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\textsubscript{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\textsubscript{2} reuse is a way to mitigate CO\textsubscript{2} emissions. This research has two concurrent goals. First, the researcher will review current companies reusing CO\textsubscript{2} collected via carbon capture technology to see how the CO\textsubscript{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.
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Introduction

The ultimate goal of carbon capture and sequestration (CCS) and reuse is the reduction of anthropogenically-produced CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ reuse is a way to mitigate CO₂ emissions, perhaps serving reduce the effects of climate change for future generations.

The average atmospheric CO₂ reached 400 ppm in the spring of 2015 (Figure 1) (NASA, 2016a). Scientists are projecting that CO₂ 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 CO₂ concentration since 1979 (U.S. Department of Commerce, 2015).
In the United States, power-generating units contributed 37% of the CO₂ 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 CO₂ emissions than coal per energy unit but nevertheless are still producing CO₂.

![Figure 2. Summary of CO₂ emissions by sector (Environmental Protection Agency, 2016a).](image)

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, CO₂ 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 CO₂, or converted to other chemical forms for reuse. There are several methods for capturing the CO₂, including pre-combustion capture, post-combustion capture and oxyfuel combustion (Figure 3).
An additional aspect of carbon capture is the pipeline transport of CO₂ 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 CO₂ can be reused. One major use for captured CO₂ that is being practiced in several locations is Enhanced Oil Recovery (EOR). In EOR, CO₂ is injected into an oil reservoir, which helps improve the oil flow rate. The injected CO₂ remains underground permanently. Another use is CO₂-based geothermal power that utilizes supercritical CO₂ to extract geothermal heat in circumstances where the heat doesn’t easily reach the surface. There are several additional potential uses for captured CO₂ 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 CO₂
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 CO₂ reuse and storage. (Global CCS Institute, 2011).

<table>
<thead>
<tr>
<th>Short-Term</th>
<th>Long-Term</th>
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<tbody>
<tr>
<td>Algae Biomass Cultivation*</td>
<td>Enhanced Oil Recovery (EOR)</td>
</tr>
<tr>
<td>Polymer Processing</td>
<td>Enhanced Coal Bed Methane Recovery (ECBM)</td>
</tr>
<tr>
<td>Liquid Fuels</td>
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<tr>
<td></td>
<td>Enhanced Uranium Leaching</td>
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*In the CCS 2011 report it is noted that algae utilization could be a semi-permanent method of CO₂ 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 CO₂ utilization. If numerous companies are going to pursue carbon capture and CO₂ reuse, it will require community understanding. If individuals don't understand CO₂ reuse then they might not be enticed to select products created through CO₂ 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 CO₂ and how it relates to climate change.

To assess the capability of community members to learn basic concepts on CO₂, 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.
Carbon (CO₂) Capture, Storage and Reuse

An introduction for the rest of us!

Presented by Michelle Lempert
Environmental Assessment Masters Program
North Carolina State University

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 CO₂. 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; CO₂-based polymers; polymer processing; enhanced oil recovery; sodium bicarbonate or baking soda or NaHCO₃; hydrochloric acid or HCl; bleach or NaOCl; formic acid or CH₂O₂; methanol or CH₃OH; dimethyl-ether or C₂H₆O; 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: \( CO_2; \text{carbon dioxide}; \text{reuse}; \text{carbon capture}; \text{CCS}. \)

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 CO₂ utilization are using waste CO₂ 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 CO₂ 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 CO₂ 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 CO₂? A number of companies were included that are not using waste CO₂ in their processes. For example, some companies are using atmospheric CO₂ and others using methane (CH₄). Still other companies are not using CO₂ at all, but were included for comparison/explanatory purposes. For example, a sample of companies producing bioplastics that are not using
CO₂ 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 CO₂ 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 CO₂. A chart of the companies referred to in the text is in Appendix B.
Short-Term CO₂ Reuse/Storage Methodologies

Algal Biomass

Introduction on Algal Biomass

Algae can utilize CO₂ 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 CO₂ from power, steel and cement plant facilities can be utilized in the production of algal biomass. Approximately 1.8 tonnes of CO₂ can be consumed for each tonne of algae biomass created. (Global CCS Institute, 2011).

There are multiple avenues in which CO₂ can be provided to algae for enhancing growth of their biomass, including flue gas from power, steel and cement plants; supercritical CO₂ from power, steel and cement plants; and CO₂ absorbed directly from the atmosphere. Different strains of algae prefer different sources of CO₂. 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 CO₂ 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 O₂. ATP and NADPH are formed. During the dark phase, also known as the Calvin cycle, CO₂ 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.](image)
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, 1-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](image)

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).](image)

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 Solayzme), 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 CO₂ from a dedicated flue gas or supercritical CO₂ source will be a way to reuse the CO₂ though not necessarily permanently removing it from the atmosphere. Using CO₂ in the process of algae cultivation is different from other uses of CO₂ reuse in that it may result in either semi-permanent or non-permanent storage of CO₂. However, if biofuels replace fossil fuels, then it will prevent the introduction of anthropogenic combustion-related CO₂ into the atmosphere. Partnerships between CO₂-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\textsubscript{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\textsubscript{2} into plastic has been shown to be more carbon friendly than traditional plastics: Polyethercarbonate polyols with 20\% CO\textsubscript{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\textsubscript{2}-Based Polymers

Novomer is one of the few companies using CO\textsubscript{2} to make polymers. Their product, Converge®, is about 50\% CO\textsubscript{2}. Converge® and uses CO\textsubscript{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\textsubscript{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).
Another company that is researching using CO₂ to make plastic is Bayer. They are researching making polyols utilizing CO₂ 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 CO₂ 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 CO₂-based polymers being trademarked by other companies. Forms of bioplastics that don’t utilize CO₂ are more common. For instance, Newlight Technologies and Calysta Energy are using CH₄ 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 CO₂, 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\(_2\)O\(_2\)) 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).
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\textsubscript{3}OH) and CO in the presence of sodium methoxide (CH\textsubscript{3}NaO).

