels

Introduction to Liquid Fuels

CO_2 can be used in the production of several fuels including methanol (CH_3OH), dimethyl-ether (C_2H_6O), and synthetic gas (syngas), among others. Syngas is a mixture of CO, H_2, and sometimes CO_2. H_2 is a fuel that could potentially be used more in the future. It's often an intermediate in the formation of other liquid fuels. Methanol can be used as a fuel. In addition, methanol can be used to make plastics as well as a feedstock for fibers, and for bacteria feed, among other uses. Ethanol (C_2H_6O) most often come from corn, but can also come from other sources including sugar cane, sorghum, and algae. Currently it comprises 10% of most gasoline purchased at many gas stations (Figure 11).

Methanol Ethanol

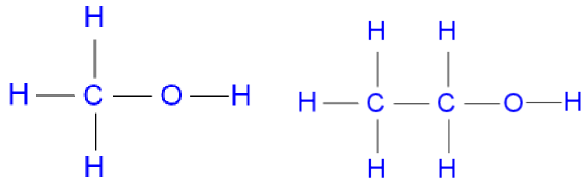

Figure 11. Chemical formulation of methanol and ethanol (Images from gcsescience.com, 2015).

Company Development

Phytonix has a process using CO_2 to create biobutanol and biopentanol, which are drop-in fuels, and n-butanol, which can be used to create jet fuels and plastics. Their trademark is an engineered cyanobacterium that secretes n-butanol. CO_2 is a feedstock for their cyanobacteria (Phytonix, 2016).

Joule Unlimited Inc. has several patents for ethanol and diesel-equivalent products. The website discusses their primary fuel products: the Sunflow®-E, solar-derived ethanol, and Joule Sunflow®-D, a hydrocarbon diesel fuel produced from sunlight and CO_2. Waste CO_2 plus bacteria are converted to fuels and chemicals. They have a pilot site in Hobbs, NM, and are preparing for commercial level operations. They are entering a partnership with HeidelbergCement to mitigate CO_2 from cement manufacturing, and they are currently securing their latest round of financing of $40 million for their operations (Joule Unlimited Inc., 2015a; Joule Unlimited Inc., 2015b; Joule Unlimited Inc., 2015c).

Carbon Recycling International (CRI), located in Iceland, established the George Olah Plant in 2012. The plant collects CO_2 from a nearby geothermal power plant. The geothermal plant produces less CO_2 than a traditional coal plant, but the CO_2 is concentrated and easier to capture. The George Olah Plant can produce about 5 million liters (about 1.32 million gallons) of methanol/year. Their methanol has the trade name Vulcanol™. It's named that because it's made with energy from a volcano. Their technology, Emission to Liquid (ETL), is used to convert energy to liquid fuel. The methanol can be either blended with gasoline for cars or used to produce biodiesel blends (Carbon Recycling International, 2012; IASS Workshop Potsdam Germany, 2013).

Dioxide Materials™ is a start-up with the plan to collect CO_2 from power plants and develop it into syngas to create gasoline, diesel fuel, jet fuel, and industrial chemicals. They also have developed patents for home sensors to lower HVAC carbon footprint by adjusting thermostat based on building/home occupancy. They have successfully received several grants and awards including an ARPA-E Award for nearly 4 million dollars in 2012 (U.S. Department of Energy, ARPA-E, 2013). However, the most recent information on their website is from 2013 (Dioxide Materials™, 2012).

It appears based on various articles that Haldor Topsøe is studying methanol synthesis from CO_2; however the research couldn't find any mention on methanol from CO_2 on the website. It may be something they are researching but not currently doing (Haldor Topsøe A/S). Another company, Sunfire, has the Power-to-Liquid technology to convert H_2O and CO_2 into synthetic gas, diesel and kerosene. They can collect CO_2 from multiple sources. CO_2 + H are reduced to CO + H_2, and they are synthesized into fuel using the Fischer-Tropsch process, a reaction that converts CO and H_2 to fuels (Sunfire, 2015, 2016).

Carbon Sciences was a company mentioned in The Global CCS Institute's 2011 report, but it could not be found. Phycal, LLC was another company mentioned in that report that might not exist anymore.

Additional Research

There has been considerable research in the finding of a catalyst that will assist in the conversion of CO_2 to CO, to be made into fuels. Owing to the stability of CO_2, converting CO_2 to CO is a slow process requiring a catalyst. Gold and silver can be used as catalysts, but they are expensive. Research in that area has found other potential catalysts, for instance using relatively inexpensive carbon fibers (Bullis, 2013); a copper tetramer that binds CO_2 (Stone, 2015b), a four-atom thick compilation of cobalt metal and cobalt-oxygen molecules (Herkewitz, 2016); or a nano-porous silver electrocatalyst (Materials Today, 2014). Future research is still needed to determine the most energy-efficient catalyst that works in large-scale operations (Tweed, 2013).

Urea-Yield Boosting

Introduction on Urea-Yield Boosting

Urea-yield boosting is a category of CO_2 utilization that is considered to be a mature technology. In urea (CH_4N_2O) production, there is often a small surplus of ammonia. This surplus ammonia can be reacted with flue gas CO_2 to produce additional urea. This process is known as urea-yield boosting. This is unlikely to be a growing category of CO_2 utilization. Urea is not considered a permanent form of CO_2 storage.

Urea is developed commercially from ammonia (NH_3) and CO_2. There is a two-step process where the ammonia and CO_2 react at a high temperature and pressure to form ammonium carbamate ($CH_6N_2O_2$) which is then dehydrated to urea (Encyclopaedia Brittanica, 2016).

Urea is used in nearly 50% of the world's nitrogen fertilizer production. Urea-Ammonium Nitrate (UAN) is one of the most common fertilizers. Additional uses for urea include utilization as a de-icer, as a component of animal feed, as a browning agent in pretzels, as an ingredient in lotions and other hygiene products, and as an ingredient in tooth whitening products. It's an industrial precursor for many products including barbiturates, urethanes, polyurethane foams, formaldehyde and urea-formaldehyde resins. It's also used as a flavor-enhancer in cigarettes, as a raw material in glues and plastics, and as a flame-proofing agent, and a NOx-reducing reactant in diesel exhaust (Office Zone, 2007).

Company Development

Mitsubishi Heavy Industries, LTD. has installed flue gas capture plants at some urea production plants to capture CO_2 for urea yield boosting. They provide a CO_2 capture product to clients in many countries. They have a proprietary energy-efficient CO_2 absorbent called KS-1™. CO_2 is fed into system for synthesis of urea. Also, they have developed KM CDR Process® capture technology for CCS projects. They have clients in Malaysia, India, United Arab Emirates, Pakistan, Vietnam, and Bahrain. In these projects, flue gas is captured from the steam reformer, usually natural gas fired, to produce additional urea (Figure 12) (Mitsubishi Heavy Industries Ltd., 2005, 2010, 2016a, 2016b).

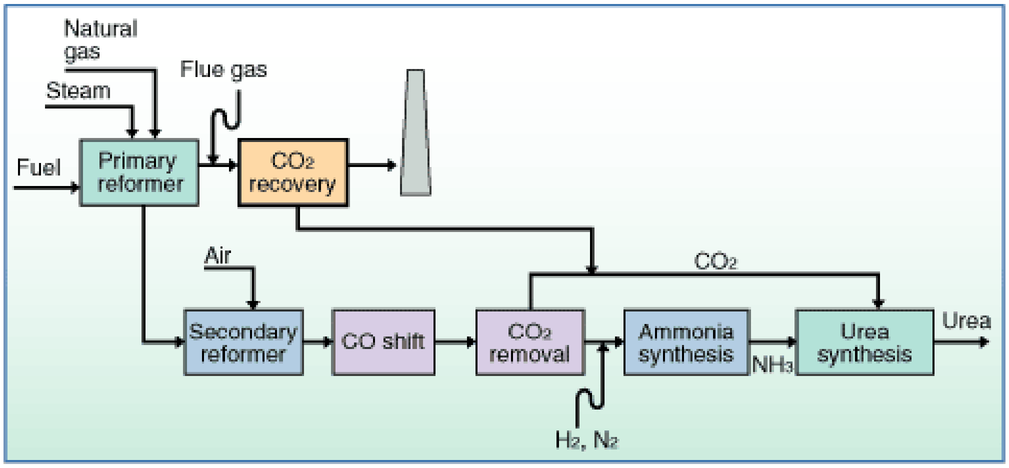

Figure 12. Urea Synthesis in ammonia and urea plants. (Mitsubishi Heavy Industries, 2016a).

Long-Term CO_2 Reuse/Storage Methods

Bauxite Residue Carbonation

Introduction to Bauxite Residue Carbonation

Nearly all of the aluminum ever produced has been refined from bauxite ore. Around 75% of the aluminum ever produced is still being used today (The Aluminum Association, 2016). Still, aluminum is being produced in large quantities, most heavily in Australia, China, Brazil, India and Guinea (Geology.com, 2016). In 2007, 120 Mtpa of aluminum was produced, and there is a large amount of residue output that needs to be handled and stored every year (Power et al., 2011).

The production of aluminum from bauxite ore results in a hazardous bauxite residue slurry with a pH of approximately 13. The goal of bauxite residue carbonation is to neutralize the bauxite residue by lowering the pH and making it less hazardous and easier to handle and store.

Company Development

At Kwinana in Western Australia, Alcoa operates a plant where gaseous CO_2 from a nearby ammonia plant is combined with the red mud slurry. This lowers the pH of the slurry to as low as 9. Additionally, the CO_2 is permanently sequestered by this process. The Kwinana power plant permanently sequesters about 70,000 tonnes of CO_2 a year (Alcoa Inc., 2016a).

Beyond Alcoa's work in Australia, it doesn't appear that other companies are using CO_2 to neutralize bauxite residue. However, researchers are exploring other methods to neutralize bauxite residue, including neutralizing with SO_2, with mineral acids, and seawater remediation. (Power et al., 2011). Additionally, Alcoa is pursuing beneficial reuses of bauxite slurry, including using it to neutralize acidic soil, acidic mines, in construction fill, and in wastewater treatment (Alcoa Inc., 2016b).

Enhanced Coal Bed Methane Recovery (ECBM)

Introduction to ECBM

Enhanced Coal Bed Methane Recovery (ECBM) is used in coal beds that cannot (or can no longer) be used for coal mining. CO_2 is injected into the subsurface coal seam. It replaces methane, which is collected, and the CO_2 is permanently sequestered within the coal (Bergen, 2012; Global CCS Institute, 2011).

A major limitation of this process is that the injected CO_2 actually decreases the permeability and injectivity of the coal, which thereby reduces the amount of methane that can be released. Various combinations of N_2 and CO_2 injection have been tested to circumvent this problem. There is initial faster recovery of CH_4 with N_2; while pure CO_2 allows for a greater total CH_4 recovery. Combining N_2 and CO_2 allows for greater and faster CH_4 recovery, overall. Flue gas, which consists of a combination of N_2 and CO_2, and only about 13% CO_2, might help to keep the coal permeability high while allowing for the greatest total CH_4 displacement (Wang et al., 2015; Pini et al., 2011).

This appears to have been a heavily-researched category in the past, but without much currently activity. Several pilot projects were conducted in the 1990's, but it does not appear to have been actively tested recently. For the purposes of this review, it was challenging to find any new sources discussing ECBM. One article in the Coal Bed Methane (CBM) Review was published in 2014, but all of the other sources of information were from 2011 or earlier (Litynski et al., 2014).

Calcium Carbonate / Concrete Curing

Introduction to Calcium Carbonate

CO_2 can be bound to calcium to create calcium carbonate ($CaCO_3$). Calcium carbonate has a multitude of uses including a component of building materials such as limestone and marble, a food supplement, in blackboard chalk, filler in the paper industry, and a component in paints. It's also used in mortar for bonding bricks, concrete blocks, roofing shingles, rubber compounds, and tiles. It can be used to neutralize acidic soil and water, such as for neutralizing acid pollution in lakes, and to neutralize SO_2 from power plants. It can also be formed into quicklime (CaO) (IMA-NA, 2016; University of York, 2016).

Company Development

Calera had a process of carbonate mineralization in which they converted CO_2 to carbonate (CO_3) and bound it to calcium or magnesium to create calcium carbonate ($CaCO_3$) or magnesium carbonate ($MgCO_3$) (Figure 13). Their source of CO_2 was a 1,000 MW power plant at nearby Moss Landing. Calcium carbonate can be used as supplementary cementitious material (SCM), replacing some of the portland cement. It can also be used as the sole cement or binder system. It has been used in sidewalks, and in flatwork in office buildings. It can also be used to make countertops, plant holders, and benches. Calera could produce an average of 5 tons of SCM/day. Calera had pilot plants and have proposed increasing production though source information regarding these particular activities is limited to 2011 (Calera, 2016). The CEO who left Calera, Brent Constantz, founded Blue Planet, Ltd. (Blue Planet Ltd., 2015; US Green Building Council, 2016). Additionally, Leonardo DiCaprio has joined the Blue Planet's board government and policy advisory board (EcoWatch 2016). Blue Planet uses Liquid Condensed Phase (LCP™) Technology to convert CO_2 into carbonates ($CaCO_3$). They create CarbonMix™ materials: aggregates, concrete, roofing granules, cool pigments, titanium oxide and pure CO_2 (Blue Planet Ltd., 2015).

CCS Materials Inc. was a company mentioned in The Global CCS Institute's 2011 report that doesn't appear to exist anymore.

