Carbon Capture & Recycling Industry Overview

A Review and Analysis of Technologies and Organizations that Recycle Industrial Carbon Dioxide Emissions into Beneficial New Products.

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An industry is emerging with a new option to mitigate industrial carbon dioxide (CO_2) emissions while generating additional revenue.

Dubbed "Carbon Capture and Recycling" (CCR), this new industry dispels the notion that CO_2 is a liability that needs to be buried – as is the case with carbon capture and sequestration (CCS) – and instead views the gas as a resource to be capitalized upon, using it as a feedstock in the production of valuable products such as fuel, building materials, animal feed, specialty chemicals, and plastics, among other things. In the near-term, this new industry represents a paradigm change that could avert the need to resolve complex issues associated with CCS and instead prompt renewed action on CO_2 mitigation. Such action is essential as a carbon-constrained world emerges.

CCR approaches fall into three categories:

Biological:

A biological organism rapidly absorbs CO_2 to produce a product (e.g. algae oil refined to fuel)

Chemical and catalytic:

Chemical and catalytic: a catalyst prompts donor electrons to break or augment the carbon-oxygen bond in CO_2 molecules, then combines the carbon with other elements to produce a product (e.g. concentrated solar reforms CO_2 into CO, which then combines with hydrogen to produce synthetic diesel fuel)

Mineralization:

Through the use of feldspars and carbonization, CO_2 is locked into solid structures that can then be incorporated into products (e.g. CO_2 is reduced via anorthite to produce aluminum oxide, which is then sold to the advanced ceramic and chemical processing industries)

By absorbing, rearranging, and combining CO_2 to produce new products, well-established markets of sizeable proportion (i.e. the market for gasoline alone is approximately $700 billion per year) are fed, and new revenue streams are established for their producers.

The CCR industry is nascent, but already is comprised of at least 136 total entities (37 biological, 63 chemical/catalytic, 23 mineralization, 1 blended approach, and 12 uncategorized entities), as profiled in this report. These entities vary in size from unfunded concept to >$50 million. They have received government and private funding totaling approximately $1 billion. Some are offering full spectrum solutions from capture to reuse, others focus on reuse and need viable capture solutions to promote their value proposition.

These entities and others are working to overcome the challenges associated with commercializing and deploying CCR technologies. These challenges include: being able to recycle carbon year round, in various climactic conditions; thermodynamic and thermochemical logistics and efficiencies; scalability; proximity to necessary resources; and many others. With the emerging array of technologies and producers, as well as the current slate of technological challenges, this industry would benefit from models that promote diversity of innovation as well as financial diversity, rather than placing "bets" on single technologies and producers.

This report takes an initial look at this emerging industry and the innovators within it, given that little aggregated, public data is currently available. It examines the rationale for CCR, current CCR approaches, the forces emerging to shape such approaches, and focuses the majority of its content on providing snapshots of the innovators leading the creation of this new industry,including their respective stages of development as they march towards commercialization.

Future themes in this research arena will focus on "matchmaking" partial solution providers into full-spectrum solutions as well as the market potential for different CCR solutions with global deployability analysis.

Outlook: An Impending Carbon Constrained World

Much has been said about the science of climate change and to what degree it can be used to predict the future. To date, there is no perfectly accurate formula for judging the degree of climate change that the world will experience for each given increase in the concentration of atmospheric CO_2.

Yet what is clear is that despite the effort of various politicians and governments to use this lack of certainty to prevent the enactment of climate stabilization policies, a carbon-constrained future is itself a certainty. The handwriting is on the wall showing that it's not a matter of "if" but a matter of "when".

Various local and national governments around the world, representing a significant portion of global GDP, are pursuing policies to address greenhouse gas (GHG) emissions, including CO_2. California, Hawaii, and Minnesota have enacted climate legislation, and a broader Regional Climate Action Initiative is being pursued.[1] The U.S. House of Representatives passed the Waxman-Markey climate and energy bill, and the U.S. Senate came close to proposing bipartisan legislation in 2010, both of which President Obama supports. Europe has implemented a cap-and-trade program, and China has established GHG intensity targets, with more stringent targets virtually assured. The world as a whole made progress towards passing a binding agreement at the UNFCCC COP 16 in Mexico in late 2010. The message is clear: a carbon- constrained world is coming.

Affected Fuels and Relative Carbon Intensities

Unmitigated carbon emissions from fossil sources are incompatible with a carbon-constrained world. These fossil sources will be a primary target as world governments work to cut carbon emissions.

As Table 1 illustrates, while coal is dense in energy, it is a carbon-intense fuel, thus making it a primary target of government regulation.

Table 1

Technology Effect on Fossil Carbon Intensity

Fuel » Technology (HHV eff.)	English units:	Carbon Content (lb/MBtu)	Heat Rate (Btu/kWh)	Fossil Carbon Emission CO_2 (ton/MWh)	Fossil Carbon Emission C (ton/MWh)
Coal »					
Typical existing (0.341)		56.9	10,000	1.04	0.28
Pulverized, 95% scrubbed (0.376)		56.9	9,087	0.95	0.26
Advanced, IGCC (0.467)		56.9	7,308	0.76	0.21
Natural gas »					
Existing steam plant (0.331)		31.9	10,300	0.60	0.16
Advanced, CC (0.538)		31.9	6,350	0.37	0.10
Advanced, CT (0.427)		31.9	8,000	0.47	0.13
Advanced, fuel cell (0.637)		31.9	5,361	0.31	0.09

Source: U.S. Department of Energy

Table 2 makes this point even more clearly, indicating that for every million BTUs (MBTUs) of energy obtained, coal releases about 57 pounds of carbon, oil releases 47 pounds of carbon, and natural gas releases 32 pounds.[2] Biomass, given that it's a closed-loop carbon cycle, produces no direct net carbon emissions.[3]

Table 2

Fuel Effect on Fossil Carbon Intensity

Name of Fuel	Heat Content - HHV (Btu/lb)	(MJ/kg)	Carbon Content (lb-C/lb)	(kg-C/kg)	Fossil Carbon Intensity (lb-C/MBtu)	(kg-C/MJ)
Coal	13,700	31.798	0.78	0.78	56.9	24.5
Oil	18,000	41.778	0.85	0.85	47.2	20.3
Natural gas	23,800	55.240	0.76	0.76	31.9	13.8
Wood (dry)	8,000	18.568	0.45	0.45	Zero*	Zero*

Source: EPRI

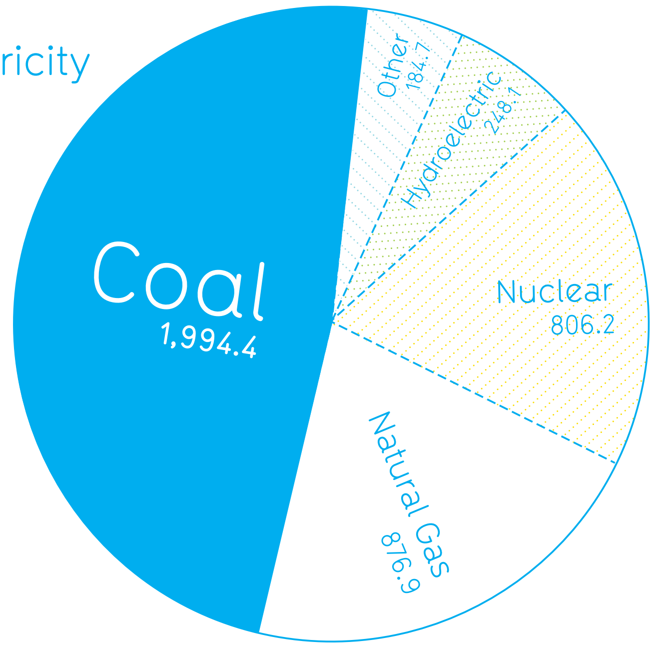
Fossil Fuels Into the Future

Although a carbon-constrained world is inevitable, the world has a thorny issue to deal with: global demand for energy, both for livelihood and for pure economic growth, as well as an existing, sizeable, carbon-intense infrastructure.

Energy consumption can help improve lives. In order to achieve an improved standard of living, developed countries have encouraged the consumption of energy at a very fast rate. This is due to the fact that electrical energy consumption is an indicator of economic condition. Consequently, nations around the world place great importance in providing energy for their peoples.

Much of the current energy provision and consumption comes from coal, and will continue to do so far into the future. Coal can be used to generate electricity day or night, rain or shine, at a price that people can afford. Thus, it is an appealing fuel and is in widespread use. As Figure 1 indicates, coal supplies approximately 49% of total U.S. energy needs.[4]

Figure 1
U.S. Net Electricity Generation, 2008
(Million MWh)

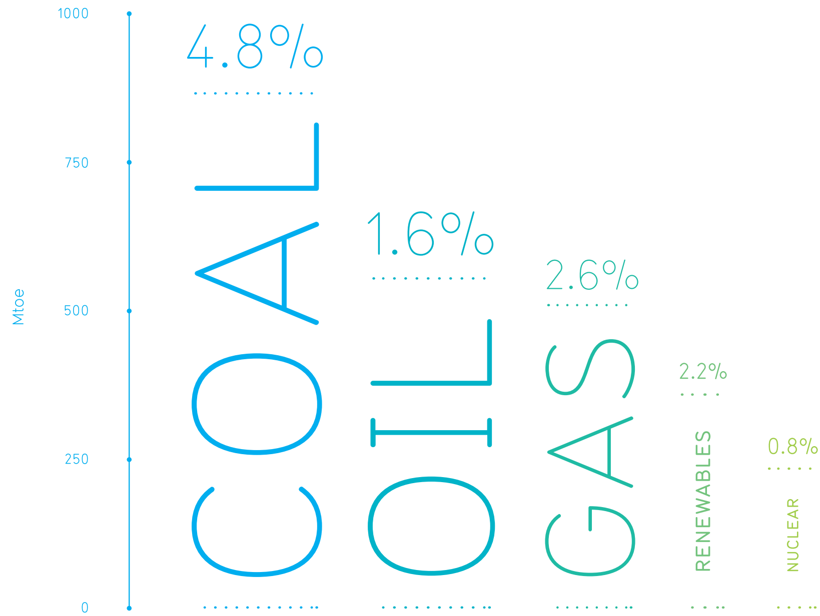


Source: Energy Information Administration

Coal's percentage is much higher in other countries. For instance, China utilizes coal for about 70% of its total energy consumption.[5] In fact, China has enough coal to sustain its economic growth (at current rates) for a century or more. Overall, the countries of non-OECD Asia (including China) account for 90% of the projected increase in world coal consumption from 2006 to 2030.[6]

Furthermore, in addition to existing infrastructure, utilities across the country are building dozens of old-style coal plants that will cement the industry's standing as the largest industrial source of greenhouse gases for years to come.[7] More than 30 traditional coal plants have been built since 2008 or are under construction.[8] Coal's average demand growth over the past five years was 3.5 percent, much faster than for oil or natural gas.[9] The extra coal the world burned in 2009 relative to 2004 was about equal to the entire energy consumption of Germany and France in 2009 combined.[10] Figure 2 illustrates how between 2000 and 2007, coal demand grew at a rate more than double that of renewable fuels.

Figure 2
Increase in Primary Demand, 2000-2007
% = Average Annual Rate of Growth



Source: International Energy Administration

This data indicates that while fossil fuels such as coal may eventually be phased out, their sunset is far from upon us. The recent Japanese earthquake and tsunami may push this sunset out even further, as pressing safety concerns about nuclear power could lead countries to raise coal usage to make up for energy shortfalls.[11] These trends place coal and other fossil fuels in direct conflict with the emerging carbon constrained world.

Challenges with CCS Necessitate a Parallel Path

To solve the challenge, the world is going to need technologies that can effectively capture carbon molecules directly from power plants' flue gas, prevent those molecules from being emitted directly into the atmosphere, and do so at an affordable price or, even better, be a source of revenue.

Carbon capture and sequestration (CCS), one of several "clean coal" components, is currently the dominant funded technological solution. CCS is a process of isolating CO_2 emissions from point sources, such as coal based power plants, capturing and then storing them away from the atmosphere, underground in natural geological formations such as aquifers, coal bed methane formations, depleted oil or gas reservoirs, deep in the ocean, or in other similar locations.

In theory, CCS is a viable solution to the carbon challenge, with great potential to store CO_2 away from the atmosphere and thereby prevent adverse climatic impacts. Yet the path to CCS deployment has revealed challenges that question why it is currently the only aggressively pursued path. CCS challenges include:

Energy Efficiency:

Capturing and compressing CO_2 requires significant energy and would increase the fuel needs of a coal based plant with CCS by 25%-40%.[12]

Cost:

Capturing, compressing, and storing CO_2 from new coal based plants is estimated to increase the cost of energy from such plants with CCS by 21-91%.[13] CCS retrofits are estimated to be even more expensive.

'NIMBYism':

While the potential for "leakage" – where stored CO_2 leaks back into the atmosphere – is small, estimated at less than 1% over 100 years,[14] the mere thought – and fear – of it happening, and envisioning the potential adverse affects, such as creating an asphyxiating CO_2 cloud above residential areas, is likely to prompt intense protest by people living near proposed sequestration sites. Such "not in my backyard" ("NIMBY") protests have successfully thwarted previous industrial projects.

Geographic Constraints:

While the U.S. has a significant 130 gigatons (Gt) sequestration potential,[15] for CCS to work, CCS formations should be located away from population centers (given NIMBYism) and close to CO_2 producing power plants (given the logistics and expense associated with moving CO_2 long distances). Such situations aren't necessarily the case, as power plant locations weren't chosen with CCS in mind, thus necessitating a costly piping network to move CO_2 from where it's produced to where it needs to be buried.

Funding Deployment:

Governments have proven unreliable when it comes to funding CCS. The FutureGen project, an essential step to overcoming CCS challenges, consumed significant time and money, and was temporarily abandoned in early 2008 after the Department of Energy (DOE) declined to provide additional financial support to help cover the projected $1.8 billion in costs. While the Obama administration devoted $3.4 billion in stimulus spending to foster "clean-coal" plants that can capture and store greenhouse gases, new investments in traditional coal plants total at least 10 times that amount — more than $35 billion.[16] In Europe, leaders agreed in March 2007 to equip up to 12 power plants with CCS technology by 2015, to allow Europe to carry on burning coal while meeting its greenhouse gas reduction targets. But member states are disputing who is able to choose which projects are selected, and dealing with regulations and environmental challenges.[17] Altogether, there are now just eight operating global CCS projects.[18]

An Emerging Option: Carbon Capture and Recycling (CCR) »

CCR refers to the capture of industrially sourced CO_2 emissions and subsequent use of these emissions as a feedstock for the production of new products, such as fuel, animal feed, specialty chemicals, and building materials. CCR has the potential to create a new carbon paradigm that frames CO_2 as an asset to be used rather than a liability to be buried. At a minimum, as some have projected, CCR can be a gateway to CCS, helping to offset CCS costs and facilitating public acceptance of carbon mitigation.[19]

Some CCR technologies incorporate carbon capture into its overall process, thus enabling flue gas to be fed directly into its system. Others require carbon to be captured and isolated before entering its system, for they only operate on a relatively pure stream of CO_2.

Carbon capture processes tend to focus on using amine absorbers and cryogenic coolers.[20] Because the cost of CO_2 capture using current technology is on the order of $150 per ton of carbon,[21] new processes are being explored. These processes include absorption (chemical and physical), adsorption (physical and chemical), low-temperature distillation, and gas separation membranes,[22] among others.

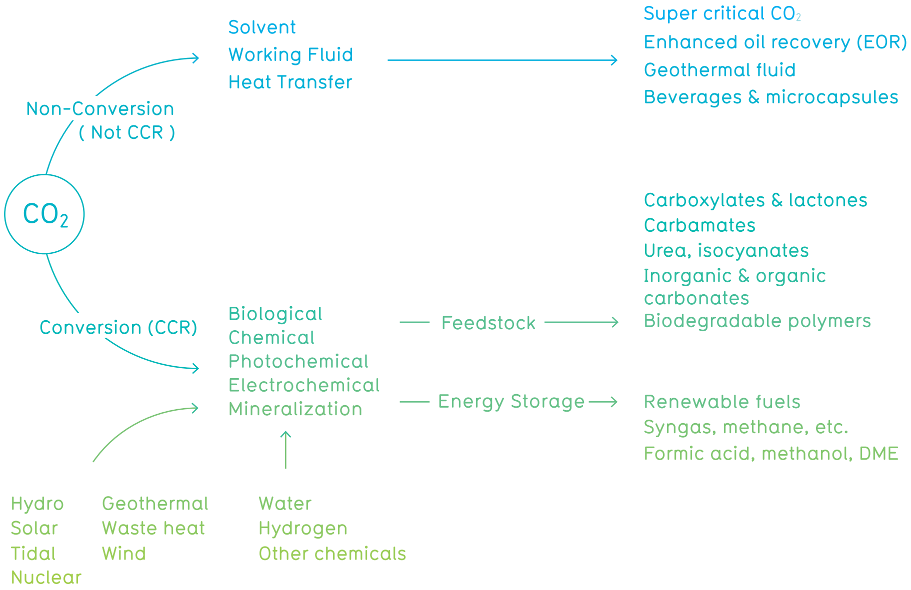
The carbon capture process is well explored and its development is well funded, as compared to the carbon recycling process. Numerous demonstration projects are underway or completed,[23] and significant research and writings have been undertaken on the topic.[24] Thus, this report focuses its scope on carbon recycling processes and entities.

Although the potential for CO_2 recycling depends on how one determines the size of the deployable market (see the 'Demand Side" discussion in the "CCR Market Outlook" section), one attempt to quantify the potential from all the CCR approaches pegs CO_2 emission reductions of at least 3.7 Gt/year.[25] Others that include more biological elements project even greater potential.

CCR Basics

Figure 3 provides a simple overview of the different factors, inputs, and outputs that are a part of various CCR technologies.

Figure 3
Different Pathways for Utilizing CO_2



Source: DNV

CCR Categories

CCR approaches fall into three categories:

Biological:

A biological organism (e.g. algae) rapidly absorbs CO_2 to produce a product (e.g. algae oil refined to fuel).

Chemical and catalytic:

A catalyst prompts donor electrons to break or augment the carbon-oxygen bond in CO_2 molecules, then combines the carbon with other elements to produce a product (e.g. concentrated solar breaks CO_2 into CO, which then combines with hydrogen to produce synthetic diesel fuel).

Mineralization:

Through the use of feldspars and carbonization, CO_2 is locked into solid structures that can then be incorporated into products (e.g. CO_2 is reduced via anorthite to produce aluminum oxide, which is then sold to the advanced ceramic and chemical processing industries)

While it remains to be seen which approaches in practice are able to deliver the greatest benefit, a recent report concluded that, at a threshold of 5Mt per annum of global CO_2 reuse potential, the following CCR technologies hold the most promise: CO_2 for use in fertilizer; CO_2 as a feedstock in polymer processing; algae production; mineralization (including carbonate mineralization, concrete curing and bauxite residue processing); and liquid fuels (including renewable methanol and formic acid).[26]

Biological

Phototrophic algae absorb a tremendous amount of CO_2 as they grow, and yield an oil rich molecule that can be refined into transportation fuel, bioplastics, or sold as a high-value omega-3 nutritional supplement or animal feed, among other uses. This ability presents an opportunity to make productive use of the CO_2 from power plants and other sources.

The amount of CO_2 absorbed depends on the algal strain, but estimates for the amount of CO_2 that are required for making biodiesel from algae are approximately 0.02 +/- 0.004 tons of CO_2 per gallon of biodiesel (tCO_2/gal). For example, NREL reports an example that 60 billion gallons of biodiesel would require 900 - 1,400 $MtCO_2$.[27] This quantity of CO_2 is 36%-56% of total US power plant emissions.[28]

Algae absorb approximately double their weight in CO_2. So one kilogram of algae absorb approximately 2.0 kilograms of CO_2 during their growth. If an alga cell is 25 percent oil, then each gallon of oil produced consumes approximately 8 kilograms of CO_2.[29] Sapphire Energy, Inc., a Southern California algae company, reports that the amount of algae it takes to extract one gallon of green crude consumes between 13-14 kg of CO_2.[30]

An even more nascent approach to biological CCR is biochar fertilizer production. Given that only one entity can be currently found using this approach to enhance charcoal with flue gas carbon (see: EPRIDA), discussion of this approach is deferred to Appendix D.

The Basics

Algae are a large group of organisms, which can be either "macro" (e.g. seaweed) or "micro". Although efforts are underway to cultivate macroalgae for fuel production (e.g. South Korea),[31] most efforts to produce fuel focus on microalgae.

Approximately 1/10th the width of a human hair, microalgae are extremely efficient "autotrophs". They take energy from the environment in the form of sunlight, sugars, or inorganic chemicals, and micronutrients (including phosphorus, iron and sulfur) and use it to create energy-rich molecules comprised of water, starch, and oil.

The percentage of oil that an algae molecule contains varies by species, with the nutrients supplied to a species, and with the stage of development of the alga cell itself. 15 to 35 percent oil is a typical range for high oil yield species.

There are estimated to be approximately 300,000 different algae strains in existence, of which approximately 30,000 have been identified. The University of Texas at Austin serves as an "algae bank" by storing these species and providing them to users as needed. Table 3 presents the most common algae species currently produced today.

Table 3

Select Commonly Produced Algae Species

Strain	Characteristics
Spirulina	Thrive in water with very high alkalinity levels, where no other algal species can. Spirulina are comprised of 55 percent protein.
Dunaliella salina	Can be grown at such high salt concentrations that it would normally kill everything else off. When nitrogen is "stressed" (i.e. the organism is starved), dunaliella are efficient producers of beta-carotene.
Haematococcus pluvialis	Microscopic green algae, encountered all over the world. Believed to be the world's richest known source of astaxanthin, a unique natural carotenoid pigment and biological antioxidant.
Chlorella vulgaris	One of the fastest, if not the fastest, growing algae species. High photosynthetic efficiency. Also can be grown heterotrophically (can get energy in the form of glucose directly in water; not limited by photosynthesis).

Table 4 presents the three primary systems for growing algae, as well as their current advantages and disadvantages.

Table 4

Primary Algae Production Systems

System	Characteristics	Pros	Cons
Open ponds/racetracks	Algae fed CO_2 and sunlight; grown in pools of either freestanding or moving water. Cheap; in operation for 30+ years.	Cheap.	Less productive (0-12g/m^2/day). Susceptible to invasive species and other contamination. Need almost perfectly flat land. Excessive evaporation.
Enclosed photobioreactors	Algae fed CO_2 & sunlight; grown in enclosed tubes or bags. Exotic, newer technology.	Highly productive (2-50 g/m^2/day). A good fit for regions with cold temperatures.	Very expensive to build and operate. Questionable durability. Heat management issues.
Enclosed heterotrophic bioreactors	Algae fed autotrophic organisms, such as sugar, rather than sunlight & CO_2; grown in dark, fully enclosed bioreactors.	Efficient way of converting sugars to oil and fuel. Comparably cheap.	Potential large-scale land use to grow sugar/starch crops to feed algae.

Algae can produce virtually any type of liquid transportation fuel, from ethanol that needs to be blended with gasoline, to biodiesel that can fuel vehicles on its own or as blended with petroleum diesel, to finished "green" diesel and gasoline, which are indistinguishable from petroleum diesel and gasoline.

Most current global algae production is not focused on the fuel market, but rather on the neutraceutical and aquaculture market, for algae are high in essential amino acids, beta-carotene, and other components beneficial to human health and fish growth. Japan is one of the world's largest consumers of algae-based neutraceuticals, primarily beta-carotene supplements.

Algae are produced in sizeable quantities for the neutraceutical and aquaculture markets. Approximately 5000 metric tons of algal biomass was generated for commercial purposes in 2007. This neutraceutical/aquaculture biomass can be sold for more than $10,000 per ton.[32] With such large margins in the neutraceutical and aquaculture markets, the amount of fuel production from algae is negligible. There are no commercial scale facilities currently in operation, yet several are planned.

Key Challenges to Biological (i.e. algae) CCR

Many barriers to large-scale CCR via algae are huge, and are more or less unchanged since the late 1970s. Some primary barriers include:

Heat disposal. Half of captured energy is thermal. How is this heat managed without either killing the algae or evaporating an excessive amount of water? In addition to technique, there are also large costs and amounts of water associated with cooling algae production systems, particularly photobioreactors (PBRs).

Harvesting the algae out of water. This problem revolves around the lack of algal density: Even in the densest situations, like PBRs, only 1 percent of a fuel production system's water is comprised of algal biomass. Techniques have to be found to improve density.

Cost of drying the algal biomass (if needed to dry biomass to extract oil). Some estimate that ½ of an algal production system's energy output is consumed in the drying process. New cheaper drying technologies or wet extraction need to be implemented in order to overcome these challenges.

Responsible techniques for extracting oil from algae. On a small scale, the chemical hexane can be used. But this chemical is harsh and thus can't be implemented on a large scale (e.g. 100M gal plant).

Utilizing CO_2 from power plants. In addition to being an input that needs to be paid for (some say as long as the price of CO_2 is below $35/ton), CO_2 can also be a liability, for once algae fuel producers acquire the CO_2, it becomes their responsibility. The consumption of this CO_2 may be a factor in climate legislation. Furthermore, many algae firms are not optimizing their systems for flue gas usage, which begs the question as to their source of plentiful CO_2.

Scalability. For algae technologies to make a difference in CCR, they need to move far out of the laboratory, beyond the level of real-world production today, and into a paradigm that sees Gt of CO_2 captured and absorbed. In addition, the technology needs to prove that it can perform year round, at times when and in locations where power plants emit carbon, not just during optimal growing cycles and in favorable locations.

Decades of development experience and recent years of high-level algae funding indicate significant interest in algae technologies and provide for a larger base of knowledge. Therefore, in addition to the main body content, further discussion on algae is provided in Appendix C. This discussion focuses on algae productivity as well as the production of transportation fuel, currently the most talked about algae end use.

Chemical and Catalytic

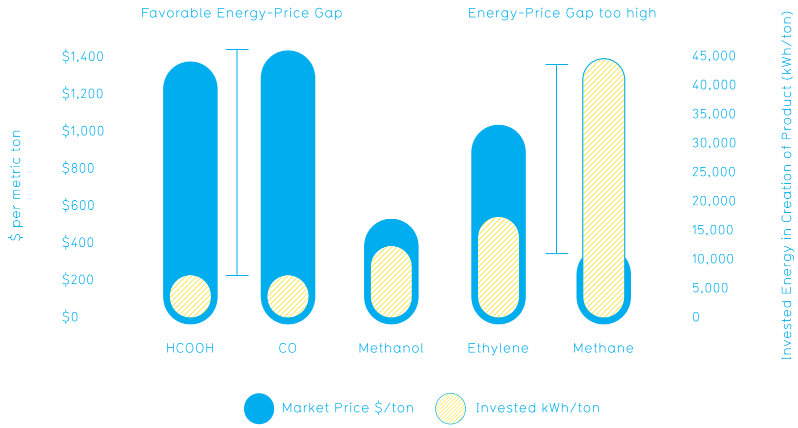
The chemical and catalytic approach to recycling CO_2 uses an energy input, often from renewable sources, along with a catalyst to either break or augment the carbon-oxygen bond in CO_2 molecules.

The result can be a variety of products and materials such as syngas, carbon monoxide (CO), formic acid (HCOOH), oxalates (C_2O_4), methane (CH_4), ethylene (C_2H_4), methanol (CH_3OH), and dimethyl ether (DME), among others.[33]

The Basics

This approach is often focused on the production of carbon monoxide and formic acid from CO_2, both of which can be used as feedstocks for other usable products, such as syngas, steel pickling, detergents, plastics, and deicing solutions. Figure 4 illustrates formic acid and carbon monoxide, both of which involve the participation of only two electrons and the use of affordable metal cathodes and require comparatively little energy for their respective market value.[34]

Figure 4
Prices and Sale of Products Converted from CO_2



Source: DNV

These systems have several common elements: they all contain photo sensitizers (such as metalloporphyrins, ruthenium or rhenium complexes with bipyride), electron mediators or catalysts, and sacrificial electron donors (such as tertiary amines or ascorbic acid).[35]

Transition-metal complexes have often been used as photochemical and thermal catalysts because they can absorb a significant portion of the solar spectrum, have long-lived excited states, can promote multi-electron transfer, and can activate small molecules through binding.[36]

The Potentials for the Reduction of CO_2 to Formic Acid, Carbon Monoxide, and Methanol

E^0 (vs. a normal hydrogen electrode, NHE, at PH=7)

$CO_2 + 2H^+ + 2e^-$	»	HCOOH	$E^0 = -0.61$ V
$CO_2 + 2H^+ + 2e^-$	»	$CO + H_2O$	$E^0 = -0.53$ V
$CO_2 + 6H^+ + 6e^-$	»	$CH_3OH + H_2O$	$E^0 = -0.38$ V

Source: U.S. Department of Energy

A recent analysis states that co-electrolyzing H_2O and CO_2 in high temperature solid oxide cells to yield syngas, and then producing gasoline or diesel from the syngas in a catalytic reactor (e.g. Fischer–Tropsch) is one of the most promising, feasible routes to CCR.[37] With an electricity price of less than 3 U.S. cents/kWh from a constant power supply (e.g. geothermal, hydroelectric, or nuclear), the synthetic fuel price could be competitive with gasoline at around $2/gal.[38] If a higher gasoline price of $3/gal is competitive, the price of electricity driving the synthetic fuel process must be 4–5 cents/kWh, which is a similar range to recent average wholesale electricity prices in the U.S.[39] Intermittent power sources would significantly increase the capital cost of the electrolyzer.[40]

Key Challenges to Chemical and Catalytic CCR

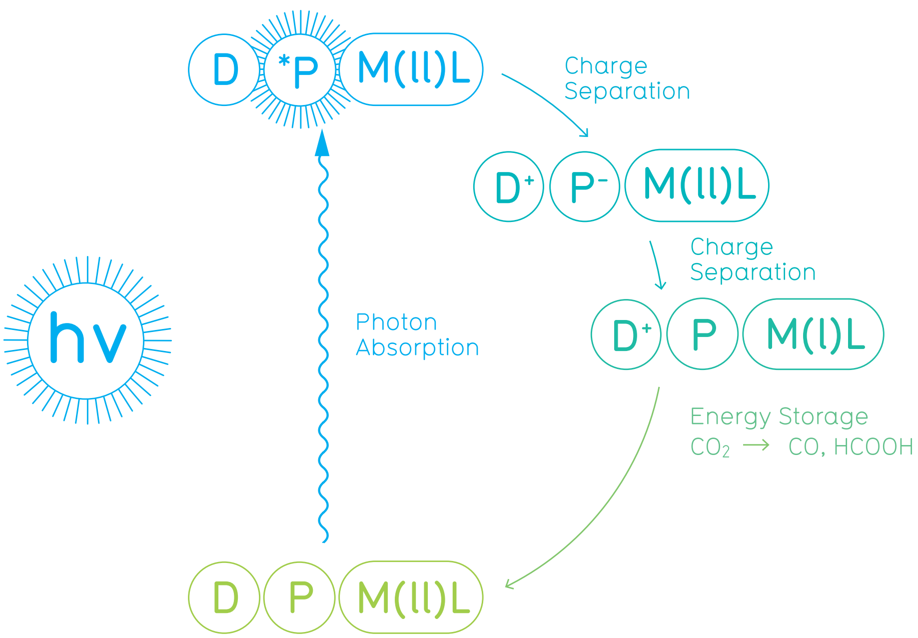
The CO_2 reduction process is thermodynamically uphill.[41] Thus, questions of economics and environmental sustainability are introduced into the reduction process.