Additionally, CO\textsubscript{2} can be combined with H\textsubscript{2} to create formic acid. However, it’s a difficult process due to the thermodynamic stability of CO\textsubscript{2} (Moret et al., 2014). Another potential method of creating CH\textsubscript{2}O\textsubscript{2} from CO\textsubscript{2} is the biological CO\textsubscript{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\textsubscript{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\textsubscript{2} can be used in the production of several fuels including methanol (CH\textsubscript{3}OH), dimethyl-ether (C\textsubscript{2}H\textsubscript{6}O), and synthetic gas (syngas), among others. Syngas is a mixture of CO, H\textsubscript{2}, and sometimes CO\textsubscript{2}. H\textsubscript{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\textsubscript{2}H\textsubscript{6}O) 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).
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$_2$O 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$_4$N$_2$O) production, there is often a small surplus of ammonia. This surplus ammonia
can be reacted with flue gas CO\textsubscript{2} to produce additional urea. This process is known as urea-yield boosting. This is unlikely to be a growing category of CO\textsubscript{2} utilization. Urea is not considered a permanent form of CO\textsubscript{2} storage.

Urea is developed commercially from ammonia (NH\textsubscript{3}) and CO\textsubscript{2}. There is a two-step process where the ammonia and CO\textsubscript{2} react at a high temperature and pressure to form ammonium carbamate (CH\textsubscript{3}N\textsubscript{2}O\textsubscript{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\textsubscript{2} for urea yield boosting. They provide a CO\textsubscript{2} capture product to clients in many countries. They have a proprietary energy-efficient CO\textsubscript{2} absorbent called KS-1\textsuperscript{™}. CO\textsubscript{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).
Long-Term CO₂ 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 CO₂ 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 CO₂ is permanently sequestered by this process. The Kwinana power plant permanently sequesters about 70,000 tonnes of CO₂ a year (Alcoa Inc., 2016a).

Beyond Alcoa’s work in Australia, it doesn’t appear that other companies are using CO₂ to neutralize bauxite residue. However, researchers are exploring other methods to neutralize
bauxite residue, including neutralizing with SO₂, 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. CO₂ is injected into the subsurface coal seam. It replaces methane, which is collected, and the CO₂ is permanently sequestered within the coal (Bergen, 2012; Global CCS Institute, 2011).

A major limitation of this process is that the injected CO₂ actually decreases the permeability and injectivity of the coal, which thereby reduces the amount of methane that can be released. Various combinations of N₂ and CO₂ injection have been tested to circumvent this problem. There is initial faster recovery of CH₄ with N₂; while pure CO₂ allows for a greater total CH₄ recovery. Combining N₂ and CO₂ allows for greater and faster CH₄ recovery, overall. Flue gas, which consists of a combination of N₂ and CO₂, and only about 13% CO₂, might help to keep the coal permeability high while allowing for the greatest total CH₄ 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**

CO₂ can be bound to calcium to create calcium carbonate (CaCO₃). 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 SO₂ 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 CO₂ to carbonate (CO₃) and bound it to calcium or magnesium to create calcium carbonate (CaCO₃) or magnesium carbonate (MgCO₃) (Figure 13). Their source of CO₂ 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 CO₂ into carbonates (CaCO₃). They create CarbonMix™ materials: aggregates, concrete, roofing granules, cool pigments, titanium oxide and pure CO₂ (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 CO₂ as limestone-like nanomaterials within the concrete. The limestone is no longer CO₂ gas. This is a permanent storage method of CO₂. 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 CO₂ 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).

![Concrete Reaction Diagram]

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

**Sodium Bicarbonate**

Skyonic is a company that has the Skymine® technology to collect CO₂, SOx and NOx from industrial facilities to turn into products such as sodium bicarbonate (NaHCO₃, 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).

![Products Made at Skyonic]

Figure 14. Products made at Skyonic

**Additional Research**

Not only can CO₂ be used to synthesize sodium bicarbonate, but sodium bicarbonate can also be used to capture CO₂ from flue gas. A recent study has shown that microcapsules containing sodium bicarbonate can absorb CO₂ from flue gas. After filling with CO₂, the capsules are taken out of the flue gas. Afterward they are heated to remove the CO₂ (Vericella et al., 2015; Stark, 2015).
Enhanced Oil Recovery (EOR)

Introduction to EOR

EOR is much more established than other methods CO₂ 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 CO₂, hydrocarbon (HC) or N₂ injection. In the process of EOR with CO₂ injection, the CO₂ is permanently sequestered underground. CO₂-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 CO₂ 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 CO₂ miscible petroleum via CO₂-EOR, with 33 wells producing about 88.1 thousand barrels of oil per day via
CO₂-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 CO₂-EOR in 2014 (data tabulated from Oil & Gas Journal, 2014).

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

EOR was actively pursued in the Permian basin in the 1970’s and 1980’s because CO₂ was cheap and oil prices were high. Several CO₂ 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 CO₂ 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 CO₂ where the CO₂ is used instead of water or brine to extract geothermal heat. The CO₂ is permanently stored underground.

**Company Development**

GreenFire is a developing ECO₂G™ technology to create CO₂ based geothermal power (Figure 15). Their methodology involves a closed loop system using supercritical CO₂ 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 CO₂-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 CO₂ 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.

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

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 CO₂ 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 CO₂, 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 CO₂ reuse, it will require community understanding. If individuals don’t understand CO₂ reuse then they might not be enticed to select products created through CO₂ 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 CO₂ 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 CO₂, 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 CO₂, 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 CO₂, 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).

![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.)](image-url)
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 others 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?”
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 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 than 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](image)

**Improvement in Test Results (Post-Questionnaire total divided by Pre-Questionnaire Total)**

![Figure 22B. Improvement in Test Results by Educational Level](image)
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?” 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.

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The community engagement project was affective in getting participants engaged and knowledgeable about CO₂, 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 CO₂ 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 CO₂ 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 CO₂. 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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Muradel Pty Ltd. 2015. Available at: http://www.muradel.com/. [accessed 2016 March 5].


New CO₂ Fuels Ltd. Available at: http://www.newco2fuels.co.il/. [accessed 2016 March 6].


SBIR-STTR America’s Seed Fund™. 2013. Biological CO₂ Fixation for the Production of Formic Acid Powered by Sugars. Available at: https://www.sbir.gov/sbirsearch/detail/409513. [accessed 2016 March 5].


Union of Concerned Scientists. 2015. Coal generates 44% of our electricity, and is the single biggest air polluter in the U.S. Available at: http://www.ucsusa.org/clean_energy/coalywind/c01.html#.VjYx3LerTZ5 [accessed 2016 March 16].