Concrete curing involves permanently storing CO_2 as limestone-like nanomaterials within the concrete. The limestone is no longer CO_2 gas. This is a permanent storage method of CO_2. Carbon Sense Solutions Inc., a company that was discussed in the Global CCS Institute's 2011 report, appears to now be the company, CarbonCure. The Carbon Sense Solutions website now goes directly to CarbonCure, CarbonCure is in the same city as Carbon Sense Solutions was, and they have the same founder, Robert Niven. CarbonCure permanently sequesters CO_2 through its concrete curing process. This is one of the more successful companies discussed in this review. Several projects use their concrete, including libraries, senior housing, university buildings, a high school, and even a winery. Developers aspiring for LEED accreditation can receive USGBC LEED points for using this concrete in their buildings (CarbonCure, 2016a).

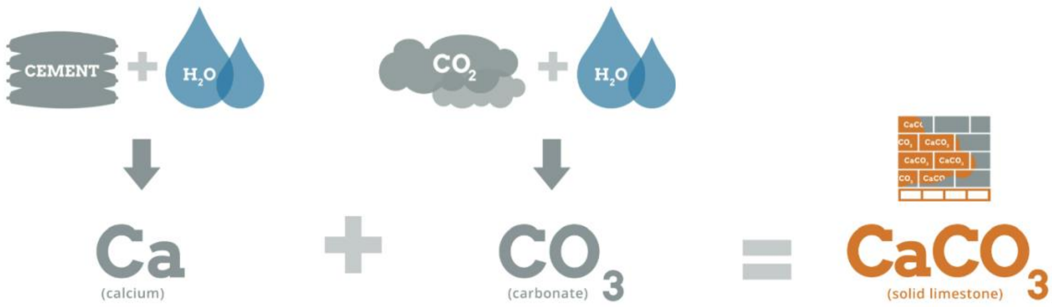

Figure 13. (Image from CarbonCure, 2016a).

Sodium Bicarbonate

Skyonic is a company that has the Skymine® technology to collect CO_2, SOx and NOx from industrial facilities to turn into products such as sodium bicarbonate ($NaHCO_3$, also known as baking soda, bleach, and hydrochloric acid (HCl). In 2014, the Skymine® facility opened in San Antonio Texas at the Capital Aggregates cement plant. Skymine® maintains the equipment and systems at the cement plant (Figure 14) (Skyonic, 2015).

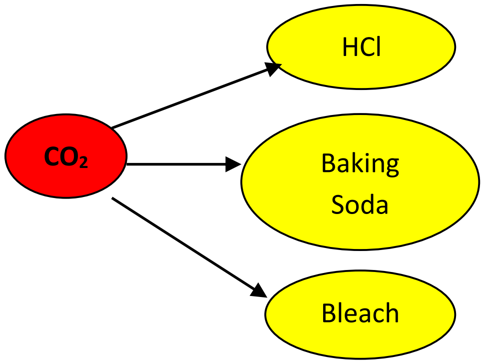

Figure 14. Products made at Skyonic

Additional Research

Not only can CO_2 be used to synthesize sodium bicarbonate, but sodium bicarbonate can also be used to capture CO_2 from flue gas. A recent study has shown that microcapsules containing sodium bicarbonate can absorb CO_2 from flue gas. After filling with CO_2, the capsules are taken out of the flue gas. Afterward they are heated to remove the CO_2 (Vericella et al., 2015; Stark, 2015).

Enhanced Oil Recovery (EOR)

Introduction to EOR

EOR is much more established than other methods CO_2 reuse. In 2010, EOR accounted for about 4% of U.S. oil production (NETL, 2010). It was commonly used in the 1970's and 1980's when oil prices were high (NETL, 2010). EOR is also referred to as tertiary oil recovery. Primary production is the oil that comes up to the surface quickly from natural pressure. This can recover from 10-25% of the oil from the well. Secondary recovery refers to water flooding, and recovers and additional 10-20% of oil from the well. Tertiary production can make it so up to 70% of oil is recovered from the well (Chevron, 2016.) The three major types of tertiary recovery include chemical flooding, thermal (steamflood) recovery, and oil displacement using CO_2, hydrocarbon (HC) or N_2 injection. In the process of EOR with CO_2 injection, the CO_2 is permanently sequestered underground. CO_2-EOR is expected to be more commonly used in the U.S as global oil prices start to increase again. In 1999 studies were predicting that increasing oil prices would stimulate increased EOR in the U.S. as well. It's cyclical, with EOR becoming more attractive when oil prices are high (EPRI, 1999).

Company Development

Trying to determine the current companies that are using CO_2 for EOR can be challenging through website searches – the companies tend to be large, publicly-owned, and they are constantly merging, buying each other out, or changing names. Large oil companies, such as Chevron and Exxon, are more stable than smaller oil companies, which sell and trade ownership of oil fields pretty regularly (Chevron Corporation, 2016).

In 2011, Anadarko was listed as an investor in the Salt Creek oil fields where EOR will likely become prominent in the future, but the Salt Creek oil fields were purchased by Linn Energy Co in 2014 and then by a private company called FourPoint Energy in 2015. FourPoint appears to be a team of wealthy private investors holding onto the Salt Creek oil fields and waiting for oil prices to rise again (Anadarko, 2015; Wilcox, 2014; Wilcox, 2015; FourPoint Energy, LLC; Linnco., 2016).

The Oil and Gas Journal produces a biennial worldwide EOR survey. The 2014 Survey Results for the U.S. only show Occidental Petroleum Corporation as producing the most CO_2 miscible petroleum via CO_2-EOR, with 33 wells producing about 88.1 thousand barrels of oil per day via

CO_2-EOR. As of 2014, there are a total of 127 wells in the U.S. producing about 265.7 thousand barrels of oil per day via this method of EOR (Table 2) (Oil & Gas Journal, 2014).

Table 2. Selected list of notable U.S. companies producing miscible petroleum with CO_2-EOR in 2014 (data tabulated from Oil & Gas Journal, 2014).

Company	# of Wells	Thousand Barrels oil/day
Anadarko	6	17.2
Hess Oil	4	18.4
Kinder Morgan	3	33.3
Chevron	7	20.2
Merit Energy	7	7.1
ExxonMobil	1	5
Denbury Resources	18	29.1
Occidental	33	88.1
Total in U.S.	127	265.7

EOR was actively pursued in the Permian basin in the 1970's and 1980's because CO_2 was cheap and oil prices were high. Several CO_2 pipelines were built at that time (EPRI, 1999). The price of oil can be variable: oil spiked in 2008 at over $144 a barrel, in February of 2016 it was as low as $26 a barrel. If the price of oil increases, then there might be increased U.S. investment in CO_2 utilization through EOR.

Enhanced Geothermal Systems (EGS)

Introduction to EGS

Geothermal power uses heat from below the earth's surface to generate electricity. In some locations, such as the Geysers in California or Reykjavik, Iceland, geothermal energy is readily available and easy to utilize. However, in most locations it is not, and enhanced geothermal becomes necessarily in situations where the heat doesn't easily come to the surface. Enhanced geothermal is a potential market for captured $CO_{2,}$ where the CO_2 is used instead of water or brine to extract geothermal heat. The CO_2 is permanently stored underground.

Company Development

GreenFire is a developing ECO_2G™ technology to create CO_2 based geothermal power (Figure 15). Their methodology involves a closed loop system using supercritical CO_2 instead of water for collecting geothermal heat. Their website states they are currently conducting "'proof of concept' projects to prepare for commercial operations in 2016" However, the news page on their website read, "The content on this page is currently being updated" in March/April of 2016 (GreenFire Energy, 2016).

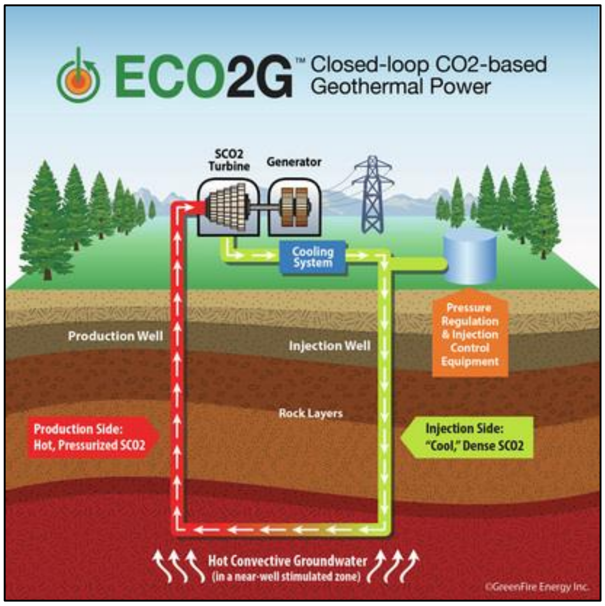

Figure 15. GreenFire's Geothermal Process (GreenFire Energy, 2016).

Limited information was found in the way of CO_2-enhanced geothermal approaches for carbon reuse/storage. The Global CCS Institute's 2011 report discussed a couple of companies, Geodynamics Limited and Symyx Technologies (Global CCS Institute, 2011). However, it appears Symyx Technologies was merged into Accelrys, Inc. in 2010, and Geodynamics Limited, an Australian company, appears to have completed a demonstration project, but it uses high-pressure water in its enhancement fluid (ARENA, 2016). The report also discussed Enhanced Energy Resources, which couldn't clearly be found.

The U.S. Department of Energy has funded several U.S. demonstration projects in the category of enhanced geothermal systems. These projects include: Ormat Technologies at Desert Peak, Churchill County, NV; Altarock Energy at Newberry Volcano, Bend, OR; Calpine Corporation at the Geysers, Middletown, CA; University of Utah's Raft Project, Raft River, ID; and Ormat Technologies at Bradys Field, Churchill County, NV. However, none of these projects appear to utilize supercritical CO_2 as stimulation fluid. The Ormat Technologies at Desert Peak project is using pressurized water, and the Altarock Energy at Newberry Volcano project is using injected water as well (U.S. Department of Energy, 2013a).

Enhanced Uranium Leaching

Enhanced uranium leaching could refer to two different processes – 1: getting uranium and other radioactive waste out of waste material so that radioactive waste is reduced. 2: assisting in the mining of uranium so that less energy is used. When performing in situ leach mining, a leaching solution is injected into a well. One company utilizing this method states that they primarily use leaching agents such as CO_2 and sodium bicarbonate in the U.S. (Uranium One, Inc., 2016), while in Kazakhstan and Australia acid leaching is primarily used, though limited details were available on how CO_2 is used for this process.

Additional Companies Utilizing Captured CO_2

Carbon Engineering in Canada created an air collection system to collect CO_2 from the atmosphere to generate pure CO_2, which can be used industrially, or sequestered underground. They are currently creating a pilot plant that demonstrates first the scrubbing of CO_2 from the air, and then the creation of solid calcium carbonate pellets to be formed into pure CO_2. The pilot project has been running over a year, and collects about a ton of CO_2 from the atmosphere daily. Carbon Engineering is financed by investors including Bill Gates and Murray Edwards (Carbon Engineering Ltd., 2016a).

DyeCoo is using supercritical CO_2 instead of water to make dyes. These dyes dissolve quickly and they don't require process chemicals. The DyeOx is their proprietary dyeing. 95% of the CO_2 is recycled after each batch. The Super Bowl 50 Nike Gold Collection contains their dyes (DyeCoo, 2015, 2016).

GreenField Specialty Alcohols Inc. is building Truly Green Farms greenhouses to utilize the waste heat and CO_2 from the GreenField ethanol plant to increase tomato yield (Greenfield Specialty Alcohols Inc., 2014, 2015).

CO_2 can additionally be used in the fracking industry for higher natural gas production. Ferus is pursuing this. This company provides the oil and gas industry with fracturing and well-stimulation fluids including N_2 and CO_2. CO_2 increases fracturing and acts as a pH buffer. The company states that the use of CO_2 for this purpose can reduce costs by 20%, increase production by 15%, and reduce water usage by up to 80%. In addition to CO_2 liquid fracturing, they are now pursuing CO_2 foam fracturing (Ferus, 2015, 2016).

Discussion

Many of the companies discussed in The Global CCS Institute's 2011 report are still operational, but some have closed. Still other companies have been founded that are exploring innovative areas of CO_2 reuse, but many are currently pursuing pilot projects, and as of now it is unclear how many of them are going to grow beyond the pilot phase. It is also unclear if CCS is going to become more commonplace in the U.S., and in the world. There has been some current backlash against the previous support for CCS. An example of this is the U.K. government cancelling a £1bn competition for CCS technology (The Guardian, 2015). Another example of this is President Obama and the EPA's Clean Power Plant Plan, which was introduced in August of 2015, but halted by the Supreme Court in February of 2016. It is currently undecided if this plan will move forward in the future (Environmental Protection Agency, 2016c).

The researcher was hoping to find several additional innovative areas of CO_2 reuse being pursued by both companies and researchers that were not discussed in The Global CCS Institute's 2011 report, but found less than expected. Potential future research could include searching journals on lib.ncsu.edu for additional CO_2 reuse possibilities. Additionally, since this current review focused on companies, supplement future research could review the results of various research that was pursued by laboratories and listed in the Global CCS Institute's 2011.

Table 3. Based on internet and research studies, this categorizes what areas of CO_2 reuse appear to have the most activity.