If electricity is taken from a cheap or wasted source such as a power plant's idle (i.e. nighttime) discharge, the issue is significantly minimized. The upgrade of a feedstock input to produce a more valuable product, even if the equation is net-energy negative, comes with significant precedent (e.g. methane into methanol). Thus, an operator simply has to look at the net cost of production given the prevailing price of electricity, as well as the opportunity costs that accompany that electricity.

Still, given the thermodynamic challenges, some suggest that economic fixation is possible only if renewable energy, such as solar energy, is used as the energy source.[42] Solar energy can be harnessed to drive CO_2 conversion by:[43]

1. Artificial photosynthesis using homogeneous and heterogeneous systems;
2. Electrochemical reduction using solar electric power;
3. Hydrogenation of CO_2 using solar-produced hydrogen.

The following diagram illustrates how a photosensitizer (P) absorbs light to become excited, a reduced complex results, a donor (D) transfers and electron from the reduced complex to a catalyst (ML), and the subsequent activation of CO_2 by the reduced catalyst.[44]



Source: U.S. Department of Energy

Still, direct thermal splitting of CO_2 requires temperatures higher than 3000°C, which is challenging for industrial applications.

Additionally, an economically viable electrochemical technology requires optimization of four key parameters: high current densities, high Faradaic Efficiency (FE), low specific electricity consumption, and long electrode lifetime.[45] In general, high current densities result in lower FE and shorter lifetimes because of competing reactions. With longer run times, FE tends to decrease (catalyst/cathode degradation) and cell voltage increase, both of which result in greater power consumption.[46]

Finally, the addition of chemicals such as sodium hydroxide and hydrochloric acid to support the CO_2 utilization reactions can significantly increase the cost of utilization. Consumable chemicals can be decreased through the use of electrolyte recovery processes and alkaline wastewater, leaving energy consumption the greatest hurdle to affordability.[47]

Companies focused on this pathway are focusing their research and development on reducing the temperature of conversion, increasing catalyst life, and decreasing the use of consumables.[48]

Mineralization

CO_2 conversion to minerals and insertion into polymers may have the benefit of sequestering CO_2 in relatively stable matrices.[49] If 10 percent of global building material demand was met by conversion of CO_2 to stable minerals, then a potential reduction of 1.6 Gt/y of CO_2 exists.[50]

The Basics

Carbon mineralization is the conversion of CO_2 to solid inorganic carbonates using chemical reactions.[51] In this process, alkaline and alkaline-earth oxides, such as magnesium oxide (MgO) and calcium oxide (CaO), which are present in naturally occurring silicate rocks such as serpentine and olivine or in natural brines, are chemically reacted with CO_2 to produce compounds such as magnesium carbonate ($MgCO_3$) and calcium carbonate ($CaCO_3$, commonly known as limestone).[52] The carbonates that are produced are stable over long time scales and therefore can be used for construction, mine reclamation, or disposed of without the need for monitoring or the concern of potential CO_2 leaks that could pose safety or environmental risks.[53]

A common approach to mineralization is through the use of feldspars, an abundant (i.e. as much as 60% of the earth's crust[54]) rock-forming mineral typically occurring as colorless or pale-colored crystals and consisting of aluminosilicates of potassium, sodium, and calcium. Other common feldspars that have been used to neutralize CO_2 are potassium-aluminum (orthoclase), sodium-aluminum (albite), and calcium-aluminum (anorthite), the last of which is what some say is the most efficient feldspar in the neutralizing process.[55]

The chemical reaction of anorthite reduced CO_2 indicates that the aluminum in anorthite is liberated as aluminum hydroxide, which is easily converted to aluminum oxide (alumina),[56] which can then be sold as raw material for a broad range of advanced ceramic products and as an active agent in chemical processing.[57]

$$CaAl_2Si_2O_8 + 2CO_2 + H_2O \gg Ca_{2^+} + 2HCO_{3^-} + 2SiO_2 + 2Al(OH)_3$$

The neutralization of one ton of CO_2 with anorthite produces about one ton of alumina plus 1.3 tons of quartz.

Carbonization is another approach to mineralization, whereby CO_2 is neutralized with carbonate minerals such as limestone. This approach in essence hastens nature's own very effective but slow CO_2 mitigation process; carbonate mineral weathering is a major consumer of excess atmospheric CO_2 and ocean acidity on geologic time scales.[58]

Carbonization employs carbonates such as wet limestone to prompt the following reaction that scrubs point source CO_2.[59]

$$CO_2 + H_2O + CaCO \gg Ca(HCO_3)_2 + CO_2 + CO_3^{2-}$$

Such reactors can effectively remove CO_2 from dilute CO_2 gas streams, allowing permanent and benign storage of much of the carbon absorbed as dissolved calcium bicarbonate.[60] Laboratory tests indicate that as much as 97 percent of the initial CO_2 could be removed from an inlet gas stream consisting of 10 percent CO_2 and dissolved into solution.[61]

The stability of the resulting product from the wet limestone scrubbing process has led some to advocate for ocean storage, stating that such storage could be done safely for many tens of thousands of years if not substantially longer.[62] Yet such an approach moves away from recycling and into sequestration, unless payment for environmental services is obtained (e.g. for neutralizing ocean acidity to ensure a healthy ecosystem).

Key Challenges to Mineralization CCR

Logistical challenges quickly arise given the quantity of feldspar required: in the case of anorthite, the ratio of anorthite to coal burned in the power plant is 9.2 to 1. Thus, the use of this efficient neutralizer effectively requires a power plant to either be located close to feldspar formations, which is hard to ensure for existing power plants, or construction of a CO_2 pipeline to ship CO_2 to the feldspar mine, which can be a pricy endeavor.

Carbonates, such as limestone, are much less plentiful than silicates in the earth's crust, thus further reducing the chances of proximity if this is the chosen route.

CO_2's conversion to minerals often consists of combinations of electrochemical reactions, for they generate the alkaline reactant and necessary mineralization reactions. Energy efficiency is undoubtedly essential.

Furthermore, the importance of seawater in the mineralization process is a major limiting factor given that the process makes the most logistical sense for those power plants close to the ocean.

Finally, the markets for some products produced via mineralization, such as baking soda, are not as large as those of other CCR-produced products, such as fuel. Thus, market saturation is at greater risk.

Financial/Government Support

To date, the predominant source of financial support for the CCR industry is from the United States government. The government has provided approximately $254.5 million over the last two years to support the development of CCR technologies, with another $158.5 million in commitments outstanding or in progress, and as much as $30 million more to be awarded shortly. This project funding has been matched with at least $165 million from private industry.

Biological technologies have received a fair amount of government support, but relatively few of the supported efforts have been explicitly focused on CCR applications, namely coupling the biological technology with an industrial CO_2 source emitter. Non-biological CCR technologies have received greater financial support and to a broader array of entities in recent years.

Of particular support has been the National Energy Technology Laboratory (NETL). NETL views CCR as a potentially viable way to augment and accelerate the development of CCS, as well as a way of offsetting the costs of CCS. Over the past two years, NETL has announced and funded two Funding Opportunity Announcements (FOAs) focused, in whole or in part, on CO_2 utilization.

In June 2009, NETL announced DE-FOA-0000015, entitled "Recovery Act: Carbon Capture and Sequestration (CCS) from Industrial Sources and Innovative Concepts for Beneficial CO_2 Use."[63] This FOA was focused on projects that were ready for immediate, pilot-level deployment of CCR technologies. NETL received several dozen responses to this FOA. In October 2009, NETL announced the $25.1 million in funding stemming from this FOA – including $17.4 million in American Recovery and Reinvestment Act (ARRA) funding and $7.7 million in private funding. The funding was in support of twelve CCR projects.[64] These "innovative concepts for beneficial CO_2 use awards" are presented in Appendix E.

Around the same time (September 2009), Arizona Public Service (APS) received a $70.5 million commitment focused on utilizing algae to recycle CO_2 emissions at APS's Redhawk natural gas power plant. APS received this award as a modification to an existing project being undertaken on hydrogasification with algae CCR (Note that APS subsequently canceled this project and thus only received $3.5 million for the project)[65]. It was the only biological CCR technology with an explicit tie to a power plant that was funded during this timeframe. Sapphire Energy, a biological CCR company with a less explicit connection to industrial CO_2 emission sources, received $104.5 million in grants and loan guarantees in late 2009.

In late July 2010, the DOE announced that six of these projects were selected to receive an additional $82.6 million in ARRA funding, bringing the total funding to $106 million from the ARRA, an amount that was matched with $156 million in private cost-share. This "Phase II" funding will be used to complete design, construct and test of pilot systems.[66] These Phase II projects were selected using three evaluation criteria: Technology Merit, Benefits, and Commercial Potential; Technical Plan, Project Management Plan, and Site Suitability; and Project Organization. The renewal applications were also evaluated against two financial criteria: Funding Plan and Financial Business Plan.

In March 2010, NETL released DE-FOA-0000253, entitled "CO_2 Utilization" focused on research products to convert captured CO_2 emissions to useful products.[67] As opposed to DE-FOA-0000015, DE-FOA-0000250 was focused on research and development level projects that still needed significant work before they could be deployed at a pilot level.

In response to this FOA, NETL received proposals on diverse approaches to produce construction materials, chemicals, polymers, and fuels using CO_2. Project proposals were narrowed down based on technical merit, technical approach, team characteristics, project management, and similar criteria. In July 2010, NETL awarded a total of $4.4 million – an amount matched by $1.5 million of non-federal cost sharing – over two-to-three years to fund six CCR projects.[68] The selected projects are described within press releases in Appendix E. Also, DOE fact sheets on these projects, as well as general information on the NETL CO_2 Utilization Core R&D Focus Area, are available on the focus area's website.[69]

NETL envisions another round of funding for CCR projects in the 2012-13 timeframe, subject to the availability of funds.

Also in July 2010, the U.S. DOE announced an award of up to $122 million over five years to a multidisciplinary team of top scientists to establish an Energy Innovation Hub aimed at developing revolutionary methods to generate fuels directly from sunlight. The Joint Center for Artificial Photosynthesis (JCAP), to be led by Caltech in partnership with the DOE's Lawrence Berkeley National Laboratory (Berkeley Lab), will bring together leading researchers in an effort aimed at simulating nature's photosynthetic apparatus for practical energy production. The goal of the hub is to develop an integrated solar energy-to-chemical fuel conversion system and move this system from the bench-top discovery phase to a scale where it can be commercialized.

In late April 2010, DOE's Advanced Research Projects Agency-Energy (ARPA-E) announced $106 million in funding for "37 ambitious research projects that could fundamentally change the way the country uses and produces energy."[70] Of that amount, $41.2 million was allocated to thirteen organizations that are focused on the production of "electrofuels", which use microorganisms to harness chemical or electrical energy to convert carbon dioxide into liquid fuels.[71] The grants were made in response to DE-FOA-0000206.[72] Altogether the FOA received over 3,600 applicants for transformational energy technologies.

Funding was focused on organizations that requested no more that $10 million, had a project duration of no more than three years, and were positively reviewed in the following categories:[73]

- Impact of the Proposed Technology Relative to State of the Art
- Overall Scientific and Technical Merit
- Qualifications, Experience, and Capabilities
- Sound Management Plan

In April 2011, ARPA-E announced another FOA focused on some types of CCR technologies. DE-FOA-0000471 is focused on "high energy advanced thermal storage", dubbed "HEATS".[74]

This FOA is focused on ARPA-E developing revolutionary cost-effective thermal energy storage technologies in three areas, one of which is "fuel produced from the sun's heat". Given that many CCR technologies, especially those produced via chemical/catalytic processes, utilize heat to feed the catalyst and prompt the chemical reaction, this FOA is particularly relevant. In fact, the FOA specifically mentions "significant improvement in a two-step solid-state catalytic process…to generate syngas by thermolysis of CO_2 and H_2O with high efficiency" as an impetus for this funding.[75]

In mid 2011, ARPA-E expects to provide twenty awards in the entire category. No single project will be awarded less than $250,000, or more than $10 million.[76] The estimated total program funding – incorporating not just "fuel produced from the sun's heat" but also the other HEATS focus areas – is approximately $30 million.[77] Thus, at this stage, an unknown amount will be allocated to CCR technologies.

In each of these cases, whether the source of funding stems from the DOE, NETL, ARPA-E, and/or ARRA, private industry cost matching is required in order prompt private investment and leverage the government's funds. Usually the cost sharing depends on the type of entity applying for the funding. For example, in the ARPA-E DE-FOA-0000471 offering, private cost sharing between at least 5 percent (for educational or non-profit stand-alone applications) and 50 percent (for "Technology Investment Agreements") is required.[78]

The government also created 46 Energy Frontier Research Centers (EFRCs), which consist of universities, national laboratories, nonprofit organizations, and private firms around the nation.[79] These centers were established in mid-2009 as part of the national effort to accelerate scientific advances in critical areas of the new energy economy. The EFRCs are receiving between $2-5 million per year for five years, with total funding at $377 million.[80] The primary focus of these EFRCs is not necessarily CCR, yet many of them perform work, such as the examination of artificial photosynthesis, that will be of assistance to some CCR approaches. Two EFRCs – the Argonne-Northwestern Solar energy Research Center and the Center for Solar Fuels and Next Generation Photovoltaics – are significantly focused on CCR technologies and received $19 million and $17.5 million respectively over five years to fund their efforts.

This identified government funding and private industry cost sharing, combined with a survey of the literature that looks at other private investments not connected to government funding, indicates that approximately $1 billion has been invested in the CCR industry to date. This figure includes existing government grants and commitments, but not FOAs outstanding at the time of publication (such as DE-FOA-0000471).

CCR Market Outlook »

Prize Capital anticipates that the CCR technology market will be driven primarily from two sides: those who demand the technologies to mitigate CO_2 and those who supply the products produced by the technologies.

Demand side refers to operators of facilities that emit point source CO_2 emissions. For a variety of reasons, such as governmental regulation or the threat of regulation (see "Outlook: An Impending Carbon Constrained World"), these operators will be motivated to mitigate their CO_2 emissions. For a variety of other reasons, possibly the inability of other technologies to meet their needs (see "Challenges with CCS Necessitate a Parallel Path"), they will demand CCR as the appropriate application.

Supply side refers to the production of products using point source CO_2 as the feedstock. Examples of such products include transportation fuel (e.g. gasoline, diesel, and aviation fuel), animal feed, construction materials (e.g. concrete and drywall), plastics, fertilizer, and payment for environmental services. Operators will therefore supply product for sale in these markets.

Thus, CCR technologies have the potential to tap into two powerful and, to a large degree, uncorrelated markets. By investigating both market sides respectively, we can gain insight into the potential economic rewards that such technologies and their companies can capture, and gain insight into the net benefits to facility operators.

Bear in mind that CCR is a nascent industry, and thus common operating parameters haven't been established. It may turn out that facility operators purchase and operate the CCR equipment themselves, much as they do SCR and other retrofit technologies. Conversely, given the differences between CCR and other point-source retrofit technologies, operators may elect to contract with CCR technology providers and rent them the resources (such as land, electricity, and water) to enable the operation of their own technologies, much as farmers do today with regard to wind power operators and the provision of land.

The following analysis can be beneficial to either mode of operation, but for the sake of simplicity it adopts the first "operator/owner" option whereby point source facility operators purchase CCR equipment and sell its' products.

To be clear, this section does not definitively answer questions about or quantify the demand and supply side characteristics, nor does it attempt to do so. It is outside the scope of this report to provide the analysis and clarity that a CCR market assessment deserves. Instead, this section provides perspective on scale and potential, while identifying key issues to be resolved and questions to be answered as more industry data becomes available.

Demand Side: Operators' Adoption Potential

Investigating the demand side involves looking at point sources of CO_2 emissions and identifying where and how CCR technologies can be retrofitted to these point sources, and subsequently reviewing CCR technology capital costs in context with the overall market to gain an aggregate view.

Through this approach, we don't seek to gain perfect clarity on the size of the CCR technology market. Instead, we aim to gain insight into the potential size of the market, as well as insight into multiple potential outcomes that take into account degrees of deployment (i.e. number of markets where CCR technology permeates), cost ranges of CCR capital, and how both of these respond to a to-be-determined level of adoption.

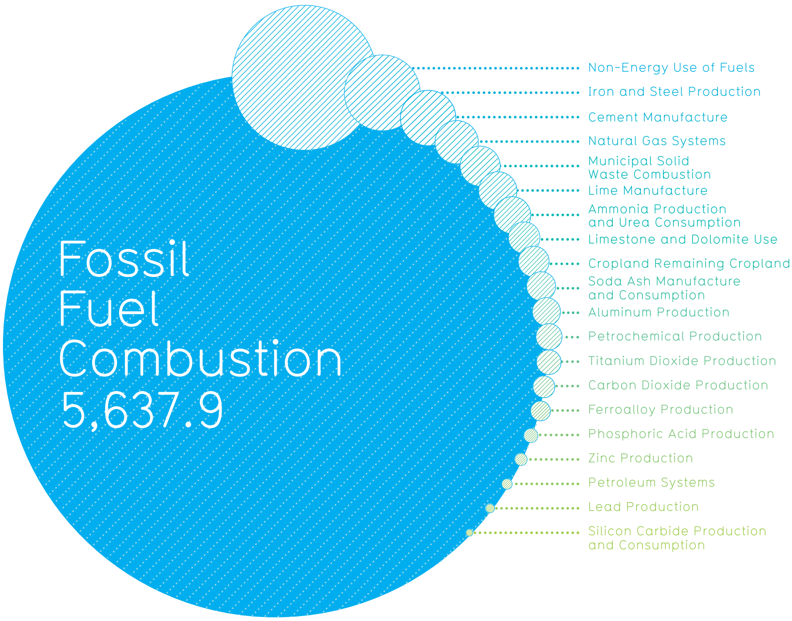
Defining the Market

Simply stated, the market for CCR technologies is any point-source CO_2 emission facility, including but not limited to power plants, mining and refining facilities, and metals and cement production. For the purposes of quantifying this market, we will isolate and examine the largest sources of emissions.

The EPA states that the largest source of CO_2 emissions globally is the combustion of fossil fuels such as coal, oil and gas in power plants, automobiles, industrial facilities and other sources.[81] Figure 5 presents the largest sources of CO_2 emissions in the United States.

Figure 5

2006 Sources of CO_2 Emissions
($Tg\ CO_2$ Eq.)



Source: U.S. EPA

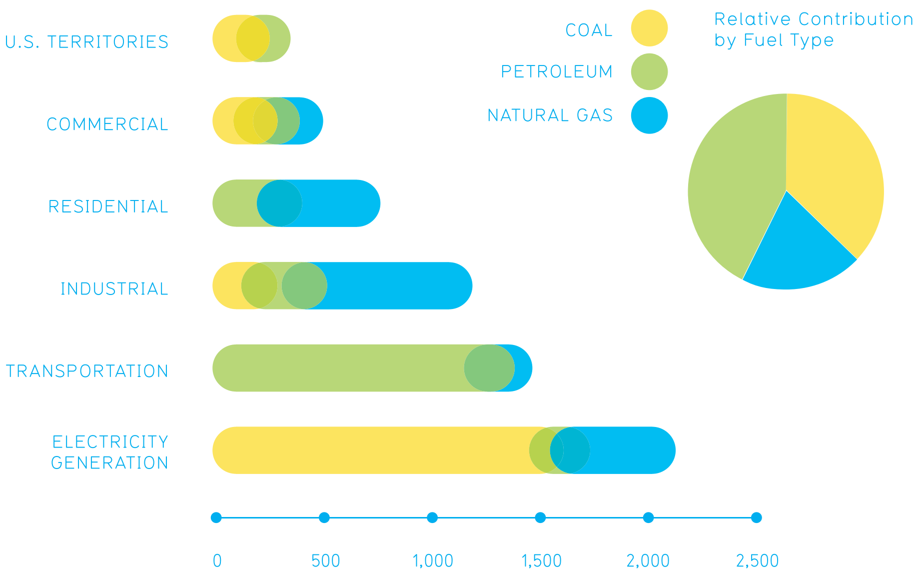
Clearly, the combustion of fossil fuels represents the largest market for CCR technologies, dwarfing the emissions of other industries.

Breaking this statistic down further and specifically honing in on point-source emissions reveals that aside from petroleum, which supplied an average of 47 percent of total fossil-fuel-based energy consumption in 2006, coal and natural gas were the largest CO_2 emitters, accounting for 27 and 26 percent of total fossil fuel consumption, respectively.[82] Figure 6 displays emissions for the electricity generation and other sectors by fuel type in 2006.

Figure 6

2006 CO_2 Emissions from Fossil Fuel Combustion, Electricity Generation Sector

(Tg CO_2 Eq.)



Source: U.S. EPA

Thus, while other sources of CO_2 are clearly applicable to CCR technologies, the dominance of fossil fuel combustion, and specifically that of coal, natural gas, and petroleum electricity generation, dwarf the market. By obtaining a sense of the CCR market potential associated with only these fuels in this single sector, we can gain meaningful insight into the overall potential of the CCR market. Reinforcing this conclusion is the fact that the utility industry is a prime target for regulation (see "Affected Fuels and Relative Carbon Intensities") and thus more likely to drive demand side growth of the CCR industry.

Quantifying the Market

The application of CCR technologies is scaled to meet installed capacity. In other words, the greater a power plant's capacity, the more CO_2 it will generally emit, and the greater the amount of CCR equipment necessary to mitigate the plant's carbon emissions. Thus, installed capacity will determine the market size of CCR technologies. This parameter for coal, natural gas, and petroleum generated electricity in the United States are presented in Table 5.

Table 5

Electric Generating Capacity (MW) Domestic, 2009

(Number of Generators / Nameplate Capacity)

Fuel Type	Domestic[83]
Coal	1,436 / 338,723
Natural Gas	5,470 / 459,803
Petroleum	3,757 / 63,254
Total	10,663 / 861,780

In its purest sense, CCR market size is represented by the absolute generating capacity, for the ideal CCR technology would be a universal retrofit. Table 5 shows these numbers to be approximately 862 GW in the United States.

Yet an alternate case introduces data that has identified the fact that some power plants are more conducive to post-combustion CO_2 capture retrofits than others.[84] Specifically, data suggests that it is unlikely that post-combustion retrofits "will prove cost-effective for older, smaller units (<300 MW size, 1950–60s vintage) that may also lack FGD or selective catalytic reduction (SCR) NOX controls. Narrowing the candidate field to boilers that are 300 MW or larger and less than about 35 years old renders a total capacity of 184 GW."[85]

An important distinction is that this data is focused only on coal-based power plants and on sequestered rather than utilized CO_2. If the value proposition of selling CO_2-based products becomes sufficiently attractive (see the next section on "Supply Side"), the market could far exceed this target. Thus, 184 GW is an effective yet conservative baseline and 862 GW is an aggressive domestic target.

To complete this analysis on the demand side market potential, a range of data indicating CCR technology capital costs is required so that we can form a dollar-denominated estimate of the market size. Unfortunately, we are currently unable to obtain substantial accurate data given the nascent stage of the industry. Innovators either don't have costs of capital themselves, or if they do they have not made it publically available (for competitive reasons).

We do however have two price points from prominent industry members: mineralization company Calera, and chemical/catalytic company Carbon Sciences. Calera was planning (and subsequently abandoned in late 2010) a facility, Calera Yallourn, in the Latrobe Valley, Australia, which following a demonstration phase would have been the first commercial-scale facility capable of capturing 200MWe of CO_2.[86] The CO_2 would have been captured from the flue gas of a local coal power station. Calera estimated that the costs associated with the facility include CAPEX requirement (including CO_2 capture and building materials) of US$300-380 million and a cost of CO_2 capture of US$45-60/ton of CO_2.[87] Details of further operating and maintenance costs are not available. Alternately, Carbon Sciences projected that placing its CCR facility next to a 500-megawatt coal unit would cost about $250 million.[88]

CCR technologies differ to the extent that we cannot assume that these costs of capital are representative, either for other similar approaches or, more dramatically, for other (i.e. biological) approaches. Also note that a CCR-only snapshot only looks at the cost of carbon recycling capital. Given that many CCR technologies either work better with or require pure CO_2, additional capital for carbon capture may be required. Furthermore, given the various requirements of Calera's approach (such as proximity to sea water) and Carbon Sciences' approach, we acknowledge that these aren't necessarily universal applications.

Still, recognizing that Calera projects its cost of capital to be $1.5-1.9 billion per GW (at least for the Yallourn project) yields an aggregate domestic industry size of $276 billion (for $1.5B/GW @ 184 GW) to $1.6 trillion (for $1.9B/GW @ 862 GW). Additionally, recognizing that Carbon Sciences projects its cost of capital to be $500 million per GW yields an aggregate domestic industry size of $92 billion (for $500M/GW @ 184 GW) to $431 billion (for $500M/GW @ 862 GW). Combined, these are interesting data points that provide some level of insight into the market's potential.

Gaining clarity on the actual demand side market size – including differentiating technologies and projecting deployments within a given approach – is a high priority for a variety of reasons, from attracting investment dollars into the industry to informing policy makers seeking to assist and deploy such technologies. Prize Capital intends to address these issues in future work as the industry develops and more information becomes available.

Supply Side: Production of Products

Investigating the supply side market potential involves examining the opportunities within the markets where CCR technologies produce products, the amount of CO_2 produced by the target sector, and translating that amount of CO_2 into quantity of product produced using various CCR techniques to see what portion of the market CCR technologies can satisfy. Through this approach, we gain insight into the potential revenue streams that production of material within these markets can generate for the technology owners and operators.

Defining the Market

CCR technologies can in theory produce virtually any carbon-based material. We anticipate that as the sector matures, new products and revenue streams will be identified. For the purpose of this analysis, we limit the scope of the market to those products that are already being targeted by CCR technologies that we are tracking.

We also focus our review on those markets that cannot be fully saturated if a meaningful number of power plants are equipped with the given CCR technology.

With these factors in mind, Table 6 presents primary CCR markets, the CCR category that is focused on producing product for that market, as well as the approximate market size.

Table 6

Select CCR Supply Side Markets and Affiliated Technology Categories

Market	CCR Category	Annual Market Size
Crude Oil	Biological; Chemical/Catalytic	6.99 billion barrels = 1.07 billion tons (2010, U.S.)[A]
Animal Feed	Biological	708 million metric tons (2009, global)
Cement	Mineral Conversion	88 million tons (2010, U.S.)
Plastics	Biological; Chemical/Catalytic	245 million tons[89] (2008, global)
Electricty	Biological	3.873 trillion kWh (2008 est., U.S.)[90]
Fertilizer	Biological	57.8 million tons (2004, U.S.)[91]
Payment for Environmental Services	Mineral Conversion	N/A

A Assuming 138.8 Kg/barrel of oil, and 907.18474 Kg/ton

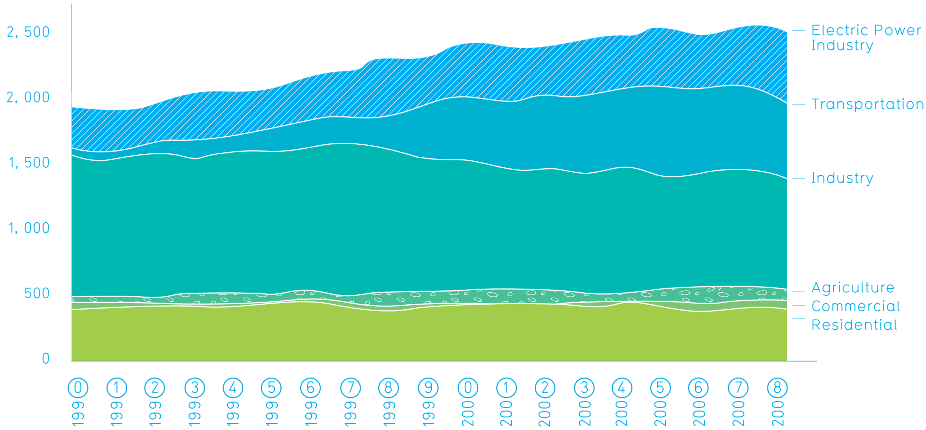
Quantifying the Market

To reiterate, the electric power industry is the greatest potential market for CCR technologies, and thus the greatest opportunity to produce materials that can satisfy the aforementioned markets. Figure 7 illustrates how the industry's overall greenhouse gas emissions far surpass those of other industries, and thus provides the greatest source of feedstock (i.e. CO_2) for CCR technologies to utilize.

Figure 7

Emissions Allocated to Economic Sectors

($Tg\ CO_2\ Eq.$)



Source: U.S. EPA

Also as previously mentioned, the sources of CO_2 in the electric power industry come almost exclusively from the combustion of fossil fuels, specifically coal, natural gas, and petroleum. We therefore focus on the combustion of these three fuels in the electricity generation sector to establish parameters for the amount of CO_2 feedstock produced and available for recycling into new products.

Table 7 presents the aggregate level of domestic CO_2 emissions from these three fuels in the electric power industry.

Table 7
Domestic Production of CO_2 from Electricity Generation
(Million Tons of CO_2)

Source of CO_2	Production of CO_2/Year[92]
Baseline: 184 GW	**948.5**
184 GW Coal	
Domestic: 862 GW	**2,153.6**
339 GW Coal	1,747.6
460 GW Natural Gas	373.1
63 GW Petroleum	32.9

As in other portions of this report, the dearth of specific, real-world information due to industry nascency prevents us from pinpointing accurate CO_2-to-product conversion ratios at this time. Also, conversion efficiencies are not the same for CCR technologies within a given category (e.g. mineral conversion), much less across different categories (e.g. mineral conversion vs. catalytic). Still, to gain some perspective on the industry's potential, technology nuances are simplified within this assessment by choosing representative and respectable ratios based on existing literature and anecdotal information.

Accordingly, we assume a ratio of two tons of CO_2 recycled for every ton of material produced as an aggressive target (which, by the way, may still be conservative, given that some CCR technologies are projecting to produce as many if not more tons of product than the amount of CO_2 they take in), and four tons of CO_2 recycled for every ton of material produced as out conservative target. These assumptions yield the amount of production potential presented in Table 8.

Table 8
Production of Raw Material Using CCR Technologies

Feedstock Quantity	Conservative (4:1) Conversion Ratio	Aggressive (2:1) Conversion Ratio
948.5M tons CO_2/yr	237.13M tons/yr	474.25M tons/yr
2,153.6M tons CO_2/yr	717.87M tons/yr	1,076.8M tons/yr

Recognizing the likely scenario where different CCR technologies will be applied to different CO_2 production scenarios and locations, an eyeball comparison of Table 8 with Table 6 indicates the ability for CCR technologies to tap into multiple markets without saturating them. At the same time, we see the ample availability of feedstock CO_2 to dominate a market, should any one technology take off. For instance, in our aggressive scenario, feedstock CO_2 could feasibly supply the U.S. with all of its crude oil needs.