Union of Concerned Scientists. 2015. Coal generates 44% of our electricity, and is the single biggest air polluter in the U.S. Available at: http://www.ucsusa.org/clean_energy/coalywind/c01.html#.VjYx3LerTZ5 [accessed 2016 March 16].


Union of Concerned Scientists. 2015. Coal generates 44% of our electricity, and is the single biggest air polluter in the U.S. Available at: http://www.ucsusa.org/clean_energy/coalywind/c01.html#.VjYx3LerTZ5 [accessed 2016 March 16].


Appendix A – Community Engagement Project Presentations

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

4/14/2016

Carbon (CO₂) Capture, Storage and Reuse
An introduction for the rest of us!

What is climate change?
• Changes caused by man-made activities
• Higher temperatures and erratic weather
• Caused by greenhouse gases such as carbon dioxide (CO₂)
• Greenhouse gases trap energy from the sun

What is Carbon Dioxide (CO₂)?
• Makes soda fizzy!
• Major contributor to climate change
• Heat-trapping blanket

Where does CO₂ come from?
• Both human and non-human sources
• 3 biggest emitters of CO₂ in the U.S.:
  – Powerplants
  – Fuel for vehicles
  – Factories
  (Steel & General industrial Plants)

Let’s Talk about Power Plants!
• Coal Fired Power Plants
• Natural Gas Power Plants
• Renewable Energy

OZONE LAYER

TRA P!
What is Carbon Capture?

- Carbon capture = capturing the CO₂ before it goes into the air. It can capture up to 90% of the CO₂.

![Carbon Capture Diagram]

3 Ways to Capture CO₂

- Pre-Combustion Capture
- Post-Combustion Capture
- Oxygen Capture

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. Flux gas is released. That’s the smoke you are coming out of a power plant! The CO₂ is captured directly from the flux gas.

What Happens Next?

- Pipeline Transport!
- Then:
  - Underground Storage or...
  - Or, CO₂ can be reused!

What can CO₂ be reused for?

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

Permanent Storage of CO₂

- Oil wells
- Underground between rocks
- Ocean
- Long-term storage of CO₂ is safe.

Or, CO₂ 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 CO₂ can be Reused

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

Barriers to Carbon Capture

- Expensive
- Takes more space
- Concerned citizens

Challenging the Barriers

- Technology gets cheaper over time.
- Reusing the CO₂ will bring in $$$
- It's been tested and shown to be safe.
- And finally, less CO₂ in the atmosphere leads to a healthier planet!

CO₂ Capture Site — Opened in 2012
George Olah Geothermal Power Plant in Iceland
Renewable methanol: Vulcain™

Summary

- CO₂ is being released into our atmosphere from human sources.
- CO₂ acts as a heat-trapping blanket, trapping heat in the earth's atmosphere.
- Carbon capture is a process of capturing CO₂ from power plants and industrial factories that can remove up to 90% of the CO₂. The CO₂ can be stored or used to make products.
- Carbon capture can help us to reduce the amount of CO₂ that is released into our atmosphere!
Some Resources to Learn More

- International Energy Agency: http://www.iea.org/topics/ccs/
- ENSO Network on CO2: http://www.ensoenergy.org/
- Global CCS Institute: http://www.globalccsinstitute.com/
- World Resources Institute: http://www.wri.org/our-work/project/carbon-dioxide-capture-and-storage-cs

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 the CO2 is, a) what carbon capture & storage is, and why it’s important. I’ll tell you why it’s important to you. My whole life has been a natural gas. Part of it’s that I like exercise. I like to push myself. But really, I like the way the Earth turned itself to nature. I have beautiful places. And the idea of us dealing with our beautiful planet is upsetting to me.

2. What is climate change? It’s the same as the hole in the ozone layer.

3. Back in the late 1990s, 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 single-handedly causing the hole in the ozone layer. The ozone layer is a very thin environmental issue, and it’s completely unrelated to climate change.

4. What is climate change? a) Climate change denotes 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 CO2.

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

5. Now we are going to talk about CO2. What is CO2? 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. Or go ahead and drink that Pepsi or Coke. How many oska people do we have? (Pepsi? Hot tea?)

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 5 blankets, and it keeps you warm by trapping heat. That’s what carbon dioxide is doing to our planet. It’s like a big giant planetary blanket that’s warming the planet.

5. What is causing all of the extra CO2?

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 facilities, such as steel and cement plants.

6. Let’s talk about Power Plants!

a) The type of power plant that releases the most CO2 is the coal-fired power plant.

b) Followed by natural gas-fired power plants.

c) There’s also nuclear power, and renewable energy such as hydro power, wind and solar, all of which cause less greenhouse gases than coal or natural gas.

7. 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 CO2 that is released.

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

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

b) Post-combustion capture – after the heat 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? okay?) Pre-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. This 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) It can be permanently stored underground.

c) 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 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 be recycled?

a) Cement and other building materials.

b) Coal and other minerals, even bicycles and cars.

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

d) Plastic for bottles, packaging and other uses.

e) Emissions, which is a common fertilizer for growing food.

13. Also, algae can use carbon dioxide in their growing processes and they grow really fast. It’s the algae can be used to make gasoline, fuel for planes, surfboards, fertilizers, animal food, and even food for people. Some new consumer products being made out of algae include VeggieEgg and Algae.

14. Some companies are finding ways to make plastics out of carbon dioxide. One company called Nexant has created a plastic that is 80% carbon dioxide. This plastic can be made into garbage bags, paint, clothing and packaging, among other things.

15. 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 that house or park or school.

16. However, a carbon capture will likely get less expensive as the technology gets better. Just like laptop computers in the late 1990s, 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.

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

c) It’s been said and the technology has been shown to be safe.

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

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

20. 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, 255,000 tons of CO2 have been captured. The goal is to capture 1 million tons of CO2/year once it’s fully operational.

21. This is a carbon capture plant in Ireland. It was completed in 2012. At this plant, CO2 is captured from a geothermal power plant. The CO2 is used to make a renewable method called VULCANOL. Vulcanol can be blended with gasoline, or used as a chemical feedstock for making materials.

22. 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

Carbon (CO₂) Capture, Storage and Reuse
An introduction for the rest of us!

What is climate change?
• Climate change describes changes that are taking place on our planet due to man-made activities.
• These changes include higher temperatures, and more erratic weather patterns.
• These changes are due to greenhouse gases such as carbon dioxide (CO₂). Greenhouse gases trap energy from the sun.