Categories That Appear to be Pursued by Multiple Companies	Categories that Appear to be Pursued by Limited Companies	Categories that Appear to not be Pursued as Heavily
Algae Biomass Cultivation	Concrete Curing	Urea-Yield Boosting
Polymer Processing	Mineral Carbonization	Enhanced Coal Bed Methane Recovery (ECBM)
Liquid Fuels	Formic Acid Production	Bauxite Residue Carbonation
Enhanced Oil Recovery (EOR)		Enhanced Geothermal Systems (EGS)
		Enhanced Uranium Leaching

Algae biomass utilization, polymer processing, and liquid fuels are the categories of CO_2 reuse being the most actively studied and piloted by start-up companies. Other areas such as concrete curing, mineral carbonization and formic acid production are being pursued by limited numbers of companies. Enhanced oil recovery is occurring, but it's not being pursued by start-up companies – it's a more established area of reuse. It was still harder to find companies pursuing other methods of CO_2 reuse (Table 3). As researchers continue to explore new ways to more inexpensively create power, fuel and consumer products, more ideas might arise for reusing CO_2, but currently a lot more research and innovation needs to occur to make this happen.

Educational Component: Community Engagement Project

Purpose of Project

The purpose for the community engagement portion of this project was to create basic educational materials to disseminate information to the public on CCS and reuse applications. If companies are going to pursue carbon capture and CO_2 reuse, it will require community understanding. If individuals don't understand CO_2 reuse then they might not be enticed to select products created through CO_2 reuse processes, and/or accept the integration of CCS projects into their neighborhoods (Ziegler, 2010). In order to understand the importance of CCS and reuse, an individual must initially have a basic understanding of CO_2 and how it relates to climate change. The educational materials were created so that recipients would first gain a basic understanding on climate change and greenhouse gasses such as CO_2, and then build upon that knowledge by learning about carbon capture, sequestration, and reuse.

Methods

To assess the capability of community members to learn basic concepts about CO_2, climate change, and CCS and reuse, a 12-minute test lecture with accompanying slides was presented to the Raleigh Talkmasters Toastmasters club in Raleigh on 4-14-16 at 7:15 a.m. (Figures 25-26). They filled out a pre-presentation questionnaire, post-presentation questionnaire, and demographic questions (Figure 16). The Toastmasters members will be referred to henceforth as Test Group 1.

Separately, an additional test group named Test Group 2 volunteered to view a presentation on carbon capture, sequestration and reuse. They filled out the same pre- and post-questionnaire as Test Group 1 (Figure 16). Test Group 2 received both a PowerPoint presentation in PDF format and the questionnaire via email. This presentation provided basic information on CO_2, climate and carbon capture & reuse knowledge. This was a more in-depth communication piece than was shown to the Toastmasters club because it wasn't accompanied by a lecture (Figure 27).

Both test groups were instructed to fill out the pre-questionnaire before the presentation, fill out the demographic information, and then not to look at the test until after the presentation. Test Group 1 was specifically told at the beginning of the presentation to flip over the test so they couldn't see it until after the presentation. Test Group 2 was instructed to first open the word document and fill out the pre-presentation questionnaire and demographic information, then open the PDF and read the entire document, and finally fill out the post-questionnaire. They were instructed not to look back at the PDF while filling out the post-questionnaire (Figure 16).

Pre-Presentation Questionnaire
Carbon Capture, Storage & Reuse
April, 2016

Please choose the best answer to each of the following questions:

1. Is climate change directly related to the hole in the ozone layer? Yes____; **No X**
2. Which of the following descriptions is most accurate to describe carbon dioxide?
    a. It's an acidic gas that affects the ozone layer.
    b. It's like a heat-trapping blanket that makes the earth warmer.
    c. It burns the lungs of sensitive individuals when the amount in the atmosphere is slightly elevated.
3. Which of the following is NOT a method of carbon dioxide (CO_2) reuse?
    a. It can be used to make fuels
    b. It can be used to grow algae
    c. It can be used to make ceramics
    d. It can be used to make plastics for packaging
    e. It can be used to make fertilizer
    f. It can be used to make foods
4. Which of the following is NOT a barrier to carbon capture technology?
    a. It's only about 30-50% efficient, making it a rather ineffective technology at the present time.
    b. The technology is expensive and is likely to make electricity cost more.
    c. The technology requires more space than is generally allotted for a power plant.
    d. Individuals and/or communities might react strongly against the technology when it's implemented in their communities.
5. What are some human activities that can lead to climate change? **(Examples listed, but several responses accepted)**
    1. Burning fuel in vehicles
    2. Burning fuel for electricity
    3. Industrial factories
6. What are some future problems that climate change is likely to cause? **(Examples listed, but several responses accepted)**
    1. Fluctuating erratic temperatures
    2. More flooding
    3. More extreme weather events
7. Which of the following forms of electricity creation releases the most carbon dioxide (CO_2) into the atmosphere?
    a. Natural Gas
    b. Ethanol
    c. Coal
    d. Gasoline
    e. Wood-burning
8. Do you think carbon capture, storage, and reuse is a good thing to implement? Yes____; No____; Maybe_____;
    Why or why not?____

Demographic Questions:
1. Please indicate your age: ___________
2. Please indicate your gender: Male______; Female______; Other________
3. Please indicate your race/ethnicity:
____ White/European American
____ African American
____ Latino/Hispanic
____ Native American
____ Asian
____ Pacific Islander
____ Other: ______________
4. Please indicate your highest level of education completed.
____ Some school
____ High school
____ Some college/Associate's degree
____ Bachelor's degree (4 years)
____ Some Graduate Work
____ Graduate/Professional degree (2 or more years after Bachelor's degree)

Figure 16. Pre-and Post Questionnaire and Demographic Questions Provided to both Test Groups. (Please note, only the pre-presentation questionnaire is shown here, but it is identical to the post-questionnaire.)

The objective was to have about 20 respondents in each test group. For both test groups, the first 7 questions in the pre- and post- quiz were each assigned one point per correct answer, for a possible total score of 7 for each respondent. For questions 1-4 and 7, the respondents were either given a score of 0 or 1. For questions 5 and 6, the respondents were either given 0.5 points for one correct answer, or 1 point for 2 or 3 correct answers. Additionally, for question 8, the number of Yes, No and Maybe responses were tabulated separately (Figure 17, Table 4).

Test Group 1

There were approximately 22 potential respondents in Test Group 1. However, some individuals arrived late and other didn't fill out the questionnaire. Though the goal was to talk to everyone and explain the purpose of this project, a few individuals were under the impression that this questionnaire was for their own self-assessment, and didn't fill it out completely. A number of these individuals didn't turn in a questionnaire. 13 individuals both filled out the questionnaire and turned it in. One was disqualified for not filling out the second section, which resulted in just 12 valid questionnaires. Several of the 12 individuals who did turn in the questionnaire were not very focused on the post-questionnaire and some hadn't even started it at the conclusion of the meeting. For instance, some were socializing while attempting to complete the questionnaire, and simultaneously being ushered out of the room. A number of these respondents skipped questions in the second section (particularly questions 5-6), but their responses were still tabulated.

The average age of the respondents in Test Group 1 was 47. Five were female and 7 were male. One respondent had attended some college, 5 had a 4-year degree, 5 had a graduate degree, and 1 declined to provide his educational level.

Test Group 2

The researcher initially sent the presentation and questionnaire to 29 volunteers for Test Group 2, but only 18 respondents returned the completed questionnaire. One was disqualified for not filling out the post-questionnaire, resulting in 17 valid questionnaires.

The average age of the respondents in Test Group 2 was 42. Twelve were female and 5 were male. Test Group 2 had 2 respondents with just a high school education, 7 who had attended some college, 2 with a 4-year degree, and 6 with a graduate degree.

Test-Group Specific Results

Test Group 1

Test Group 1 achieved an average score of 48% on the pre-questionnaire, and an average score of 73% on the post-questionnaire, achieving an average of 25% increase in score (Figure 17, 19). On average, those in Test Group 1 increased their total score by 153% (Figure 23). In the pre-questionnaire, 7 responded that carbon capture was a good idea, 4 responded maybe, and 1 declined to respond. In the post- presentation questionnaire, 10 responded that it was good idea, and 2 declined to respond (Figure 18).

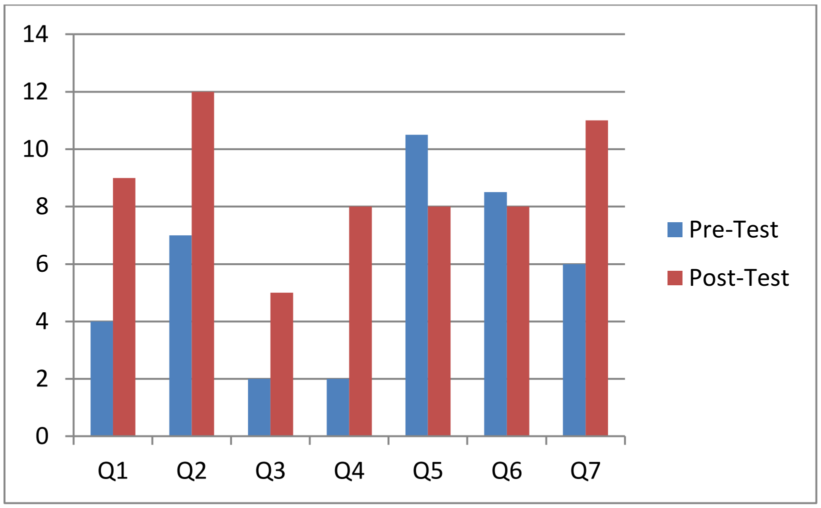

Figure 17. Test Group 1: Correct answers in Pre-questionnaire vs. Post-questionnaire for Questions 1-7.

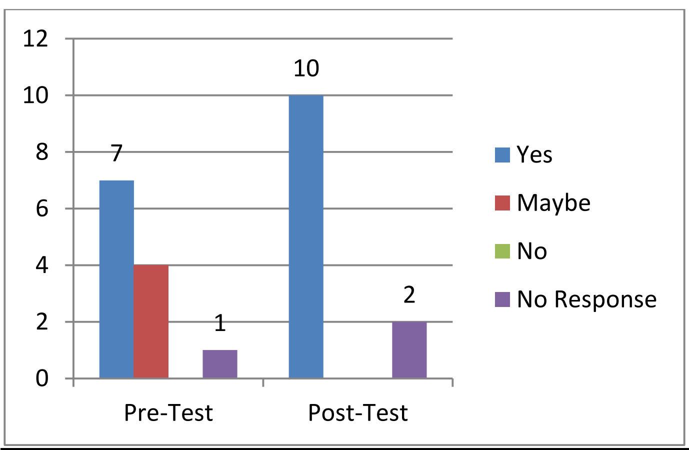

Figure 18. Test Group 1: Response to question: "Do you think carbon capture, storage, and reuse is a good thing to implement?"

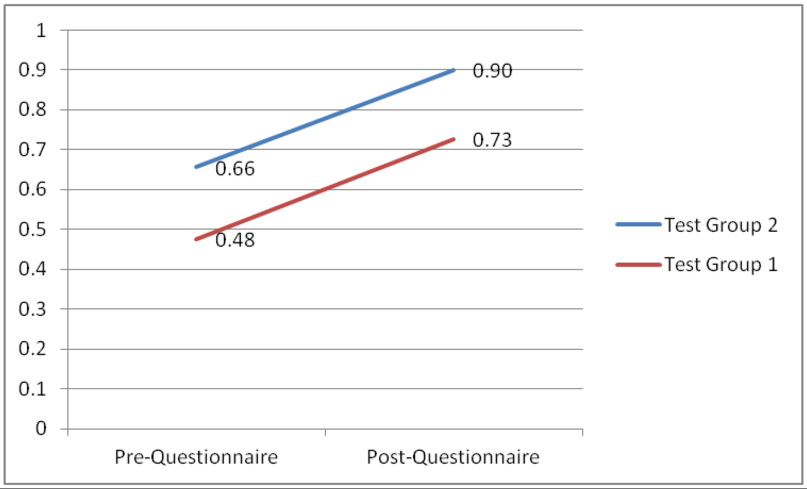

Figure 19. Percentage of Correct Answers for Test Group 1 & 2 for Questions 1-7 in the Pre- and Post-Questionnaire.

Test Group 2

Test Group 2 achieved an average score of 66% on the pre-questionnaire, and an average score of 90% on the post-questionnaire, achieving an average of 24% increase in score (Figures 19-20). On average, those in Test Group 2 increased their total score by 137% (Figure 23). In the pre-presentation questionnaire, 5 responded that carbon capture was a good idea, and 12 responded maybe. In the post-questionnaire, 13 responded that carbon capture was good idea, and 4 responded maybe (Figure 21).

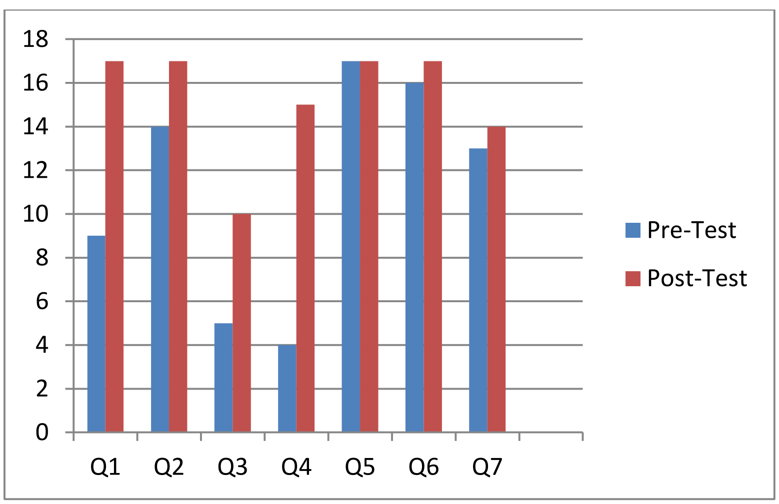

Figure 20. Test Group 2: Number of correct answers in Pre-questionnaire vs. Post-questionnaire for Questions 1-7. Total right answers for pre-questionnaire: 78. Total right answers for post-questionnaire: 107.