The revenue implications become clear once we look at the going rates for the various commodities. At $100 per barrel, crude oil would sell for about $650 per ton. At current rates, algae based animal feed sells for between $2,000 and $5,000 per ton (which admittedly would drop rapidly should product supply become more available), and a metric ton of cement can sell for between $50 and $100. One study pegs cumulative gross revenue for CCR-produced products through 2020 at approximately $1.9 billion.[93]

Gaining clarity on the actual supply side market size – including pinpointing conversion ratios, projecting the mixture of products produced and how the introduction of this new material into various markets can affect market rates – is a high priority for a variety of reasons, most prominently so that we can project revenues to CCR technology operators as well as returns on investment. Prize Capital intends to address these issues in future work as the industry develops and more information becomes available.

Select CCR Company Overviews »

As with any nascent industry, it's impossible to know all the various entities working in the space, nor would it be particularly valuable to report on all the entities even if they were known.

The challenge of reporting on this industry is that at this stage of development, many concepts will always remain concepts, while several funded ideas may flame out before this report goes to print. Furthermore, there are a couple of comparatively advanced entities, and literally hundreds that are between the conceptual and Series A financing level.

These challenges are particularly acute in the biological space, where we are tracking hundreds of entities, many of which have little funding, and a couple of which have more than $100 million in private funding.

Thus, in the biological space, this report presents select overviews only of those entities that are either applying or have applied their technologies to the utilization of power plant flue gas. Other biological companies that have the potential to utilize flue gas – but aren't known to explicitly do so at this time – are presented in Appendix B.

In presenting chemical/catalytic and mineralization entities, we've sought to be comprehensive, but fully acknowledge that not all entities are presented.

In this section, we present information that we envision will be of assistance to decision makers, prospective technology operators, prospective investors, and others. This information includes a brief overview of the technology, mention of any partnerships or demonstrations, basic company facts (including contact information), as well as five specific statistics that we've sought to obtain from each of the presented entities:

Energy efficiency (MWh/ton of converted CO_2)
Conversion metric (Ton of CO_2 » ? quantity of product)
Land Footprint (Tons/acre of capacity)
Water Footprint (Gal/ton of CO_2 recycled)
Able to use raw flue gas (i.e. ~12% CO_2) instead of pure CO_2?

These five statistics may help determine if, how, and where a technology can be successful. As the overviews indicate, many entities have not yet identified these statistics or prefer not to reveal them at this stage. We envision this changing in the future as the industry develops, accurate knowledge becomes more available, and entities more transparent.

We acquired the data presented in each entity overview via primary and secondary research. Scientific journals, trade publications, press releases, and other secondary sources were reviewed, and more than two hundred conversations took place with industry members, experts, academics, and government agencies.

In some cases, we learned of non-biological entities but discovered that they were either at such a preliminary stage, confidential, or other roadblocks were established that prevented us from constructing overviews. In such cases, entities are summarized in Appendix A. We aim to continue tracking these entities, ideally collecting sufficient information to present them in the body of future versions of this document.

For those overviews presented in the document's body, the reviewed entity was provided an opportunity to correct and add information before finalizing the content.

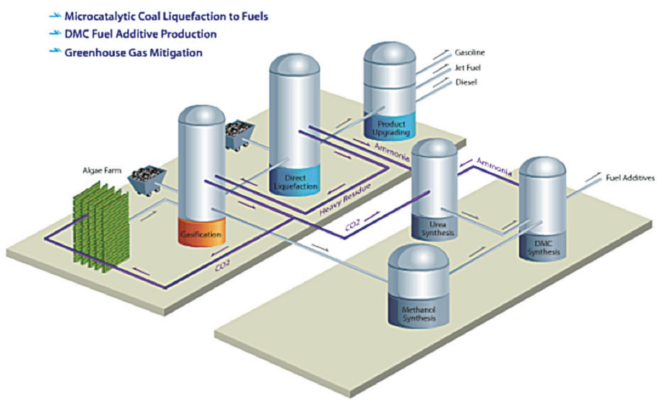
Biological »

Year Initiated: 2008
Level of Funding: N/A
Weblink: algaeatwork.com
Phone: 303.541.9112

Location: Boulder, CO
Number of Employees: 3
Project Leader(s): James T. Sears
E. jimsears@algaeatwork.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

algae@work℠



A2BE Carbon Capture

A2BE Carbon Capture is developing bio-secure, scalable, climate adaptive, and highly cost effective technology for producing valuable fuel and food from CO_2 using algal photosynthesis and bio-harvesting. The core of this technology is embodied in the published US patent application 20070048848: "Method, apparatus and system for biodiesel production from algae" as well as a separate mechanical and a PCT patent application.

The A2BE Carbon Capture solution is unique in that it addresses carbon capture and recycle as well as the production of biofuels, animal feed protein, and fertilizer in a single integrated plant.

CO_2 can originate from stationary sources such as fossil fuel fired power or heat plants, other types of biofuel plants producing ethanol from starch or cellulose, and CO_2 from gasification/Fischer-Tropsch processes such as coal-to-liquids and natural gas-to-liquids.

The core technology is the photo-bioreactor algae growing/harvesting (PBR) machine. Each PBR machine is 350' long and 50' wide consisting of twin 20' wide x 10" deep x 300' long, transparent plastic "algae water-beds".

The company's primary product is Teraderm, which is live algae fertilizer. Teraderm fixes nitrogen from the atmosphere, lives for generations in the soil, and is sequestered in the soil when it dies.

In 2010, Pennsylvania provided almost $1.5 million to A2BE, Accelergy, and Raytheon Co. to fund the study of the nation's first integrated CBTL (Coal-Biomass to Liquids) pilot demonstration.

Partnerships & Demonstrations

The company is aligned with Accelergy, a company that creates synthetic fuel from coal (CTL) using technology developed at ExxonMobil, as well as Raytheon Co. and Battelle. The entities are working together on a two-acre CTL demonstration in Pennsylvania as well as a larger Chinese deployment that is being developed with the Chinese Academies of Sciences.

Year Initiated: 2009
Level of Funding: >$14 million
Weblink: algaesystems.com
Phone: 847.800.6696

Location: San Francisco, CA
Number of Employees: 10
Project Leader(s): Matthew Atwood
E. matwood@algaesystems.com

Energy Efficiency (MWh/ton of converted CO_2): 0.629
Conversion Metric (Ton of CO_2 → ? quantity of product): 71 gal fuel
Land Footprint (Tons/acre of capacity): 0
Water Footprint (Gal/ton of CO_2 recycled): 23000 gal wastewater treated
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Algae Systems

Algae Systems has developed an integrated platform of technologies to produce drop-in carbon-negative fuels and treated wastewater from municipal wastewater and CO_2.

Algae System's has pioneered a technology dubbed OMEGA: Offshore Membrane Enclosures for Growing Algae.

The technology, initially developed at NASA, is derived from the space program's effort to "close the loop" between the waste streams produced and resource streams required by astronauts during long-duration spaceflight.

OMEGAs float on the water column, which provides a mechanical support structure, wave and wind action to provide the necessary mixing and temperature control of the algae culture.

OMEGAs receive municipal wastewater effluent as a primary input, which supplies the water and nutrients algae need to grow. OMEGA's use of wastewater stops the nutrients therein from disrupting aquatic ecosystems, stopping or reversing the formation of oceanic "dead zones," and is a low-cost alternative to traditional wastewater treatment.

Algae Systems uses passive dewatering techniques that greatly reduce the cost of otherwise expensive and energy-intensive dewatering, and double as membrane-level wastewater treatment providing the ability to recover valuable freshwater for reuse.

Algae Systems has coupled the OMEGA technology with systems for extracting CO_2 from the air, and for converting the dewatered algal biomass to drop-in fuels using hydrotreatment.

Partnerships & Demonstrations

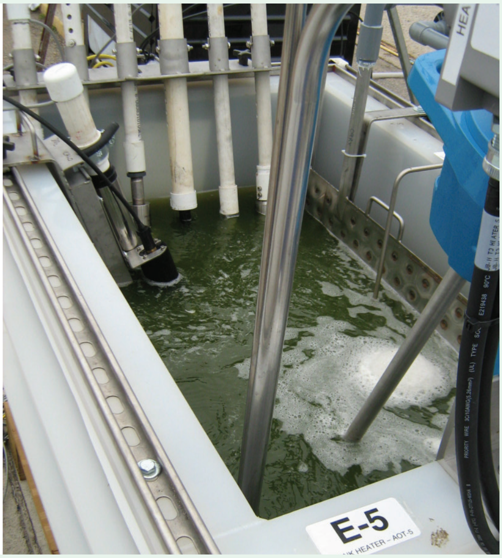
Algae Systems has partnerships with Det Norske Veritas and Global Thermostat, the latter of which is focused on producing algae from CO_2 captured from the air. Algae Systems is funded by EBJ Capital Group and in 2010 acquired the assets and intellectual property from GreenFuel Technologies Company. The company is completing a substantial Series-A financing round to develop an open-water pilot project in Q3 2011.

Year Initiated: 2010
Level of Funding: $1,522,149
Weblink: aquaflowgroup.com
Phone: +64.3.543.8227

Location: Hopewell, VA
Number of Employees: 5
Project Leader(s): Paul Dorrington
E. paul@aquaflowgroup.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

AQUAFLOW



Aquaflow Bionomic Consortium

In 2010, UOP was awarded a $1.5 million cooperative agreement from the U.S. DOE for a project to demonstrate technology to capture carbon dioxide and produce algae for use in biofuel and energy production. The funding will be used for the design of a demonstration system that will capture carbon dioxide from exhaust stacks at Honeywell's caprolactam manufacturing facility in Hopewell, Va., and deliver the captured CO_2 to a cultivation system for algae. Wastewater from the manufacturing facility will be used for the algae cultivation.

At the demonstration site, UOP will design cost-effective and efficient equipment to capture CO_2 from the exhaust stacks of the facility and deliver it in a controlled and efficient process to a pond near the plant, where algae will be grown using automated control systems from Honeywell Process Solutions and technology developed by Aquaflow Bionomic Corp.

This project supports ongoing development efforts from Honeywell's UOP for a range of process technologies to capture carbon dioxide and produce green fuels and chemicals. UOP has already commercialized the UOP/Eni Ecofining™ process to produce Honeywell Green Diesel™ fuel from biological feedstocks, and demonstrated the Green Jet™ fuel process.

The project will also support the independent evaluation of the use of RTP® rapid thermal processing technology from Envergent Technologies, a joint venture between UOP and Ensyn Corp. The RTP system can be used to convert waste biomass from the algae production into pyrolysis oil, which can be burned to generate renewable electricity.

Partnerships & Demonstrations

The company is working with Honeywell-Resins and Chemicals, Honeywell-Process Solutions, Envergent, Aquaflow Bionomic, Vaperma, and International Alliance Group in Hopewell, Va.

Year Initiated: 2007
Level of Funding: $1 million
Weblink: polygenomx.com
Phone: +617.5510.3166

Location: Chinchilla, Australia
Number of Employees: N/A
Project Leader(s): Peter Rowe
E. peter.rowe@polygenomx.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

BioCleanCoal– "Green Box" Project

In 2007, Linc Energy entered into a Memorandum of Understanding (MOU) and then a Joint Venture (JV) contract with the aim of creating an algae bioreactor that has the ability to absorb CO_2 at one end, and to produce oxygen and biomass from the other. The project name for this unit was the 'Green Box'.

The JV was with BioCleanCoal, a now defunct Queensland based Biotechnology company that specialized in the breeding and propagation of useful algae and plant species for the conversion of CO_2 to oxygen and biomass.

BioCleanCoal had two sister companies: BioAdapt International Pty Ltd and BioFuelGenomics Pte Ltd. BioAdapt International was a company formed to commercialize a scientific breakthroughs in molecular biological research that resulted in the consistent advanced growth of trees by up to 39%. BioFuelGenomics was a company formed to commercialize the scientific breakthrough of polyploid creation in biofuel feedstocks. The company's objective was to increase biofuel feedstock production by means of advancing feedstock growth

The project completed after twelve months operations at Linc Energy's Chinchilla coal gasification plant. The result of the demonstration was positive. Linc Energy owns patents on this technology, subsequently merged the project/technology other Linc Energy carbon projects (under Linc Energy's "carbon solutions" business) and is evaluating partners and funding options to move forward with the technology.

The founder of BioCleanCoal has since moved to PolyGenomX, where he is a major shareholder.

Partnerships & Demonstrations

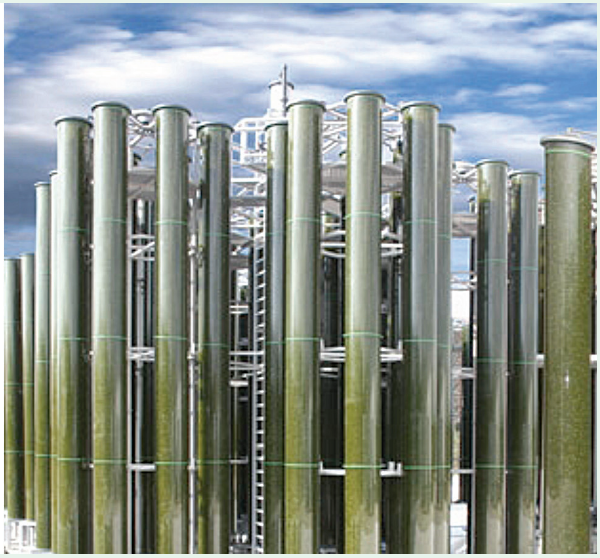
The first 'Green Box' demonstration unit operated for twelve months at Chinchilla between 2009 and 2010. The JV with Linc Energy was owned on a 60/40 basis with Linc Energy owning 60% and having the day to day management and BioCleanCoal owning the remaining 40%.

Year Initiated: 2006
Level of Funding: N/A
Weblink: biopetroleo.com
Phone: N/A

Location: Alicante, Spain
Number of Employees: N/A
Project Leader(s): Bernard A.J. Stroïazzo-Mougin
E. info@biopetroleo.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

BFS
bio fuel systems



BioPetroleo

BioPetroleo captures CO_2, processes it via phytoplankton (marine biomass), and then produces "blue petroleum" artificial crude oil.

BioPetroleo's system is simple and based on what occurs in nature. The sun gives off electro magnetic waves; these waves are the transporter for energy, which are captured by the company's machine along with the CO_2 from the atmosphere. Photosynthesis and mitosis takes place (mitosis is the splitting of the cells). Mitosis becomes the transporter for photosynthesis. Once the biomass has been accumulated it is then split into two, carbons and hydrocarbons.

BioPetroleo adapts and modifies natural strains of algae to boost their reproduction rates and enable them to produce energy compounds from which the company is able to harvest greater levels of biomass than would be obtained from any other system using land-based crops (palm, sunflower, rape seed, etc.) or from conventional photobioreactors

The carbons help obtain electricity and secondary distillated water. Hydrocarbons once extracted produce fuel and byproducts. Once this has occurred, the process starts from the beginning again, with added CO_2 from production processes.

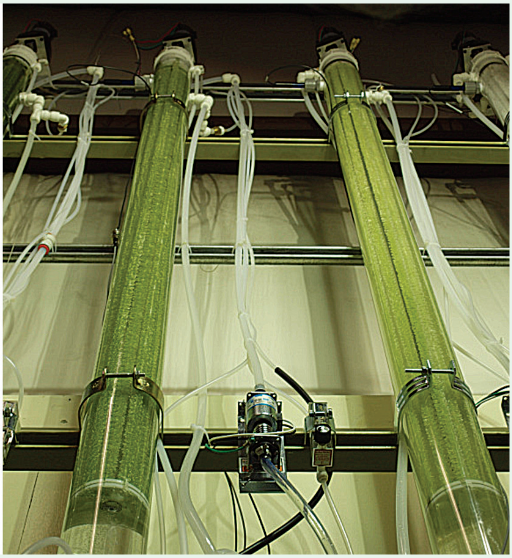
Using biomass after a drying process, the company can also produce BIO-Coal, which can be used to make electricity via Stirling type motors or steam turbines with a high energetic efficiency.

Partnerships & Demonstrations
The company is connected to the University of Alicante, Spain, where its technology was pioneered. The company has a pilot plant, dubbed Blue Petroleum ONE, in Alicante.

Year Initiated: 2009
Level of Funding: N/A
Weblink: bioprocessalgae.com
Phone: 402.315.1630

Location: Portsmouth, RI
Number of Employees: N/A
Project Leader(s): Jim Stark
E. jim.stark@gpreinc.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



BioProcess Algae, LLC

BioProcess Algae designs, manufactures, and operates integrated systems that enable efficient, economical cultivation of algae biomass and secreted metabolites.

The technology at the heart of Bioprocess cultivators is a unique high surface area, biofilm-based approach to enhance light penetration, productivity, harvest density and gas transfer – all traditional bottlenecks to low-cost algae cultivation.

The Grower Harvester™ technology is a flexible platform that allows for economical production of biomass and secreted metabolites.

BioProcess is a joint venture among Clarcor (NYSE: CLC), BioProcessH2O, LLC, Green Plains Renewable Energy, Inc. (NASDQ: GPRE), and NTR plc.

Partnerships & Demonstrations

The company is currently running a demonstration plant at the Green Plains Renewable Energy, Inc. ethanol plant in Shenandoah, Iowa. Grower Harvester™ bioreactors have been tied directly into the plant's CO_2 exhaust gas since October 2009. The demonstration was funded in part by a $2.1 million award by the Iowa Office of Energy Independence.

Year Initiated: 2009
Level of Funding: N/A
Weblink: carbon2algae.com
Phone: 416.803.9435

Location: Toronto, Canada
Number of Employees: N/A
Project Leader(s): Douglas Kemp-Welch
E. tcripe@carbon2algae.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Carbon2Algae (C2A) Solutions

C2A has a process system—dubbed "Gas infusion" —for capturing CO_2, growing algae and producing bio-fuels and secondary high value products.

The company has been licensed to use an ultra efficient gas infusion technology for the transfer of CO_2 into liquids for algae feedstock production and to remove oxygen that can become toxic to algae.

inVentures Technologies developed and patented the system and is one of the owners of C2A. The Aquasea Group has developed and provisionally patented proven high yield algae growth/harvest technologies that have been licensed to C2A. C2A also has the rights to an organic removal technology from Mitton Valve Technology to assist in lipid extraction and has a provisional patent on another mechanical process.

For dewatering the company has agreements in place with two technology providers and, through inVentures, has access to an organic sieve technology for removing water from the algae oil.

C2A's Gas inFusion equipment will dissolve CO_2 to a molecular level (sub-1 micron), which the company says will sharply accelerate algae's growth rates.

Partnerships & Demonstrations

C2A wants to establish a pilot to verify its ability to separate CO_2 from flue gas streams into water at a coal-fired power plant. The gas infusion technology will selectively infuse the most miscible gas in flue gas into water where it can be utilized to enhance the growth of algae or bacteria for biofuel production. C2A is currently working with the National Research Council to attract a group of thermal power producers to participate in the project.

Year Initiated: 2010
Level of Funding: $50,000
Weblink: carbonitum.com
Phone: 780.905.8560

Location: Edmonton, Canada
Number of Employees: 1
Project Leader(s): Doug Cornell
E. doug.cornell@carbonitum.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Carbonitum Energy Corporation

The company is developing a novel Photobiological Integrated Carbon Capture and Recycle Technology (PICCART) to convert the carbon dioxide emitted by large stationary facilities into methane for return to the facility, offsetting the required fossil fuel input.

As well as capturing nearly all carbon dioxide emissions from such a facility, the company projects that the PICCART process could reduce annual operating costs of a 500MW power plant by over $80M.

Partnerships & Demonstrations

In April 2010, the company was awarded a $50,000 Alberta Innovation Voucher. It also signed an agreement with National Institute for Nanotechnology as Service Provider.

Year Initiated: N/A
Level of Funding: N/A
Weblink: bioalgene.com
Phone: 206.734.7323

Location: Seattle, WA
Number of Employees: N/A
Project Leader(s): Stan Barnes
E. stanb@bioalgene.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): 50
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Columbia Energy Partners & BioAlgene

Washington-based Columbia Energy Partners (CEP) is financing the conversion of unscrubbed flue gas from Portland General Electric's 600MW coal-fired plant in Boardman, Ore., into algal oil for the production of biodiesel. Seattle-based BioAlgene is providing the algae strains for the project.

The project is in the demonstration and evaluation phase. If the results of this phase are positive, the company plans to move forward with engineering details and the construction of larger, in-ground algae tanks while continuing to research the process.

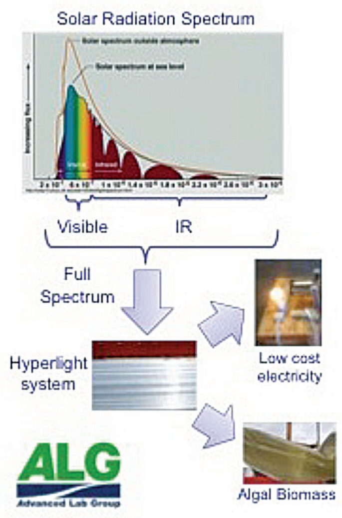
The current project is five acres, but in order to mitigate all emissions from the power plant, 30,000 acres is required. Subsequent phases may expand to between 7,500 and 30,000 acres using military land currently adjacent to the facility.

Partnerships & Demonstrations
Columbia Energy Partners and BioAlgene are partnering with each other as well as Portland General Electric for the demonstration facility on 5 acres in Boardman, OR.

Year Initiated: 2009
Level of Funding: $1.5 million
Weblink: combinedpowercoop.com
Phone: 619.564.4303

Location: Santee, CA
Number of Employees: 8
Project Leader(s): John King
E. john.king@combinedpower.coop

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



Combined Power Cooperative

Combined Power has developed a portfolio of patent-pending renewable energy technologies.

The Company's first product, Hyperlight™, is an ultra-low cost reflector assembly for use in the solar field of a Concentrated Solar Power (CSP) plant. As the single most expensive part of a CSP plant, the reflector field can account for up to 45% of a plant's total cost. Combined Power states that its reflector field costs an order of magnitude less than those of competitors.

Hyperlight™ also functions as a photobioreactor (PBR) for the production of algae biomass for conversion into biofuel and other valuable products, effectively mitigating the thermal build-up issue that is common in other PBRs. The company states that with the revenue from solar electricity, Hyperlight™ is the only PBR that can pay for its own construction and operation at an arbitrarily large scale.

The company has built a working prototype system, which is already online, and has existing product sales of its core technology. The company was awarded a $1 million California Energy Commission contract in early 2011.

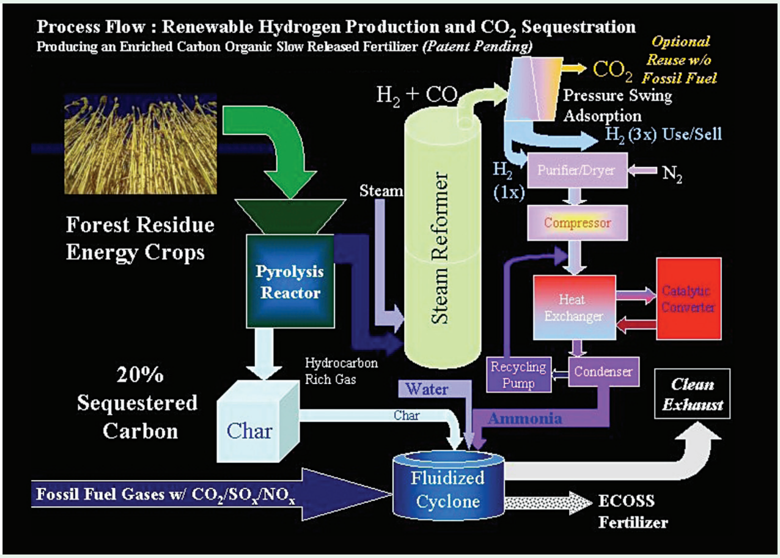
Partnerships & Demonstrations

The company signed a Letter of Intent with San Diego State University to deploy technology at full scale in 2011 in Imperial County, CA. It also received a Letter of Support from Southern California Gas Company for subsequent deployment.

Year Initiated: 2002
Level of Funding: $0
Weblink: eprida.com
Phone: 678.905.9070

Location: Atlanta, GA
Number of Employees: 1
Project Leader(s): Danny Day
E. info@eprida.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



EPRIDA

EPRIDA utilizes CO_2 to produce biochar, a soil fertilizer that increases productivity.

The Eprida process is based on three key insights:

1. As demonstrated by "terra preta" in the Amazon basin, charcoal acts like a coral reef for soil organisms and fungi, creating a rich micro ecosystem where organic carbon is bound to minerals to form rich soil.
2. Low temperature charcoal can be made by a hybrid pyrolysis process whereby biomass such as wood chips or agricultural waste is heated in a sealed vessel. Once started, this process gives off heat while it drives off steam and hydrogen, which can be captured, purified and used for energy. Hydrogen can be used to make transitional fuels such as GTL biodiesel today, or used directly in a fuel cell to make electricity.
3. Ammonia (NH_3), CO_2 and water (H_2O), can be combined in the presence of charcoal to form ammonium bicarbonate (NH_4HCO_3) fertilizer inside the pores of the charcoal. About 30% of the hydrogen derived from the biomass will make enough ammonia to combine with all of the charcoal from the same biomass to scrub CO_2 flue gases from a power plant, converting all of the ingredients into a slow-release nitrogen fertilizer on charcoal.

The overall process can put almost all of the carbon that was removed from the air by the biomass back into the soil in a stable form, effectively removing net CO_2 from the air. When used with biomass and coal, the process will scrub about 60% of the CO_2 out of the flue gases from the coal, as well as all of the SO_X and NO_X, turning these compounds into high-carbon fertilizer.

Partnerships & Demonstrations
None

Year Initiated: 2009
Level of Funding: N/A
Weblink: eni.com
Phone Number(s): N/A

Location: Gela, Sicily
Number of Employees: N/A
Project Leader(s): Paola Maria Pedroni
E. paola.pedroni@eni.it

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Eni Technology

Eni Technology is currently working on a 500MW NGCC power plant to capture about 15% of the CO_2 emissions to produce algae biomass.

The biomass, thus obtained would be harvested and digested to produce methane. The residual sludge obtained contains nitrogen, phosphorus and a few other nutrients, which are directly sent to cultivation ponds for algae to grow.

The biomass productivity is about 30g/m^2/day to 60g/m^2/day. Research is underway to commercialize and double the productivity of the algal biomass.

In a preliminary mass balance calculation, assuming near-theoretical productivities, a 700 ha system was projected to be able to mitigate 15% of the annual CO_2 emissions from a 500 MWe NGCC power plant. The R&D focuses on how to increase the productivities of algal mass cultures under outdoor operating conditions.

Partnerships & Demonstrations

The testing activities are performed at the company's Gela refinery, where a small-scale (one hectare) pilot plant made up of photobioreactors and open pools. The plant was designed by Saipem and built in Gela. The start-up was in late 2009.

Year Initiated: 2010
Level of Funding: $993,284
Weblink: gastechnology.org
Phone: 847.768.0500

Location: Des Plaines, IL
Number of Employees: N/A
Project Leader(s): Serguei Nester
E. serguei.nester@gastechnology.org

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Gas Technology Institute

Partnerships & Demonstrations
GTI is working with the University of California San Diego, the University of Connecticut, San Diego Gas and Electric Company, and Southern California Gas Company on its DOE-funded macroalgae project, and Aquaflow Bionomic on a conversion demonstration project.

Year Initiated: 2008
Level of Funding: $10.3 million
Weblink: ginkgobioworks.com
Phone: 877.422.5362

Location: Boston, MA
Number of Employees: 7
Project Leader(s): Jason Kelly
E. jason@ginkgobioworks.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Ginkgo BioWorks

Formed in 2008, Ginkgo BioWorks is developing an "electrofuels chassis" by using engineered E. coli to convert carbon dioxide and electrical energy into short, branched-chain alkanes— molecules that cannot be produced using other known biosynthetic pathways.

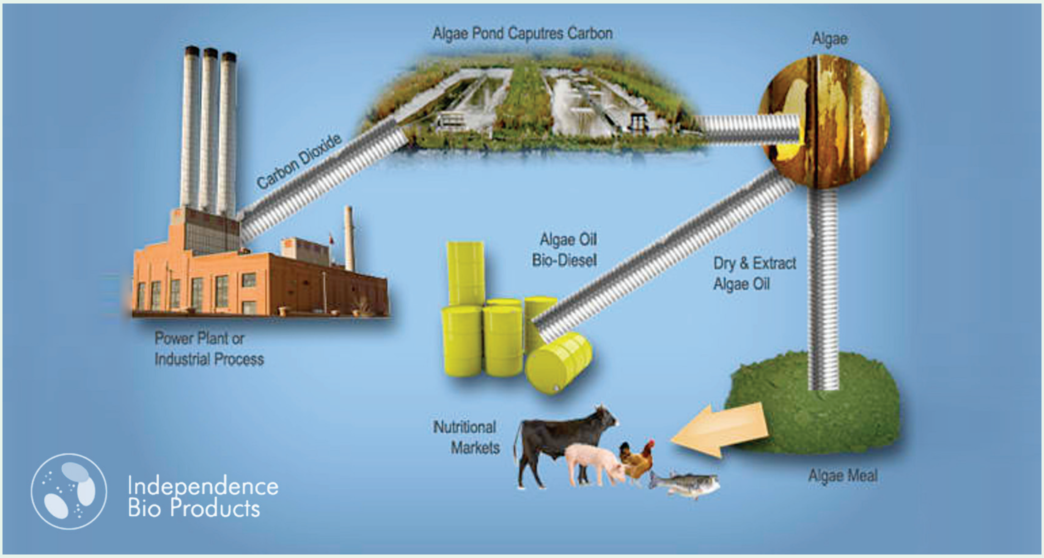
The target liquid fuel is isooctane, which fits well into the existing transportation fuel system in the United States.

Partnerships & Demonstrations
In 2010, the company received a $6 million ARPA-E grant. The firm previously received a $150,000 loan from the city of Boston for the firm's South Boston facility and a $4.1 million contract from ITI Life Sciences in Scotland for researching another new way of putting together genetic parts.

Year Initiated: N/A
Level of Funding: N/A
Weblink: independencebio-products.com
Phone: 614.789.1765

Location: Dublin, Ohio
Number of Employees: N/A
Project Leader(s): Ron Erd
E. ron.erd@independencebioproducts.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



Independence Bio Products

Independence Bio-Products has developed a system to produce algae oil and algae protein, while using power plant flue gas as a source of carbon dioxide.

The company captures industrial carbon dioxide, produces algae oil for conversion to biofuels and bioproducts, and high protein algae solids for fish, pig and chicken feed.