What is Carbon Dioxide (CO₂)?
• Carbon dioxide, also known as CO₂, is what makes your soda pop fizzy!
• It is also one of the major contributors toward climate change.
• CO₂ can act as a heat-trapping blanket, trapping warmer air into our earth's atmosphere.

Where does CO₂ come from?
• CO₂ can be released into the air from both human and non-human sources.
• The three biggest sources of CO₂ produced by humans are:
  — Making electricity in power plants.
  — Fumes in cars and other vehicles.
  — Industrial factories such as cement and steel plants.

Let's Talk about Power Plants!
• The type of power plant that releases the most CO₂ into the atmosphere is coal-fired power plants, followed by natural gas-fired power plants.
  — Coal is mined from the earth and used to create electricity.
  — Natural gas is also extracted from the earth and is also used to create electricity.
What is Carbon Capture?

- In small amounts, CO₂ is not harmful. However, the large collective releases of CO₂ are building up in our earth's atmosphere and contributing to climate change.

- Carbon capture involves capturing the CO₂ from power plants, cement plants and steel plants before it goes into the air. It can capture up to 90% of the CO₂. Therefore, it is a greenhouse gas!

3 Ways to Capture CO₂

- There are 3 ways to capture CO₂ from a power plant:
  - Post-combustion capture—after the fuel is burned
  - Pre-combustion capture—before the fuel is burned
  - Oxyfuel combustion capture—combustion air is mixed with CO₂ to form a product stream that is enriched in CO₂, making it easier to separate as a pure stream.

- Post-combustion capture, which is the most well-understood method, will be explained on the next slide.

What Happens Next?

- After CO₂ 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 CO₂

- CO₂ can be stored permanently underground in the following types of places:
  - Oil wells that have already exhausted their oil
  - Deep underground in zones between rock layers
  - Deep in the ocean
  - Long-term storage of CO₂ is safe.

Or, CO₂ can be Reused!

- Alternatively, CO₂ can be reused! There are many clever ways to reuse CO₂, including using it to make:
  - Cement and building materials
  - Chemicals such as bleach
  - Car and truck fuels
  - Fertilizers
How CO₂ can be Reused

- Additionally:
  - Algae can use CO₂ in their growing process and they grow real fuel! The algae can be used to make gasoline, fuel for planes, sunscreen, fertilizers, animal feed, and even food for people!
  - Some companies are finding ways to make plastics out of CO₂.
  - One company, however, has created a plastic that is 50% CO₂. 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 CO₂ 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 CO₂ 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 CO₂ in the atmosphere leads to a healthier planet!

Summary

- CO₂ is being released into our atmosphere from human sources.
- CO₂ acts as a heat-trapping blanket, trapping heat in the earth's atmosphere.
- Carbon capture is a process of capturing CO₂ from power plants and industrial factories.
- Carbon capture can help us to reduce the amount of CO₂ that is released into our atmosphere!