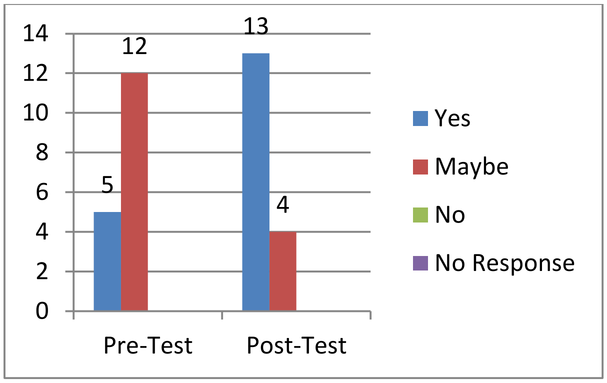

Figure 21. Test Group 2: Response to question: "Do you think carbon capture, storage, and reuse is a good thing to implement?"

Discussion/General Results

It would have been preferential to have more respondents in each group – the goal was around 20 respondents in each test group. However, there were only 12 participants in Test Group 1 and 17 participants in Test Group 2.

Both Test Group 1 and Test Group 2 experienced a significant increase in test scores between the pre-questionnaire and the post-questionnaire. It was previously noted that a few individuals in Test Group 1 were not very focused on the post-questionnaire and some hadn't even started it at the conclusion of the meeting, and they were socializing while attempting to complete the questionnaire, and simultaneously being ushered out of the room. A couple of these respondents skipped questions in the second section but their responses were still tabulated. Some respondents had correct answers to questions 5-6 in the pre-questionnaire but skipped these questions in the post-questionnaire. They were given scores of 0 on skipped questions. This led to the total scores on questions 5 and 6 being less in the post-questionnaire than on the pre-questionnaire for Test Group 1. For this reason, the post-questionnaire scores were lower they could have been if the respondents filled out the questionnaires more completely (Figure 17, Table 4).

The results indicated a significant increase in knowledge for all educational levels and for both test groups. From the pre-questionnaire to the post-questionnaire, those with a high school level education increased their total score on questions 1-7 from 36% to 71% or by 200%; those with some college increased their score from 68% to 88% or by 129%; those with a bachelor's degree increased their score from 48% to 80%, or by 166%, and those with a graduate degree increased their score from 64% to 84%, or by 131%. On average, those in Test Group 1 increased their total score by 153%, and those in Test Group 2 increased their total score by 137% (Figures 22a, 22b, 23). The two groups increased their percentage of correct answers by 25% and 24%, respectively (Figure 19).

Test Group 1 initially had 48% correct answers, and Test Group 2 initially had 66% correct answers. One possible explanation for the significantly greater initial knowledge level of Test Group 2 might be that it was composed of volunteers, and primarily those who were either knowledgeable and/or enthusiastic about learning about the subject matter would volunteer for this type of project. Furthermore, due to social proximity to the researcher, they might have had similar knowledge due to sharing similar interests. Additionally, since Test Group 2 filled out the questionnaire at home, they might have had more time to ponder their responses.

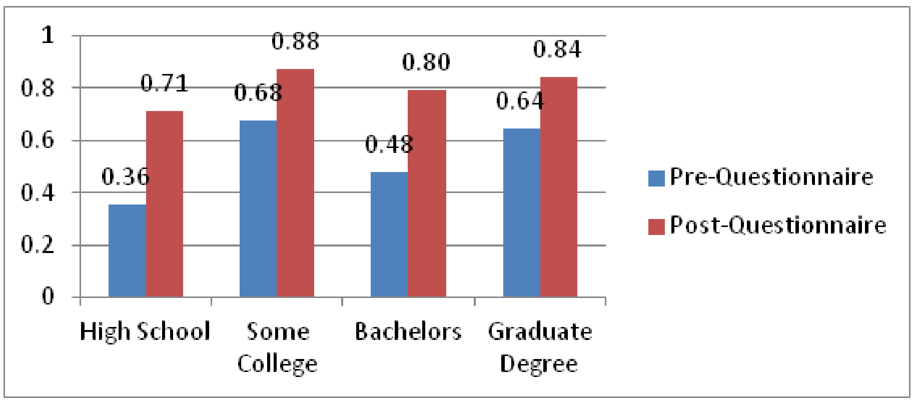

Figure 22A. Changes in Test Results by Educational Level

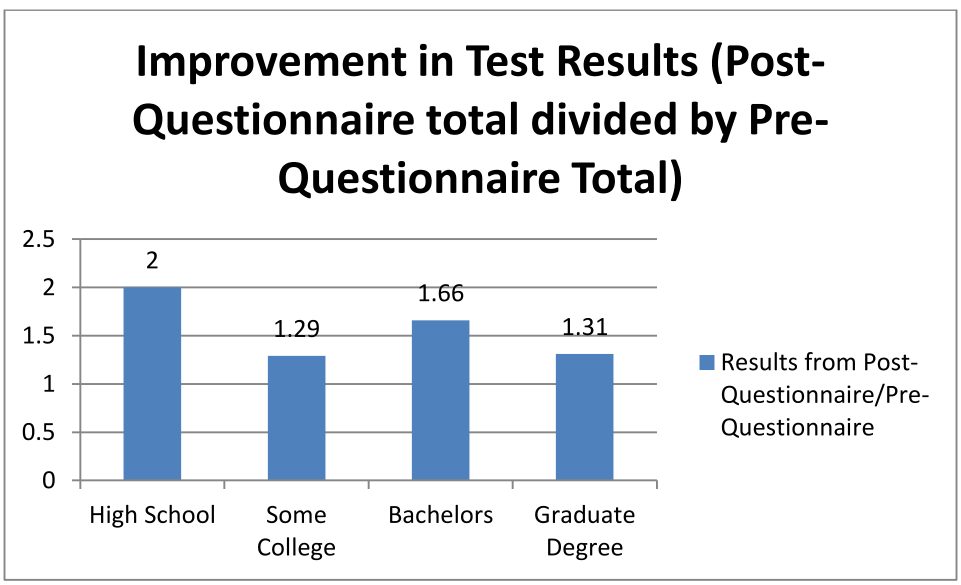

Figure 22B. Improvement in Test Results by Educational Level

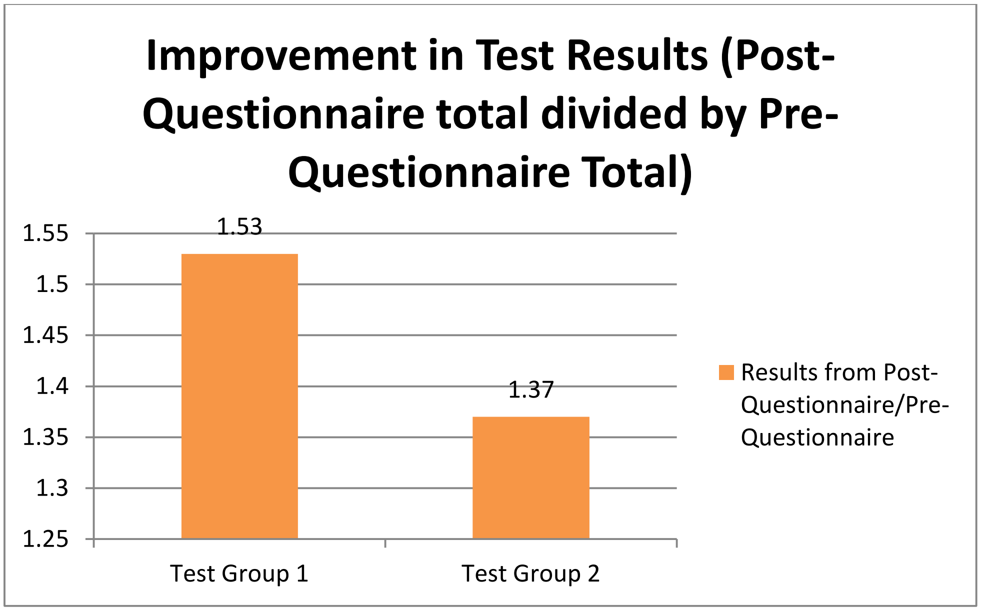

Figure 23. Improvement in Test Results for each Test Group

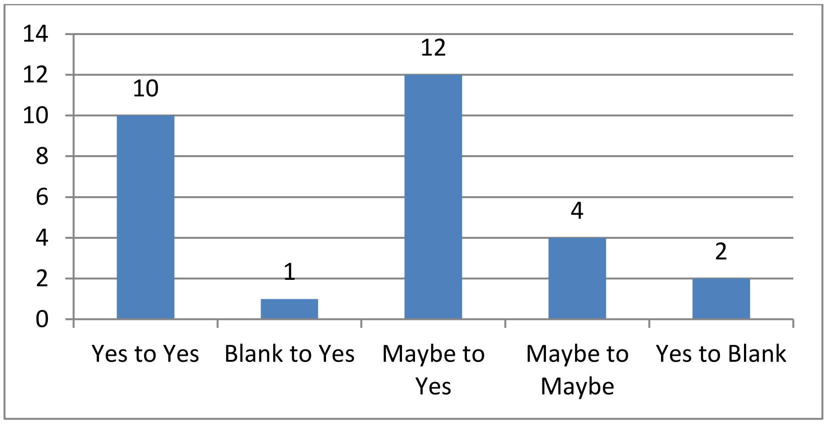

Figure 24. Changes to answer to Question: "Do you think carbon capture, storage, and reuse is a good thing to implement?"

The communication piece was affective in increasing the respondent's knowledge, and it got the respondent's engaged. When considering both test groups, 12 of the 29 total respondents changed their answer from maybe to yes in answer to the question, "Do you think carbon capture, storage, and reuse is a good thing to implement (Figure 24)?" This is a significant change after only a short introduction on the topic matter. Additionally, their answers to the questions indicated an increase in basic climate knowledge between the pre-questionnaire to the post-questionnaire. For example, in the pre-questionnaire, only 13 of the 29 respondents correctly answered the question, "Is climate change directly related to the hole in the ozone layer." However, 26 of the respondents answered this question correctly in the post-questionnaire. In the pre-questionnaire, only 6 of the 29 respondents correctly answered the question, “Which of the following is NOT a barrier to carbon capture technology?” In the post-questionnaire, 23 respondents answered this question correctly (Figure 16, Table 4).

To evaluate the researcher’s effectiveness, an experienced Toastmaster evaluated the presentation. The evaluator wrote the following comments, “The speech was very well outlined and explained at beginning; sufficient depth for time period allotted; great visual examples; there was a clear introduction and background on why it was important; you are such a fun person; you achieved the goal of keeping attention because of the slides and the fun nature of your speech. You achieved your goals of teaching and keeping attention.” Additionally, some suggestions to improve the speech included: “move lectern so you don’t block the slides; and polish the conclusion.” This presentation provides pertinent information that is easily understood by people with a high school education, and could be further polished and practiced, and presented to a community group located near a currently operating or potential carbon capture and sequestration project. Additionally, the slides that were viewed by Test Group 2, which had more complete information, would make an excellent online resource for someone who was researching these topics.

Table 4. Answers to Questions 1-7 and Demographics for all Respondents.

#	Q1 Pre	Q2 Pre	Q3 Pre	Q4 Pre	Q5 Pre	Q6 Pre	Q7 Pre	Q1 Post	Q2 Post	Q3 Post	Q4 Post	Q5 Post	Q6 Post	Q7 Post	Age	M/F	Education
TG1a	0	0	0	0	1	1	1	0	1	1	0	1	1	1	42	M	Bachelors
TG1b	0	0	0	0	0.5	0.5	1	1	1	0	1	1	0	1	40	M	no answer
TG1c	0	1	0	1	1	1	1	1	1	0	1	1	1	1	32	F	Some College
TG1d	0	0	0	0	0.5	0	0	0	1	0	1	0	0	0	64	F	Grad Degree
TG1e	0	0	1	0	1	1	0	1	1	1	0	0	0	1	43	F	Grad Degree
TG1f	0	0	1	0	1	0	1	1	1	0	1	0	1	1	64	F	Bachelors
TG1g	1	1	0	0	1	1	1	1	1	0	1	1	1	1	66	M	Bachelors
TG1h	1	1	0	0	1	1	0	1	1	1	1	1	1	1	45	F	Grad Degree
TG1i	0	1	0	1	1	1	0	0	1	1	1	1	1	1	55	M	Bachelors
TG1j	1	1	0	0	1	1	0	1	1	1	1	1	1	1	38	M	Grad Degree

TG1l	1	1	0	0	1	1	1	1	1	0	0	1	1	1	38	M	Grad Degree
TG1 m	0	1	0	0	0.5	0	0	1	1	0	0	0	0	1	38	M	Bachelors
TG2 A	0	0	0	0	1	1	0	1	1	0	0	1	1	0	48	F	HS
TG2 B	1	1	1	0	1	1	1	1	1	1	0	1	1	1	52	M	Grad degree
TG2 C	0	0	0	0	1	1	1	1	1	1	1	1	1	0	36	F	HS
TG2 D	1	1	0	0	1	1	1	1	1	0	1	1	1	1	53	M	Some college
TG2 E	0	1	0	0	1	1	1	1	1	1	1	1	1	1	36	F	Bachelors
TG2 F	1	1	0	0	1	1	1	1	1	1	1	1	1	1	35	F	Grad degree
TG2 G	1	1	1	0	1	1	0	1	1	0	1	1	1	1	29	F	Some college
TG2 H	1	1	0	1	1	1	1	1	1	0	1	1	1	1	51	F	Grad degree
TG2I	1	1	1	1	1	1	1	1	1	1	1	1	1	1	37	F	Some college
TG2 J	0	0	0	0	1	1	1	1	1	1	1	1	1	1	39	F	Bachelors
TG2 K	1	1	0	0	1	1	1	1	1	1	1	1	1	1	37	F	Grad degree
TG2 L	1	1	1	0	1	1	0	1	1	1	1	1	1	1	51	F	Some college
TG2 M	0	1	0	0	1	1	0	1	1	0	1	1	1	0	37	F	Some college
TG2 N	0	1	0	1	1	1	1	1	1	1	1	1	1	1	49	M	Grad degree
TG2 O	0	1	0	0	1	1	1	1	1	0	1	1	1	1	38	M	Some college
TG2 P	0	1	0	0	1	1	1	1	1	0	1	1	1	1	40	F	Some college
TG2 Q	1	1	1	1	1	0	1	1	1	1	1	1	1	1	48	M	Grad degree

The community engagement project was affective in getting participants engaged and knowledgeable about CO_2, climate change, and carbon capture, sequestration and reuse. A significant number of participants in two separate test groups changed their answer to the question, “Do you think carbon capture, sequestration, and reuse is a good thing to implement,” from “maybe” to “yes” after either viewing or hearing the presentation on carbon capture, sequestration and reuse (Figure 24).