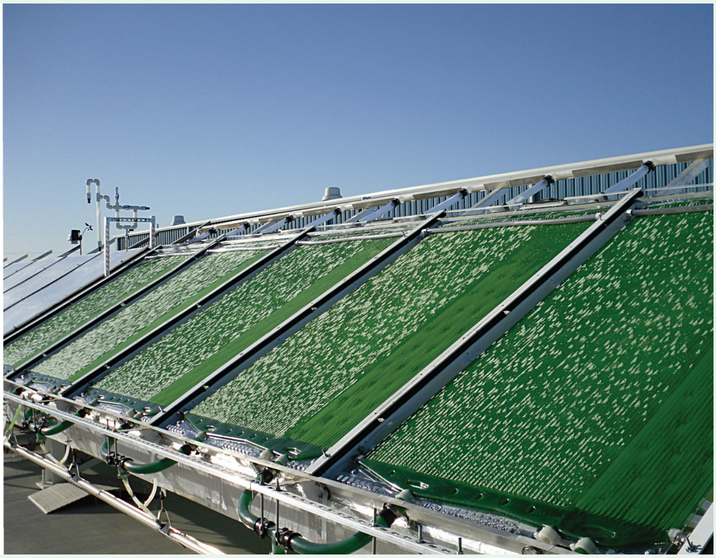
The exhaust gas from the power plant is fed to the algae ponds. The algae consume the CO_2, affix the carbon and release oxygen via photosynthesis. The company harvests the algae and separates it into algae oil and Algamaxx™ animal feed.

Partnerships & Demonstrations
The company is demonstrating the use of carbon dioxide from flue gas at FirstEnergy's Burger Power Plant in Shadyside, OH.

Year Initiated: 2007
Level of Funding: N/A
Weblink: jouleunlimited.com
Phone: 617.354.6100

Location: Cambridge, MA
Number of Employees: ~60
Project Leader(s): William J. Sims
E. bsims@joulebio.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



Joule Biotechnologies

Joule Unlimited, Inc. has created a platform, called Helioculture™ technology, which leverages highly engineered photosynthetic organisms together with a novel SolarConverter® system to directly convert sunlight and waste CO_2 into fungible, renewable transportation fuels and chemicals. Joule's founders are Noubar Afeyan and David Berry of Flagship VentureLabs, and its notable advisors include Harvard Medical School Professor of Genetics George Church.

Joule's solar fuels, including diesel and ethanol, will meet today's vehicle fuel specifications and infrastructure, and will be competitive with current alternatives at costs as low as $20/bble and $0.60/gal respectively.

Joule says that its direct-to-fuel conversion requires no biomass feedstocks, agricultural land or fresh water, and leverages a highly scalable system capable of producing up to 15,000 gallons of diesel and 25,000 gallons of ethanol per acre annually. Such yields would far eclipse productivity levels of current biofuel processes.

Joule says that its SolarConverter system facilitates the entire process— from sunlight capture to product synthesis and separation—by minimizing process steps. This represents an advantage over biomass-derived biofuels, including newer algae- and cellulose-based forms, which are hindered by varying obstacles: costly biomass production, numerous processing steps, substantial scale-up risk and capital costs.

Partnerships & Demonstrations

Joule has an operational pilot plant in Leander, Texas and has secured an initial site in New Mexico as part of its siting program for demonstration and commercial production.

Year Initiated: 2009
Level of Funding: >$5 million
Weblink: mbdenergy.com
Phone: +61.3.9415.8711

Location: Melbourne, Australia
Number of Employees: N/A
Project Leader(s): Larry Sirmans
E. larry.sirmans@mbdenergy.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

MBD Energy, Ltd.

MBD Energy is a privately owned company that is developing an integrated carbon capture technology based on algae, with the aim of generating multiple product lines including plastics, transport fuel and animal feed.

The company states that its "Algal Synthesiser" technology captures flue emissions at the source, harnessing waste greenhouse gases as growth-promoting feedstock for conversion into oil-rich algal biomass." The continuously harvested output consists of 35% algae oil, 65% algae meal and the by-products of water and oxygen. The intellectual property in projects of this nature is around the algal strains used and the methods of achieving maximum yields.

The company is currently focusing its research on capturing CO_2 for two power stations – Loy Yang and NSW's Eraring energy. They claim that for every two tons of carbon captured, the MBD technology can produce almost 1 ton of algae, of which one-third can be made into oil products and two-thirds into meal. To capture 50% of the CO_2 emissions from the Loy Yang's power plant, the company requires a $1.2 billion facility which will generate of $740 million of meal income a year and $660 million of oil income. This will also provide an additional benefit of carbon-credits of about $225 million, while using just 10MW energy.

The ultimate operating project is planning an 80-hectare site that recycles more than 70,000 metric tons of CO_2 from the flue gas, and producing 2.9 million gallons of oil plus 25,000 metric tons of algae meal.

Partnerships & Demonstrations

The Australian government's Advanced Manufacturing Cooperative Research Centre (AMCRC) is partnering with MBD Energy to support two key projects—a research and development facility based at James Cook University (JCU) Townsville Campus and the construction of a commercial algal synthesiser at SE Queensland's Tarong Power Station. MBD is reportedly also using equipment from OriginOil for this project. The AMCRC provided $5 million Australian for this effort.

Year Initiated: 2007
Level of Funding: $66 million
Weblink: opxbiotechnologies.com
Phone: 303.243.5190

Location: Boulder, CO
Number of Employees: N/A
Project Leader(s): Charles Eggert
E. ceggert@opxbio.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

OPX Biotechnologies

OPX Biotechnologies engineers microorganisms to renewable hydrogen and carbon dioxide inputs to produce "BioAcrylic" and biodiesel-equivalent fuel. It is exploring catalysts that can be used to convert the fuel into jet fuel.

The company's OPX EDGE™ (Efficiency Directed Genome Engineering) technology platform optimizes microbes and bioprocesses to manufacture bioproducts with equivalent performance and improved sustainability at lower cost compared to petroleum-based alternatives.

The company identifies the genes that control microbial metabolism and then implements a comprehensive genetic change strategy to simultaneously optimize microbial production pathways and vitality as well as overall bioprocess productivity.

The company states that OPX EDGE includes a first-of-its-kind, massively parallel, full genome search technology known as SCALEs.

The OPX EDGE technology is 1,000 to 5,000 times faster than conventional genetic engineering methods, meaning OPXBIO creates optimized microbes and bioprocesses within months rather than years.

In 2010, the company and its partners NREL and Johnson Matthey received $6 million in DOE ARRA funding to support its technology's development. As of July 2011, the company had raised $60 million with venture investors Altira Group, Braemar Energy Ventures, DBL Investors, Mohr Davidow Ventures, US Renewables Group and X/Seed Capital.

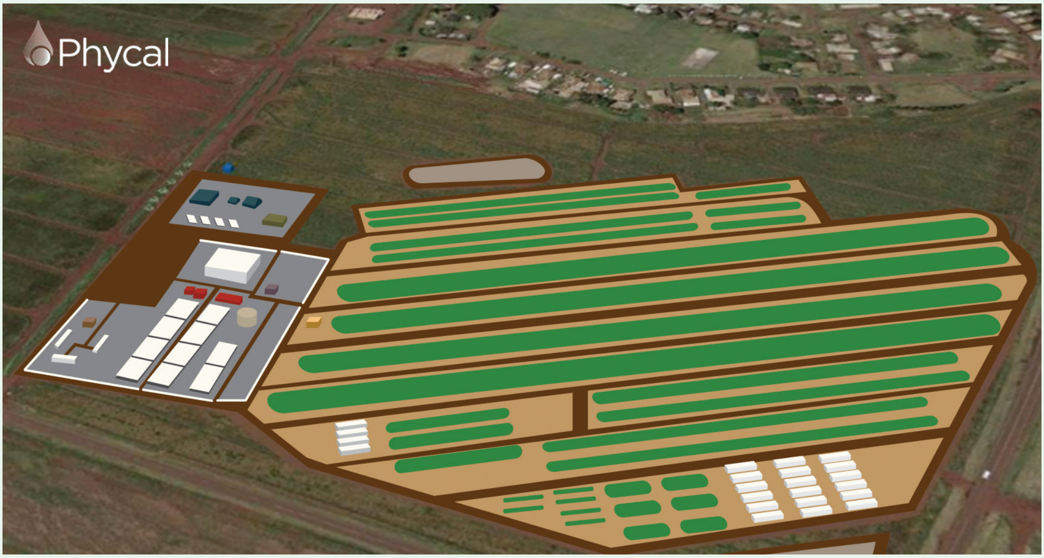
Partnerships & Demonstrations

The company is partnering with NREL and Johnson Matthey to develop and optimize their novel, engineered microorganism that directly produces a biodiesel-equivalent electrofuel from renewable hydrogen and carbon dioxide. The company has also established a joint development agreement with The Dow Chemical Company to collaborate on the large-scale demonstration of the process for BioAcrylic production.

Year Initiated: 2006
Level of Funding: >$70 million
Weblink: phycal.com
Phone: 440.460.2477

Location: Highland Heights, OH
Number of Employees: 45
Project Leader(s): Kevin Berner
E. kevin.berner@phycal.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



Phycal

Phycal, Inc. is developing an integrated system for producing renewable biofuels and their co-products (such as proteins, methane, hydrogen, animal or human nutritional products) from algae using 1) industrial flue gas directly injected into algae ponds as a nutrient, and 2) various sugars fed to the algae.

The company's processes are broken into four areas:

- Heteroboost™ - a finishing process that increases the oil content of the algae just prior to extraction by supplementing final growth stages with sugar
- Aqueous Extraction—extraction of oil from algae still in a liquid media, eliminating the need for extensive dewatering and drying
- Integrated Production System—Including pond design and operations, reductions in internal energy consumption, water management, and reductions in nutrient costs
- Biotechnology – the long-term development of biocontained, engineered strains of algae with increased oil productivity, increased biomass productivity, oils tailored for specific products, and/or optimum carbon capture.

In 2010, Phycal and its partners SSOE Engineering; GE Global Research; Aqua Engineers; Seambiotic; Kuehnle AgroSystems, Inc.; Group 70; and the NASA Glenn Research Center received approximately $51.5 million in a DOE award to design, build, and operate a CO_2-to-algae-to-biofuels facility at a nominal thirty-acre site in Central Oahu (near Wahiawa and Kapolei), Hawaii. The project will use two patented technologies, Heteroboost™ and Olexal™

Partnerships & Demonstrations

Phycal and its partners are using its DOE award to design, build, and operate a CO_2-to-algae-to-biofuels facility at a 34-acre site in Central Oahu, Hawaii. This pilot will allow Phycal to complete technical qualification and confirm the ability to produce product at acceptable cost targets.

Year Initiated: 2008
Level of Funding: €25 million
Weblink: rwe.com
Phone: +201.12.28563

Location: Niederaussem, Germany
Number of Employees: N/A
Project Leader(s): Georg Wiechers
E. georg.wiechers@rwe.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

RWE AG

German based RWE energy is capturing carbon dioxide from the Niederaussem power station and converting it into algae biomass. It initiated the project in 2008.

They are using photobioreactors erected on an area of 600 m^2; up to 1,000 m^2, is available for extensions. The system can produce up to 6,000 kg algae (dry substance) per year, binding 12,000 kg of CO_2.

The company is working to overcome inefficiencies. For instance, high CO_2 concentrations could cause the algae suspension to become acidic, thereby stunting algae growth.

The pilot system captures up to 300 kilograms of CO_2 per hour. The process itself requires a great deal of energy, both to capture the CO_2 and to convert it to a usable intermediate; it also marginally reduces the plant's effectiveness by approximately eight percent.

Partnerships & Demonstrations

RWE is working with Jacobs University, Bremen, the Jülich Research Centre and the Phytolutions company on its 600 m^2 Niederaussem demonstration plant.

Year Initiated: 2007
Level of Funding: ~$150 million
Weblink: sapphireenergy.com
Phone: 858.768.4700

Location: San Diego, CA
Number of Employees: >140
Project Leader(s): Jason Pyle; Cynthia Warner
E. jason.pyle@sapphireenergy.com; cj.warner@sapphireenergy.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

Sapphire Energy

Sapphire Energy

Sapphire Energy has developed proprietary technology along the entire algae-to-energy value chain from biology, cultivation, harvest and extraction to refining resulting in a scalable process to produce a renewable and low carbon substitute for fossil-based crude oil.

Sapphire applies the principals of bio-agriculture by developing algae that are optimized for growing an industrial organism. The seeds are bread to resist disease or predators, to make the algae easy to harvest, and to produce oils that leverage the existing refining, transportation and distribution systems

Sapphire's green crude drop-in fuels—jet, diesel and gasoline—are completely compatible with existing infrastructure and engines.

Sapphire's algae are grown in open "racetrack" ponds with salty, non-potable water. The company claims an approximate 70% reduction in lifecycle carbon emissions compared to petroleum-based fuels.

Investors in Sapphire Energy include Bill Gates' Cascade Investment, ARCH Venture Partners, the Wellcome Trust, and Venrock, the venture capital arm of the Rockefeller family. The company has raised approximately $100 million from private sources.

In late 2009, Sapphire was awarded nearly $104.5 million as part of the American Recovery and Investment Act and the Biorefinery Assistance Program, authorized through the 2008 Farm Bill. The grant is from the U.S. DOE for $50 million and the loan guarantee from the USDA for $54.5 million.

Partnerships & Demonstrations

In mid-2011, Sapphire and the Linde Group entered into a multi-year agreement to co-develop a system to deliver anthropogenic CO_2, such as those emitted from power plants, to Sapphire's algae ponds. Linde will supply all of the CO_2 to Sapphire`s demonstration facility that it plans to open in Columbus, New Mexico in 2011. Sapphire is also collaborating with the DOE's Joint Genome Institute; U.C. San Diego; The Scripps Research Institute; and the University of Tulsa.

Year Initiated: 2003
Level of Funding: N/A
Weblink: seambiotic.com
Phone: +972.3.6911688

Location: Ashkelon, Israel
Number of Employees: N/A
Project Leader(s): Noam Menczel
E. noam@seambiotic.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Seambiotic

Seambiotic

Seambiotic is utilizing flue gas from coal burning power stations for algae cultivation in open "race-track" ponds.

Seambiotic cultivates a few selected species of marine autotrophic microalgae with high content of lipids and carbohydrates as equivalent to the production of biodiesel and ethanol.

The company is demonstrating their process with an electric utility company - a coal-burning power plant in the southern city of Ashkelon operated by the Israel Electric Company (IEC).

Seambiotic's eight shallow algae pools, covering about a quarter-acre, are filled with the same seawater used to cool the power plant. A small percentage of gases are siphoned off from the power plant flue and are channeled directly into the algae ponds.

Originally when the prototype started operating, a common alga called Nannochloropsis was culled from the sea and used in the ponds. Within months, the research team noticed an unusual strain of algae growing in the pools- skeletonema - a variety believed to be very useful for producing biofuel.

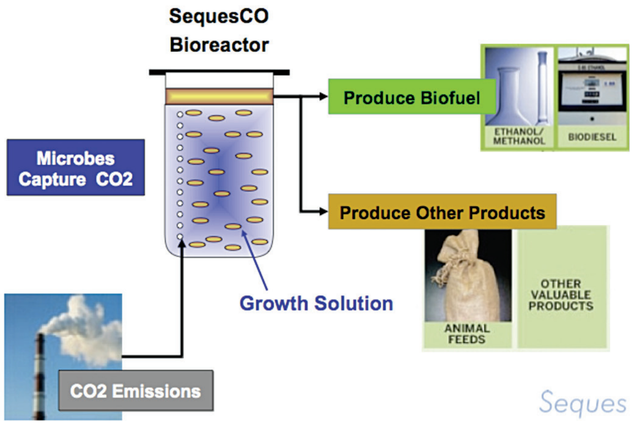
Partnerships & Demonstrations
Seambiotic is working with the Israel Electric Company (IEC) and is demonstrating its process at the IEC site in Ashkelon.

Year Initiated: 2009
Level of Funding: N/A
Weblink: sequesco.com
Phone: N/A

Location: San Francisco, CA
Number of Employees: N/A
Project Leader(s): Lisa Dyson
E. information@sequesco.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Sequesco
Recycling Carbon To Fuel The World



Sequesco

Sequesco uses a microbial process to capture carbon dioxide emissions from industrial flue gases and convert the emissions into biomass.

Unlike algal or agricultural approaches to capturing carbon dioxide for biofuel production, Sequesco's technology does not rely on photosynthesis.

Sequesco claims its bacteria grow ten times faster than most algae raised for biodiesel, and because they are non-photosynthetic, they can be grown 24 hours a day in all weather. Area isn't a constraint for the bacteria, so they can be cultured in conventional, low-cost bioreactors.

Over time, the firm plans to further modify the microbes to coax them into producing more lipid- and carbohydrate-rich biomass — which, in turn, would mean more biodiesel and ethanol. Its long-term goal is to make it a one-step process: CO_2 to biofuel.

Partnerships & Demonstrations
None

Year Initiated: 2006
Level of Funding: $511,327
Weblink: sunrise-ridge.com
Phone: 432.940.4419

Location: Austin, Texas
Number of Employees: N/A
Project Leader(s): Norman Whitton
E. norm.whitton@sunrise-ridge.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Sunrise Ridge Algae, Inc.

Sunrise Ridge Algae is a private Texas corporation engaged in research, development and commercialization of aquatic biomass technology for reduction of water and greenhouse gas pollutants and production of renewable fuel feed stocks.

Sunrise Ridge focuses its development activities in two major areas: The scale up of aquatic biomass production (including nutrient sourcing, farm design and management, and harvesting and drying systems); The scale up of biomass conversion processes (including integration with industrial facilities, end-use options for fuel products, and improving the value of products).

In 2010, the company received an approximately $500,000 grant from the DOE in ARRA funds to pursue its project. This project will involve the cultivation of algae using CO_2 from cement plant waste stack gas. The harvested algae will be converted into liquid fuel and carbonaceous char using catalyzed thermochemical conversion technology. The liquid fuel may serve as a diesel fuel replacement or extender, while the char can be burned as fuel instead of coal in the cement factory kilns.

Partnerships & Demonstrations
Sunrise Ridge has more than 5 years experience in algae and other next-generation biofuels systems, and operates a biomass farm and pilot scale conversion facilities near Katy, Texas. Sunrise Ridge will collaborate with URS Group, Texas Lehigh Cement Company, UOP LLC, and the Houston Technology Center for the DOE-funded demonstration project.

Year Initiated: 2010
Level of Funding: $2.6 million
Weblink: vattenfall.com/en
Phone: 0355.28.87.30.67

Location: Senftenberg, Germany
Number of Employees: N/A
Project Leader(s): Hartmuth Zeiss
E. hartmuth.zeiss@vattenfall.de

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Vattenfall MiSSiON Project

Swedish energy group Vattenfall, the third largest electricity provider in Germany, launched a pilot project in the middle of 2010 using algae to absorb greenhouse gas emissions from a coal-fired power plant in eastern Germany.

The project is dubbed “MiSSiON”: Microalgae Supported CO_2 Sequestration in Organic Chemicals and New Energy.

This trial run will continue until October 2011. It’s taking place in the Lausitz mining region.

The gas emitted at the Senftenberg brown-coal-fired plant is being pumped through a kind of broth using algae cultivated in 12 plastic tanks. The goal is to find out what kinds of algae work with brown coal dust and then, how economical algal CO_2 reduction is.

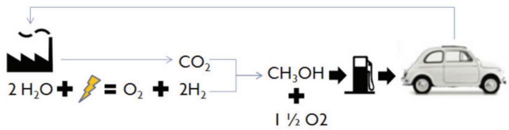
Partnerships & Demonstrations
A $2.6 million demonstration project in Senftenberg, Germany.

Chemical & Catalytic »

Year Initiated: 2006
Level of Funding: N/A
Weblink: carbonrecycling.is
Phone: +354.578.6878

Location: Reykjavík, Iceland
Number of Employees: N/A
Project Leader(s): KC Tran
E. kc.tran@carbonrecycling.is

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



Carbon Recycling International

Carbon Recycling International has developed a clean technology that enables direct conversion of renewable energy to fuel for small-scale plants.

Energy sources can be from any renewable source such as geothermal, hydro, wind, or solar.

The process consists of a system of electrolytic cracking and catalytic synthesis, leading to an integrated electrochemical plant design.

The Emission-to-Liquid manufacturing process captures CO_2 emissions from a power plant or industrial source, and reacts with hydrogen made by electrolysis using water and renewable energy, to produce renewable methanol (RM) and pure oxygen.

Implementation of the CRI technology to produce RM can be done in phases and in a modular construction approach. The process is free of CO_2 emissions.

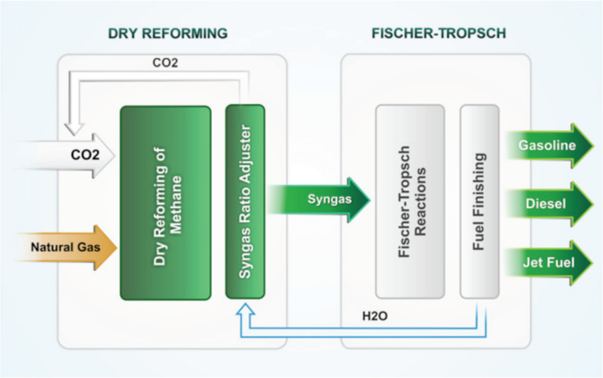
RM can be blended with different grades of gasoline for existing automobiles and hybrid flexible vehicles. The capture of carbon dioxide results in a net reduction of carbon dioxide from power generation.

Partnerships & Demonstrations
CRI has a pilot scale plant that was completed and under operation since 2007. It is an experimental facility for testing process flow sheets for carbon dioxide to liquid fuels. The lab can produce .05 million liters a year for fuel blending demonstration. In Q2 2011, the company completed its first commercial scale plant in Svartsengi, with capacity of 5 million liters per year, to gain operating experience and to improve plant economics for building larger plants.

Year Initiated: 2008
Level of Funding: >$830,000
Weblink: carbonsciences.com
Phone: 805.456.7002

Location: Santa Barbara, CA
Number of Employees: N/A
Project Leader(s): Byron Elton
E. byron@carbonsciences.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): 150 gallons of fuel [95]
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



Carbon Sciences

Carbon Sciences converts CO_2 into basic hydrocarbons – C1 (methane), C2 (ethane), and C3 (propane) – which can then be utilized to make higher-grade fuels like gasoline and jet fuel.

The company uses novel, natural catalysts (biocatalysts) to perform chemical reactions – reacting CO_2 directly with methane – and to avoid the need for high temperatures or pressures.

The recycling process has five main stages. After rudimentary purification and regeneration of the biocatalysts, the CO_2 is transferred to a Biocatalytic Reactor Matrix where mass quantities of biocatalysts function in a matrix of liquid reaction chambers breaking down CO_2 and turning it into hydrocarbons. Liquids are then filtered and gases are extracted through condensers ready for conversion to higher-grade fuel.[94]

The company is also developing an approach to turn CO_2 into precipitated calcium carbonate. The target markets for this product are the paper, plastics, and pharmaceutical manufacturers.

Life of the biocatalysts is one issue that the company is working to address. The biocatalysts can become poisoned by nitrous oxide, sulfur dioxide, and other impurities, all of which can shorten the biocatalysts life and/or reduce their cost effectiveness.

The company's intellectual property is focused on a novel catalyst to extract H from CH_4, and a membrane reactor that acts as a filter to direct hydrocarbon production.

Partnerships & Demonstrations

The company, which is planning to pursue a licensing model, thinks China and the United States are both likely markets for its technology, specifically at coal-fired plants and large industrial processes, such as steel factories and natural gas facilities. The company states that recycling CO_2 from a 500 megawatt coal unit would cost ~$250 million.[96]

Year Initiated: 2010
Level of Funding: €4.5 million
Weblink: catalyticcenter.rwth-aachen.de
Phone: + 49.241.80.28 59 4

Location: Leverkussen, Germany
Number of Employees: N/A
Project Leader(s): Thomas E. Müller
E. Thomas.Mueller@CatalyticCenter.RWTH-Aachen.de

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

CAT Catalytic Center

Researchers from Bayer MaterialScience and Bayer Technology Services are working together with RWE Power AG and academic partner RWTH Aachen University on the production of polyether polycarbonate polyols (PPPs) that will be processed into polyurethanes and will involve the chemical bonding of CO_2, which will be an integral raw material in this sustainable process. The key technology for this is catalysis.

These polyols are one of two components – the other being diisocyanates – used to produce polyurethane polymers, which can be used to produce a polyurethane insulation for use in mattresses or footwear.

The project is dubbed the "Dream Production" project. "Dream Production" is based on a forerunner project "Dream Reactions", which was initiated by Bayer Technology Services and also funded by the BMBF.

The CO_2 used for the project will come from RWE Power's lignite-fired power plant at Niederaussem. This is where the electricity generator operates a CO_2 scrubbing system at its coal innovation center, by which the carbon dioxide is captured from the flue gas. For the Dream Production project the CO_2 scrubber will be equipped with an additional liquefaction system so that the carbon dioxide can be transported to Leverkusen. The CO_2 liquefaction system will be designed and operated with flexibility to meet various CO_2 pressures and purities on a scale ranging from kilograms up to tons.

Partnerships & Demonstrations

During the next three years the German Federal Ministry of Education and Research (BMBF) will invest a total of more than €4.5 million in the initiative, the project supervision of which is the German Aerospace Center (DLR). At the heart of the "Dream Production" project, sits the construction and commissioning of a pilot plant at Chempark Leverkusen.

Year Initiated: 2003
Level of Funding: N/A
Weblink: catelectric.us.com
Phone Number(s): 860.912.0800

Location: Groton, CT
Number of Employees: 4
Project Leader(s): Peter D. Pappas
E. peter@mcmil.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Catelectric Corporation

Catelectric Corporation has developed and laboratory proven a system of electronic control for catalytic reactions. The system operates effectively on gaseous or liquid reactants and electrical energy required to operate the system is very low. The benefits of the system are:

- Control of the rate of reaction and acceleration of that rate by several fold over that of a state of the art catalytic system.
- Selectivity of product – increased yield of favored products and decreased production of others.
- Expansion of the set of effective catalysts, including substitution of non-noble for noble catalysts.
- Enabling reactions previously not feasible.
- Mitigation of catalyst poisoning.

In a sponsored research project at the Department of Chemistry at the University of Connecticut, a catalytic reactor with the Catelectric control system has been proven to convert CO_2 into products of value, with product selectivity approaching 100%.

In addition to a wide variety of hydrocarbon products of value, significant amounts of free molecular oxygen are also produced.

The process is done in a single catalytic reactor with no moving parts other than the fluid (e.g. flue gas and product). It uses a non-noble metal oxide catalyst costing under \$5.00/pound. Produced products include paraformaldehyde, H_2, CO, methane, ethylene, ethane, propane, propylene, cyclic hydrocarbons and alcohols and in excellent yields. Hundreds of hydrocarbons can be selectively produced, including larger molecules (to date up to C-42). In the flue gas CO_2 treatment application, the process will use the waste heat in the gas to drive the reaction.

Partnerships & Demonstrations
Catelectric is affiliated with the Technology Incubation Program of the University of Connecticut.

Year Initiated: N/A
Level of Funding: N/A
Weblink: ceramatec.com
Phone Number(s): 801.978.2163

Location: Salt Lake City, UT
Number of Employees: 8
Project Leader(s): Joseph Hartvigsen
E. jjh@ceramatec.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

CERAMATEC

Ceramatec, Inc.

Ceramatec uses its in-house technologies like the plasma reformer, SOEC, and compact Fischer-Tropsch process to convert CO_2 into syngas, which can then be converted to a liquid fuel.

The Ceramatec cold plasma system uses a novel patented process called GlidArc®. The reformer utilizes a gliding plasma arc to create radicals, ions, and excited states (translational, vibrational and electronic) within the vaporized fuel stream to promote breaking of chemical bonds.

This approach processes a wide variety of fuels and provides for saturation of aromatics (i.e. hydrogenation), liberation of deeply bound sulfur (if present), and hydrolysis (hydro-cracking) of large hydrocarbons.

Ceramatec has tested its plasma fuel reformer on a variety of fuels including commercial diesel, JP-8, NATO F-76, S-8, JP 10 and bio-fuels. The reformer does require an electric input to generate the plasma but since the plasma is cold in nature, this requirement is minimal.

Ceramatec's high temperature solid oxide co-electrolysis Cell (SOEC) can be operated in a reverse mode to electrolyze steam and CO_2 to generate syngas. A 4-kW co-electrolyzer stack module was operated for more than 1,000 hours to produce syngas.

Finally, Ceramatec has a compact, transportable fixed bed Fischer Tropsch process. This process has also been proven at a laboratory scale and operated for substantial periods of time.

Partnerships & Demonstrations

Ceramatec is working with the Idaho National Laboratory to develop its SOEC technology.

Year Initiated: 2001
Level of Funding: N/A
Weblink: patft.uspto.gov
Phone Number(s): 918.333.5794

Location: Bartlesville, OK
Number of Employees: 2
Project Leader(s): Jinhua Yao
E. N/A

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

ConocoPhillips

Jinhua Yao and James Kimble, both of ConocoPhillips, invented a catalyst and process for converting CO_2 into oxygenates.

The catalyst is comprised of copper, zinc, aluminum, gallium, and a solid acid. The technology and process were disclosed in United States Patent Application 20030060355, which was filed in 2001, and United States Patent 6,664,207, which was granted in 2003, and 7,273,893, which was granted in 2007.

These patents together focus on the direct recycling of CO_2 into liquid fuels such as methanol and dimethyl ether.

The patents describe a process comprising the steps of: (a) contacting the carbon dioxide-containing feed with a catalyst composition comprising a solid acid in a reaction zone under reaction conditions sufficient to convert at least a portion of the feed stream into oxygenates, CO_2-containing feed comprising at least 90 volume percent CO_2 and hydrogen, and solid acid comprising a zeolite; and (b) recovering at least a portion of the oxygenates from the reaction zone.

Partnerships & Demonstrations
None.

Year Initiated: 2010
Level of Funding: N/A
Weblink: dismukes.rutgers.edu
Phone Number(s): 732.445.1489

Location: Piscataway, NJ
Number of Employees: 2
Project Leader(s): Charles Dismukes
E. dismukes@rci.rutgers.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

Cube Catalytics, LLC

Cube Catalytics enables zero carbon hydrogen feedstock and fuel at and below the cost of steam reforming of methane and natural gas.

The company has developed a line of catalysts used in electrolyzers and solar fuel cells to produce clean fuels with zero carbon emission. It is also developing a cheap polymer based electrolyzer based upon these catalysts. The fuel that is currently being generated is hydrogen from water.

The company's bio-mimic catalyst is integrated into a Catalytic Solar Cell, which enables direct solar oxidation of water.

The company is developing this technology further to enable production of methanol (CH_3OH) from CO_2 and water.

The technology was developed by Charles Dismukes at Rutgers University and proven in his laboratory.

Partnerships & Demonstrations

The company is closely affiliated with Rutgers University.

Year Initiated: 2007
Level of Funding: N/A
Weblink: dnv.com
Phone Number(s): 614.761.6920

Location: Dublin, OH
Number of Employees: 8
Project Leader(s): Narasi Sridhar
E. narasi.sridhar@dnv.com

Energy Efficiency (MWh/ton of converted CO_2): 6-7
Conversion Metric (Ton of CO_2 → ? quantity of product): 1
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): 0.5
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

Det Norske Veritas (DNV)

In DNV's "ECFORM" process, which the company has been working on since 2007, tin or proprietary alloys are used as the cathodes that convert CO_2 to formate / formic acid. While this process generates formic acid, the process can be tuned to generate carbon monoxide.