Some Resources to Learn More

- International Energy Agency: http://www.iea.org/topics/ccs/
- ENSO Network on CCS: http://www.ensconetwork.org/
- Global CCS Institute: http://www.globalccsinstitute.com/
- World Resources Institute: http://www.wri.org/how-work/project-grouping-strong-carbon-and-storage-ccs/
**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.**
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<tbody>
<tr>
<td>Algae Systems LLC (estim. 2011), Daphne, AL</td>
<td>Algae</td>
<td>no</td>
<td>Atmospheric CO₂</td>
<td>An offshore photobioreactor (PBR) system. A test project in Daphne, AL is testing the use of wastewater in conjunction with algae for wastewater treatment and expanded algae creation.</td>
<td>Reclamation of wastewater into drinking/reuse water. Testing the creation of jet fuel, diesel, gasoline and fertilizer.</td>
<td>This company shut down operations in 2015 but hopes to raise money to reopen (UTV44, 2015).</td>
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<tr>
<td>Algenol (2006), Fort Myers, FL</td>
<td>Algae</td>
<td>yes</td>
<td>Industrial Sources of CO₂</td>
<td>The DIRECT TO ETHANOL® process involves the use of a proprietary flexible plastic film PBR to create ethanol from algae, sunlight and CO₂. CAPTURES TECHNOLOGY® uses proprietary algae and a proprietary collection method.</td>
<td>Ethanol; gasoline, jet and diesel fuel.</td>
<td>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 with Dow Chemical Company (Morsella, 2011). In 2015 the company reduced its workforce and the CEO resigned (Algenol 2015a, 2015c). They were 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.</td>
</tr>
<tr>
<td>Arizona Center for Algae Tech and Innovation (AzCATI) (2010), Mesa, AZ</td>
<td>Algae</td>
<td>no</td>
<td>flue gas CO₂ and other sources</td>
<td>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 raceway ponds and the ARID Raceway.</td>
<td>n/a</td>
<td>Established through a grant from the Science Foundation Arizona.</td>
</tr>
<tr>
<td>BPA, LLC. Bioprocess (Algae (2009), Omaha, NE)</td>
<td>Algae</td>
<td>no</td>
<td>waste CO₂</td>
<td>Grower Harvester™ bioreactors convert light and CO₂ into microbial feedstock.</td>
<td>Animal feed, chemicals, fuel, nutraceuticals, fish feed.</td>
<td>There doesn't appear to be news releases from more recent years than 2014 on the website.</td>
</tr>
<tr>
<td>Cellana (2009), San Diego, CA</td>
<td>Algae</td>
<td>no</td>
<td>Atmospheric CO₂</td>
<td>Produced &gt;20 metric tonnes of algae in Kona Demonstration Facility to date using Alduo™ technology (Photobioreactor systems coupled with open ponds).</td>
<td>ReNew ™ line of products: omega-3 EPA/DHA oils (human nutrition), Animal Feed, Biofuel Feedstocks.</td>
<td>In 2013 Cellana entered into a multi-year commercial-scale agreement with Neste Oil (Cellana 2015b). The energy department awarded Cellana $3.5 Million in 2014 to develop cost-competitive biofuels from algae (Cellana 2014). The website was viewable on 4/2/2016 but not on 4/3/2016.</td>
</tr>
<tr>
<td>Heliae (2008), Gilbert, AZ</td>
<td>Algae</td>
<td>no</td>
<td>Mix of atmospheric and CO₂ feedstocks.</td>
<td>Heliae's proprietary brand PhycoTerra™ has its own website: <a href="http://phycoterra.com">http://phycoterra.com</a>. The company's methods and processes appear to be in a research phase (Heliae Development LLC, 2016).</td>
<td>Astaxanthin ingredient and PhycoTerra™.</td>
<td>The company has switched direction and focus multiple times, and it is uncertain where their research and focus will settle. A joint venture with Sincere Corporation in Japan to found Alvita - an algal development company near an incineration facility in Saga City, Japan to recycle CO₂ (Heliae Development, 2015b). Another joint venture with Schott involving new oval glass tubes for PBRs that increased output of biomass by &gt;22% (Heliae Development, 2015a).</td>
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<tr>
<td>Company</td>
<td>Reuse Category</td>
<td>Carbon Source</td>
<td>In Global CCS 2011?</td>
<td>ST or LT</td>
<td>What They Do, Processes, Trademarks</td>
<td>Products Created</td>
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<td>HY-TEK Bio, LLC (2008), Dayton, MD</td>
<td>Algae</td>
<td>no</td>
<td>CO₂ from flue gas</td>
<td>ST</td>
<td>HTB-1 is a unique strand of freshwater algae that is not genetically modified. It thrives in high concentrations of CO₂. A PBR system, an advanced flue gas injection technology with micro bubbles, and LED lights to increase photosynthesis.</td>
<td>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.</td>
</tr>
<tr>
<td>MicroBio Engineering (2005), Santa Barbara, CA</td>
<td>Algae</td>
<td>no</td>
<td>unsure</td>
<td>ST</td>
<td>A consulting and engineering firm for the design and construction of algae production facilities. Their RNEW® process combines wastewater treatment, recycling of nutrients, and production of algae biofuel feedstock in warmer climates. They fabricate Algae Raceways™ featuring APAC™ technology, ranging from 22 to 101m².</td>
<td>Biofuels, wastewater reclamation, additional high-value products.</td>
</tr>
<tr>
<td>Muradel (2010), Victoria, Australia</td>
<td>Algae</td>
<td>no</td>
<td>likely atmospheric CO₂</td>
<td>ST</td>
<td>Green2Black™ technology, paddlewheel ponds and sub-critical wastewater reactor (SCWR) technology. The following goals were listed on their website: plans to upgrade their demonstration plant, reach steady-state operations, and to complete demonstration technology of Green2Black™.</td>
<td>Animal feed, oleochemicals, crude oil, fertilizers and building materials.</td>
</tr>
<tr>
<td>OpenAlgae (2008), Austin, TX</td>
<td>Algae</td>
<td>no</td>
<td>most likely atmospheric CO₂</td>
<td>ST</td>
<td>Patented membrane technology extracts oils without solvents.</td>
<td>Algal oil, biomass.</td>
</tr>
<tr>
<td>Pond Biofuels (2007), Markham, ON</td>
<td>Algae</td>
<td>no</td>
<td>flue gas from industry</td>
<td>ST</td>
<td>The Pond Biofuels system uses microalgae to convert CO₂ into algae and subsequently into biofuel.</td>
<td>Bio-oil and biodiesel.</td>
</tr>
<tr>
<td>Proterro, Inc. (2008), Bronxville, NY</td>
<td>Algae</td>
<td>no</td>
<td>Waste CO₂</td>
<td>ST</td>
<td>Partners with companies such as Matrix Genetics, which utilize cyanobacteria for the creation of products</td>
<td>Industrial and food grade sugars; nutritionals including organic acids, amino acids, nutrients and vitamins.</td>