The presentation provides pertinent information that is easily understood by people with a high school education, and could be further polished and practiced, and presented to a community group located near a currently operating or potential carbon capture and sequestration project. Additionally, the slides that were viewed by Test Group 2, which had more complete information, would make an excellent online resource for someone who was researching these topics.

Engaging the community with educational materials can make individuals more receptive to CCS projects planned near where they live. It might also make individuals more aware of carbon-friendly products, so that as consumers they make more carbon-friendly purchasing choices. Finally, it might make them more engaged so they seek out additional knowledge on CCS and reuse in the future.

Conclusion

Governments have the authority to create the laws and regulations about CO_2 emissions that will dictate whether CCS will become more commonplace in the future, but it is the companies and laboratories that will be the innovators who will devise more efficient and innovative ways to reuse CO_2 that is captured from industry. And finally, individuals on the ground level should be further educated so that they will understand the threat of climate change, and the importance of CCS and reuse. These individuals might need to determine whether to allow a CCS project into their neighborhood, or they might need to choose whether or not to use products made with reused CO_2. Most importantly, they might need to decide whether or not to vote for government officials who not only understand that climate change is real, but who want to fight to curb climate change with all the reasonable tools and innovations available.

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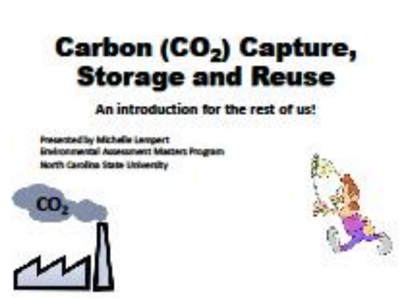
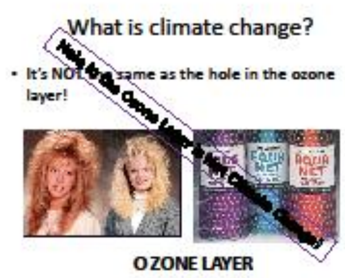
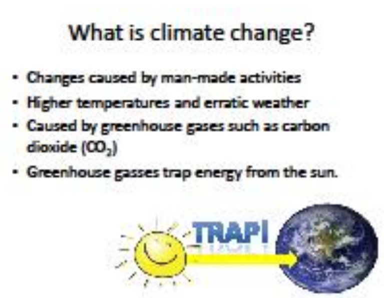
Appendix A – Community Engagement Project Presentations

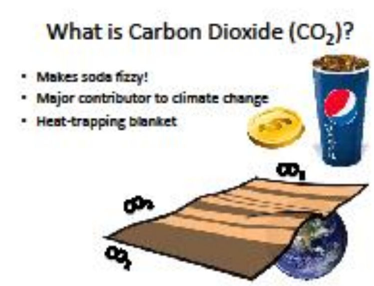
Figure 25. Copy of PowerPoint Presented at Toastmasters on 4/14/2016 (Test Group 1)

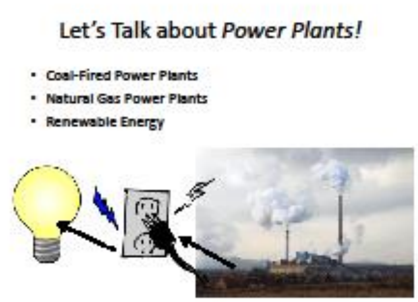
4/14/2016











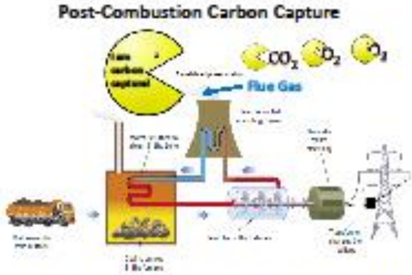
1

What is Carbon Capture?

- Carbon capture = capturing the CO_2 before it goes into the air. It can capture up to 90% of the CO_2!

3 Ways to Capture CO_2

Post-Combustion Carbon Capture



Post-combustion capture is the most common and well-understood method of carbon capture. In a power plant, coal is burned to produce steam, which drives a turbine to produce electricity. Flue gas is released. That's the smoke you see coming out of a power plant! The CO_2 is captured directly from the flue gas.

What Happens Next?

- Pipeline Transport!
- Then:
  - Underground Storage or…
  - It can be made into something new!

Permanent Storage of CO_2

- Oil wells

- Underground between rocks

- Ocean

- Long-term storage of CO_2 is safe.

Or, CO_2 can be Reused!

- It can be used to make:
  - Cement and building materials
  - Chemicals such as bleach
  - Fuel for cars and trucks
  - Plastic for bottles, packaging
  - Fertilizers

Additional Ways CO_2 can be Reused

- Algae
  - which can be used to make products
- Plastics

Barriers to Carbon Capture

- Expensive
- Takes more space
- Concerned citizens

Challenging the Barriers

- Technology gets cheaper over time.
- Reusing the CO_2 will bring in $$
- It's been tested and shown to be safe.
- And finally, less CO_2 in the atmosphere leads to a *healthier* planet!

CCS Capture Site – opened in 2014
Boundary Dam
Saskatchewan, Canada

CO_2 Capture Site – Opened in 2012
George Olah Geothermal Power Plant in Iceland
Renewable methanol: Vulcanol™

Summary

- CO_2 is being released into our atmosphere from human sources.
- CO_2 acts as a heat-trapping blanket, trapping heat in the earth's atmosphere.
- *Carbon capture* is a process of capturing CO_2 from power plants and industrial factories that can remove up to 90% of the CO_2. The CO_2 can be stored or used to make products.
- Carbon capture can help us to reduce the amount of CO_2 that is released into our atmosphere!

1

Some Resources to Learn More

- International Energy Agency: http://www.iea.org/topics/ccs/
- ENGO Network on CCS: http://www.engonetwork.org/
- Global CCS Institute: http://www.globalccsinstitute.com/
- World Resources Institute: http://www.wri.org/our-work/project/carbon-dioxide-capture-and-storage-ccs
- Energy.gov Office of Fossil Energy: http://www3.epa.gov/climatechange/ccs/federal.html

Figure 26. Copy of Text of Presentation. *This is the text that was practiced, but it wasn't followed word-for-word. Improvising and humor was added to the speech to keep the audience engaged.

1. Welcome! Thank you for attending this informational session. My goal is that by the end of this presentation you will have a basic understanding of what climate change is, what CO_2 is, a) what carbon capture & storage is, and why it's important. I'll tell you why it's important to me: My whole life I've been a nature girl. Part of it's that I like exercise, I like to push myself. But mostly, I like feeling tuned in with nature. I love beautiful places. And the idea of us messing with our beautiful planet is upsetting to me.

2. What is climate change? It's <u>not</u> the same as the hole in the ozone layer!

a. Back in the late 1980's, I was in junior high school. Back then, big hair was in. I was the master of the big hair, and at one point, my best friend accused me of singlehandedly causing the hole in the ozone layer. The ozone layer is a very different environmental issue, and it's completely unrelated to climate change.

3. What is climate change?

a. Climate change describes changes on our planet that are taking place due to man-made activities.

b. These changes include higher temperatures, and more erratic weather patterns.

c. These changes are due to greenhouse gases such as carbon dioxide also known as CO_2.

d. Greenhouse gases such as CO2 trap energy from the sun, making the earth warmer.

4. Now we are going to talk about CO_2. What is CO_2?

a. It's what makes your soda fizzy. When you open your Pepsi can, it is fizzy but it does not contain enough carbon dioxide to warm up the planet. So go ahead and drink that Pepsi or Coke. (How many coke people do we have? Pepsi? Hate soda?)

b. Carbon dioxide is one of the major contributors to climate change.

c. To better understand how carbon dioxide works, imagine that it's a cold morning. You don't want to get out of bed. So you get under a blanket, or if you're like me, 2 or 6 blankets, and it keeps you warm by trapping in heat! That is what carbon dioxide is doing to our planet, it's a like a big giant planetary blanket that's warming the planet.

5. What is causing all of the extra CO_2?

a. Well, it does occur naturally in the atmosphere. However, humans are releasing even more carbon dioxide into the air.

b. The three biggest sources of carbon dioxide produced by humans include (can I get a drum roll?)

c. Power plants that make electricity

d. Fuel in cars and other vehicles,

e. Industrial factories such as steel and cement plants.

6. Let's talk about Power Plants!

a. The type of power plant that releases the most CO_2 into the atmosphere is coal-fired power plants

b. Followed by natural gas-fired power plants.

c. There's also nuclear power, and renewable energy such as hydropower, wind and solar, all of which cause less greenhouse gasses than coal or natural gas.

7. a. Carbon capture involves capturing the carbon dioxide from power plants, cement plants and steel plants before it goes into the air. It can capture up to 90% of the CO_2 that is released!

8. There are 3 ways to capture carbon dioxide from a power plant/factory:

a. Pre-combustion capture – before the fuel is burned

b. Post-combustion capture – or, after the fuel is burned at the power plant.

c. Oxyfuel combustion capture – this one is a bit more complicated but involves burning fuel in pure oxygen instead of normal air, which is also nitrogen and other substances.

9. (would someone read this, please?) Post-combustion capture is the most common and well-understood method of carbon capture. In a power plant, coal is burned to produce steam, which drives a turbine to produce electricity. Flue gas, which is a mixture of carbon dioxide, nitrogen, and other gases, is released. That's the smoke you see coming out of a power plant! The carbon dioxide is captured directly from this gas.

10. What happens next?

a. After carbon dioxide is collected, it travels to a new location through a pipeline. At this point, one of two things can happen:

b. 1. It can be permanently stored underground.

c. 2. It can be turned into something new – it can be used to make many different products!

11. Carbon dioxide can be stored underground in the following types of places:

a. Oil wells that have already had the majority (or all) of the oil pumped out

b. Deep underground in pores between rocks

c. Deep in the ocean

d. And yes, long-term storage is safe.

12. Alternatively, carbon dioxide can be reused! What can it be reused for?

a. cement and other building materials,

b. bleach and other chemicals, even baking soda;

c. fuels for cars and trucks – fuels such as methanol, ethanol and biodiesel, and even jet fuel.

d. plastic for bottles, packaging and other uses,

e. urea, which is a common fertilizer for growing food.

13. Also,

a. Algae can use carbon dioxide in their growing process and they grow really fast! b. The algae can be used to make gasoline, fuel for planes, sunscreens, fertilizers, animal feed, and even food for people! Some neat consumer products being made out of algae include VeganEgg and Algenist.

c. Some companies are finding ways to make plastics out of carbon dioxide. One company called Novomer has created a plastic that is 50% carbon dioxide. This plastic can be made into garbage bags, paint, clothing, and packaging, among other things.

14. You may be asking yourself, why aren't more companies capturing & reusing carbon? Many reasons, including:

a. Carbon Capture technology can be expensive, and can make electricity cost more.

b. Implementing this technology requires more space than a power plant without carbon capture.

c. Also, some community members might be worried about the safety of new carbon dioxide pipelines or storage sites, especially if it's near their house or parks or schools.

15. However,

a. carbon capture will likely get less expensive as the technology gets better. Just like laptop computers! In the late 1990's, a laptop was upwards of $3,000. Now it's $300. Same thing with carbon capture – if it's done more, then it will get cheaper.

b. Reusing the carbon dioxide might help offset some of the costs of collecting it.

c. It's been tested and the technology has been shown to be safe.

d. And finally, less carbon dioxide in the atmosphere leads to a healthier planet!

16. Here is an example of a carbon capture and storage plant. It's in Canada.

It opened in 2014. It's on track to be fully operational by the end of 2016. It uses Post-Combustion carbon capture on a coal-fired power plant. So far, 625,000 tons of CO_2 have been captured. The goal is to capture 1 million tons of CO_2/year once it's fully operational.