The company states that the ECFORM process demonstrates the greatest probability of profitability and lowest net CO_2 generation when the following conditions are met:

- The CO_2 is delivered in pure or mostly-pure form;
- Process heat or other renewable energy forms are available;
- Catalyst performance can be maintained for a long period of time (greater than 4000 h);
- Process volumes are manageable (<100 tons per day);
- Electrolyte consumables are significantly reduced or completely eliminated;
- Opportunities for other energy management scenarios are available.

ECFORM at present requires approximately 6 to 7 MWh/ton of converted CO_2, including auxiliary processing energy.

Partnerships & Demonstrations

As part of its research, DNV has assembled a demonstration reactor in a solar-powered trailer. Additionally, a semi-pilot size reactor with a superficial area of 600 cm^2 (capable of reducing approximately 1 Kg/d of CO_2) powered by renewable energy was built as a demonstration project. Scale-up developments are under way.

Year Initiated: 2007
Level of Funding: $0
Weblink: dotyenergy.com
Phone Number(s): 803.788.6497

Location: Columbia, SC
Number of Employees: 1
Project Leader(s): F. David Doty
E. david.doty@dotyenergy.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

Doty WindFuels

Doty WindFuels proposes to use off-peak wind energy to electrolyze water to produce hydrogen, which is then added to CO_2 to reform CO_2 into water and CO, which is then chemically reformed into liquid hydrocarbon fuels including gasoline and jet fuel.

Doty claims technical advances in the:

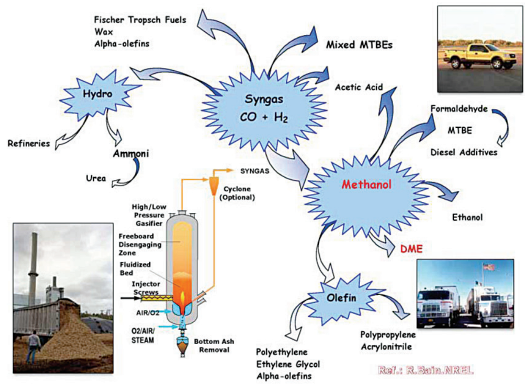
- Efficiency of production of syngas;
- Reduction in the losses seen in recycling of the unreacted Fischer-Tropsch;
- Cost-effectiveness of gas-to-gas recuperators with high thermal effectiveness (up to 97%);
- Catalysts;
- Plant integration;
- Efficiency of conversion of waste heat from the FT reactor and electrolyzer to electricity.

Partnerships & Demonstrations
None.

Year Initiated: 2008
Level of Funding: $200,000
Weblink: ecoglobalfuels.com
Phone Number(s): 848.702.3779

Location: New York, NY
Number of Employees: 3
Project Leaders: Roger Green; Ross Spiros
E. ecoglobalfuels@earthlink.net

Energy Efficiency (MWh/ton of converted CO_2): 0.7
Conversion Metric (Ton of CO_2 → ? quantity of product): 0.0565 ethanol; 0.0378 methanol; 0.231 methane
Land Footprint (Tons/acre of capacity): 1460 per year
Water Footprint (Gal/ton of CO_2 recycled): 166
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N



Eco Global Fuels

The company uses a catalytic process to produce ethanol, methanol, and methane from CO_2 and hydrogen.

It uses a proven, patentable Hydroxy generator technology to produce cheap hydrogen. The hydrogen is combined with CO_2 from coal/gas power plant emissions.

The company's technology produces 8 parts pure oxygen to 1 part hydrogen. The oxygen is fed into gas/coal power plant turbines to burn pure (i.e. no nitrogen from the air), producing a pure carbon black that can be used for several products, such as keeping the CO_2 on the ground (such as biochar).

Altogether, relevant products the technology can produce are olefin, formaldehyde, carbon black car/truck tires, carbon fertilizers and carbon graphite.

Partnerships & Demonstrations
The company is working with an Australian university, which has validated the reliability and cost efficiency over several months period. The technology was provided with an Australian Research and Development Grant. The company is looking for investors to scale-up their technology.

Year Initiated: 2010
Level of Funding: N/A
Weblink: energyscienceinternational.com
Phone Number(s): 559.477.4292

Location: Fresno, CA
Number of Employees: 3
Project Leader(s): Keith Rahn
E. krahn@energyscienceinternational.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Energy Science International

Energy Science International (ESI) uses flue gas to create syngas, a mixture of carbon monoxide (CO) and hydrogen (H_2), through a combination of several technologies.

Its proprietary plasma gasification system converts carbonaceous materials to an ultra pure syngas and methanol.

Sabatier and Reverse Water Gas Shift technologies are used to process CO_2 a byproduct of the overall combined processes and imported CO_2 from other industrial processes and combustion flue gas streams into methane and CO.

Hydrogen is produced through a proprietary process developed by the founders of ESI and mixed with the CO to produce additional syngas.

Altogether, the company is focused on applying its energy conversion technologies to multiple sources of energy including; traditional coal, petrochemical, municipal waste, sewage, hazardous waste, and transportation vehicle tire recovery, various bio-mass, traditional renewable sources, and industrial energy sources.

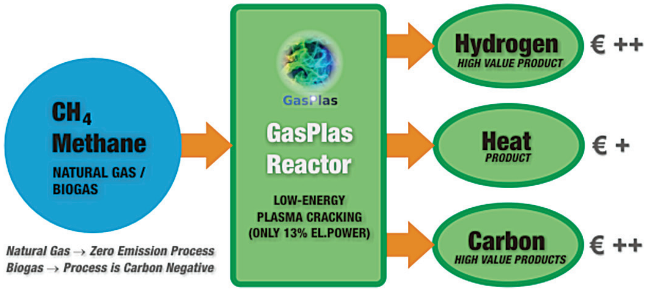
Partnerships & Demonstrations

The company's first demonstration will be with the U.S. government at a military installation. The demonstration should begin in 2011. The technology will be available for license after the demonstration is completed, which is estimated in approximately the next two years.

Year Initiated: N/A
Level of Funding: N/A
Weblink: gasplas.com
Phone Number(s): +47.91595161

Location: Oslo, Norway
Number of Employees: N/A
Project Leader(s): Per Espen Stoknes
E. per.espen@gasplas.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N



GasPlas

GasPlas has developed a plasma technology that produces hydrogen, heat, and carbon structures in a distributed and environmentally sustainable manner. The technology is applicable to CO_2 reduction.

The hydrogen is extracted from hydrocarbons such as methane by means of low-energy plasma cracking and generates dry carbon rather than carbon dioxide.

Targeted carbon markets include biofuels, carbon-to-soil sequestration, carbon enriched fertilizer, and ammonia.

Partnerships & Demonstrations

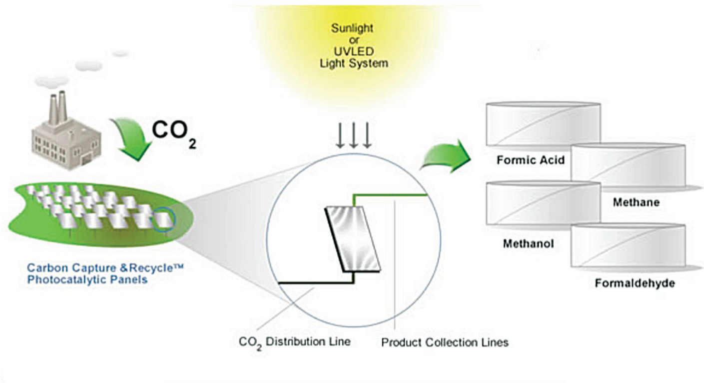
Initial laboratory proof of concept was achieved in June 2009.

GasPlas is working with Environmental science at University of East Anglia, Norner Innovations AS, Materials and Chemistry at Sintef research division, and Bayerngas Norge AS on a research project focused on advanced carbon structures.

Year Initiated: 2007
Level of Funding: $147,095
Weblink: gonano-technologies.com
Phone Number(s): 208.892.2000

Location: Moscow, Idaho
Number of Employees: N/A
Project Leader(s): Tim Kinkeade
E. tk@gonano-9.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N



GoNano Technologies

GoNano Technologies uses a photocatalyst consisting of silica nanosprings coated with a combination of titanium dioxide and proprietary dopants to convert CO_2 to useful and commercially valuable feedstock chemicals, including methanol, formic acid, and formaldehyde.

GoNano Technologies says its CO_2 recycling process is the only photocatalytic carbon recycling system that offers a selectable product output based on input and flow rate.

The nanospring technology platform was developed over a decade long collaboration between Washington State University and University of Idaho.

In 2010, the National Science Foundation awarded GoNano Technologies a Phase I Small Business Innovative Research (SBIR) grant of ~$150K. The grant is helping GoNano to continue the research and marketing of its technology in the United States and Canada.

Partnerships & Demonstrations

In May 2011, 3M, through its New Ventures Business, invested in GoNano Technologies Inc. Terms of the transaction have not been disclosed.

Year Initiated: 2009
Level of Funding: $0
Weblink: homiangz.com
Phone Number(s): 303.774.8327

Location: Longmont, CO
Number of Employees: 3
Project Leader(s): Qingchun Zhao
E. qzhao@homiangz.com

Energy Efficiency (MWh/ton of converted CO_2): 10
Conversion Metric (Ton of CO_2 → ? quantity of product): 0.4
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): 120
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Homiangz, LLC

Homiangz's core technology is based on a Nobel-prize-winning technology that can use CO_2 to produce methane and methanol.

The company projects that the technology is capable of producing one-third of all natural gas.

The technology is in the very early stages of development. The company has theoretically worked out how the technology works and is now looking to establish a facility to demonstrate the performance.

Partnerships & Demonstrations
None.

Year Initiated: 2009
Level of Funding: N/A
Weblink: liquidlightinc.com
Phone: 732.230.2498

Location: Monmouth Junction, NJ
Number of Employees: 5
Project Leader(s): Kyle Teamey
E. kyle@llfuels.com

Energy Efficiency (MWh/ton of converted CO_2): Product Dependent
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): 0.3 to 1
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): 0.5 to 3
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Liquid Light, Inc.

Liquid Light is developing a catalytic platform for the conversion of CO_2 to a wide variety of chemicals and fuels.

Originally discovered at Princeton University, the company's catalysts are efficient, stable, and allow for the selective conversion of CO_2 to one product at a time.

Over a dozen products have been made to date, including carboxylic acids, aldehydes, ketones, and alcohols. Only CO_2 and water are consumed in the process and it can be powered by any source of electric power or sunlight.

Working in close collaboration with Princeton, Liquid Light is continuing to advance the capabilities and efficiency of catalysts and processes. Recent advances include high efficiency conversion of CO_2 to butanol.

Partnerships & Demonstrations

The company's technology is based on groundbreaking discoveries from the laboratory of Professor Andrew Bocarsly at Princeton University. Liquid Light has exclusive rights to Professor Bocarsly's work at Princeton and is continually advancing the science at the company's own laboratories.

Liquid Light also recently obtained exclusive rights to advanced catalysts from the laboratory of Professor Shannon Stahl at the University of Wisconsin.

The company received seed funding from Redpoint Ventures.

Year Initiated: 2005
Level of Funding: $0
Weblink: losalamossolar energy.com
Phone Number(s): 505.660.6992

Location: Pojoaque, NM
Number of Employees: 3
Project Leader(s): Reed Jensen
E. contact@losalamossolarenergy.com

Energy Efficiency (MWh/ton of converted CO_2): 44%
Conversion Metric (Ton of CO_2 → ? quantity of product): .7ton CH_3OH
Land Footprint (Tons/acre of capacity): 84 gal MeOH/acre/day
Water Footprint (Gal/ton of CO_2 recycled): 217
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

Los Alamos Solar Energy

At its plant in Pojoaque, the company has successfully demonstrated its ability to "split CO_2" using solar energy to produce electricity and fuel.

This process, called SOLAREC™ (Solar Reduction of Carbon), uses ultra-high temperatures created by focusing the energy from the sun to split CO_2 into its component parts: carbon monoxide and oxygen. The carbon monoxide is then reacted chemically to produce fuel with no harmful CO_2 emissions.

The company believes that it can succeed in accomplishing all of the keys to economic success for high temperature solar driven thermolysis of CO_2, which it lists as:

- Limit blackbody re-radiation to under 20% by optically mating the dish to the receiver through small apertures with high quality optics;
- Provide large surface area, correct flow and temperature profile multichannel reactor body for heat transfer and back reaction quenching;
- Efficient use of cool-down energy to drive efficient on-board Brayton engine and collective on ground combined cycle engine;
- Use of engine rejected heat to provide release energy for gases in the back-end separation steps.

Partnerships & Demonstrations

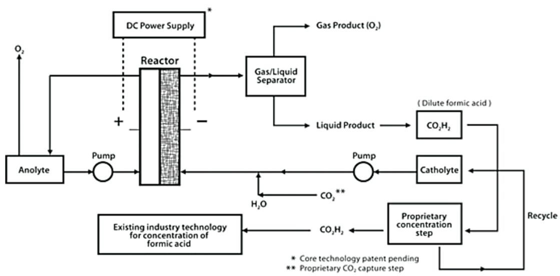
None.

Year Initiated: 2007
Level of Funding: $5 million
Weblink: mantraenergy.com
Phone Number(s): 604.535.4145

Location: South Surrey, Canada
Number of Employees: 7
Project Leader(s): Larry Kristof
E. larry@mantraenergy.com

Energy Efficiency (MWh/ton of converted CO_2): 5
Conversion Metric (Ton of CO_2 → ? quantity of product): ~965kg of formic acid/formate
Land Footprint (Tons/acre of capacity): ~100 metric tons
Water Footprint (Gal/ton of CO_2 recycled): 108
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

MANTRA ENERGY ALTERNATIVES LTD



Mantra Energy Alternatives Ltd.

Mantra is focused on electrochemical reduction of CO_2, using the gas as a feedstock for the production of formic acid or formate, both being non-volatile organic chemicals.

Mantra owns the intellectual property PCT applied for WO 2007/041872 A1, Continuous Co-current Electrochemical Reduction of Carbon Dioxide. This was acquired from Professor Colin Oloman, who developed the technology at the University of British Columbia. Worldwide patenting is underway in China, U.S., India and Australia.

Mantra claims that progress has been made with the development of ERC:

- The energy requirement has been reduced by a third;
- The process efficiency raised from 50% to 90% (a figure claimed to be acceptable in an electrochemical process);
- The physical structure has been improved and energy flow eased;
- The cathode catalyst has been upgraded, its efficiency and lifetime improved;
- A complete turnkey system suitable for industry has been conceived and the separate parts tested.

Mantra's system requires concentrated CO_2, but the stream does not have to be pure. The system can have provision to upgrade the 12 percent CO_2 flue gas input to a concentration suitable for ERC. Approx. >80 percent CO_2 concentrate is feasible in the system process.

Partnerships & Demonstrations

Mantra is partnered with Kemira ChemSolutions, a subsidiary of Kemira Oyj, in its production and sale of formic acid. Mantra has a demonstration project with LaFarge in Canada, a demonstration project with KC Cotrell in Korea, and an MOU with Green Commerce Innovation Corporation of Richmond, BC ("GCIC") focused on the cultivation of business opportunities for Mantra in China.

Year Initiated: 2009
Level of Funding: N/A
Weblink: morphic.se/en/
Phone Number(s): 46(0)586.673.90

Location: Karlskoga, Sweden
Number of Employees: N/A
Project Leader(s): Martin Valfridsson
E. martin.valfridsson@morphic.se

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

Morphic Technologies

Morphic Technologies obtained a patent for a process that uses wind turbines combined with CO_2, water and excess electricity to manufacture a form of liquid biofuel that can be used in vehicles and to power all kinds of machinery.

The company has verified the effectiveness of the process independently with several scientific laboratories, and is currently in the process of seeking investors to help bring their clean, patented method for converting greenhouse gas to fuel into mass production so they can get their product onto the open market.

This process for converting greenhouse gas to fuel uses a Brayton engineering cycle in combination with a supercritical carbon dioxide turbine to harness the energy in atmospheric carbon. The Brayton cycle consists of a solar heated fluid that passes through a complex series of cooling systems that in turn generate energy for carbon dioxide turbine.

The benefit of using the Brayton cycle/carbon dioxide turbine combination to power the carbon removal process is that it makes a large-scale industrial application of CO_2 removal possible without burning additional hydrocarbons.

Instead, the energy needed to remove wasted carbon from the atmosphere can be generated using solar heat provided by sunlight.

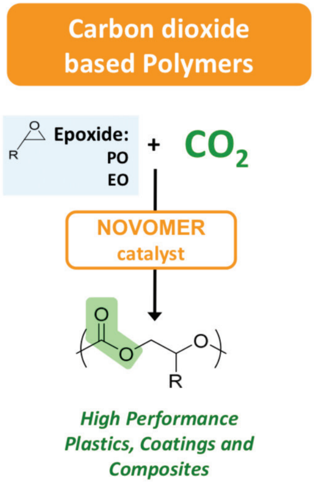
Partnerships & Demonstrations

The technology has been demonstrated on laboratory scale.

Year Initiated: 2005
Level of Funding: >$40 million
Weblink: novomer.com
Phone Number(s):
781.419.9860x112

Location: Waltham, MA
Number of Employees: 30
Project Leader(s): Jim Mahoney
E. jmahoney@novomer.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): 2 tons
Land Footprint (Tons/acre of capacity): 400
Water Footprint (Gal/ton of CO_2 recycled): 0
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



Novomer, Inc.

Novomer's technology uses CO and CO_2 as feedstocks to synthesize a variety of low-cost chemicals and high performance polymers. Novomer's CO technology platform can produce a host of chemicals, including acrylic acid, acrylate esters, butane diol, and tetrahyrdofuran. Novomer's CO_2-based polymers can be used in a variety of applications, including coating resins (e.g., interior can coatings), flexible & rigid packaging applications (e.g., films, bottles), composite resins, and polyurethane foams.

The company uses a proprietary catalyst technology developed by Geoff Coates at Cornell University, which the company says is straightforward to synthesize despite being a relatively complex organometallic compound. The catalyst technology enables CO and CO_2 to react with petrochemical epoxides to create key intermediates such as succinic anhydride and a family of polymers that are up to 50 percent by weight CO_2, respectively.

Novomer can form both high molecular weight (MW) thermoplastics and low MW polymers for thermoset resin applications such as coatings, adhesives, and foams.

In July 2010, Novomer was awarded an approximately $2.1 million ARRA award from the DOE to pursue its technology. In the competitive second phase of the award, the company was awarded an additional ~$18.5 million to expand and further develop its operations.

Novomer has business operations in Waltham, MA; R&D facilities in Ithaca and Rochester, NY; and manufacturing partnerships with Albemarle Corporation and Kodak Specialty Chemicals.

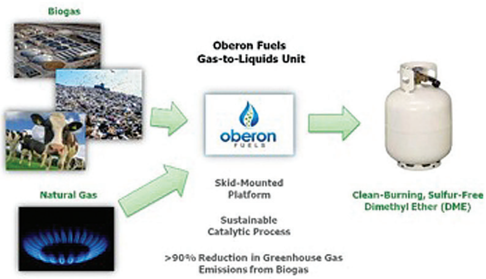
Partnerships & Demonstrations

Novomer is collaborating with Dutch life sciences and materials company DSM, focused on low MW polymers for coating and ink resins. The company also has applications development partnerships with a major polymer producer focused on films, a major consumer packaged goods company focused on bottles, as well as other confidential relationships. Albemarle Corporation and Kodak Specialty Chemicals are Novomer's manufacturing scale-up partners.

Year Initiated: N/A
Level of Funding: $0
Weblink: oberonfuels.com
Phone Number(s): 858.754.3201

Location: La Jolla, CA
Number of Employees: 4
Project Leader(s): Neil Senturia
E. neil@blackbirdv.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y (w/filter)



Oberon Fuels

Oberon Fuels operates a portable process to convert methane and CO_2 into dimethyl ether (DME) and distilled water.

The Oberon Fuels process consists of three major steps: syngas production, methanol synthesis, and simultaneous DME synthesis and separation via catalytic distillation.

While the first two process steps are common in large-scale industrial applications, further development of these processes for small-scale applications is open for improvement and implementation.

Catalytic synthesis of DME coupled with purification is a well-researched topic that is both promising and feasible, but has not been industrially implemented to date.

Commercially available ion exchange catalysts are ideal for use in the final DME-production process, relieving the need for any immediate catalyst development. Oberon may use the technical expertise of CD Tech, a company experienced in catalytic distillation, to ensure the success of this unique reactor – separator set-up.

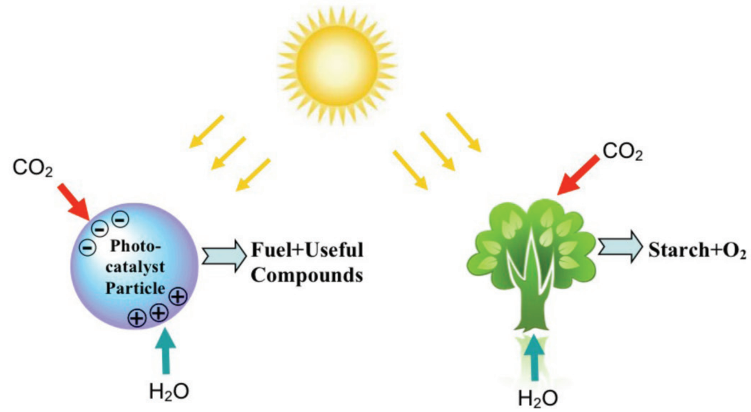
The ideal amount of CO_2 is about 30% by volume, but the process can be tuned to tolerate between 0 and 50%, making it well suited to digester and landfill biogas.

Partnerships & Demonstrations
None.

Year Initiated: 2010
Level of Funding: $1,248,508
Weblink: phosphortech.com
Phone Number(s): 404.664.5008

Location: Lithia Springs, GA
Number of Employees: 10
Project Leader(s): Hisham Menkara
E. hisham@phosphortech.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



PhosphorTech Corp

In 2010, PhosphorTech received an approximately $1 million grant from the DOE to develop and demonstrate an electrochemical process using a light-harvesting CO_2 catalyst to reform CO_2 into products such as methane gas and other useful hydrocarbons. The project duration is three years.

The objectives of this project are to develop and demonstrate a novel CO_2 catalytic structure having high CO_2 reduction potential, high absorption in the visible part of the solar spectrum, and high utilization of infrared solar energy. Both a low-cost solution manufacturing and a higher-cost vacuum deposition process will be developed and optimized to achieve a semiconducting structure with optical and electrical properties consistent with those of high quality films.

PhosphorTech Corporation was formed in 1998 with the support of the Advanced Technology Development Center at the Georgia Institute of Technology. The purpose of PhosphorTech is to develop and manufacture new photonic materials and nanotechnologies for energy-efficient applications ranging from solid-state lighting to emissive displays.

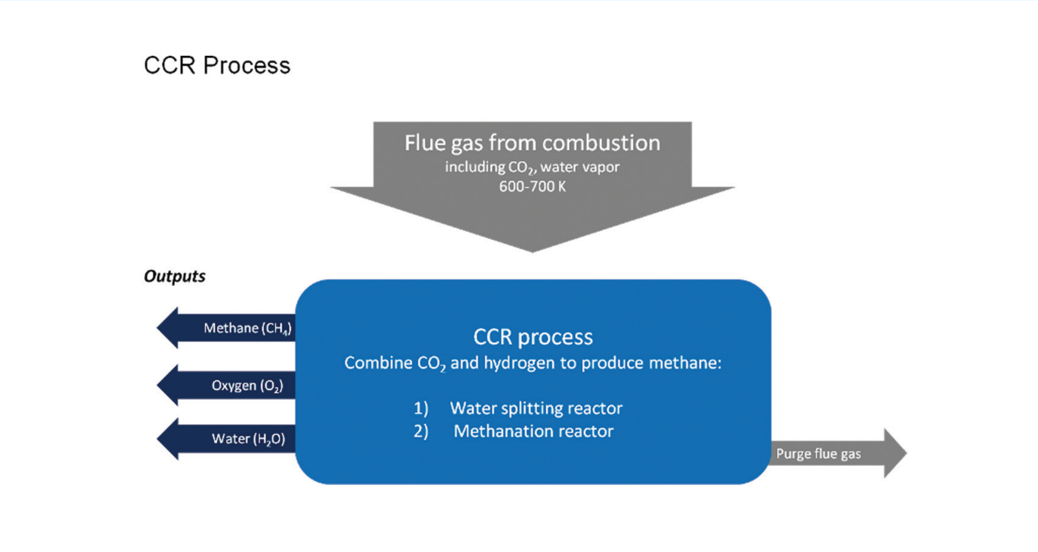
A semiconductor such as TiO_2 is used as a manmade photocatalyst to convert CO_2 into useful materials. The process is similar to how natural plant cholrophyll converts CO_2 into starch and O_2.

Partnerships & Demonstrations
PhosphorTech is working with the Georgia Institute of Technology.

Year Initiated: 2007
Level of Funding: $0
Weblink: rco2.no
Phone Number(s):
+47.48.19.69.98

Location: Langhus, Norway
Number of Employees: 5
Project Leader(s): Andreas Jul Røsjø
E. andreas.rosjo@rco2.no

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N



RCO2

RCO2 is a Norwegian R&D company established in 2006. Currently it is focusing its efforts into environmental technologies aiming to reduce emissions from combustion processes.

Accordingly, the company has developed a catalytic gas reactor that includes a catalyzer or process to create hydrogen and oxygen by splitting water. It also includes a process with a catalyzer that creates methane from reactions wherein CO, CO_2 and hydrogen participate according to a methanation reaction scheme.

The company has filed for and received patent no. WO 2008/054230.

Partnerships & Demonstrations
None.

Year Initiated: 2009
Level of Funding: ~$16.6 million
Weblink: suncatalytix.com
Phone Number(s): 617.253.5537

Location: Cambridge, MA
Number of Employees: N/A
Project Leader(s): Daniel Nocera
E. nocera@mit.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

Sun Catalytix

Sun Catalytix Corporation

Sun Catalytix is focused on using newly discovered catalytic materials to enable generation of affordable renewable fuel from sunlight and water.

The company's technology builds on water-splitting discovery work from the lab of Professor Daniel Nocera at the Massachusetts Institute of Technology.

In early 2010, the company was awarded a $4.1 million ARPA-e contract

The company's ARPA-E program is continuing the advancement of its catalytic technology in two parallel directions: electrolysis cells and photoelectrochemical cells.

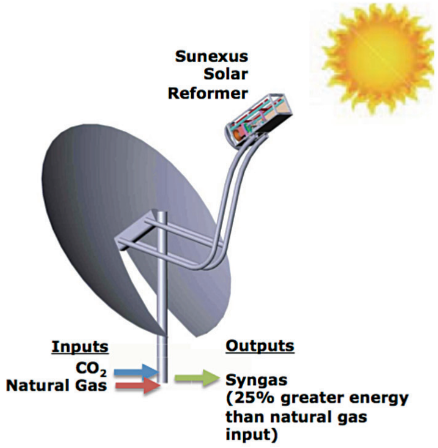
In 2009, Polaris Venture Partners provided $3 million in seed funding for Sun Catalytix. Tata Limited, Polaris, and others followed with $9.5 million in Series B Funding in late 2010.

Partnerships & Demonstrations
Sun Catalytix works closely with the Massachusetts Institute of Technology, where its technology was founded. It has exclusively licensed patents from the university.

Year Initiated: 2009
Level of Funding: $1.3 million
Weblink: sunexusenergy.com
Phone Number(s): 916.290.9350

Location: Sacramento, CA
Number of Employees: <10
Project Leader(s): Robert Schuetzle
E. rschuetzle@prfuels.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): Varies
Water Footprint (Gal/ton of CO_2 recycled): 0
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Depends on plant configuration



Sunexus

Sunexus has developed a system that processes CO_2 and natural gas or methane in a catalytic reaction to produce syngas.

The heat that enables the reaction is provided by solar energy, and the output syngas has significantly more energy than the incoming natural gas. The company states that the solution provides the dual benefit of recycling CO_2 and producing an enhanced syngas with renewable solar energy.

In the Sunexus process, a concentrating dish is used to focus solar energy onto the reactor. The dish tracks the sun throughout the day to optimize heat input. The Sunexus Solar Reformer transfers the solar energy to the reaction zone and heats the proprietary reforming catalyst to the target temperature. Natural gas and CO_2 are fed into the reformer, and the result is the production of syngas [H_2 + CO] that has greater energy than the natural gas input. The output syngas can be used in most standard turbines to generate electricity or can be used to produce fuels or chemicals.

The Sunexus technology can also be used with other concentrating solar technologies, including power towers.

Sunexus' intellectual property includes its work on the solar reforming catalyst, the solar micro-channel reactor, the control system and commercial system design including dish and power tower designs.

Partnerships & Demonstrations

The Sunexus technologies were developed under seed funding and a $1M+ DOE grant during 2009-10 with the goal of demonstrating utilization of CO_2 using solar energy. Pacific Renewable Fuels & Chemicals (PRFC), along with Sandia National Laboratories, Pratt & Whitney Rocketdyne, and Infinia Corporation, led the consortium of developers. A pilot demonstration unit has been completed and successfully tested in Sacramento, CA.

Year Initiated: 2011
Level of Funding: $79,980
Weblink: sustainableinnov.com
Phone Number(s): 860.652.9690

Location: Glastonbury, CT
Number of Employees: N/A
Project Leader(s): Trent Molter
E. trent.molter@sustainableinnov.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

Sustainable Innovations, LLC

Sustainable Innovations is developing an Electrochemical Greenhouse Gas Recycling System (EGGRS) that captures GHGs and converts them electrochemically to chemical commodities, such as methanol (CH_3OH), ammonia (NH_4) and sulfuric acid (H_2SO_4).

The electrochemical process requires only water and GHG to produce the liquid hydrocarbons with oxygen as a by-product.

In March 2011, the company received an approximately $80,000 Small Business Innovation Research (SBIR) grant from the EPA to fund the first phase of a two-phase project. This first phase will demonstrate feasibility of greenhouse gas (CO_2, NO_x and SO_x) conversion. A top-level design for directly coupling the EGGRS system to a large-scale emitter also will be undertaken.

Phase 2 of the program will scale up the technology and generate a demonstrator/prototype to be tested at an offsite location using real world GHG emissions.

Partnerships & Demonstrations

The EPA funds the company for the first phase of a project that will, in its second phase, lead to real world demonstration.

Mineralization »

Year Initiated: 2009
Level of Funding: ~$16 million
Weblink: alcoa.com | co2solution.com | codexis.com
Phone Number(s): 905.320.6260

Location: Pittsburgh, PA | Point Comfort, TX
Number of Employees: N/A
Project Leader(s): Jonathan Carley
E. jonathan.carley@co2solution.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Alcoa, CO_2 Solution & Codexis

In April 2011, Alcoa, Codexis, Inc. and CO_2 Solution, Inc. announced a pilot program focused on utilizing carbon dioxide to treat bauxite residue, a major waste product of the aluminum production process. The project will test a scrubbing process that combines captured carbon dioxide, enzymes and alkaline clay to create a mineral-rich neutralized product that could be used for environmental reclamation projects.