</tr>
<tr>
<td>Qualitas Health, Imperial, TX</td>
<td>Algae</td>
<td>no</td>
<td>local emitters of CO₂</td>
<td>ST</td>
<td>Closed and open pond systems using a proprietary growth medium. Wet oil extraction method under exclusive license of Valicor™ (Valicor, 2015).</td>
<td>Vegetarian food supplements, pharmaceutical ingredients and omega-3 products. Almega PL™ is a long chain polyunsaturated fatty acid (LC-PUFA) Omega-3 product.</td>
</tr>
<tr>
<td>Company</td>
<td>Reuse Category</td>
<td>In Global CCS 2011?</td>
<td>Carbon Source</td>
<td>ST or LT*</td>
<td>What They Do, Processes, Trademarks</td>
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<tr>
<td>Sapphire Energy (2007), San Diego, CA</td>
<td>Algae</td>
<td>no</td>
<td>Sourced from the company Linde, which appears to source CO₂ from industry (The Linde Group, 2016; Sapphire Energy Inc., 2011a).</td>
<td>ST</td>
<td>An open pond system for growing algae. A demonstration algae farm in Columbus, NM in 2010.</td>
<td>Omega-3 oils, aquaculture, animal feed ingredients and renew able fuels.</td>
</tr>
<tr>
<td>Subitec (2000), Stuttgart-Degerloch, Germany</td>
<td>Algae</td>
<td>no</td>
<td>CO₂ from flue gas</td>
<td>ST</td>
<td>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.</td>
<td>Pharmaceuticals, cosmetics, food supplements, feed ingredients, lipids/carbs, biofuels, biogas.</td>
</tr>
<tr>
<td>TerraVia (fka Solazyme) (2003), S. San Francisco, CA</td>
<td>Algae</td>
<td>yes as Solazyme</td>
<td>not mentioned</td>
<td>ST</td>
<td>TerraVia™. Bioengineering of microalgae, fermenting sugar and algae to make oils.</td>
<td>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.</td>
</tr>
<tr>
<td>Company</td>
<td>Reuse Category</td>
<td>In Global CCS 2011?</td>
<td>Carbon Source</td>
<td>ST or LT*</td>
<td>What They Do, Processes, Trademarks</td>
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<td>Algix (2010), Meridian, MS</td>
<td>Algae/Polymer</td>
<td>no</td>
<td>Atmospheric (most likely)</td>
<td>ST</td>
<td>Algae to Solaplast®</td>
<td>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.</td>
</tr>
<tr>
<td>Skyonic (2005), Austin, TX</td>
<td>Baking soda, bleach, hydrochloric acid</td>
<td>yes</td>
<td>First facility uses CO$_2$ from the coal fired Capitol Aggregates Cement plant in San Antonio, TX</td>
<td>ST</td>
<td>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.</td>
<td>Baking soda (sodium bicarbonate), bleach and hydrochloric acid (HCl)</td>
</tr>
<tr>
<td>Alcoa (1886 in Pittsburgh, 1963 in Kwinana)</td>
<td>Bauxite</td>
<td>yes</td>
<td>CO$_2$ from an ammonia plant</td>
<td>LT</td>
<td>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.</td>
<td>Alcoa is pursuing reuses of bauxite slurry, including using it to neutralize acidic soil, acidic mines, in construction fill, and in wastewater treatment.</td>
</tr>
<tr>
<td>Braskem</td>
<td>Bioplastics/Gasoline additives</td>
<td>no</td>
<td>Atmospheric CO$_2$</td>
<td>ST</td>
<td>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.</td>
<td>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. Additionally, ethyl tert-butyl ether (ETBE) is made from sugar cane and can replace the traditional gasoline additive methyl tert-butyl ether (MTBE).</td>
</tr>
<tr>
<td>Blue Planet (2012), Los Gatos, CA</td>
<td>Carbonates</td>
<td>no</td>
<td>Flue gas CO$_2$</td>
<td>LT</td>
<td>Liquid Condensed Phase (LCP™) Technology to convert CO$_2$ into carbonates (CaCO$_3$).</td>
<td>CarbonMx™ materials: aggregates, concrete, roofing granules, cool pigments, titanium oxide; pure CO$_2$.</td>
</tr>
<tr>
<td>Calera (2007), Los Gatos, CA</td>
<td>Carbonates</td>
<td>yes</td>
<td>Raw flue gas from a 1000 MW power plant at nearby Moss Landing</td>
<td>LT</td>
<td>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.</td>
<td>Cement or binder system in concrete products, wallboard and cement board products, supplementary cementitious material (SCM) for sidewalk, flatwork in a commercial office buildings, countertops, plant holders and benches.</td>
</tr>
<tr>
<td>Company</td>
<td>Reuse Category</td>
<td>Carbon Source</td>
<td>ST or LT*</td>
<td>What They Do, Processes, Trademarks</td>
<td>Products Created</td>
<td>Comments, News and Status of Company, Monetary Data and Grants</td>
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<tr>
<td>Southern Company</td>
<td>CCS</td>
<td>CO₂ from coal plant</td>
<td>LT</td>
<td>They have designed CCS projects in Mississippi and Alabama, in addition to other CCS research projects.</td>
<td>Sequestration of CO₂</td>
<td>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).</td>
</tr>
<tr>
<td>Total, Paris, France</td>
<td>CCS</td>
<td>n/a</td>
<td>LT</td>
<td>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)</td>
<td>Sequestration of CO₂</td>
<td>The company has invested in several R&amp;D projects including Australia's Cooperative Research Centre for Greenhouse Gas Technologies, and Canadian, French and European research projects on CCS.</td>
</tr>
<tr>
<td>Carbon Engineering</td>
<td>CO₂</td>
<td>Atmospheric CO₂</td>
<td>ST or LT</td>
<td>Capturing pure CO₂ from air using a contractor. The chemical solution used for capture is regenerated.</td>
<td>Creating pure CO₂ to sell</td>
<td>A demonstration plant has been running over a year, and collects about 1 ton of CO₂ from the atmosphere daily (Carbon Engineering, 2016b). Carbon Engineering is financed by several investors including Bill Gates and Murray Edwards.</td>
</tr>
<tr>
<td>Climeworks</td>
<td>CO₂</td>
<td>Atmospheric CO₂</td>
<td>ST or LT</td>
<td>Capturing CO₂ from air. Two options: Demonstrator: 8 kg CO₂/day; Kollektor: 135 kg CO₂/day. Available in multiples of 35 kg per hour (300 metric tons per year).</td>
<td>Synthetic fuels, food, beverage; injected into greenhouses for increasing crop yield and stabilizing temperature</td>
<td>Current round of $3 Million in financing by Zürcher Kantonalbank (ZKB) and a group of private investors (Climeworks, 2011, 2014).</td>
</tr>
<tr>
<td>CarbonCure</td>
<td>Concrete Curing</td>
<td>flue gas from industry</td>
<td>LT</td>
<td>CarbonCure retrofits concrete plants with their process which integrates CO₂ into concrete as limestone-like nanomaterials that disperse throughout the concrete.</td>
<td>Concrete with a lower carbon footprint.</td>
<td>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).</td>
</tr>
<tr>
<td>Anadarko Petroleum Corp</td>
<td>EOR</td>