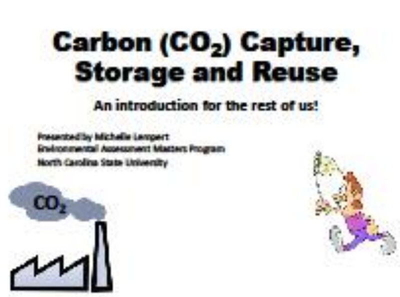
17. This is a carbon capture plant in Iceland. It was completed in 2012. At this plant, CO_2 is captured from a geothermal power plant! The CO_2 is used to make a renewable methanol called VULCANOL. Vulcanol can be blended with gasoline, or used as a chemical feedstock for making materials.

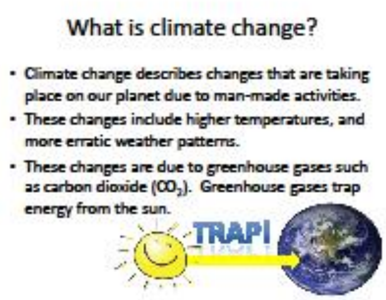
18. Read summary slide

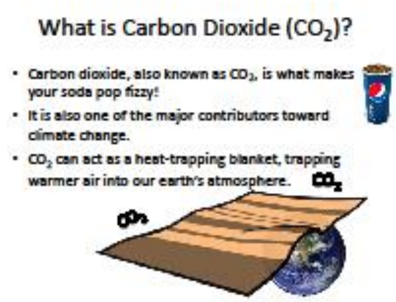
19. Here are some resources if you'd like to learn more. I'm happy to send you a more detailed PowerPoint, if you'd like.

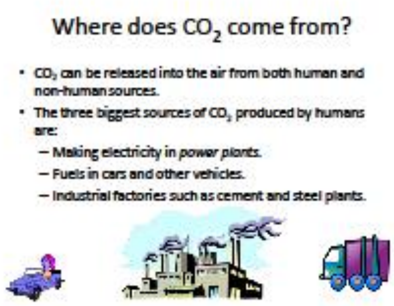
Figure 27. Copy of Powerpoint given to Test Group 2

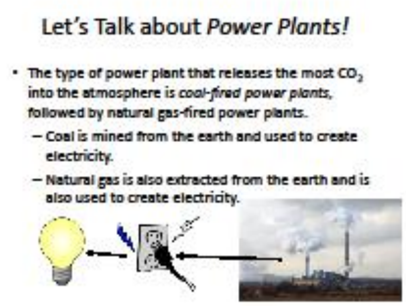
4/8/2016







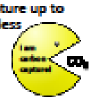




1

What is Carbon Capture?

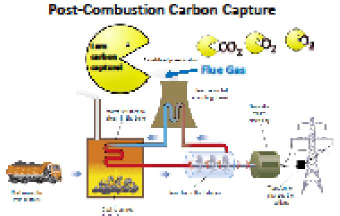
- In small amounts, CO_2 is not harmful. However, the large collective releases of CO_2 are building up in our earth's atmosphere and contributing to climate change.
- *Carbon capture* involves capturing the CO_2 from power plants, cement plants and steel plants before it goes into the air. It can capture up to 90% of the CO_2. Therefore, there is less greenhouse gas!



3 Ways to Capture CO_2

- There are 3 ways to capture CO_2 from a power plant:
  - *post-combustion capture* – after the fuel is burned
  - *pre-combustion capture* – before the fuel is burned
  - *oxyfuel combustion capture* – Normal air is a mixture of oxygen and nitrogen. In oxyfuel capture, the fuel is burned in pure oxygen instead of normal air. This makes the CO_2 more easy to separate out as a pure gas.
- *Post-combustion capture*, which is the most well-understood method, will be explained on the next slide.

Post-Combustion Carbon Capture



Post-combustion capture is the most common and well-understood method of carbon capture. In a power plant, coal is burned to produce steam, which drives a turbine to produce electricity. Flue gas is released. That's the smoke you see coming out of a power plant! The CO_2 is captured directly from the flue gas.

What Happens Next?

- After CO_2 is collected, it travels through a pipeline to a new location where one of two things happens next:
  - It can be permanently stored underground.
  - It can be reused to make many different products!

Permanent Storage of CO_2

- CO_2 can be stored permanently underground in the following types of places:
  - Oil wells that have already had the majority (or all) of the oil pumped out
  - Deep underground in pores between rocks
  - Deep in the ocean
- Long-term storage of CO_2 is safe.

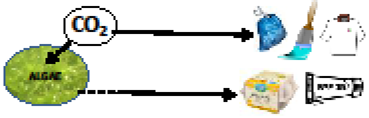
Or, CO_2 can be Reused!

- Alternatively, CO_2 can be reused! There are many clever ways to reuse CO_2, including using it to make:
  - Cement and building materials
  - Chemicals such as bleach
  - Car and truck fuels
  - Plastic for bottles, packaging
  - Fertilizers

1

How CO_2 can be Reused

- Additionally:
  - Algae can use CO_2 in their growing process and they grow *really* fast! The algae can be used to make gasoline, fuel for planes, sunscreens, fertilizers, animal feed, and even food for people!
  - Some companies are finding ways to make plastics out of CO_2. One company, Novomer, has created a plastic that is 50% CO_2. This plastic can be used to make many products including garbage bags, paint, clothing and packaging.



Barriers to Carbon Capture

- Carbon Capture technology can be expensive, and can make electricity cost more.
- Power plants with carbon capture technology will need more space to implement the technology.
- Some communities might be concerned about new CO_2 pipelines or storage sites, especially if it's near their house or parks or schools.

Challenging the Barriers

- However, carbon capture will likely get less expensive as the technology gets better.
- Reusing the CO_2 might help offset some of the costs.
- Small-scale test projects have been implemented extensively to test the safety of carbon capture and storage.
- And finally, less CO_2 in the atmosphere leads to a *healthier* planet!

Summary

- CO_2 is being released into our atmosphere from human sources.
- CO_2 acts as a heat-trapping blanket, trapping heat in the earth's atmosphere.
- *Carbon capture* is a process of capturing CO_2 from power plants and industrial factories.
- Carbon capture can help us to reduce the amount of CO_2 that is released into our atmosphere!

Some Resources to Learn More

- International Energy Agency: http://www.iea.org/topics/ccs/
- ENGO Network on CCS: http://www.engonetwork.org/
- Global CCS Institute: http://www.globalccsinstitute.com/
- World Resources Institute: http://www.wri.org/our-work/project/carbon-dioxide-capture-and-storage-ccs
- Energy.gov Office of Fossil Energy: http://www3.epa.gov/climatechange/ccs/federal.html

Appendix B – Chart of Companies

**In this section, ST and LT refer to Short-Term vs. Long-Term Storage methods. Unless stated otherwise, the reference for the tabular information below is the company website (included in the reference list above). The column “In Global CCS 2011?” refers to inclusion in The Global CCS Institute’s 2011 report. The researcher attempted to include the most current and accurate data on companies, however the confirmation of current and accurate information from websites and print media was a limiting factor.

Company	Reuse Category	In Global CCS 2011?	Carbon Source	ST or LT*	What They Do, Processes, Trademarks	Products Created	Comments, News and Status of Company, Monetary Data and Grants
Algae Systems LLC (estim. 2011), Daphne, AL	Algae	no	Atmospheric CO_2	ST	An offshore photobioreactor (PBR) system. A test project in Daphne, AL is testing the use of w astew ater in conjunction w ith algae for w astew ater treatment and expanded algae creation.	Reclamation of w astew ater into drinking/reuse w ater. Testing the creation of jet fuel, diesel, gasoline and fertilizer.	This company shut dow n operations in 2015 but hopes to raise money to reopen (UTV44, 2015).
Algenol (2006), Fort Myers, FL	Algae	yes	Industrial Sources of CO_2	ST	The DIRECT TO ETHANOL® process involves the use of a proprietary flexible plastic film PBR to create ethanol from algae, sunlight and CO_2. CAPTURES TECHNOLOGY® uses proprietary algae and a proprietary collection method.	Ethanol; gasoline, jet and diesel fuel.	A $25 Mill investment in 2015 and $40 million in 2014 from BioFields (Algenol 2015b). Apparently at one point they at least had a plan to collaborate w ith Dow Chemical Company (Morsella, 2011). In 2015 the company reduced its w orkforce and the CEO resigned (Algenol 2015a, 2015c). They w ere named the 3rd hottest company in bioenergy globally, and the hottest American company according to BiofuelsDigest (Algenol 2014), so it is unclear if they are fully operational or not.
Arizona Center for Algae Tech and Innovation (AzCATI) (2010), Mesa, AZ	Algae	no	flue gas CO_2 and other sources	ST	A national testbed. Strain identification and isolation. equipment testing, analysis, biomass production, education and training. AzCATI's current production capacity is approximately 300,000 liters. Use of PBRs, open racew ay ponds and the ARID Racew ay.	n/a	Established through a grant from the Science Foundation Arizona.
BPA, LLC. Bioprocess Algae (2009), Omaha, NE	Algae	no	w aste CO_2	ST	Grow er Harvester™ bioreactors convert light and CO_2 into microbial feedstock.	Animal feed, chemicals, fuel, nutraceuticals, fish feed.	There doesn't appear to be new s releases from more recent years than 2014 on the w ebsite.
Cellana (2009), San Diego, CA	Algae	no	Atmospheric CO_2	ST	Produced >20 metric tonnes of algae in Kona Demonstration Facility to date using Alduo™ technology (Photobioreactor systems coupled w ith open ponds).	ReNew ™ line of products: omega-3 EPA/DHA oils (human nutrition), Animal Feed, Biofuel Feedstocks.	In 2013 Cellena entered into a multi-year commercial-scale agreement w ith Neste Oil (Cellana 2015b). The energy department aw arded Cellana $3.5 Million in 2014 to develop cost-competitive biofuels from algae (Cellana 2014). The w ebsite w as view able on 4/2/2016 but not on 4/3/2016.
Heliae (2008), Gilbert, AZ	Algae	no	Mix of atmospheric and CO_2 feedstocks.	ST	Heliae's proprietary brand PhycoTerra™ has its ow n w ebsite: http://phycoterra.com/. The company's methods and processes appear to be in a research phase (Heliae Development LLC, 2016).	Astaxanthin ingredient and PhycoTerra™.	The company has sw itched direction and focus multiple times, and it is uncertain w here their research and/or focus w ill settle. A joint venture w ith Sincere Corporation in Japan to found Alvita - an algal development company near an incineration facility in Saga City, Japan to recycle CO_2 (Heliae Development, 2015b). Another joint venture w ith Schott involving new oval glass tubes for PBRs that increased output of biomass by >22% (Heliae Development, 2015a).

Company	Reuse Category	In Global CCS 2011?	Carbon Source	ST or LT	What They Do, Processes, Trademarks	Products Created	Comments, News and Status of Company, Monetary Data and Grants
HY-TEK Bio, LLC (2008), Dayton, MD	Algae	no	CO_2 from flue gas	ST	HTB-1 is a unique strand of freshw ater algae that is not genetically modified. It thrives in high concentrations of CO_2. A PBR system, an advanced flue gas injection technology w ith micro bubbles, and LED lights to increase photosynthesis.	Omega-3s, soaps, soy milk thickeners, lubricants, carbs, proteins for food supplements. HTB-1 is high in Lutein/Zeaxanthin, vitamin compounds used in eye surgery.	The Maryland Clean Energy Center (MCEC) named HY-TEK Bio entrepreneur of the year (HY-TEK Bio, 2014b). Aw arded $500K in carbon use competition (HY-TEK Bio, 2014c).
Matrix Genetics (2007), Seattle, WA	Algae	no	Atmospheric CO_2/ Waste CO_2	ST	Genetically engineered cyanobacteria.	Biofuels, pigments, spirulina for foods and cosmetics, astaxanthin for food supplements, health foods and antioxidants.	Partnering w ith Proterro, a biotech company using PBR technology to convert w aste CO_2 into products (Matrix Genetics, 2016). Avista Development invested in them in 2012 (Matrix Genetics 2012).
MicroBio Engineering (2005), Santa Barbara, CA	Algae	no	unsure	ST	A consulting and engineering firm for the design and construction of algae production facilities. Their RNEW® process combines w astew ater treatment, recycling of nutrients, and production of algae biofuel feedstock in w armer climates. They fabricate Algae Racew ays™ featuring APIAC™ technology, ranging from 22 to 101m^2.	Biofuels, w astew ater reclamation, additional high-value products.	n/a
Muradel (2010), Victoria, Australia	Algae	no	likely atmospheric CO_2.	ST	Green2Black™ technology, paddlew heel ponds and sub-critical w ater reactor (SCWR) technology. The follow ing goals w ere listed on their w ebsite: plans to upgrade their demonstration plant, reach steady-state operations, and to complete demonstration technology of Green2Black™.	Animal feed, oleochemicals, crude oil, fertilizers and building materials.	$4.4 Million grant through the Australian Renew able Energy Agency (ARENA) (Lane, 2015). Joint venture w ith Murdoch University, Univ of Adelaide and SQC Pty Ltd (Aban Australia Pty Ltd w as a source of funding) (Aban Infrastructure Private Limited, 2014).
OpenAlgae (2008), Austin, TX	Algae	no	most likely is atmospheric CO_2.	ST	Patented membrane technology extracts oils w ithout solvents.	Algal oil, biomass.	New s on w ebsite w as all from 2011 or earlier. This may not be an operational company.
Pond Biofuels (2007), Markham, ON	Algae	no	flue gas from industry	ST	The Pond Biofuels system uses microalgae to convert CO_2 into algae and subsequently into biofuel.	Bio-oil and biodiesel.	They set up a pilot bioreactor plant in St Marys, ON to collect CO_2 from a cement plant (Global Cement, 2014).
Proterro, Inc. (2008), Bronxville, NY	Algae	no	Waste CO_2	ST	Partners w ith companies such as Matrix Genetics, w hich utilize cyanobacteria for the creation of products	Industrial and food grade sugars; nutritionals including organic acids, amino acids, nutrients and vitamins.	Investor companies listed on their w ebsite include Battelle Ventures, Braemar Energy Ventures, Cultivian Sandbox and Middleland Capital (Proterro Inc., 2015).
Qualitas Health, Imperial, TX	Algae	no	local emitters of CO_2	ST	Closed and open pond systems using a proprietary grow th medium. Wet oil extraction method under exclusive license of Valicor™ (Valicor, 2015).	Vegetarian food supplements, pharmaceutical ingredients and omega-3 products. Almega PL™ is a long chain polyunsaturated fatty acid (LC-PUFA) Omega-3 product.	NutraIngredients Startup Ingredient of the year (Qualitas Health, 2015). $8.5 Million investment by Israeli kibbutz investors (Qualitas Health, 2012).