Scientists and engineers from Alcoa Technical Center in Pittsburgh will lead the three-year project, which has an investigation phase that runs through December 2011. Upon successful completion of this phase, the project will proceed to a pilot-testing phase at Alcoa's Point Comfort alumina refinery in Texas.

The pilot builds off of a two-year collaboration between CO_2 Solution and Codexis focused on validating the use of custom carbonic anhydrase (CA) enzymes and processes to significantly reduce the cost of carbon dioxide capture from power plants and other large industrial sources of carbon pollution. CA is an enzyme that efficiently manages carbon dioxide in nature, and the collaboration to date has created CA biocatalysts with substantially improved stability and performance under industrial conditions.

In 2010, Alcoa received a $1 million grant from the DOE to fund a first lab-scale phase. Based on its success, the company received an additional $12 million from the DOE to fund the second phase, which includes construction of the pilot plant.

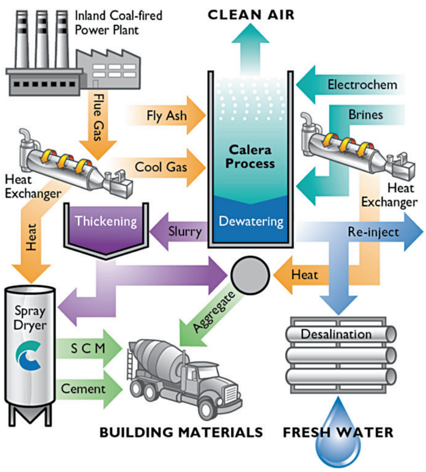
Partnerships & Demonstrations

Alcoa's pilot-scale process will demonstrate the high efficiency conversion of flue gas CO_2 into bicarbonate and carbonate using an in-duct scrubber system featuring an enzyme catalyst. The bicarbonate/carbonate scrubber blow down can be sequestered as solid mineral carbonates after reacting with alkaline clay, a by-product of aluminum refining. The carbonate product can be utilized as construction fill material, soil amendments, and green fertilizer.

Year Initiated: 2007
Level of Funding: ~$86.5 million
Weblink: calera.com
Phone Number(s): 408.340.4600

Location: Los Gatos, CA
Number of Employees: N/A
Project Leader(s): Austin Maguire
E. amaguire@calera.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): 2 tons
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



Calera Corporation

Calera, in partnership with Bechtel, EPRI, U.S. Concrete, and Khosla Ventures, uses seawater or other water sources to scrub the CO_2 out of flue gas. The CO_2 is absorbed into the water and reacts with it to form carbonic acid, H_2CO_3. Further processing strips both the hydrogen ions, allowing calcium and magnesium ions to react with the remaining CO_3 ion. The $CaCO_3$ and $MgCO_3$ form a solid precipitate, and the water left over (called the supernatant) is demineralized of about 80 percent of its original calcium and magnesium. Freshwater is a byproduct of this process. Calera refers to its process as Mineralization via Aqueous Precipitation, or MAP for short.

The precipitate aggregates to create supplementary cementitious material (SCM), which can be used to make concrete, asphalt, and other building applications. Each ton of this new mineral carbonate material produced utilizes approximately ½ ton of CO_2.

In July 2010, Calera was awarded an approximately $1.7 million ARRA award from the DOE to pursue its technology. In the competitive second phase of the award, the company was awarded an additional ~$19.9 million to complete the detailed design, construction, and operation of a building material production system that at smaller scales has produced carbonate-containing aggregates suitable as construction fill or partial feedstock for use at cement production facilities. The building material production system will ultimately be integrated with the absorption facility to demonstrate viable process operation at a significant scale.

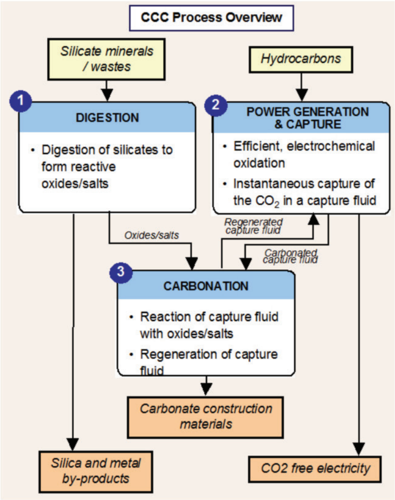
Partnerships & Demonstrations

Calera has a demonstration plant at Moss Landing, California that can capture 30,000 T/year of a CO_2. The Calera Yallourn project, which is in development in the Latrobe Valley in Australia, was anticipated to capture more than 300,000 T of CO_2 and produce more than one million T/year of building materials, but it has reportedly been abandoned. The company received about $50 million from Khosla Ventures, $15 million from Peabody Energy, and $19.9 million from the DOE.

Year Initiated: 2010
Level of Funding: £40,000
Weblink: cambcarbcap.wordpress.com
Phone Number(s): N/A

Location: Cambridge, U.K.
Number of Employees: 2
Project Leader(s): Robin Francis
E. info@cacaca.co.uk

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N



Cambridge Carbon Capture

Cambridge Carbon Capture (CCC) performs mineral carbonation, converting silicates to solid carbonates through a process that mimics the natural process by which CO_2 is removed from the atmosphere. The company's technology also produces electricity.

The company claims to have achieved a number of breakthroughs that reduce the energy and capital requirements for mineralization. The process combines carbon free power generation with the production of useful materials and, in some cases, the remediation of wastes such as combustion ashes, metal production wastes, and mine tailing.

The company claims that:

- Advanced digestion processes are used to convert silicate minerals (or wastes) to reactive oxides/salts in a low energy process;
- Hydrocarbon fuels are efficiently, cleanly and cheaply converted to electricity via direct electrochemical oxidation using a fuel cell;
- Output solid carbonates are created that can be used as construction aggregates, with other high value by-products isolated.

In 2011, the company was the regional winner of the Shell Springboard competition for smart ideas to cut carbon.

Partnerships & Demonstrations

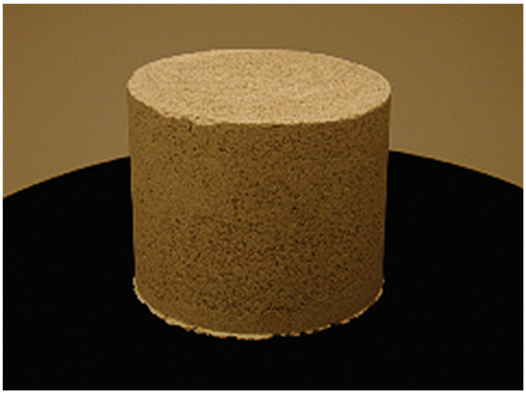
The CCC process has been proven at laboratory scale and development partners are being engaged for scale up and commercialization. Development partners include University of Cambridge, Nottingham University and other expert research and technology organizations. Funding partners include the Technology Strategy Board, EEDA and HEFC.

Year Initiated: 2010
Level of Funding: $1,473,861
Weblink: ccsmat.com
Phone Number(s): 203.254.9926

Location: Piscataway, NJ
Number of Employees: N/A
Project Leader(s): J. Norman Allen
E. nallen@ccsmat.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

CCSMaterials



CCS Materials, Inc.

The company is working to create an energy efficient, CO_2-consuming inorganic binder that will act as a suitable substitute for Portland cement in concrete.

The process being developed by CCS Materials will enrich CO_2 in a concrete admixture. It utilizes a binding phase based on carbonation chemistry.

Utilizing this chemistry requires no pyro-processing and eliminates the need for large Portland cement kilns, thereby saving significant amounts of energy and reducing CO_2 emissions in the process. Processing of Portland cement requires very high temperatures (approximately 1,450 °C) whereas the processing of CO_2-containing product requires much lower temperatures resulting in less energy use.

Furthermore, the microstructure and chemistry resulting from CCSM's process creates a much stronger material than what is created with traditional Portland cement processing.

The company is investigating the dependence of the reaction rate and carbonation yield on temperature, pressure and particle size.

The company envisions significantly reducing the energy required to make concrete by approximately 60 percent and lowering total CO_2 emissions by approximately 90 percent. This will permit the sequestration of large amounts of CO_2 via construction materials.

In July 2010, the team was awarded an approximately $800K award from NETL, bringing the total value of this project to approximately $1.5 million.

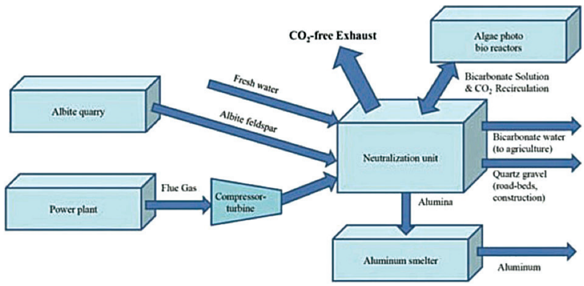
Partnerships & Demonstrations
The company is partnering with the Ceramic and Composite Materials Center, lead by Professor Richard Riman, at Rutgers University to develop its technology.

Year Initiated: 2004
Level of Funding: N/A
Weblink: cuycha.com
Phone Number(s): +358.50.594.1670

Location: Rajamäki, Finland
Number of Employees: 3
Project Leader(s): Ilkka Nurmia
E. Ilkka.nurmia@cuycha.com

Energy Efficiency (MWh/ton of converted CO_2): Varies
Conversion Metric (Ton of CO_2 → ? quantity of product): 1.16T alumina
Land Footprint (Tons/acre of capacity): Varies
Water Footprint (Gal/ton of CO_2 recycled): ~600
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Cuycha



Cuycha Innovation Oy

Cuycha dubs their process "CCN", and focuses it on the production of alumina, quartz sand, and lithium.

It starts with capturing CO_2 from raw flue gas using a patented washing technique. The exiting CO_2 solution passes into a neutralization tank filled with crushed feldspar. From there, the neutralization solution passes into a settling tank where the insoluble aluminum compounds settle. The solution can then exit the process or it can be recycled into the CO_2 dissolution process.

The company also says its CCN-process is a cost-effective way to separate rare elements from large quantities of silicate minerals. For example spodumene, a variation of feldspar, contains large amounts of lithium, a strategic metal for the rechargeable battery industry. One ton of spodumene will yield, besides the alumina mentioned above, around 200 kg of lithium carbonate. Other recoverable metals include rare earths, and heavy metals like tantalum.

Partnerships & Demonstrations

In 2011, Cuycha is partnering with CircleLink Holdings and others to deploy a low or zero emission aluminum production pilot plant in the Republic of South Africa. Cuycha indicates that not only will this pilot be used to prove and test the CCN process, but also will test many new ideas to recycle other harmful byproducts of industry into useful commodities. Cuycha speculates that a similar project could deploy in neighboring Botswana.

Year Initiated: 2008
Level of Funding: ~£300,000
Weblink: staff.ncl.ac.uk/michael.north/
Phone Number(s): +44(0)191.222.7128

Location: Newcastle upon Tyne, UK
Number of Employees: N/A
Project Leader(s): Michael North
E. michael.north@ncl.ac.uk

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): 2 Tons
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Dymeryx (Newcastle University—Professor M. North Group)

Michael North, Professor of Organic Chemistry at Newcastle University, is looking at transforming CO_2 into useful chemical compounds called cyclic carbonates for industrial use.

The North group has recently developed a bimetallic aluminium (salen) complex and shown that it will catalyze the insertion of CO_2 into epoxides to form commercially important cyclic carbonates. The synthesis of cyclic carbonates is currently operated commercially at high temperatures and pressures making it unsuitable for use with waste CO_2. The North group's results show that the complex will catalyze the reaction at room temperature and one atmosphere pressure and will tolerate all of the impurities present in power station flue gas (NO_x, SO_x etc), thus giving it the potential to exploit waste CO_2 from a power plant (or an oxy-fuel combustion system)

The group states that the synthesis of cyclic carbonates is highly exothermic and does not require any energy input, other than to drive pumps. Indeed, the reactor will need to be cooled and may generate hot water or even steam which could be used to drive a turbine.

In ongoing work, the lab has developed versions of a catalyst that does not require a tetrabutylammonium bromide cocatalyst and shown that these one-component catalysts can be immobilized and used in a continuous flow reactor.

Ongoing work is concerned with: Optimizing the structure of the catalyst with respect to catalyst activity and catalyst lifetime; Minimizing the cost of production of the catalyst; Studying the use of CS_2 and related species instead of CO_2 to allow a wide range of heterocycles to be synthesized.

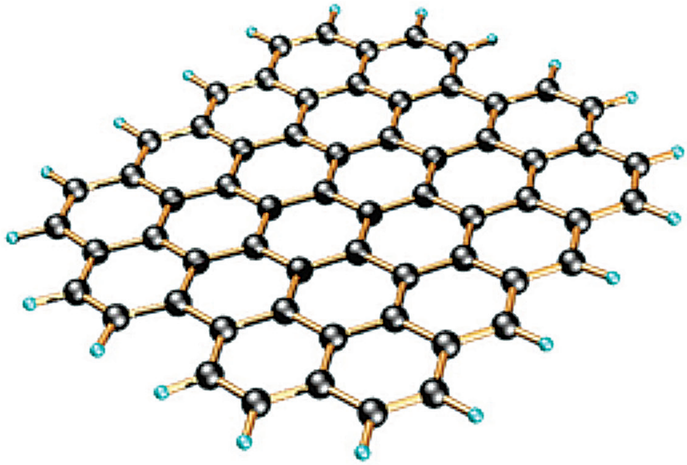
Partnerships & Demonstrations

The Group is collaborating with the group of Professor Ian Metcalfe at Newcastle Chemical Engineering. The technology has been patented and a spinout company (Dymeryx) established to commercialize the technology in partnership with appropriate investors.

Year Initiated: 2009
Level of Funding: $1,125,000
Weblink: hightempphysics.com
Phone Number(s): 415.309.4750

Location: San Rafael, CA
Number of Employees: 4
Project Leader(s): Jon Myers
E. jon@htphysics.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): 460 lbs.
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N



High Temperature Physics, LLC

High Temperature Physics has developed and proven a novel, patents-pending technology enabling large scale, low-cost production of valuable nanomaterials from CO_2 and a constituent commonly found in seawater. Other materials can be introduced to the process as well.

The nanomaterials produced by the High Temperature Physics process include graphenes, graphene composites and non-carbon nanomaterials including nano-silicon composites.

Graphenes are of considerable interest for applications in energy storage, energy production, computer processing, advanced materials, catalysis and medicine. HTP projects that its technology will be capable of producing a virtually unlimited amount of graphenes at breakthrough prices in the range of graphite powders three orders of magnitude larger.

The company is targeting partners in three major graphite application segments:

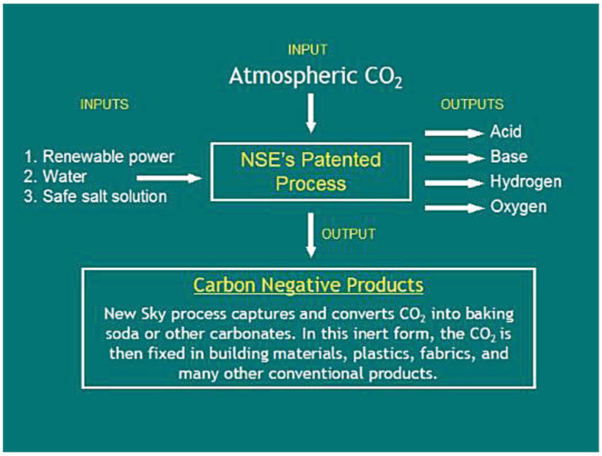
- Energy storage
- Power transmissions
- Advanced materials

Partnerships & Demonstrations
All current partnerships and demonstrations are under Non-Disclosure Agreements preventing public disclosure without permission of the counterparty.

Year Initiated: 2009
Level of Funding: N/A
Weblink: newskyenergy.com
Phone Number(s): 650.793.1107

Location: Boulder, CO
Number of Employees: 12
Project Leader(s): Deane Little
E. deane@newskyenergy.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



New Sky Energy

The company has developed a chemical system that turns CO_2 and salt solution into valuable products.

The initial prototype reactor could take water, a salt solution, as well as atmospheric CO_2 and, with an electric charge, turn it into an acid, a base, hydrogen and oxygen. Then, in a second step, the base reacts with CO_2 to form safe carbonates such as baking soda or limestone.

The company claims a key advantage of its process is that it doesn't have to produce chlorine gas to convert CO_2.

The plan is to scale the prototype reactors up physically and then out, similar to the way batteries are scaled by stacking electrodes.

Partnerships & Demonstrations

The company has a large pilot project in the Fresno area, which is funded by a water agency that sells irrigation water to farms and one of the partners is a desalination plant. Using a reactor that could fill a tractor trailer, New Sky aims to prove that their system can desalinate water, precipitate the sodium sulfate salt, and end up with clean water and useful products that are worth more than the water's value.

Year Initiated: 2008
Level of Funding: ~£2.6 million
Weblink: novacem.com
Phone: +44(0)20.7594.3581

Location: London, UK
Number of Employees: 20
Project Leader(s): Stuart Evans
E. info@novacem.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Novacem
Carbon negative cement

Novacem

The company uses magnesium oxide (MgO) and hydrated magnesium carbonates to produce cement.

Its production process uses accelerated carbonation of magnesium silicates under elevated levels of temperature and pressure (i.e. 180ºC/150bar). The carbonates produced are heated at low temperatures (700ºC) to produce MgO, with the CO_2 generated being recycled back in the process.

The company states that the use of magnesium silicates eliminates the CO_2 emissions from raw materials processing. In addition, the low temperatures required allow use of fuels with low energy content or carbon intensity (i.e. biomass), thus further reducing carbon emissions. Additionally, production of the carbonates absorbs CO_2; they are produced by carbonating part of the manufactured MgO using atmospheric/industrial CO_2.

Overall, the company states that the production process to make 1 ton of Novacem cement absorbs up to 100 kg more CO_2 than it emits, making it a carbon negative product.

Partnerships & Demonstrations

Novacem works closely with companies across the cement value chain. From 2008-10 it led a £1.5m, government backed R&D project with partners including Laing O'Rourke and Rio Tinto Minerals. In 2010 it established a collaboration with Lafarge focused on developing Novacem technology towards industrial pilot plant stage. It is also developing collaborations with other companies in cement, construction chemicals, mining and construction.

Year Initiated: 2006
Level of Funding: N/A
Weblink:
energyefficiencypsi.com
Phone: 419.332.7373 x105

Location: Fremont, OH
Number of Employees: 2
Project Leader(s): Tom Kiser
E. tkiser@professionalsupplyinc.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Professional Supply Incorporated (PSI)

The company has developed an experimental technology called a "liquid chimney" that captures the greenhouse gas escaping from coal and natural-gas furnaces and turns it into a harmless material that could be used in construction or even dropped into the ocean to rebuild coral reefs.

The chimney captures the CO_2 in the exhaust of a natural gas boiler and mixes it with treated water to produce hot water that is recycled to save energy and calcium carbonate that is harmless to the environment. The company states that the technology can transfer gas heat to water at up to 98 percent efficiency.

Partnerships & Demonstrations
The company installed its first prototype at a POM Wonderful facility in Los Angeles, CA in 2006.

Year Initiated: 1990
Level of Funding: N/A
Weblink: svminerals.com
Phone Number(s): 800.637.2775

Location: Overland Park, KS
Number of Employees: N/A
Project Leader(s): K. K. Patel
E. generalinfo@svminerals.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Searles Valley Minerals, Inc.

Searles Valley Minerals Inc. has captured CO_2 from an onsite coal-fired plant for over 20 years to produce sodium carbonate (Na_2CO_3) that is used in making glass and as a water softener.

The company captures and processes approximately 900 tons of CO_2 per day at the facility.

The facility is located in Trona, California.

Partnerships & Demonstrations
Searles has a facility located in Trona, California.

Year Initiated: 2005
Level of Funding: ~$32.25 million
Weblink: skyonic.com
Phone Number(s): 512.436.9276

Location: Austin, TX
Number of Employees: N/A
Project Leader(s): Joe Jones
E. joe@skyonic.com

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Skyonic Corporation

Skyonic's SkyMine® technology removes CO_2 from industrial waste streams through co-generation of saleable carbonate and/or bicarbonate materials, while also cleaning SO_x and NO_2 from the flue gas, and removing heavy metals such as mercury.

Skyonic's process revolves around mixing sodium hydroxide with flue gases. According to the company, the system performs three functions: It acts as SO_x/NO_x scrubber; It scrubs 99.9 percent of the SO_x gases, 99 percent of the NO_x and 97 percent of the mercury; It mitigates 96 percent of the carbon dioxide that flows through it; And it extracts saleable green chemicals and minerals including sodium carbonates, sodium bicarbonates, magnesium carbonates, hydrogen, hydrochloric acid, bleach, chlorine, and eventually metals like germanium.

The process is scalable, allowing an industrial or power plant owner to configure the degree of CO_2 removal anywhere from 10 to 99 percent.

The company envisions the solid carbonates and bicarbonates being sold for use in bio-algae applications, among other uses.

In early 2010, the company received a $3 million grant from the DOE to fund the first phase planning and design of a commercial-scale plant. In mid 2010, the company received an additional $25 million from the DOE to fund the second phase, which includes construction of the plant. Skyonic had previously raised approximately $4.25 million in two rounds of funding, including an investment from TXU.

Partnerships & Demonstrations

In April 2010, Skyonic installed a small demo system at Capital Aggregates in San Antonio, Texas, that state's largest cement plant. The demo unit is a 32-foot column running a large amount of CO_2 and producing bicarbonate of soda. The firm is looking to transform that into a commercial-scale plant in early 2011. A commercial-scale plant capable of converting 75 tons of CO_2 a year into bicarbonates is slated to start working in the middle of 2012, funded by the DOE grant.

Select CCR University and Laboratory Overviews »

Year Initiated: 2011
Level of Funding: N/A
Weblink: N/A
Phone Number(s): +65.6516.3284

Location: University Town, Singapore
Number of Employees: 3
Project Leader(s): Lee Yuan Kun
E. micleeyk@nus.edu.sg

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

NATIONAL RESEARCH FOUNDATION
Prime Minister's Office, Republic of Singapore

Campus for Research and Technological Enterprise (CREATE)

Researchers from Singapore and China are conducting a research project aimed at using biological and electrochemical technologies to completely capture and convert carbon dioxide in industrial emissions into energy.

The project will make use of sunlight as well as photochemical and photosynthetic processes by first treating the emissions with photochemical and electrochemical processes to convert most of the CO_2 into energy resources such as methane. The gas with thinner CO_2 will then be used to grow microalgae.

The researchers involved in the five-year project are from China's Peking University and Singapore's Nanyang Technological University, and the National University of Singapore.

The project is one of three energy research projects to be housed under the Campus for Research Excellence and Technological Enterprise program. The National Research Foundation (NSF) of Singapore supports it.

Partnerships & Demonstrations
The CREATE research center is currently being established in University Town, Singapore.

Biological »

Year Initiated: 2010
Level of Funding: $4.2 million
Weblink: wyss.harvard.edu/viewpage/106/synthetic-biology
Phone Number(s): 617.432.6401

Location: Cambridge, MA
Number of Employees: 4
Project Leader(s): Pamela Silver
E. pamela_silver@hms.harvard.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Harvard Medical School – Wyss Institute

The Wyss Institute for Biologically Inspired Engineering at Harvard University has been awarded a $4.2 million grant from the Department of Energy (DOE) to develop new approaches for advanced microbial biofuels.

Wyss researchers will be developing a bacterium that uses electricity, which could come from renewable sources, to convert carbon dioxide into gasoline. The bacterium would act like a reverse fuel cell: where fuel cells use a fuel to produce electricity, this bacterium would start with electricity and produce a fuel.

The Wyss project, entitled "Engineering a Bacterial Reverse Fuel Cell," will focus on developing new approaches for advanced microbial biofuels. It will be led by Pamela Silver with Synthetic Biology co-pioneers George Church, of Harvard Medical School, and Jim Collins, of Boston University and the Howard Hughes Medical Institute, who are all founding core faculty members of the Wyss Institute, as well as Peter Girguis of Harvard's Organismic and Evolutionary Biology Department.

Partnerships & Demonstrations
None.

Year Initiated: 2010
Level of Funding: $3,948,493
Weblink: lbl.gov
Phone Number(s): 510.220.3649

Location: Berkley, CA
Number of Employees: N/A
Project Leader(s): Steven Singer
E. swsinger@lbl.gov

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Lawrence Berkeley National Laboratory

In 2010, the LBNL received almost $4 million from the DOE's Advanced Research Projects Agency-Energy (ARPA-E) program to genetically engineer new strains of a common soil bacterium, Ralstonia eutropha, now used in the production of bioplastics, so that it can be used in the production of advanced biofuels, including diesel and jet fuel.

Ralstonia eutropha is already endowed with a natural ability to take hydrogen and carbon dioxide and make bioplastics and fatty acids, and techniques already exist for cultivating the microbe on an industrial scale. Singer and his colleagues want to re-route the microbe's existing metabolic pathways for biofuel production.

The technology will use electricity that can be generated from renewable sources to convert water to hydrogen. This hydrogen can then be combined by the bacterium with carbon dioxide collected from a power plant to make fuel.

A key to the project's success will be the combination of the microbial system with a new electrochemical catalytic system that generates hydrogen from water.

Partnerships & Demonstrations

The Laboratory is working closely with Berkeley Lab's Earth Sciences Division and with the Joint BioEnergy Institute.

Year Initiated: 2010
Level of Funding: $1.7 million
Weblink: mit.edu/biology/sinskey/www
Phone Number(s): 617.253.5106

Location: Cambridge MA
Number of Employees: N/A
Project Leader(s): Anthony Sinskey
E. asinskey@mit.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Massachusetts Institute of Technology – Sinskey Laboratory

Professor Anthony Sinskey of biology and health sciences and technology received a $1.7 million ARPA-E grant in 2010 to engineer a bacterium that can metabolize hydrogen, carbon dioxide, and oxygen and produce butanol, which can be used as a motor fuel.

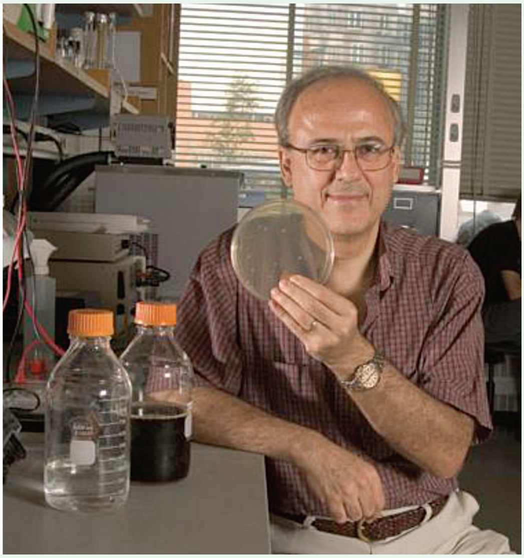
Key challenges include getting the organism to make abundant amounts of butanol – without then being poisoned by it – and designing a high-performance bioreactor system that can deliver the mix of gases needed for the biological process to occur.

Partnerships & Demonstrations
The research is being performed in collaboration with Michigan State University.

Year Initiated: 2010
Level of Funding: $3.2 million
Weblink: web.mit.edu/bamel/index.shtml
Phone: 617.253.4583

Location: Cambridge, MA
Number of Employees: N/A
Project Leader(s):
Gregory Stephanopoulos
E. gregstep@mit.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



Massachusetts Institute of Technology - Stephanopoulos Laboratory

Professor Gregory Stephanopoulos of chemical engineering received $3.2 million from a 2010 ARPA-E grant to develop a two-stage microbe-based process that would make oil from hydrogen and CO_2, or electricity.

In the first stage of the process, an anaerobic organism would utilize hydrogen and CO_2 to produce an organic compound, such as acetate.

In the second stage, the acetate would be used by an aerobic microbe, which would grow and in the process produce oil that can easily be converted into biodiesel.

Partnerships & Demonstrations
Harvard University and the University of Delaware are collaborating on the research.

Year Initiated: 2010
Level of Funding: $2.3 million
Weblink: musc.edu/mbes/faculty/may.html
Phone: 843.792.7140

Location: Charleston, SC
Number of Employees: N/A
Project Leader(s): Harold May
E. mayh@musc.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Medical University of South Carolina

This ARPA-E funded project will develop a microbially catalyzed electrolysis cell that uses electricity (e.g. from solar PV) to convert carbon dioxide into liquid alcohol fuels.

The scientists use electric currents to stimulate microbes gathered from the floors of local breweries and wineries and from Charleston Harbor sediment.

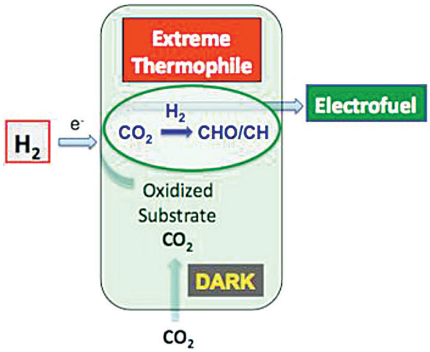
The process will produce butanol and will also be able to produce ethanol.

Partnerships & Demonstrations
The research team has a strong connection with Microbial Fuel Cell Technologies, LLC in this area of research.

Year Initiated: 2010
Level of Funding: $2.729 million
Weblink: che.ncsu.edu/extremophiles/
Phone Number(s): 919.515.4452

Location: Raleigh, NC | Athens, GA
Number of Employees: N/A
Project Leader(s): Robert Kelly | Michael Adams
E. rmkelly@eos.ncsu.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



North Carolina State University – Hyperthermophile Research Group

The DOE's Advanced Research Projects Agency (ARPA-E) has awarded a grant for more than $2.7 million to North Carolina State University (in collaboration with the University of Georgia) to support research into the creation of biofuels using microbial organisms, called extremophiles, that live in high-temperature environments. The technology uses organisms that utilize carbon dioxide and hydrogen to produce biofuels directly.

The researchers will be working with the microbes *Metallosphaera sedula* and *Pyrococcus furiosus.* These microbes take carbon dioxide from the environment and produce complex molecules, including one called acetyl-CoA that can serve as a building block for biofuels.

The researchers plan to genetically engineer Pyrococcus to include elements of Metallosphaera, creating a "superbug" that would be capable of taking carbon dioxide and hydrogen and producing biofuels. The researchers hope to engineer the microbes to produce butanol.

Partnerships & Demonstrations
The University is working with the University of Georgia.

Year Initiated: 2010
Level of Funding: $3.9 million
Weblink: microbiology.osu.edu/faculty/tabita-f-robert
Phone: 614.292.4297

Location: Columbus, OH
Number of Employees: 2
Project Leader(s): Robert Tabita
E. tabita.1@osu.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Ohio State University

Robert Tabita, professor of microbiology, natural resources, and plant cellular and molecular biology, is working with S.T. Yang, professor of chemical and biomolecular engineering, and scientists at Battelle to develop butanol as an alternative fuel to gasoline.

The project, "Bioconversion of Carbon Dioxide to Biofuels by Facultatively Autotrophic Hydrogen Bacteria," received $3.9 million from ARPA-E for an industrially scalable bioreactor approach to incorporate genetically engineered bacteria that metabolizes carbon dioxide, oxygen and hydrogen to produce butanol.