<td>CO₂</td>
<td>LT</td>
<td>Oil is recovered.</td>
<td>Oil is recovered.</td>
<td>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.</td>
</tr>
<tr>
<td>Chevron</td>
<td>EOR</td>
<td>unsure</td>
<td>LT</td>
<td>Chevron is utilizing EOR technology. However, the company appears to be using steam and surfactants rather than CO₂ for EOR.</td>
<td>Oil is recovered.</td>
<td>n/a</td>
</tr>
<tr>
<td>Company</td>
<td>Reuse Category</td>
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<td>Ferus (2001), Calgary AB and Denver, CO</td>
<td>EOR</td>
<td>no</td>
<td>ST</td>
<td>LT</td>
<td>Fracturing with CO₂ fluid and N₂ gas. The CO₂ increases fracturing output and acts as a pH buffer. Use of CO₂ can reduce costs by 20%, increase production by 15%, and reduce water usage by up to 80%.</td>
<td>They provide the oil and gas industry with fracturing and well-stimulation fluids including N₂ and CO₂. In addition to CO₂ liquid fracturing, they are now pursuing CO₂ foam fracturing.</td>
</tr>
<tr>
<td>Mantra Energy (2007), Surrey, BC Canada</td>
<td>Formic Acid/ Liquid Fuels</td>
<td>yes as Mantra Venture Group</td>
<td>Industrial CO₂</td>
<td>ST</td>
<td>Their technology is Electro-Reduction of CO₂ (ERC), to convert CO₂ into useful chemicals and products. There's a pilot plant for ERC to convert CO₂ from cement plant in Richmond, BC into formic acid and salts.</td>
<td>Formic acid, CO₂, 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.</td>
</tr>
<tr>
<td>ETOGAS Gmbh (2011), Germany (SolarFuel until 2013)</td>
<td>Fuels</td>
<td>no</td>
<td>Waste CO₂</td>
<td>ST</td>
<td>Power-to-gas method: Renewable electricity is used to make renewable H₂, which is combined with CO₂ to be refined into synthetic natural gas.</td>
<td>H₂ and synthetic natural gas</td>
</tr>
<tr>
<td>Haldor Topsoe (1940), Lyngby, Denmark</td>
<td>Fuels</td>
<td>mentioned</td>
<td>various sources</td>
<td>ST</td>
<td>Haldor Topsoe is studying methanol synthesis from CO₂ using solid oxide electrolysis cell (SOEC).</td>
<td>Methanol</td>
</tr>
<tr>
<td>Joule Unlimited Inc. (2007), Bedford, MA</td>
<td>Fuels</td>
<td>yes</td>
<td>Industrial waste CO₂</td>
<td>ST</td>
<td>They have a pilot site in Hobbs, NM, and are preparing for commercial level operations. SolarConverter® technology; CO₂-to-fuel. Engineered bacteria are catalysts to convert CO₂ into ethanol or hydrocarbons.</td>
<td>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).</td>
</tr>
<tr>
<td>Sunfire Gmbh (2010), Dresden, Germany</td>
<td>Fuels</td>
<td>no</td>
<td>can come from multiple sources</td>
<td>ST</td>
<td>Sunfire has the Pow-er-to-Liquids, Pow-er-to-Gas and Gas-to-Pow-er technology to convert CO₂ into fuels. Pow-er-to-Liquids converts H₂O and CO₂ into CO and H₂ (syngas) to fuel products. Pow-er-to-Gas converts H₂O to H₂ and O₂, and H₂ reacts with CO₂ to form CH₄ using steam electrolysis.</td>
<td>Gasoline, kerosene, diesel, methanol</td>
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<tr>
<td>Carbon Recycling International (2006), Reykjavik, Iceland</td>
<td>Fuels/Chemicals</td>
<td>yes</td>
<td>CO₂ from nearby Geothermal Power Plant</td>
<td>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 CO₂ to methanol.</td>
<td>ST</td>
<td>Geely Auto vehicles will arrive in Iceland to run on Vulcanol™ methanol in a 1-year fleet test (Carbon Recycling International, 2016).</td>
</tr>
<tr>
<td>Dioxide Materials™ (2010), Champagne, IL</td>
<td>Fuels/Chemicals</td>
<td>no</td>
<td>CO₂ from power plants and other sources</td>
<td>Producing CO₂ or &quot;synthesis gas&quot; from CO₂ emitted by power plants. Additionally, CO₂ produced by homes back to fuels/chemicals. Use of patent-pending catalysts and electrolyzer.</td>
<td>ST</td>
<td>Most recent news on the website is from 2013.</td>
</tr>
<tr>
<td>New CO₂ Fuels Ltd. (NCF) (2011), Rehovot, Israel</td>
<td>Fuels/Chemicals</td>
<td>no</td>
<td>Technology can adapt for multiple sources of CO₂</td>
<td>Converts CO₂ and H₂O into syngas and further into synthetic fuels and chemicals. Solar panels heat a reactor to convert CO₂ into CO and O₂. Simultaneously, the same device converts H₂O to H₂ and O₂. The CO and H₂ are known as syngas.</td>
<td>ST</td>
<td>The technology was developed by professor Jacob Karni and his team at the Weizmann Institute of Science (Rousseau, 2015). New CO₂ Fuels Ltd. is a subsidiary of GreenEarth Energy Limited.</td>
</tr>
<tr>
<td>Phytonix - the future of fuel® (2009), Black Mountain, NC</td>
<td>Fuels/Chemicals</td>
<td>no</td>
<td>not sure</td>
<td>Sustainable Chemistry Powered by the Sun™. Producing chemicals from CO₂ using an engineered cyanobacteria that secretes n-butanol.</td>
<td>ST</td>
<td>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.</td>
</tr>
<tr>
<td>GreenFire Energy (2010), Emeryville, CA</td>
<td>Geothermal</td>
<td>yes</td>
<td>ECO2G™. GreenFire Energy is conducting &quot;proof of concept&quot; projects to prepare for commercial operations. ECO2G™ uses supercritical carbon dioxide (SCO₂) as the fluid in a closed-loop geothermal system.</td>
<td>Geothermal energy</td>
<td>ST</td>
<td>News page on website read, &quot;The content on this page is currently being updated&quot; on 3/13/16 and on 3/19/16 and on 4/2/2016.</td>
</tr>
<tr>
<td>Liquid Light</td>
<td>MEG</td>
<td>no</td>
<td>Industrial CO₂</td>
<td>Mono-ethylene glycol (MEG) from CO₂. They are attempting to do this more efficiently (for instance plant material - to ethanol - to MEG).</td>
<td>ST</td>
<td>Liquid Light has a technology agreement with Coca-Cola (Bioplastics Magazine, 2015). Liquid Light, Inc. has partnered with Public Service Electric and Gas (PSE&amp;G) and Princeton researchers to convert CO₂ and water into formic acid in an electrochemical cell. This process will use solar power for its energy (Quick, 2014; White et al., 2014).</td>
</tr>
<tr>
<td>Company</td>
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<tr>
<td>Lanzatech (2006), Skokie, IL and worldwide</td>
<td>Microbial</td>
<td>no</td>
<td>Gas from steel manufacturing and hydrothermal vents - CO, H₂, H₂S, CH₄.</td>
<td>ST</td>
<td>Lanzatech uses CO/CO₂ to create biofuels and chemicals. Their process involves fermentation of a proprietary microbe -- acetogens (gas-fermenting organisms.) Ethanol, acetic acid, l-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.</td>
<td>Ethanol, acetic acid, l-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.</td>
</tr>
<tr>