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Renewable Algal Energy LLC (RAE) (2007), Johnson City, TN	Algae	no	Atmospheric CO_2	ST	Native, not genetically modified algae.	Fuels, human nutrition, animal nutrition, cosmetics.	Agreement with Neste Oil to buy RAE's crude algae oil for feedstock for biodiesel (Renewable Algal Energy, 2014). They received $3 Million funding in 2010 from the DOE. (Algae Industry Magazine.com, 2010).
Sapphire Energy (2007), San Diego, CA	Algae	no	Sourced from the company Linde, which appears to source CO_2 from industry (The Linde Group, 2016; Sapphire Energy Inc., 2011a).	ST	An open pond system for growing algae. A demonstration algae farm in Columbus, NM in 2010.	Omega-3 oils, aquaculture, animal feed ingredients and renewable fuels.	Sapphire partnered with Monsanto to research algae genes in 2011 (Sapphire 2011b). More recent press releases seem less positive: lots of changing leadership, and the most recent press release is more than a year old.
Subitec (2000), Stuttgart-Degerloch, Germany	Algae	no	CO_2 from flue gas	ST	Patented Flat Panel Airlift (FPA) PBR: a uniquely designed inexpensive plate reactor which is a closed system. Subitec has two main areas of patented work: PBRs with improved light input, and bioreactors for the cultivation and manufacturing of microorganisms.	Pharmaceuticals, cosmetics, food supplements, feed ingredients, lipids/carbs, biofuels, biogas.	In 2013 a new site was obtained. Several international projects are in conception phases and the first production plant for European customers was scheduled to be delivered for start-up in 2014. 2012 financing by eCapital and the KfW. Latest news on website includes speaking at conferences such as the European Algae Biomass Conference, and a nomination by Venture Capital-Pitch as one of the most innovative start-ups in the state in 2016 (Subitec, 2014). Venture Capital-Pitch invests in start-ups (Venture Capital- Pitch, 2016).
T2 Energy (2012), Lake Vista, CA	Algae	no	Power plant flue gas CO_2.	ST	Proprietary LipiTrigger™ growth enhancer. Non-genetically modified algae.	Biomass and oils. Omega-3 sources - EPA (Eicosapentaenoic Acid)/DHA (Docosahexaenoic Acid). Chemical/fuels C-18 for vinyl, motor oil, paint, adhesives, cosmetics, polymers for plastics, feeds and proteins, biofuels.	Selected in 2015 to participate in the Autodesk cleantech partner program. (T2energy, 2015b). Awarded $1 Million from State of CA in 2015 to accelerate development of proprietary algae technology (T2energy, 2015a).
TerraVia (fka Solazyme) (2003), S. San Francisco, CA	Algae	yes as Sola-zyme	not mentioned	ST	TerraVia™. Bioengineering of microalgae, fermenting sugar and algae to make oils.	This company has recently changed its focus, and is now focusing primarily on food products and skin products, and they have many trademarks including AlgaWise, AlgaVia, Thrive culinary algae oil, and AlgaPur. The AlgaPur is a line of algal oils used to make Algenist, a skin care line.	Joint venture with agrobusiness/food company, Bunge to focus on oils for foods and products for animal nutrition (TerraVia 2015b). Joint venture with BASF to launch a microalgae surfactant (TerraVia 2015a). Website completely revamped between March and April 2016 with a new focus on foods/skin products. Solazyme was publicly traded on the NASDAQ.

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Algix (2010), Meridian, MS	Algae/ Polymer	no	Atmospheric (most likely)	ST	Algae to Solaplast®	Solaplast comes in many resin grades and different variations can be used in: agriculture, packaging, consumer goods, construction, industrial, shoe soles, carpeting and flooring, among other things.	Modesto, CA may sell algae that grows in its wastewater to Algix (Algae Industry Magazine, 2015).
Skyonic (2005), Austin, TX	Baking soda, bleach, hydrochloric acid	yes	First facility uses CO_2 from the coal-fired Capitol Aggregates Cement plant in San Antonio, TX	ST	Skymine® technology. The first location opened in San Antonio, TX in 2014. The plant will reduce its carbon emissions by 83,000 tons, annually. The company also founded the Skyscraper and Skycycle technology.	Baking soda (sodium bicarbonate), bleach and hydrochloric acid (HCl)	The SkyCycle plant is in process. This is a process that uses waste heat rather than electricity to run the carbon capture system (Hendricks, 2016).
Alcoa (1886 in Pittsburgh, 1963 in Kwinana)	Bauxite	yes	CO_2 from an ammonia plant	LT	Carbonation trial in 2000 to mix CO_2 with bauxite residue. The Kwinana residue carbon capture plant is currently sequestering nearly 70,000 tonnes of CO_2 a year.	Alcoa is pursuing reuses of bauxite slurry, including using it to neutralize acidic soil, acidic mines, in construction fill, and in wastewater treatment.	n/a
Braskem	Bio-plastics/Gasoline additives	no	Atmospheric CO2	ST	Using ethanol from sugar cane to make a more sustainable polyethylene, Green PE. Green PE removes up to 2.15 metric tons of CO_2 from the atmosphere for each ton produced.	Polyethylene is used by the automotive industry and manufacturers of cosmetics, packaging, toy, personal hygiene and cleaning products. Green PE can be used in these applications. Additonally, ethyl tert-butyl ether (ETBE) is made from sugar cane and can replace the traditional gasoline additive methyl tert-butyl ether (MTBE).	It is not clear if these products are currently being used, and if so, what percentage of Braskem's chemical and petrochemical portfolio is comprised of biofuels and biochemicals.
Blue Planet (2012), Los Gatos, CA	Carbo-nates	no	Flue gas CO_2	LT	Liquid Condensed Phase (LCP™) Technology to convert CO_2 into carbonates ($CaCO_3$).	CarbonMix™ materials: aggregates, concrete, roofing granules, cool pigments, titanium oxide; pure CO_2.	The CEO who left Calera went on to found Blue Planet, Ltd. (U.S. Green Building Council, 2016; Kanellos, 2010). Leonardo DiCaprio has joined the company's board government and policy advisory board (Chow, 2016).
Calera (2007), Los Gatos, CA	Carbo-nates	yes	Raw flue gas from a 1000 MW power plant at nearby Moss Landing	LT	Converting CO_2 to carbonate (CO_3) and binding it to Ca and Mg. Since the minerals are no longer in the form of CO_2, long-term storage does not require monitoring.	Cement or binder system in concrete products, wallboard and cement board products, supplementary cementitious material (SCM) for sidewalks, flatwork in a commercial office buildings, countertops, plant holders and benches.	The CEO changed in 2010 and I don't see much news or updates since that time period. The CEO who left Calera went on to found Blue Planet, Ltd. (U.S. Green Building Council, 2016).

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Southern Company (1997), Atlanta, GA	CCS	no	CO_2 from coal plant	LT	They have designed CCS projects in Mississippi and Alabama, in addition to other CCS research projects.	Sequestration of CO_2	It is unclear how far forward these projects have gone. The Plant Barry project appears to have been withdrawn due to size and costs (except for a smaller pilot project at the site), but it appears they were planning to attempt a smaller CCS project in the same location (MIT, 2016a). It's not clear where they are in this process. The Kemper project in Mississippi is a much costlier project that has had similar roadblocks (MIT, 2016b).
Total, Paris, France	CCS	no	n/a	LT	Implemented and operated the Lacq CCS demonstration project for more than 3 years utilizing oxyfuel combustion. Lacq refers to a gas treatment plant in Lacq, France (Total, 2016b, 2016c)	Sequestration of CO_2	The company has invested in several R&D projects including Australia's Cooperative Research Centre for Greenhouse Gas Technologies, and Canadian, French and European research projects on CCS.
Carbon Engineering (2009), Calgary, Alberta, Canada	CO_2	no	Atmospheric CO_2	ST or LT	Capturing pure CO_2 from air using a contractor. The chemical solution used for capture is regenerated.	Creating pure CO_2 to sell	A demonstration plant has been running over a year, and collects about 1 ton of CO_2 from the atmosphere daily (Carbon Engineering, 2016b). Carbon Engineering is financed by several investors including Bill Gates and Murray Edwards.
Climeworks (2011), Zurich, Switzerland	CO_2	no	Atmospheric CO_2	ST or LT	Capturing CO_2 from air. Two options: Demonstrator: 8 kg CO_2/day; Kollektor: 135 kg CO_2/day. Available in multiples of 35 kg per hour (300 metric tons per year).	Synthetic fuels, food, beverage; injected into greenhouses for increasing crop yield and stabilizing temperature	Current round of $3 Million in financing by Zürcher Kantonalbank (ZKB) and a group of private investors (Climeworks, 2011, 2014).
CarbonCure (fka Carbon Sense Solutions) (2007), Dartmouth, Nova Scotia, Canada	Concrete Curing	yes, as Carbon Sense Solu-tions - same founder	flue gas from industry	LT	CarbonCure retrofits concrete plants with their process which integrates CO_2 into concrete as limestone-like nanomaterials that disperse throughout the concrete.	concrete with a lower carbon footprint.	This is one of the more successful companies I have researched. Several projects boast using their concrete, including libraries, senior housing, university buildings, a high school, and even a winery. Buildings can receive USGBC LEED points for using this concrete. There's an agreement between Argos and CarbonCure for Argos to produce ready-mixed concrete (CarbonCure, 2016b).
Anadarko Petroleum Corp (1959), US	EOR	men-tioned	CO_2	LT	n/a	Oil is recovered.	Linn Energy took over Anadarko's salt creek oil field in 2014, where EOR was being employed. Then they sold it to FourPoint Energy LLC and EnerVest Ltd. in 2015.
Chevron (1879), San Ramon, CA	EOR	yes	unsure	LT	Chevron is utilizing EOR technology. However, the company appears to be using steam and surfactants rather than CO_2 for EOR.	Oil is recovered.	n/a

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Ferus (2001), Calgary AB and Denver, CO	EOR	no	Industrial Sources of liquid CO_2	LT	Fracturing with CO_2 fluid and N_2 gas. The CO_2 increases fracturing output and acts as a pH buffer. Use of CO_2 can reduce costs by 20%, increase production by 15%, and reduce water usage by up to 80%.	They provide the oil and gas industry with fracturing and well-stimulation fluids including N_2 and CO_2. In addition to CO_2 liquid fracturing, they are now pursuing CO_2 foam fracturing.	Ferus is privately-held by The Energy and Minerals Group and is part of the Ferus Group of Companies.
Mantra Energy (2007), Surrey, BC Canada	Formic Acid/ Liquid Fuels	yes as Mantra Venture Group	Industrial CO_2	ST	Their technology is Electro-Reduction of CO_2 (ERC), to convert CO_2 into useful chemicals and products. There's a pilot plant for ERC to convert CO_2 from cement plant in Richmond, BC into formic acid and salts.	Formic acid, CO, formaldehyde and hydrocarbons. Formic acid and formate salts can be used in agriculture, for textiles and leather, pharmaceuticals, oil well drilling, and de-icing. CO can be used to make methanol, synthetic natural gas, gasoline and diesel.	Has successfully demonstrated operation of ERC for greater than 2,500 hours. Has obtained bridge financing from Old Main Capital of Miami (MantraEnergy, 2016).
ETOGAS Gmbh (2011), Germany (SolarFuel until 2013)	Fuels	no	Waste CO_2	ST	Power-to-gas method: Renewable electricity is used to make renewable H_2, which is combined with CO_2 to be refined into synthetic natural gas.	H_2 and synthetic natural gas	Audi has commissioned them to build a power-to-gas plant (Worldcrunch, 2015).
Haldor Topsøe (1940), Lyngby, Denmark	Fuels	men-tioned	various sources	ST	Haldor Topsøe is studying methanol synthesis from CO_2 using solid oxide electrolysis cell (SOEC).	Methanol	It's clear based on various articles that the company has pursued this, however there isn't any mention on methanol from CO_2 that I can find on the website. It may be something they are researching but not currently doing (Columbia University, 2014).
Joule Unlimited Inc. (2007), Bedford, MA	Fuels	yes	Industrial waste CO_2	ST	They have a pilot site in Hobbs, NM, and are preparing for commercial level operations. SolarConverter® technology; CO_2-to-fuel. Engineered bacteria are catalysts to convert CO_2 into ethanol or hydrocarbons.	USA Ethanol and diesel equivalent products for diesel, jet fuel and gasoline. They expect to provide Joule Sunflow®-E and Joule Sunflow®-D for approximately $1.20/US gallon ($50/barrel).	They are entering into a partnership with HeidelbergCement to mitigate CO_2 from cement manufacturing (Joule Unlimited, Inc., 2015b). Latest round of financing is $40 Million (Joule Unlimited, Inc., 2015c).
Sunfire GmbH (2010), Dresden, Germany	Fuels	no	can come from multiple sources	ST	Sunfire has the Power-to-Liquids, Power-to-Gas and Gas-to-Power technology to convert CO_2 into fuels. Power-to-Liquids converts H_2O and CO_2 into CO and H_2 (syngas) to fuel products. Power-to-Gas converts H2O to H2 and O2, and H2 reacts with CO_2 to form CH_4 using steam electrolysis.	Gasoline, kerosene, diesel, methanol	Press releases on the site were in German and I couldn't translate them. Article states that Audi is backing their project, along with the German federal government, to create their "synthetic diesel-like liquid" Article states that the company received funding from Bilfinger Venture Capital, Total Ventures, KfW, and Electranova Capital, a venture capital fund financed by Allianz and EDF (Stone, 2015a).