Battelle will help design a water tank with a dividing membrane to keep the bacteria in an environment rich with carbon dioxide and hydrogen. The butanol, researchers hope, would pass through the membrane, where it would be collected as fuel.

The team anticipates at least a twofold productivity improvement over current levels and a cost that can be competitive with gasoline.

Partnerships & Demonstrations
Ohio State University is working with Battelle on this project.

Year Initiated: 2010
Level of Funding: $1.5 million
Weblink: che.psu.edu/faculty/curtis/
Phone Number(s): 814.863.4805

Location: University Park, PA
Number of Employees: 2
Project Leader(s): Wayne Curtis
E. wrc2@psu.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Pennsylvania State University – Curtis Lab

This ARPA-E funded project is focused on producing an organism capable of using electricity to ultimately produce gasoline from carbon dioxide.

The team will engineer hydrocarbon biosynthesis genes from an oil producing algae into a hydrogen-consuming bacteria for efficient biofuel production.

The project also includes innovative concepts for engineering microbial fuel cells and bioreactor systems.

Partnerships & Demonstrations

The Curtis Lab is collaborating with plant molecular biologist Joe Chappell at the University of Kentucky.

Year Initiated: 2007
Level of Funding: >$4 million
Weblink: lbl.gov
Phone: 361.265.9201

Location: Corpus Christi, TX
Number of Employees: 1
Project Leader(s): Carlos Fernandez
E. cj-fernandez@cwp.tamu.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

AgriLIFE RESEARCH
Texas A&M System

Texas A&M – Texas AgriLife Research

Projects at the AgriLife Research Mariculture Laboratory in Corpus Christi are designed to establish and optimize a cost-effective prototype system for high-density microalgae in open systems (raceways), using seawater and flue gas carbon dioxide captured from power-generating plants.

In 2007, General Atomics and Texas AgriLife Research formed a strategic, collaborative alliance to research, develop, and commercialize biofuel production through farming microalgae in Texas and California. The U.S. Department of Defense awarded a multi-year grant to General Atomics and AgriLife Research for algae research and development. Soon after, Texas AgriLife Research, with General Atomics as a partner, was awarded a $4 million grant from the State of Texas Emerging Technology Fund to develop an algae test facility at the Texas AgriLife Research Pecos (Texas) Research Station.

Texas AgriLife Research comprises its College Station headquarters, 13 research centers reaching from El Paso to Beaumont and Amarillo to Weslaco, and associated research stations. A member of The Texas A&M University System, AgriLife Research has 1,700 employees, 375 of which are doctoral-level scientists who are nationally recognized experts in their fields. AgriLife Research collaborates with more than 30 nations. In 2009, expenditures will be more than $170 million.

Partnerships & Demonstrations
AgriLife Research partnered with the Barney M. Davis Power Plant to test utilizing flue gas from its natural-gas power plant to grow microalgae.

Year Initiated: 2010
Level of Funding: $6,757,360
Weblink: fabe.osu.edu/fabe/yebo_li.html
Phone Number(s): 614.292.6131

Location: Wooster, OH
Number of Employees: N/A
Project Leader(s): Yebo Li
E. li.851@osu.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Touchstone Research Laboratory / Ohio State University

Touchstone and OSU will use a novel phase change material to enclose raceway ponds where they will cultivate algae using CO_2 from combustor flue gas.

The algal lipids will be recovered to produce biofuel and the algae biomass will be used in an anaerobic digestion process to produce electricity and recover nutrients.

This project will pilot-test an open-pond algae production technology that can capture at least 60 percent of flue gas CO_2 from an industrial coal-fired source to produce biofuel and other high value co-products. A novel phase change material incorporated in Touchstone's technology will cover the algae pond surface to regulate daily temperature, reduce evaporation, and control the infiltration of invasive species. Lipids extracted from harvested algae will be converted to a bio-fuel, and an anaerobic digestion process will be developed and tested for converting residual biomass into methane.

In 2010, this project received approximately $520K in Phase I and subsequently $6.2 million in Phase 2 DOE ARRA funding.

Partnerships & Demonstrations
Partners for the DOE funded project include Touchstone, The Ohio State University Ohio Agricultural Research and Development Center, and GZA GeoEnvironmental, Inc. The host site for the pilot project is Cedar Lane Farms in Wooster, Ohio.

Year Initiated: 2010
Level of Funding: $4 million
Weblink: seas.ucla.edu/~liaoj
Phone: 310.825.1656

Location: Los Angeles, CA
Number of Employees: N/A
Project Leader(s): James C. Liao
E. liaoj@seas.ucla.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

University of California Los Angeles – Liao Laboratory

Researchers from the James Liao Laboratory at the UCLA Henry Samueli School of Engineering and Applied Science are working on recycling carbon dioxide for the biosynthesis of higher alcohols.

The researchers have been working on a genetically modified cyanobacterium. Their research paper was published in the December 9, 2009 print edition of the journal Nature Biotechnology. They successfully modified a cyanobacterium to consume carbon dioxide and generate the liquid fuel isobutanol. This isobutanol can prove to be of great potential as a gasoline alternative. The whole process happens with the help of sunlight through photosynthesis.

Current technologies using biological photosynthesis to convert sunlight to liquid transportation fuels are relatively inefficient. Conversely, man-made solar cells are more efficient in energy conversion, but the electricity generated presents a storage problem. This project will develop microorganisms using synthetic biology and metabolic engineering to derive energy from electricity instead of light for CO_2 fixation and fuel synthesis.

In early 2010, Liao was awarded $4 million by the DOE's ARPA-E to develop a method for converting carbon dioxide into liquid fuel isobutanol using electricity as the energy source instead of sunlight. The process would store electricity in fuels that can be used as high-octane gasoline substitutes. Later in the year, Liao received the Presidential Green Chemistry Challenge Award from EPA for his work.

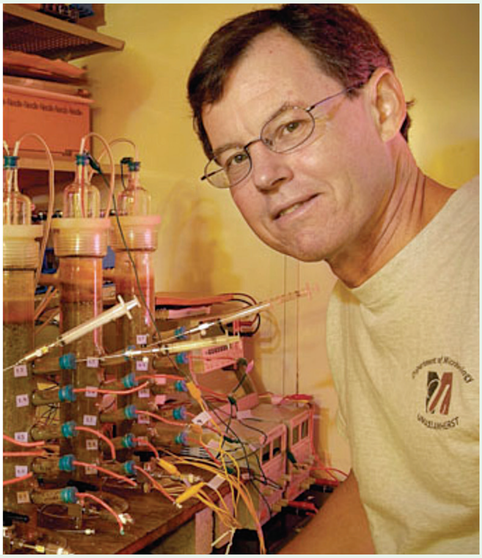
Partnerships & Demonstrations

Sponsored by KAITEKI Institute Inc. (TKI), the strategic arm of one of Japan's largest chemical companies, Liao and his team are researching ways to recycle and convert CO_2 into chemicals that can be used to produce a variety of industrial products, including car bumpers, packaging materials, DVDs and even diapers.

Year Initiated: 2010
Level of Funding: $1 million
Weblink: bio.umass.edu/micro/faculty/lovley.html
Phone Number(s): 413.545.9651

Location: Amherst, MA
Number of Employees: N/A
Project Leader(s): Derek Lovley
E. dlovley@microbio.umass.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



University of Massachusetts Amherst

This ARPA-E funded project will develop a "microbial electrosynthesis" process in which microorganisms use electric current to convert water and carbon dioxide into butanol at much higher efficiency than traditional photosynthesis and without need for arable land.

This new technology is based on the research group's discovery that some bacteria feed on electrons delivered by electrodes. The microbes live on the electrodes and use electrons released from them as their food source.

The technology is basically a new form of photosynthesis in which carbon dioxide and water are combined to produce organic compounds and oxygen is released as a byproduct.

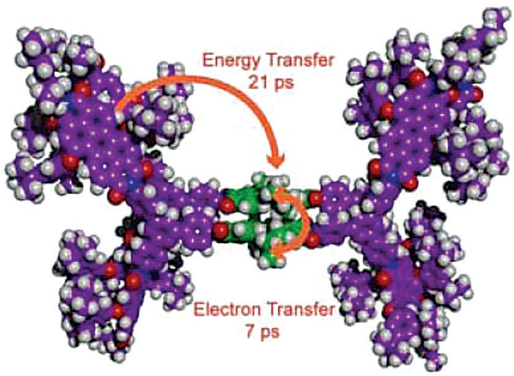
Partnerships & Demonstrations
The laboratory is working with the University of California San Diego and Genomatica

Chemical & Catalytic »

Year Initiated: 2007
Level of Funding: $19 million
Weblink: ansercenter.org
Phone Number(s): 847.467.1423

Location: Evanston, IL
Number of Employees: 24
Project Leader(s): Michael R. Wasielewski
E. m-wasielewski@northwestern.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



Argonne-Northwestern Solar Energy Research Center (ANSER)

Argonne-Northwestern Solar Energy Research (ANSER) Center's Bio-Inspired Systems for Fuels Subgroup seeks to develop molecular assemblies that use solar energy to oxidize water and generate hydrogen. Just as photofunctional proteins have a specific environment that promotes solar fuel formation, researchers are developing self-ordering and self-assembling components that can integrate the functions of light harvesting, charge separation, and catalysis.

Research in this field is focused on understanding the fundamental principles needed to develop integrated artificial photosynthetic systems. These principles include how to promote and control: 1) energy capture, charge separation, and long-range directional energy and charge transport; 2) coupling of separated charges to multi-electron catalysts for fuel formation; and 3) supramolecular self-assembly for scalable, low-cost processing from the nanoscale to the macroscale.

ANSER was established in July of 2007 as a direct result of the recognition that both institutions have considerable synergistic research ongoing in the solar energy field and that the strengths of both programs can be combined to greatly amplify their effectiveness and to significantly advance the important societal need to produce renewable energy using environmentally benign means.

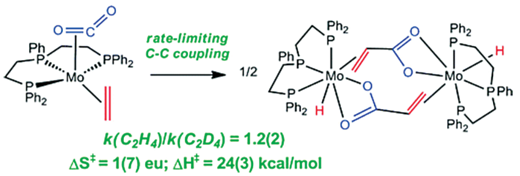
Partnerships & Demonstrations

In 2009, the ANSER Center was awarded a $19 million, 5-year. grant from the DOE to serve as one of its Energy Frontier Research Centers.

Year Initiated: 2010
Level of Funding: $524,615
Weblink: research.brown.edu/research/profile.php?id=1246969729
Phone Number(s): 401.863.3385

Location: Providence, RI
Number of Employees: N/A
Project Leader(s): Wesley Bernskoetter
E. wb36@brown.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



Brown University

Researchers are assessing the viability of CO_2 reduction with ethylene using low-valent molybdenum as a catalyst to produce acrylic acid or valuable acrylate compounds.

The goal of the work is to provide core research and development necessary for establishing whether low-valent molybdenum catalysts will enable viability of CO_2 as a reactant in the production of acrylate compounds. This project has three phases:

- Scope of CO_2 and ethylene coupling: This research will expand the range of molybdenum complexes capable of coupling CO_2 and ethylene by defining the available ligand (a molecule bonded to a central metal atom) architectures which facilitate acrylate formation. The approach for this effort will synthesize two sets of molybdenum complexes shown by computational analysis to provide promising reaction thermodynamics and compare the relative reactions in CO_2 and ethylene coupling of each using multiple spectroscopic methods.
- Reductive Elimination of Acrylate Products: This phase will evaluate computational and experimental investigations to determine the catalytic parameters necessary to enhance reductive acrylate elimination. This approach will utilize molybdenum complexes developed in Phase I via comparative rate experiments and mechanistic probes to access the relative importance of multiple variables that determine the favorability of reductive acrylate elimination.
- Design and prepare an optimized molybdenum catalyst for a bench-scale reaction to test the feasibility of molybdenum catalyzed acrylate formation from CO_2: This approach will correlate the structure and reactivity relationships in ligand supports for molybdenum found to be most influential in Phases I and II.

Partnerships & Demonstrations

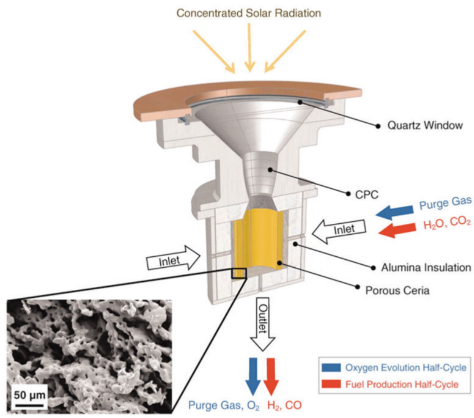
In July 2010, the team was awarded approximately $417K from NETL, bringing the total value of this project to approximately $525K. The university is working with Draper Laboratory on elements of this project.

The Laboratory is working closely with Berkeley Lab's Earth Sciences Division and with the Joint BioEnergy Institute.

Year Initiated: 2010
Level of Funding: N/A
Weblink: addis.caltech.edu
Phone: 626.395.2958

Location: Pasadena, CA
Number of Employees: 7
Project Leader(s): Sossina M. Haile
E. smhaile@caltech.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



W C Chueh et al. Science 2010;330:1797-1801

California Institute of Technology (Caltech)

A team from Caltech, ETH Zürich and the Paul Scherrer Institute have devised a solar reactor for the two-step, solar-driven thermochemical production of fuels. In a paper published in the journal Science, they report stable and rapid generation of fuel over 500 cycles. They achieved solar-to-fuel efficiencies of 0.7 to 0.8%, and showed that the efficiency was largely limited by system scale and design, rather than by its chemistry.

The basis for the system is a solar-driven thermochemical cycle for dissociating H_2O and CO_2 using nonstoichiometric ceria (CeO_2). The design of the reactor exposes porous ceria directly to concentrated solar radiation, heating it to between 1,420 and 1,640 °C, thereby liberating oxygen from its lattice. The material then readily strips oxygen atoms from carbon dioxide and water, forming CO and hydrogen, respectively, which are combined to create fuels.

The researchers found that both the efficiency and the cycling rates in the reactor were limited largely by thermal losses, resulting from conductive and radiative heat transfer. A thermodynamic analysis of efficiency based solely on the material properties of CeO_2 suggests that values in the range of 16 to 19% are attainable, even in the absence of sensible heat recovery.

Given that, the team anticipates that reactor optimization and system integration will result in substantial increases in both efficiency and fuel production rates. Furthermore, they note, the abundance of cerium, which is comparable to that of copper, is such that the approach is applicable at scales relevant to global energy consumption.

Partnerships & Demonstrations
None.

Year Initiated: 2008
Level of Funding: N/A
Weblink: zsw-bw.de
Phone: +49(0)711.7870.252

Location: Stuttgart, Germany
Number of Employees: 15
Project Leader(s): Michael Specht
E. michael.specht@zsw-bw.de

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

Center for Solar Energy and Hydrogen Research (ZSW)

Together with the company SolarFuel and the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), the Centre for Solar Energy and Hydrogen Research (ZSW) has developed a new method for electricity storage and to guarantee grid stability in electricity grids with a high percentage of renewable power generation.

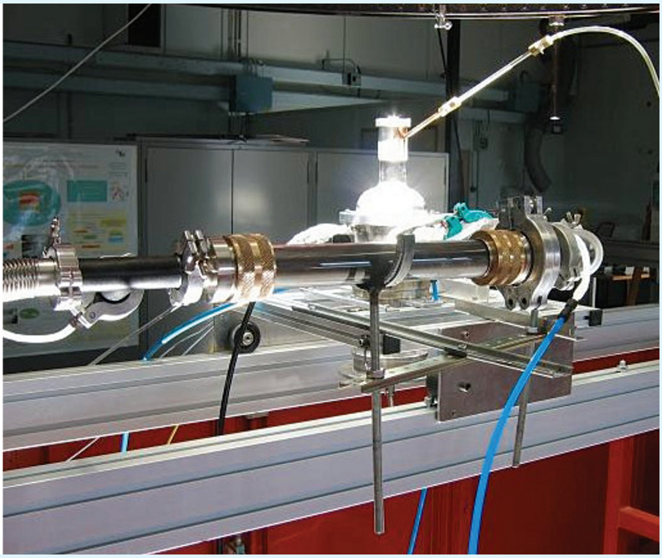
In this concept, excess renewable electricity from fluctuation sources (e.g. from wind turbines) is used for hydrogen generation via water electrolysis. In a downstream process, hydrogen and CO_2 are converted to methane that is fed into the gas grid as SNG (Substitute Natural Gas). The renewable energy carrier methane can be efficiently stored in the natural gas infrastructure and distributed according to customers' needs.

Partnerships & Demonstrations
In November 2009, a pilot plant for the production of $1 m^3/h$ CH_4 was commissioned. This 25 kWel pilot plant was coupled with a biogas plant using CO_2 resulting from biomass digestion. ZSW and its partners are planning the construction of a demonstration plant in 2012 that will utilize 250 kWel. In 2015, a commercial plant providing about 6 MWel is planned. ZSW is working with SolarFuel and the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES).

Year Initiated: 2009
Level of Funding: N/A
Weblink: promes.cnrs.fr
Phon: +33.4.68.30.77.30

Location: Font-Romeu, France
Number of Employees: 2
Project Leader(s): Stéphane Abanades and Marc Chambon
E. stephane.abanades@promes.cnrs.fr

Energy Efficiency (MWh/ton of converted CO_2): 15–50
Conversion Metric (Ton of CO_2 → ? quantity of product): 0.64 tons
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N



National Center for Scientific Research (CNRS)

Researchers at the National Center for Scientific Research (CNRS), France, are studying a solar thermochemical process for the recycling and upgrading of CO_2 emissions for the production of synthetic fuels.

Their approach consists of splitting carbon dioxide to form carbon monoxide and oxygen in two distinct steps. Zn- and SnO-rich nanopowders were first synthesized in a high-temperature solar chemical reactor via the thermal dissociation of ZnO or SnO_2; the produced nanoparticles then react efficiently with CO_2, which generates CO and the initial metal oxide that can be recycled.

The concentrated solar energy provides the requisite high temperature process heat. The metal oxides (ZnO/Zn and SnO_2/Sn), although reacting in each individual reaction, are not consumed in the overall chemical-looping process because of its recycling, and thus, it can be considered as a catalyst for the CO_2-splitting reaction.

This reactor was operated in a controlled atmosphere (N_2 or Ar flow) at a reduced pressure (about 20 kPa, 0.2 bar) and a reaction temperature of about 1600 °C.

They found that the produced nanopowders are more reactive with CO_2 than standard commercial powders. Zn can be oxidized by CO_2 from 360 °C with both high reaction rates and final chemical conversions of greater than 90%. The CO_2 dissociation with SnO requires higher temperatures (about 500-800 °C), and reaction rates are lower than for Zn. They also found that the influence of the amount of CO_2 was also significant, because the reaction rates increased with the CO_2 mole fraction.

Partnerships & Demonstrations

The technology was demonstrated on a laboratory scale.

Year Initiated: 2010
Level of Funding: N/A
Weblink: dri.edu/kent-hoekman
Phone: 775.674.7065

Location: Reno, NV
Number of Employees: 4
Project Leader(s): S. Kent Hoekman
E. kent.hoekman@dri.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Desert Research Institute

A laboratory-scale reactor system was built and operated to demonstrate the feasibility of catalytically reacting carbon dioxide (CO_2) with renewably-generated hydrogen (H_2) to produce methane (CH_4) according to the Sabatier reaction: CO_2 + $4H_2$ CH_4 + $2H_2O$.

A cylindrical reaction vessel packed with a commercial methanation catalyst (Haldor Topsøe PK-7R) was used. Renewable H_2 produced by electrolysis of water (from solar- and wind-generated electricity) was fed into the reactor along with a custom blend of 2% CO_2 in N_2, meant to represent a synthetic exhaust mixture.

Reaction conditions of temperature, flow rates, and gas mixing ratios were varied to determine optimum performance. The extent of reaction was monitored by real-time measurement of CO_2 and CH_4.

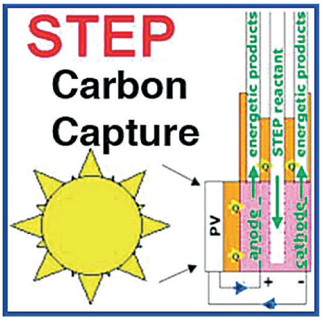
Maximum conversion of CO_2 occurred at 300–350 °C. Approximately 60% conversion of CO_2 was realized at a space velocity of about 10,000 h–1 with a molar ratio of H_2/CO_2 of 4/1. Somewhat higher total CO_2 conversion was possible by increasing the H_2/CO_2 ratio, but the most efficient use of available H_2 occurs at a lower H_2/CO_2 ratio.

Partnerships & Demonstrations
The Institute has a partnership with RCO2 AS, of Norway.

Year Initiated: 2009
Level of Funding: N/A
Weblink: home.gwu.edu/~slicht
Phone Number(s): 703.726.8225

Location: Washington, D.C.
Number of Employees: N/A
Project Leader(s): Stuart Licht
E. slicht@gwu.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): 0.27 ton C or 0.64 ton CO
Land Footprint (Tons/acre of capacity): 20 tons/acre/day
Water Footprint (Gal/ton of CO_2 recycled): 0
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



George Washington University

Researchers at George Washington University (GWU) pioneered the development of the Solar Thermal Electrochemical Photo (STEP) process, which generates energetic chemicals.

The process uses visible sunlight to power an electrolysis cell for splitting carbon dioxide, and also uses solar thermal energy to heat the cell in order to decrease the energy required for this conversion process.

The electrolysis cell splits carbon dioxide into either solid carbon (when the reaction occurs at temperatures between 750°C and 850°C) or carbon monoxide (when the reaction occurs at temperatures above 950°C).

These kinds of temperatures are much higher than those typically used for carbon-splitting electrolysis reactions (e.g., 25°C), but the advantage of reactions at higher temperatures is that they require less energy to power the reaction than at lower temperatures.

The experiments in this study showed that the technique could capture carbon dioxide and convert it into carbon with a solar efficiency from 34% to 50%, depending on the thermal component. While carbon could be stored, the production of carbon monoxide could later be used to synthesize jet, kerosene, and diesel fuels, with the help of hydrogen generated by STEP water splitting.

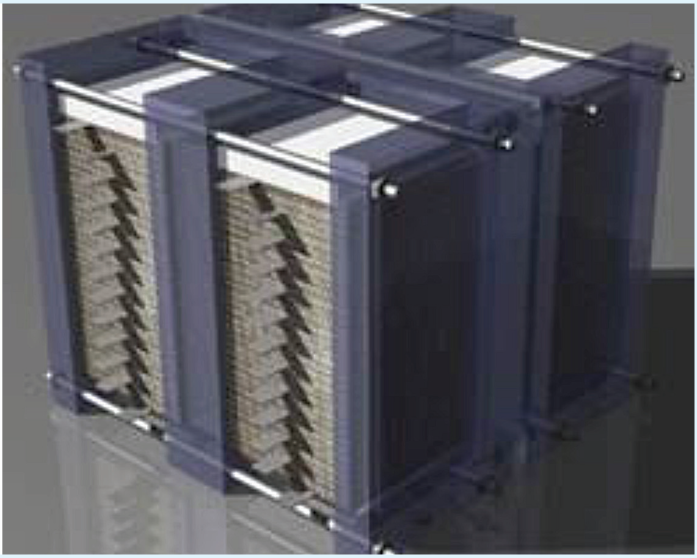
Partnerships & Demonstrations

None.

Year Initiated: 2004
Level of Funding: N/A
Weblink: inlportal.inl.gov/portal/server.pt/community/home
Phone Number(s): 208.526.4527

Location: Idaho Falls, ID
Number of Employees: 2
Project Leader(s): Carl Stoots
E. carl.stoots@inl.gov

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N



Idaho National Laboratory

Laboratory researchers Carl Stoots and James O'Brien developed a process to electrolyze steam and CO_2 to yield hydrogen and CO, which in turn are processed into syngas.

The approach focuses on pumping a combination of steam and CO_2 into a solid-oxide fuel cell stack.

Combined electrolysis, or co-electrolysis of steam and carbon dioxide, incorporates three different reactions. Steam and carbon dioxide are each electrolyzed, splitting into hydrogen, oxygen and carbon monoxide.

Another process, called the reverse shift reaction, turns carbon dioxide and hydrogen into carbon monoxide and steam. Electrolyzing the steam produced by the reverse shift reaction shifts the balance. The cell primarily generates carbon monoxide and hydrogen.

Partnerships & Demonstrations
None.

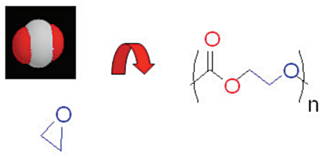
Year Initiated: 2010
Level of Funding: £4 million
Weblink: ch.ic.ac.uk/williams/index.html
Phone: +44(0)20.7594.5790

Location: London, UK
Number of Employees: N/A
Project Leader(s): Charlotte Williams
E. c.k.williams@imperial.ac.uk

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Imperial College London

Polymers from CO_2



Imperial College London – Williams Group

At Imperial College London and University College London, a research team led by Dr. Charlotte Williams is working on the reduction of CO_2 with hydrogen, electrical energy or photon energy to produce vehicle fuels.

To achieve this, they are developing nanostructured catalysts that operate using solar or other renewable energy inputs. These are used in a process that mimics CO_2 activation in nature – an 'artificial leaf' concept – that effectively reverses the polluting process of burning fossil fuels.

The group aims to reduce costs by developing new, highly active metal/metal oxide nanostructured catalysts, which can offer superior performance.

The research is part of the Engineering and Physical Sciences Research Council (EPSRC) 'Nanotechnology Grand Challenge' program and will receive a total investment of £4 million.

The group is also working on polymer production from CO_2. They have created a series of new bimetallic complexes as catalysts for the copolymerisation of carbon dioxide and cyclohexene oxide.

Partnerships & Demonstrations

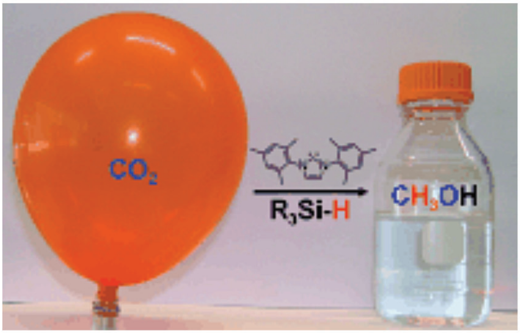
The team is collaborating with industrial partners Millennium Inorganic Chemicals, Cemex, Johnson Matthey, and E.ON.

Year Initiated: 2009
Level of Funding: N/A
Weblink: ibn.a-star.edu.sg/research_areas_7.php?id=165
Phone Number(s): +65.6824.7242

Location: Singapore
Number of Employees: N/A
Project Leader(s): Siti Nurhanna Riduan
E. siti@ibn.a-star.edu.sg

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

A*STAR Institute of Bioengineering and Nanotechnology



Institute of Bioengineering and Nanotechnology

Researchers at the Institute say they've found a low-temperature, low-energy way to turn CO_2 into methanol.

The process uses d N-heterocyclic carbenes (NHCs) as an organocatalyst, then adds hydrosilicane – a combination of silica and hydrogen – and water to make methanol.

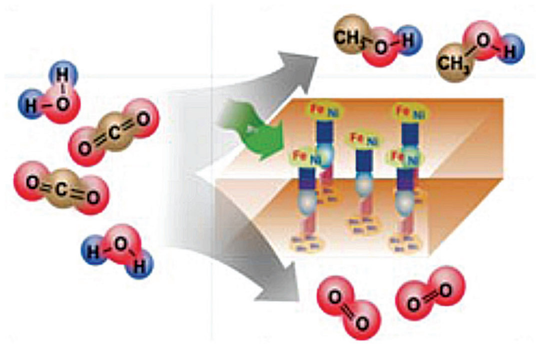
Researchers say the process can be done at room temperatures in the presence of oxygen, unlike other methods that use heavy metal catalysts. They also say the process uses much less energy and takes less time than other methods.

Partnerships & Demonstrations
None.

Year Initiated: 2010
Level of Funding: $122 million
Weblink: solarfuelshub.org
Phone: 626.395.6335

Location: Berkley, CA
Number of Employees: N/A
Project Leader(s): Nathan Lewis
E. nslewis@caltech.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



Joint Center for Artificial Photosynthesis

The mission of JCAP is to demonstrate a scalable and cost-effective solar fuels generator that, without use of rare materials or wires, robustly produces fuel from the sun 10 times more efficiently than typical current crops.

JCAP is sponsored by the DOE to research, develop, and implement techniques and devices to produce chemical fuels from sunlight, water and carbon dioxide. Facilities include research and development sites on the Caltech and LBNL campuses. The JCAP Project is a major technology project that envisions funding of $122 million dollars over five years with future five-year funding cycles possible.

JCAP researchers will focus on the construction of a solar fuels system based on its requisite components: Light absorbers; catalysts; separation membranes; and linkers (that efficiently couple light absorbers and catalysts for optimal control of the rate, yield, and energetics of charge carrier flow at the nanoscale).

JCAP partners include the California Institute of Technology, Lawrence Berkeley National Laboratory, the SLAC National Accelerator Laboratory, UC Berkeley, UC Santa Barbara, UC Irvine, and UC San Diego.

Partnerships & Demonstrations

In 2010, the U.S. Deputy Secretary of Energy announced an award of up to $122 million over five years to fund the JCAP. $22 million will be provided the first year, and $25 million will be provided the subsequent four years.

Year Initiated: 2010
Level of Funding: $1,250,067
Weblink: web.mit.edu/hatton-group/
Phone Number(s): 617.253.4588

Location: Cambridge, MA
Number of Employees: N/A
Project Leader(s): T. Alan Hatton
E. tahatton@mit.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Massachusetts Institute of Technology – The Hatton Group

In 2010, the Massachusetts Institute of Technology's Hatton Group was awarded $1 million to support its investigation of a novel electrochemical technology that uses CO_2 from dilute gas streams generated at industrial carbon emitters, including power plants, as a raw material to produce useful commodity chemicals.

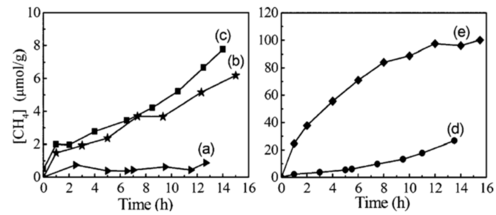
Researchers in the group, along with Siemens, are investigating the feasibility of integrating CO_2 from carbon dioxide emitting sources (power plants, manufacturing facilities, cement plants, or fertilizer facilities) into a chemical reaction process that will create organic carbonate commodity chemicals for later use. The researchers also are designing an electrochemical cell to allow for a multi-stage, continuous organic carbonate synthesis process, and conducting multiple lifecycle analyses of the electrochemical process and commodity chemicals synthesized during chemical CO_2 sequestration activities. The basis of this technology is the chemical affinity of electrochemically active carriers for CO_2 molecules that facilitate their effective capture from a dilute gas stream (effluents from carbon dioxide emitters) through formation of chemically activated species. The proposed technology will exploit the characteristics of these activated species to undergo chemical reaction with various reagents to yield commodity chemicals.