<td>BASF (1865), US HQ in Florham Park, NJ</td>
<td>Polymers/Formic Acid</td>
<td>yes</td>
<td>n/a</td>
<td>ST</td>
<td>EcoFlex® and EcoVio®. EcoFlex® is a compostable polymer from fossil fuels. EcoVio® is compostable with biobased content -- it's a mixture of EcoFlex + polyactic acid from biobased corn.</td>
<td>Foam packaging, thermoformed packaging, film, mulch films, shrink film, paper coatings.</td>
</tr>
<tr>
<td>Bayer (1863), Leverkusen, Germany</td>
<td>Polymers</td>
<td>no</td>
<td>CO₂ supplied by a power plant.</td>
<td>ST</td>
<td>CO₂ is used to make polyols, one of the two ingredients in polyurethane. Using polymers/CO₂ to create: polyurethane foam, mattresses, upholstered furniture, shoes, auto parts, insulation for buildings and refrigeration equipment.</td>
<td>CO₂ is used to make polyols, one of the two ingredients in polyurethane.</td>
</tr>
<tr>
<td>Coca-Cola (1892), Atlanta, GA</td>
<td>Polymers</td>
<td>no</td>
<td>n/a</td>
<td>ST</td>
<td>PlantBottle™ which is 30% plant material, and now Liquid Light plastic to be made from CO₂.</td>
<td>Their PlantBottle bottles are 30% plant material.</td>
</tr>
<tr>
<td>Corbion (fka CSM N.V.) (1919), the Netherlands, Amsterdam</td>
<td>Polymers</td>
<td>no</td>
<td>n/a</td>
<td>ST</td>
<td>Puralact®. Lactides and PLA resins; 2,5-furandicarboxylic acid (FDCA) for high performance PEF resin</td>
<td>PLA – in packaging and silver w ear, automotive, electronics, textiles. As a replacement for PS, PP, ABS (acrylonitrile butadiene styrene). Lactic acid into lactic monomers which are polymerized into PLA thermoplastic resin.</td>
</tr>
<tr>
<td>Natureworks (2003), Minnetonka, MN</td>
<td>Polymers</td>
<td>no</td>
<td>Atmospheric CO₂</td>
<td>ST</td>
<td>Creator of Ingeo™, a bioplastic made up of a long molecular chain of the polymer polylactic, from a plant sugar. Their sugar source is corn (NatureWorks LLC, 2009).</td>
<td>Food and beverage packaging, service ware, electronics, durable goods, fiber for clothing, home wares and personal care products. Printing toner, potentially 3D printing product.</td>
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<tr>
<td><strong>Newlight Technologies (2003), Costa Mesa, CA</strong></td>
<td>Polymers</td>
<td>no</td>
<td>Methane (CH₄) from farms, landfills and energy facilities</td>
<td>AirCarbon™ is a thermoplastic that’s about 40% O₂ 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™.</td>
<td>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.</td>
<td>20-year contract with Vinmar for 19 billion pounds of AirCarbon PHA (New light Technologies, 2016b). New light Technologies won on the Popular Science Innovation of the year award (Bugge, 2014). IKEA will purchase 50% of the material from New light’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 CO₂, into AirCarbon thermoplastics for use in its products (Lane, 2016).</td>
</tr>
<tr>
<td><strong>Novomer (2004), Waltham, MA</strong></td>
<td>Polymers</td>
<td>yes</td>
<td>Appears to have multiple sources of CO₂ including power plants and industrial</td>
<td>Chemical feedstocks are combined with CO₂ to create polymers that are about 50% CO₂. Novomer has two processes: one uses waste CO₂ 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).</td>
<td>Novomer’s CO₂-based Converge® Polyols can be 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.</td>
<td>DOE (AMO) $5 Million grant for converting waste CO₂ to chemicals. DOE (NETL) $2.5 Million grant for capturing and utilizing industrial CO₂. 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 CO₂-based polymers.</td>
</tr>
<tr>
<td><strong>Succinity (2009), Düsseldorf, Germany</strong></td>
<td>Polymers</td>
<td>no</td>
<td>Atmospheric CO₂</td>
<td>Succinity® is a joint venture between BASF and Corbion for biobased Succinic acid - produced from microorganisms and atmospheric CO₂ (Succinity, 2016).</td>
<td>Life sciences, biodegradable polymers, polyurethanes, plasticizers, industrial solvents, coatings.</td>
<td>Plant in Spain can produce 10,000 metric tons a year (Succinity, 2014).</td>
</tr>
<tr>
<td><strong>Calysta Energy (2011), Menlo Park, CA</strong></td>
<td>Polymers</td>
<td>no</td>
<td>Methane (CH₄)</td>
<td>Gas-to-Chemicals® technology for materials. FeedKind™ protein technology from methane with methane as an energy source (Byme, 2016).</td>
<td>Fibers, plastics, liquid hydrocarbons and building materials. Current focus on FeedKind™ protein for the creation of fish/livestock feed.</td>
<td>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).</td>
</tr>
<tr>
<td><strong>Uranium One, Toronto, Ontario</strong></td>
<td>Uranium</td>
<td>no</td>
<td>unsure</td>
<td>In-situ leach mining. Piping solvent or “leaching solution” to a well. In-Situ Leach mines in the US often use sodium bicarbonate and CO₂ as leaching solutions.</td>
<td>Uranium mining</td>
<td>Couldn’t find specifics on the process of how they use CO₂, where it’s being sourced from, or if it’s currently being used.</td>
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<td>Mitsubishi Heavy Industries (MHI) (1934), Japan</td>
<td>Urea/CCS</td>
<td>yes</td>
<td>ST/LT</td>
<td>MHI provides a CO₂ capture product to clients in many countries. They have a proprietary energy-efficient CO₂ absorbent called KS-1™. CO₂ 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).</td>
<td>Urea/Sequestration of CO₂</td>
<td>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 CO₂ in 2011, and storing it in 2012 (MIT, 2016b). More recently, DOE is investing in Plant Barry (Cope, 2015).</td>
</tr>
<tr>
<td>GreenField Specialty Alcohols Inc. (1989), (Commercial Alcohols until 2006), Canada</td>
<td>Greenhouse Crops</td>
<td>no</td>
<td>ST</td>
<td>Construction on Truly Green Farms greenhouses is working toward utilizing the waste heat and CO₂ from the GreenField ethanol plant to increase tomato yield.</td>
<td>Tomato yield</td>
<td>Truly Green Farms will use the waste CO₂ from the GreenField ethanol plant for their greenhouse to increase yield (Greenfield Specialty Alcohols Inc. 2015; Truly Green Farms, 2013).</td>
</tr>
<tr>
<td>DyeCoo (2008) Weesp, The Netherlands</td>
<td>Dyes</td>
<td>no</td>
<td>ST</td>
<td>Using supercritical CO₂ 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 CO₂ is recycled after each batch.</td>
<td>Textile dyeing</td>
<td>The Super Bowl 50 Nike Gold Collection clothing contains their dyes (DyeCoo, 2016).</td>
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