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Carbon Recycling International (2006), Reykjavik, Iceland	Fuels/ Chem-icals	yes	CO_2 from nearby Geothermal Power Plant	ST	A pilot plant has been running since 2007, and the George Olah plant has been in operation since 2012. Emission to Liquid™ (ETL) technology for converting CO_2 to methanol.	Their renewable methanol is called Vulcanol™ which can be blended with gasoline, and used as a chemical feedstock for synthetic materials.	Geely Auto vehicles will arrive in Iceland to run on Vulcanol™ methanol in a 1-year fleet test (Carbon Recycling International, 2016).
Dioxide Materials™ (2010), Champagne, IL	Fuels/ Chem-icals	no	CO_2 from power plants and other sources	ST	Producing CO, or "synthesis gas" from CO_2 emitted by power plants. Additionally, CO_2 produced by homes back to fuels/chemicals. Use of patent-pending catalysts and electrolyzer.	Synthesis gas can be used as a feedstock for the production of industrial chemicals and liquid fuels. Waste CO_2 is used to produce gasoline, diesel fuel, jet fuel, and industrial chemicals.	Most recent news on the website is from 2013.
New CO_2 Fuels Ltd. (NCF) (2011), Rehovot, Israel	Fuels/Che micals	no	Technology can adapt for multiple sources of CO_2.	ST	Converts CO_2 and H_2O into syngas and further into synthetic fuels and chemicals. Solar panels heat a reactor to convert CO_2 into CO and O_2. Simultaneously, the same device converts H_2O to H_2 and O_2. The CO and H_2 are known as syngas.	The syngas can be used as gaseous fuel (e.g., in power plants), or converted to liquid fuel (methanol or other synthetic fuels).	The technology was developed by professor Jacob Karni and his team at the Weizmann Institute of Science (Rousseau, 2015). New CO_2Fuels Ltd. is a subsidiary of GreenEarth Energy Limited.
Phytonix - the future of fuel® (2009), Black Mountain, NC	Fuels/ Chem-icals	no	not sure	ST	Sustainable Chemistry Powered by the Sun™. Producing chemicals from CO_2 using an engineered cyanobacteria that secretes n-butanol.	Biobutanol and biopentanol, chemicals and potential "drop-in" fuels to replace gasoline. N-butanol can be used for fuels and chemicals – including jet fuels, bio-based plastics, and synthetic rubber.	I'm not sure of the current status of their company. The news section on their website is from 2012 or earlier. However, they have hired employees since then, and their website is updated with current dates/numbers in various places.
GreenFire Energy (2010), Emeryville, CA	Geo-thermal	yes		LT	ECO2G™. GreenFire Energy is conducting "proof of concept" projects to prepare for commercial operations. ECO2G™ uses supercritical carbon dioxide (SCO_2) as the fluid in a closed-loop geothermal system.	Geothermal energy	News page on website read, "The content on this page is currently being updated" on 3/13/16 and on 3/19/16 and on 4/2/2016.
Liquid Light	MEG	no	Industrial CO_2	ST	Mono-ethylene glycol (MEG) from CO_2. They are attempting to do this more efficiently (for instance plant material - to ethanol - to MEG).	MEG is one of the ingredients in Coca-Cola's PlantBottle.	Liquid Light has a technology agreement with Coca-Cola (Bioplastics Magazine, 2015). Liquid Light, Inc. has partnered with Public Service Electric and Gas (PSE&G) and Princeton researchers to convert CO_2 and water into formic acid in an electrochemical cell. This process will use solar power for its energy (Quick, 2014; White et al., 2014).

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Lanzatech (2006), Skokie, IL and worldwide	Microbial	no	Gas from steel manufacturing and hydrothermal vents - CO, H_2, H_2S, CH_4.	ST	Lanzatech uses CO/CO_2 to create biofuels and chemicals. Their process involves fermentation of a proprietary microbe -- acetogens (gas-fermenting organisms.)	Ethanol, acetic acid, I-Propanol, acetone, lactic acid, 2,3 BDO, n-butanol, MEK, succinic acid, isoprene. Ethanol , jet fuel, and commodity chemicals such as butadiene used in nylon production or propylene used in plastics manufacture.	Collaboration w ith Global Bioenergies (GB) (LanzaTech 2016b). GB has developed a microorganism that can produce isobutene from renew able feedstock.LanzaTech has w on many aw ards including the 2015 BIO Rosolind Franklin Aw ard and the Sustainable Brand Aw ard (LanzaTech 2015a, 2015b). They had several investors in 2014, including Mitsui, Siemens Venture Capital , CICC Grow th Capital Fund I, L.P. THey also had existing investors: Khosla Ventures, Qiming Venture Partners, K1W1 and the Malaysian Life Sciences Capital Fund (LanzaTech, 2014).
BASF (1865), US HQ in Florham Park, NJ	Polymers/Formic Acid	yes	n/a	ST	EcoFlex® and Ecovio®. EcoFlex® is a compostable polymer from fossil fuels. EcoVio® is compostable w ith biobased content – it's a mixture of EcoFlex + polylactic acid from biobased corn.	Foam packaging, thermoformed packaging, film, mulch films, shrink film, paper coatings.	Succinity GmbH is a joint venture company betw een Corbion and BASF (Succinity, 2014).
Bayer (1863), Leverkusen, Germany	Polymers	no	CO_2 supplied by a pow er plant.	ST	CO_2 is used to make polyols, one of the tw o ingredients in polyurethane.	Using polymers/CO_2 to create: polyurethane foam, mattresses, upholstered furniture, shoes, auto parts, insulation for buildings and refrigeration equipment.	Bayer Material Science has invested $15 Million euros for constructing a production line in Dormagen, Germany, for using CO_2 to produce a precursor for polyurethane foam. Estimated annual production: 5,000 metric tons (Process Worldw ide, 2014). It's currently under construction (Bayer, 2015b).
Coca-Cola (1892), Atlanta, GA	Polymers	no		ST	PlantBottle™ w hich is 30% plant material, and now Liquid Light plastic to be made from CO_2.	Their PlantBottle bottles are 30% plant material.	Liquid Light has a technology agreement w ith Coca-Cola (Bioplastics Magazine, 2015).
Corbion (fka CSM N.V.) (1919), the Netherlands, Amsterdam	Polymers	no	n/a	ST	Puralact®. Lactides and PLA resins; 2,5-furandicarboxylic acid (FDCA) for high performance PEF resin	PLA – in packaging and silver w ear, automotive, electronics, textiles. As a replacement for PS, PP, ABS (acrylonitrile butadiene styrene). Lactic acid into lactide monomers w hich are polymerized into PLA thermoplastic resin.	Plans to build a 75kTpa PLA polymerization plant to open in 2018 (Corbion, 2016). Succinity GmbH is a joint venture company betw een Corbion and BASF.
Natureworks (2003), Minnetonka, MN	Polymers	no	Atmospheric CO_2	ST	Creator of Ingeo™, a bioplastic made up of a long molecular chain of the polymer polylactide, from a plant sugar. Their sugar source is corn (NatureWorks LLC, 2009).	Food and beverage packaging, service w are, electronics, durable goods, fiber for clothing, home w ares and personal care products. Printing toner, potentially 3D printing product.	They just launched a $1 Million, 8,300 square foot laboratory for methane to lactic acid conversion. (NatureWorks LLC, 2016b).

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Newlight Technologies (2003), Costa Mesa, CA	Polymers	no	Methane (CH_4) from farms, landfills and energy facilities	ST	AirCarbon™ is a thermoplastic that's about 40% O_2 and 60% C and H from methane. Methane is combined with air and a biocatalyst. C, O and H are assembled into a long-chain thermopolymer aka AirCarbon™.	AirCarbon™ can be used in applications currently using fossil fuel-based polypropylene, polyethylene, ABS, polystyrene, and TPU. It can be used in extrusion, blown film, cast film, thermoforming, fiber spinning, and injection molding applications.	20-year contract with Vinmar for 19 billion pounds of AirCarbon PHA (Newlight Technologies, 2016b). Newlight Technologies won the Popular Science Innovation of the year award (Bugge, 2014). IKEA will purchase 50% of the material from Newlight's 23,000 tonne per year, and IKEA has exclusive rights in the home furnishings industry to use Newlight's carbon capture technology to convert bio-based greenhouse gases, first from biogas and later from CO_2, into AirCarbon thermoplastics for use in its products (Lane, 2016).
Novomer (2004), Waltham, MA	Polymers	yes	Appears to have multiple sources of CO_2 including power plants and industrial	ST	Chemical feedstocks are combined with CO_2 to create polymers that are about 50% CO_2. Novomer has two processes: one uses waste CO_2 to produce polyols for use in polyurethane applications and another which uses waste carbon monoxide (CO) to produce C3 and C4 drop-in chemicals (acrylic acid, butanediol, THF).	Novomer's CO_2-based Converge® Polyols can used in coatings, adhesives, sealants, elastomers and foams. Their CO product can be transformed to acrylic acid, acrylate esters, succinic anhydride and 1,4-butanediol. This product is used to make diapers, paints, coatings, plastics, and textiles. It can also produce polypropiolactone, which is biodegradable and can be used as a packaging material.	DOE (AMO) $5 Million grant for converting waste CO_2 to chemicals. DOE (NETL) $2.5 Million grant for capturing and utilizing industrial CO_2. NYSERDA $475,000 funding for feasibility study and commercialization activities for coatings and packaging. National Science Foundation funding of $400,000 to develop a process to make CO_2-based polymers.
Succinity (2009), Düsseldorf, Germany	Polymers	no	Atmospheric CO_2	ST	Succinity® is a joint venture between BASF and Corbion for biobased Succinic acid - produced from microorganisms and atmospheric CO_2 (Succinity, 2016).	Life sciences, biodegradable polymers, polyurethanes, plasticizers, industrial solvents, coatings.	Plant in Spain can produce 10,000 metric tons a year (Succinity, 2014).
Calysta Energy (2011), Menlo Park, CA	Polymers & animal feed	no	Methane (CH_4)	ST	Gas-to-Chemicals® technology for materials. FeedKind™ protein technology from methane with methane as an energy source (Byme, 2016).	Fibers, plastics, liquid hydrocarbons and building materials. Current focus on FeedKind™ protein for the creation of fish/livestock feed.	A current round of financing for $30 Million from Cargill, the Municipal Employee Retirement System of Michigan and Old Westbury Global Real Assets Fund LLC, among others. This financing is for FeedKind™ protein (Calysta Inc., 2016b).
Uranium One, Toronto, Ontario	Uranium	no	unsure	LT	In-situ leach mining. Piping solvent or "leaching solution" to a well. In-Situ Leach mines in the US often use sodium bicarbonate and CO_2 as leaching solutions.	Uranium mining	Couldn't find specifics on the process of how they use CO_2, where it's being sourced from, or if it's currently being used.

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Mitsubishi Heavy Industries (MHI) (1934), Japan	Urea/ CCS	yes	flue gases from burning natural gas at a chemical plant.	ST/ LT	MHI provides a CO_2 capture product to clients in many countries. They have a proprietary energy-efficient CO_2 absorbent called KS-1™. CO_2 is fed into system for synthesis of urea. Also, they have developed KM CDR Process® capture technology for CCS projects (Mitsubishi Heavy Industries, Ltd., 2005, 2010, 2016a, 2016b).	Urea/Sequestration of CO_2	MHI and several other parties invested in Plant Barry, a CCS project in Mobile, AL piloted by the company Southern Company. The plant began capturing CO_2 in 2011, and storing it in 2012 (MIT, 2016b). More recently, DOE is investing in Plant Barry (Cope, 2015).
GreenField Specialty Alcohols Inc. (1989), (Commercial Alcohols until 2006), Canada	Green-house Crops	no	Waste CO_2 from ethanol plant	ST	Construction on Truly Green Farms greenhouses is working toward utilizing the waste heat and CO_2 from the GreenField ethanol plant to increase tomato yield.	Tomato yield	Truly Green Farms will use the waste CO_2 from the GreenField ethanol plant for their greenhouse to increase yield (Greenfield Specialty Alcohols Inc. 2015; Truly Green Farms, 2013).
DyeCoo (2008) Weesp, The Netherlands	Dyes	no	Waste CO_2 from industrial Processes	ST	Using supercritical CO_2 instead of water to make dyes. These dyes dissolve quickly and they don't require process chemicals. Their proprietary dyeing machine is named DyeOx. 95% of the CO_2 is recycled after each batch.	Textile dyeing	The Super Bowl 50 Nike Gold Collection clothing contains their dyes (DyeCoo, 2016).