Partnerships & Demonstrations
The Hatton Group is working with Siemens Corporate Research as part of its DOE funded effort. The duration of the project is two years.

Year Initiated: 2010
Level of Funding: N/A
Weblink: nju.edu.cn/cps/site/njueweb/fg/index.php
Phone: (86.25)83686630

Location: Nanjing, P.R. China
Number of Employees: 8
Project Leader(s): Yong Zhou | Zhigang Zou
E. zhouyong1999@nju.edu.cn | zgzou@nju.edu.cn

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



Nanjing University

Researchers at Nanjing University and Anhui Polytechnic University in China have synthesized zinc orthogermanate (Zn_2GeO_4) ultralong nanoribbons which show promising photocatalytic activity toward the reduction of CO_2 into renewable methane (CH_4) and water.

The team used a En/H_2O binary solvent system for the synthesis, and noted that this binary solvent system may provide a new route for preparing other 1D ternary oxides.

The nanoribbons delivered a CH_4 yield of ~1.5 μmol g-1 during the first hour under light illumination. Bulk Zn_2GeO_2 obtained by conventional solid-state reaction (SSR) produced only a trace amount of CH_4.

The team found that the rate of CH_4 generation over the nanoribbon could be significantly enhanced by loading of Pt or RuO_2 and especially by co-loading of Pt and RuO_2 as a co-catalyst to improve the separation of the photogenerated electron-hole pairs, as demonstrated in photocatalytic water splitting.

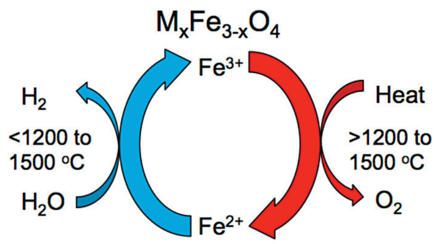
Partnerships & Demonstrations

The University worked with Anhui Polytechnic University on this project.

Year Initiated: N/A
Level of Funding: N/A
Weblink: colorado.edu/che/TeamWeimer/index.htm
Phone: 303.492.3759

Location: Boulder, CO
Number of Employees: 2
Project Leader(s): Alan Weimer
E. alan.weimer@colorado.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



National Renewable Energy Lab / University of Colorado Consortium

The consortium is focused on a low-cost approach to hydrogen generation, and subsequent combination of hydrogen with CO_2 to produce carbon monoxide, which in turn would be used to produce syngas.

The technology that was pioneered can both split water to produce hydrogen and split CO_2 to produce carbon monoxide. Both are the building blocks of synthetic transportation fuel.

The team is focused on developing and demonstrating robust materials for a two-step thermochemical redox cycle that will integrate easily into a scalable solar-thermal reactor design.

The process involves an array of mirrors to concentrate the sun's rays and create temperatures as high as 2,640 degrees Fahrenheit. The process consists of two steps – each involving reactions of a thin film of metal ferrite coating with a reactive substrate contained in a solar receiver – to split water into its gaseous components, hydrogen and oxygen.

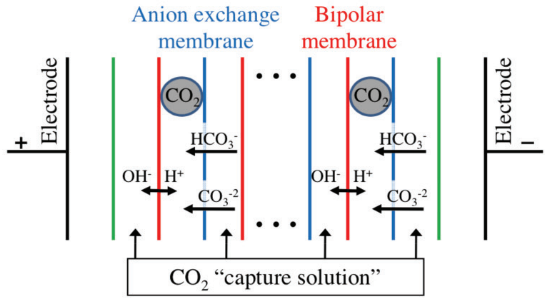
Partnerships & Demonstrations

The consortium originally worked with ConocoPhillips. The consortium is also working with the Swiss Federal Research Institute (ETH Zurich) and Sandia National Laboratories (SNL) to complete this project.

Year Initiated: 2008
Level of Funding: ~$400K/year
Weblink: parc.com/publication/2415/carbon-neutral-liquid-fuel.html
Phone: 650.812.4000

Location: Palo Alto, CA
Number of Employees: 6
Project Leader(s): Matthew Eisaman | Karl Littau
E. Leon.Wong@parc.com

Energy Efficiency (MWh/ton of converted CO_2): ≥ 0.63 (from $KHCO_3$ (aq))
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



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Palo Alto Research Center (PARC)

PARC has developed a commercially viable and energy-efficient approach to desorbing CO_2 from aqueous capture solutions.

The approach uses a novel electrochemical process developed at PARC: high-pressure bipolar membrane electrodialysis. PARC has characterized the energy consumption of this process [1] and has designed, constructed, and tested a novel high-pressure electrodialysis prototype for CO_2 separation and capture-solvent regeneration [2,3].

PARC has demonstrated that this system can be quite efficient, with energy consumption as low as 100kJ per mol of CO_2 from bicarbonate solutions [1]. In addition, high-pressure operation has been shown to reduce energy consumption by up to 30%. This approach represents an alternative to conventional regeneration approaches such as steam stripping, and is applicable to other capture solvents such as MEA.

To realize the potential of the technology, PARC is seeking additional funding and/or commercialization partners to build a complete end-to-end renewable fuel prototype unit.

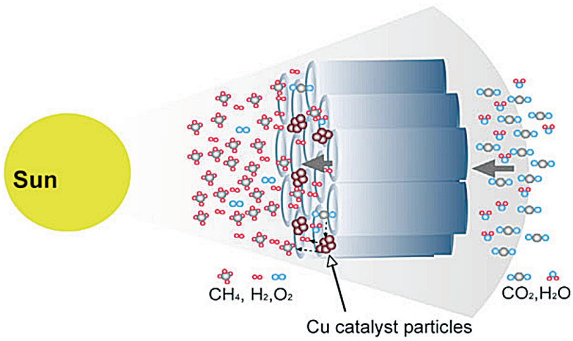
Partnerships & Demonstrations

[1] M. D. Eisaman, L. Alvarado, D. Larner, P. Wang, B. Garg, and K. A. Littau, CO_2 concentration using bipolar membrane electrodialysis, Energy & Environmental Science, 4, 1319 - 1328 (2011). [2] M. D. Eisaman and K. A. Littau, inventors; 2010 Dec. 15, Electrodialytic separation of gas from aqueous carbonate and bicarbonate solutions, US patent application 12969485. [3] M. D. Eisaman, K. A. Littau, and D. Larner, inventors; 2010 Dec. 15, High-pressure electrodialysis device, US patent application 12969465.

Year Initiated: 2009
Level of Funding: N/A
Weblink: mri.psu.edu/articles/09w/recycle/index.asp
Phone Number(s): 814.865.9142

Location: University Park, PA
Number of Employees: 4
Project Leader(s): Craig Grimes
E. cgrimes@engr.psu.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



Pennsylvania State University – The Grimes Group

Researchers (i.e. Craig Grimes, Oomman Varghese, Maggie Paulose and Thomas LaTempa) at Pennsylvania State University are working on a technology that uses sunlight and titanium oxide nanotubes to transform CO_2 into methane.

The team developed an efficient photocatalyst that can yield significant amounts of methane, other hydrocarbons, and hydrogen in a simple, inexpensive process.

The team used arrays of nitrogen-doped titania nanotubes sputter-coated with an ultrathin layer of a platinum and/or copper co-catalyst(s). The titania captures high-energy ultraviolet wavelengths, while the copper shifts the bandgap into the visible wavelengths to better utilize the part of the solar spectrum where most of the energy lies.

In addition, the thin-walled nanotubes increase the transportability of the charge carriers by reducing the chance for recombination of the electron with the hole.

The nanotube arrays were placed inside a stainless steel chamber filled with carbon dioxide infused with water vapor. The chamber was then set outdoors in sunlight; after a few hours the team measured the amount of CO_2 converted into useful fuels. The results showed 160 μL of methane per hour per gram of nanotubes, a conversion rate approximately 20 times higher than previous efforts done under laboratory conditions using pure UV light.

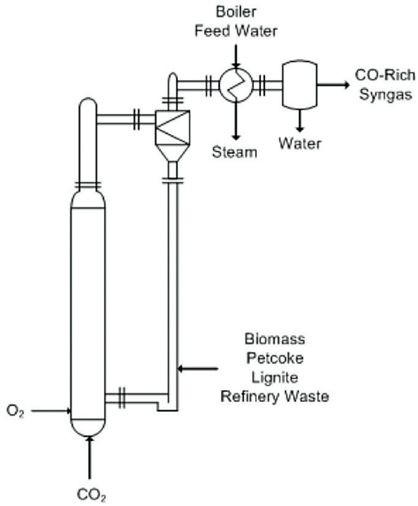
Partnerships & Demonstrations

The technology has been demonstrated at a laboratory level.

Year Initiated: 2010
Level of Funding: $1 million
Weblink:rti.org
Phone: 919.485.2742

Location: Durham, NC
Number of Employees: N/A
Project Leader(s): Jason Trembly
E. jtrembly@rti.org

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



Research Triangle Institute (RTI) International

RTI is conducting feasibility testing on the use of carbon as a reducing agent for CO_2 utilization. The chemistry for this proposed CO_2 utilization process is based on the reverse Boudouard reaction, in which carbon reduces CO_2 to produce carbon monoxide (CO): $CO_2 + C = 2CO$. The CO can then be used to create chemicals.

The scope of this work has both laboratory and modeling components. The laboratory phase is focused on carbon reactions with multiple CO_2 sources on a small scale, with the potential for larger scale testing. This phase of the research is being performed using thermogravimetric analysis (measuring small changes in weight as the temperature changes) and a bench-scale reactor system. The modeling effort is used to evaluate the overall process to demonstrate that it meets a cost target of less than $10 per ton of CO_2 sequestered with CO as the product.

In July 2010, the team was awarded an $800K award from NETL, bringing the total value of this project to $1 million.

Partnerships & Demonstrations
None.

Year Initiated: 2007
Level of Funding: N/A
Weblink: sandia.gov
Phone: 505.844.1277

Location: Albuquerque, NM
Number of Employees: N/A
Project Leader(s): Ellen Stechel
E. ebstech@sandia.gov

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

Sandia National Laboratory

Sandia National Laboratory developed a cylindrical metal machine called the Counter-Rotating-Ring Receiver Reactor Recuperator (CR5), which relies on concentrated solar heat to trigger a thermo-chemical reaction in an iron-rich composite material to recycle CO_2 into synthetic diesel fuel. The innovation is part of the laboratory's "Sunshine to Petrol" program.

The machine is designed with a chamber on each side. One side is hot, the other cool. Running through the center is a set of 14 Frisbee-like rings rotating at one revolution per minute. The outer edge of each ring is made up of an iron oxide composite supported by a zirconium matrix. Scientists use a solar concentrator to heat the inside of one chamber to 1,500°C, causing the iron oxide on one side of the ring to give up oxygen molecules. As the affected side of the ring rotates to the opposite chamber, it begins to cool down and carbon dioxide is pumped in. This cooling allows the iron oxide to steal back oxygen molecules from the CO_2, leaving behind carbon monoxide.

The process is continually repeated, turning an incoming supply of CO_2 into an outgoing stream of carbon monoxide. The carbon monoxide can then be combined with hydrogen – which can also be produced using the same machinery fed by water rather than CO_2— in a Fischer–Tropsch process to produce synthetic diesel fuel.

The laboratory is focused on improving the efficiency of the system, and expects significant advances to come from the discovery of new types of ceramics, particularly those that can release oxygen molecules at lower temperatures.

Partnerships & Demonstrations

The laboratory has a working prototype at their facility in New Mexico, and anticipates updated, progressively advanced prototypes being unveiled every three years.

Year Initiated: 2010
Level of Funding: ~$1.7 million
Weblink: ucl.ac.uk/chemistry/staff/academic_pages/nora_deleeuw
Phone: +44(0)20.7679.1015

Location: London, United Kingdom
Number of Employees: N/A
Project Leader(s): Nora De Leeuw
E. n.h.deleeuw@ucl.ac.uk

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

University College London – Department of Chemistry

University College London scientists led by Professor Nora De Leeuw will work with Johnson Matthey to mimic biological systems and produce a catalytic reactor that can convert CO_2 into useful chemicals for applications such as fuel cells in laptops and mobile phones.

The reactor will use novel nanocatalysts based on compounds formed in warm springs on the ocean floor that are considered to have triggered the emergence of life. The team's design will take inspiration from biological systems that can carry out complex processes to convert CO_2 into biological material, and exploit a wide range of computational and experimental chemistry techniques.

The research is part of the Engineering and Physical Sciences Research Council (EPSRC) 'Nanotechnology Grand Challenge' program and will receive a total investment of £4m.

The target at the end-point of Stage 1 is the fabrication of a photo-electrochemical reactor capable of harvesting solar energy to (i) recover CO_2 from carbon capture process streams, (ii) combine it with hydrogen, and (iii) catalyze the reaction into product.

In Stage 2 of the project, the prototype will be developed into a scaled-up commercially viable device, using optimum catalyst(s) in terms of (i) reactivity/selectivity towards the desired reaction; (ii) economic impact; and (iii) environmental, ethical and societal considerations.

Partnerships & Demonstrations

The researchers are working with Johnson Matthey to pursue this work. Other investigators in the project include Professor CRA Catlow, Dr. J Darr, Professor ES Fraga, Dr. G Hogarth and Dr. KB Holt.

Year Initiated: 2008
Level of Funding: N/A
Weblink: bms.med.arizona.edu/faculty/dominic-gervasio-phd
Phone: 520.621.4870

Location: Tucson, AZ
Number of Employees: 6
Project Leader(s): Don Gervasio
E. gervasio@email.arizona.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

University of Arizona

The university has developed an approach to make CO_2 into fuel using electrochemical reduction. It is a non-aqueous electrocatalytic process. This methodology can be applied to reduction of carbon dioxide for high conversion efficiency at high rates.

Ionic liquids are non-aqueous ion conductors with unusual properties including high conductivity with low activity of bulk water. Bulk water can inhibit processes like carbon dioxide reduction at low potentials because proton reduction to hydrogen is more facile in the presence of bulk water and strong reaction of water with surface, e.g., bulk water can react with non-noble metals limiting the choice of electrodes and raising costs substantially.

The University made a number of highly conductive non-protic and protic (proton containing) electrolytes in liquid and solid form. These electrolytes allow the formation of new electrochemical interfaces with previously known and used electrodes that leads unusual behavior including faster kinetics for a number of desirable processes that hardly occur or do not occur on electrode surfaces.

Partnerships & Demonstrations

The University demonstrated oxygen reduction on Pt at nearly 100% efficiency (see: "A Flourinated Ionic Liquid as a High-Performance Fuel Cell Electrolyte", Jeffery Thomson, Patrick Dunn, Lisa Holmes, Jean-Philippe Belieres, Charles A. Angell, and Dominic Gervasio ECS Trans. 13 (28), 21 (2008))

Year Initiated: 2010
Level of Funding: ~$2.3 million
Weblink: bath.ac.uk/chemistry/people/marken/
Phone: +44.0.1225.383694

Location: Bath, United Kingdom
Number of Employees: N/A
Project Leader(s): Frank Marken
E. f.marken@bath.ac.uk

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

University of Bath, Bristol, and the West of England

The Universities of Bath, Bristol and the West of England are working together to produce materials that can remove CO_2 from the atmosphere and lock it into useful products.

At the heart of the project, led by Dr. Frank Marken at the University of Bath, will be a one-step process that links catalysts directly with a novel CO_2 absorber, and is powered by solar or an alternative renewable energy source. The resulting 'carbon lock-in' products include polymers, carbohydrates, or fuels.

By combining the capture and utilization processes, the researchers claim efficiency can be improved and the energy required to drive the CO_2 reduction is minimized."

The project aims to develop porous materials that can absorb carbon dioxide and convert it into chemicals that can be used to make car fuel or plastics in a process powered by renewable solar energy. The researchers hope that in future the porous materials could be used to line factory chimneys to take carbon dioxide pollutants from the air, reducing the effects of climate change.

The project is funded with £1.4million (approximately $2.3 million U.S.) by the Engineering & Physical Sciences Research Council.

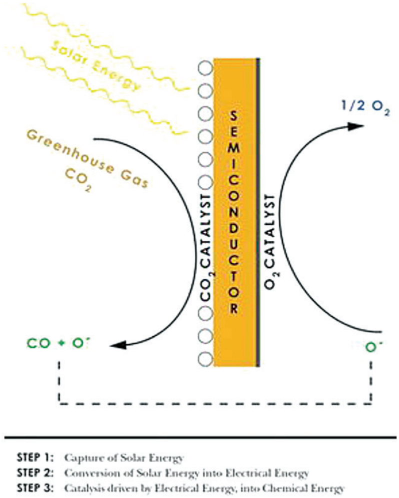
Partnerships & Demonstrations

The Bath-Bristol collaboration brings together scientists from a range of disciplines, including researchers from Bath's Institute for Sustainable Energy and the Environment (I-SEE), the School of Chemistry at the University of Bristol, and the Bristol Robotics Laboratory (BRL) and School of Life Sciences at the University of the West of England.

Year Initiated: 2007
Level of Funding: N/A
Weblink: kubiak.ucsd.edu
Phone: 858.822.2665

Location: San Diego, CA
Number of Employees: 2
Project Leader(s): Clifford Kubiak
E. ckubiak@ucsd.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



University of California San Diego – Kubiak Research Group

Clifford Kubiak, professor of chemistry and biochemistry, and his graduate student Aaron Sathrum have developed a prototype device that can capture energy from the sun, convert it to electrical energy and "split" carbon dioxide into carbon monoxide (CO) and oxygen.

The device utilizes a semiconductor and two thin layers of catalysts. It splits CO_2 to generate CO and oxygen in a three-step process. The first step is the capture of solar energy photons by the semiconductor. The second step is the conversion of optical energy into electrical energy by the semiconductor. The third step is the deployment of electrical energy to the catalysts. The catalysts convert CO_2 to CO on one side of the device and to oxygen on the other side.

Because electrons are passed around in these reactions, a special type of catalyst that can convert electrical energy to chemical energy is required. Researchers in Kubiak's laboratory have created a large molecule with three nickel atoms at its heart that has proven to be an effective catalyst for this process.

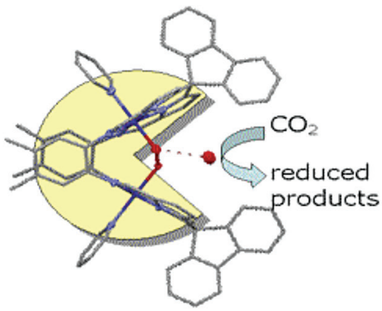
The researchers are now building the device using a gallium-phosphide semiconductor. It has twice the band gap of silicon and absorbs more energetic visible light. Therefore, they predict that it will absorb the optimal amount of energy from the sun to drive the catalytic splitting of carbon dioxide.

Partnerships & Demonstrations
None

Year Initiated: 2010
Level of Funding: N/A
Weblink: homepages.ed.ac.uk/parnold/JoB/
Phone: +44.0.131.650.5429

Location: Edinburgh, Scotland
Number of Employees: 10
Project Leader(s): Polly L. Arnold
E. Polly.Arnold@ed.ac.uk

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



University of Edinburgh – The Joseph Black Laboratory

The Joseph Black laboratory at the School of Chemistry is working on a range of reactions to put excess CO_2 to good use.

Masters and PhD students, and postdoctoral research scholars are working on a range of CO_2-related projects, including:

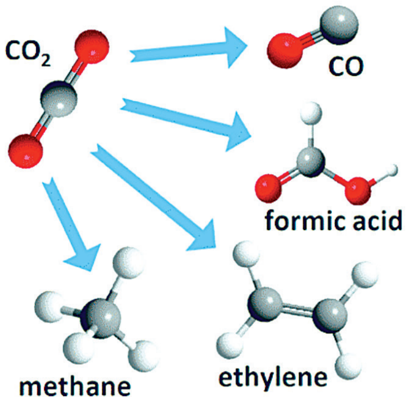
- Rakesh Barik is studying the electrochemical conversion of CO_2 by different catalysts at an electrode, and the coupling of this electrochemistry to renewable energy sources. He is funded by the Carbon Trust, and supervised by Prof. Lesley J Yellowlees (Chemistry, UoE) and Dr. Dimitri Mignard (Chemical Engineering, UoE)
- Aline Devoille is investigating the trapping and reduction of CO_2 by new supramolecular architectures that combine amines and redox active metals. She is supervised by Dr. Jason B Love (Chemistry, UoE).
- Aaron Gamboa is studying the use of asymmetric metal complexes as catalysts, for the copolymerisation of CO_2 with other biorenewable monomers, to make highly oxygenated plastics such as polycarbonates. The resulting biodegradable materials will be assessed for their applications to replace traditional plastics in food packaging, electronic devices, and medical biomaterials. He is funded by Conacyt, Mexico.
- Research Associate Dr. Andrei Gromov is studying the functionalization of nanostructured carbon materials for small-scale carbon capture from air. He is supervised by Prof. Eleanor Campbell (Chemistry, UoE) and Prof. Stefano Brandani (Chemical Engineering, UoE).

Partnerships & Demonstrations
The Joseph Black laboratory works with and is funded by: the Carbon Trust; Conacyt, Mexico; and others.

Year Initiated: 2010
Level of Funding: N/A
Weblink: scs.illinois.edu/kenis
Phone: 217.265.0523

Location: Urbana, Il
Number of Employees: 2
Project Leader(s): Paul Kenis
E. kenis@illinois.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



University of Illinois, Champaign – The Kenis Research Group

Dr. Paul Kenis and graduate student Devin Whipple of the Kenis Research Group have developed a reactor similar to the microfluidic analytical platform used by our group to facilitate the study of electrochemically converting CO_2 into other chemicals such as formic acid, methanol and carbon monoxide, renewable electricity can be stored in a chemical form that is convenient and has high energy density.

This setup employs a flowing liquid electrolyte, instead of the membrane typically use in other systems. This flowing electrolyte gives flexibility in controlling reactor conditions, thus allowing thorough study of the parameters that maximize reactor performance.

The goal is to facilitate the use of renewable energy in portable and transportation applications, and provide a means leveling the output of intermittent renewable sources such as wind and solar power.

The National Science Foundation provides funding for this project.

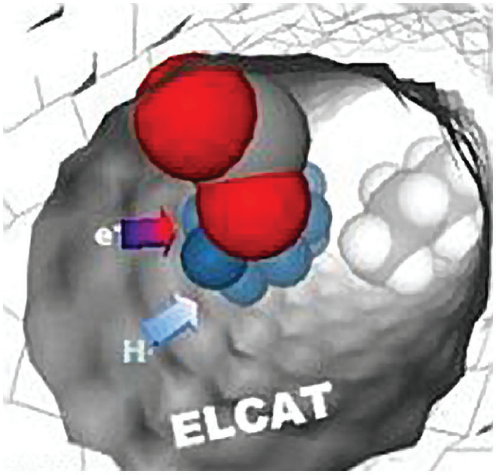
Partnerships & Demonstrations

The National Science Foundation supports the laboratory.

Year Initiated: 2004
Level of Funding: $1.1 million
Weblink: ww2.unime.it/catalysis
Phone: +39.90.393.134

Location: Messina, Italy
Number of Employees: N/A
Project Leader(s): Gabriele Centi
E. centi@unime.it

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



University of Messina

The EU provided €875,246 (US $1.1 million) in funding for ELCAT—electrocatalytic gas-phase conversion of CO_2 in confined catalysts—a 42-month project under the Sixth Framework Program (6FP) to focus on the gas-phase electrocatalysis of CO_2 to Fischer-Tropsch (FT)-like products (C1-C10 hydrocarbons and alcohols). Work began in 2004.

The project was born from the observation that with carbon dioxide confined inside carbon micropores, and electrons and protons allowed to flow to an active catalyst of noble metal nanoclusters, that gaseous carbon dioxide was reduced to a series of hydrocarbons and alcohols. The reaction products were remarkably similar to those of the Fischer-Tropsch (FT) process in which synthetic gas is converted to a series of hydrocarbons (alkanes, alkenes and so on) and water.

The ELCAT approach confines the catalyst particles within carbon nanotubes. The catalyst particles need to be quite small, due to the fact of the high number of electrons that must be transferred to generate the higher hydrocarbons. The number of electrons required is quite high—on the order of 24 for a butanol product, and an average of 46 for C8 to C9. There is no evolution of hydrogen in this process.

The ELCAT team found that it is possible to produce higher carbon hydrocarbons (C8 to C9), with productivity depending upon a number of factors such as catalyst, electrolyte and flow rates.

Partnerships & Demonstrations

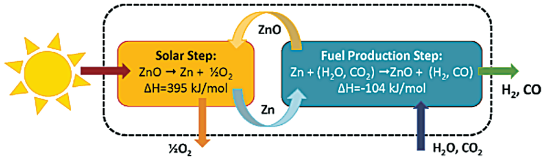
Three organizations were involved in addition to the University of Messina, Italy: Fritz-Haber-Institut der Max-Planck-Gesellschaft in Berlin, Germany; Université Louis Pasteur in Strasbourg, France; and University of Patras in Patras, Greece.

Year Initiated: 2009
Level of Funding: N/A
Weblink: me.umn.edu/labs/solar/index.shtml
Phone: 612.626.9850

Location: Minneapolis, MN
Number of Employees: 34
Project Leader(s): Jane Davidson
E. jhd@me.umn.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

UNIVERSITY OF MINNESOTA



University of Minnesota – Solar Energy Laboratory

The Solar Energy Laboratory is focused on a variety of technologies and approaches to splitting CO_2, including a multi-step solar thermochemical reactor for H_2O and CO_2 splitting.

The Lab is also working on ceria-based oxide substrates to split H_2O and CO_2. The major advantage of the partial redox approach is that the reactive material remains in the solid state throughout the cycle and challenges associated with separation of gases or collection of aerosol particles are obviated.

Finally, the Lab is working on a two-step solar thermochemical Zn/ZnO cycle for splitting H_2O and CO_2. In the first step of the cycle, zinc oxide is reduced at high temperature in a solar chemical reactor/receiver placed at the focal point of a concentrating solar system. In the second step, the zinc is oxidized back to zinc oxide at a lower temperature with water or sequestered carbon dioxide, producing hydrogen or carbon monoxide. The net effect of these two steps is the dissociation of water or carbon dioxide by solar process heat.

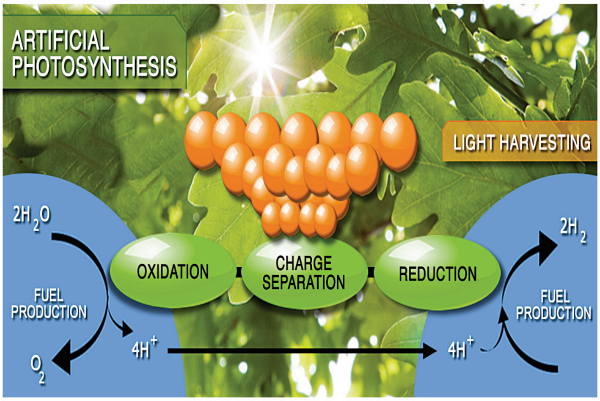
Partnerships & Demonstrations
None

Year Initiated: 2009
Level of Funding: $17.5 million
Weblink: efrc.unc.edu
Phone: 919.843.8313

Location: Chapel Hill, NC
Number of Employees: 66
Project Leader(s): Thomas Meyer
E. tjmeyer@email.unc.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

ENERGY FRONTIER RESEARCH CENTER



University of North Carolina – Energy Frontier Research Center

Funded by a DOE ARRA grant, the UNC Energy Frontier Research Center (UNC EFRC) is researching solar fuels that integrate light absorption and electron transfer driven catalysis in molecular assemblies and composite materials to create efficient devices for solar fuels; splitting water into hydrogen and oxygen and reducing CO_2 to hydrocarbons. The UNC EFRC is also focused on producing electricity in next generation photovoltaics.

Primary goals of the program are the discovery of new catalytic systems, the integration of structures, and the elucidation of mechanisms via cutting edge experimental and theoretical methods.

CCR work at UNC is focused on molecular assemblies. In this path, efficient devices will be created with integrated molecular assemblies that use solar energy for solar fuel production; splitting water into H_2 and O_2 or water reduction of CO_2 to methanol or hydrocarbons.

Specific goals include:

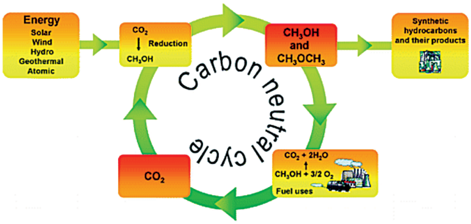
- Design and evaluate improved catalysts for electron transfer driven water oxidation and CO_2 reduction.
- Integrate solar fuel catalysts in molecular assemblies and composite materials that combine light absorption, vectorial electron transfer, and single electron transfer activation of multiple electron catalysis for fuel forming reactions.
- Design and construct prototype devices for practical solar fuels production via photocatalytic water splitting and CO_2 reduction

Partnerships & Demonstrations
In 2009, UNC was awarded $17.5 million over five years from the U.S. Department of Energy Office of Science and President Obama's American Recovery and Reinvestment Act for an innovative interdisciplinary research center to develop solar fuels from next generation photovoltaic technology. UNC EFRC partners with Duke University, North Carolina Central University, North Carolina State University, the University of Florida and Research Triangle

Year Initiated: 2007
Level of Funding: N/A
Weblink: usc.edu/dept/chemistry/loker
Phone: 213.740.5976

Location: Los Angeles, CA
Number of Employees: N/A
Project Leader(s): George Olah
E. olah@usc.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



University of Southern California – Loker Hydrocarbon Research Institute

USC's Loker Hydrocarbon Research Institute developed fundamental chemistry to transform carbon dioxide to methanol or dimethyl ether.

Improved new methods for the efficient reductive conversion of CO_2 to methanol and/or DME that the Institute has developed include bireforming with methane and ways of catalytic or electrochemical conversions.

Partnerships & Demonstrations
UOP, a Des Plaines, Ill.-based unit of Honeywell International, is funding this work. The agreement grants UOP exclusive access rights for commercialization of technology and intellectual property developed by USC researchers.

Year Initiated: 2010
Level of Funding: $0
Weblink: me.utep.edu/facultyshafirovich.htm
Phone: 915.747.6465

Location: El Paso, TX
Number of Employees: 1
Project Leader(s): Evgeny Shafirovich
E. eshafirovich2@utep.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

University of Texas at El Paso

A University faculty member is developing a novel approach to solar thermochemical splitting of CO_2 that produces CO and C for synthesis of liquid hydrocarbons.

The proposed thermochemical cycle for splitting CO_2 involves decomposition of S_nO_2 in a solar reactor and reduction of CO_2 by S_nO in the other reactor. The CO_2 reduction agent (S_nO) is regenerated within the cycle, so that the integral reaction is splitting of CO_2 to C, CO, and O_2. The decomposition of S_nO_2 occurs at temperatures lower than 2000°C, which makes the cycle feasible in industrial applications. As compared with the ZnO/Zn cycle proposed previously, the S_nO_2/S_nO cycle facilitates quenching of the decomposition product (S_nO) in the solar reactor.

Thermodynamic calculations for the reactions between S_nO and CO_2 revealed the conditions for high conversion of CO_2 into C and CO.

The technology is in an early stage of development.

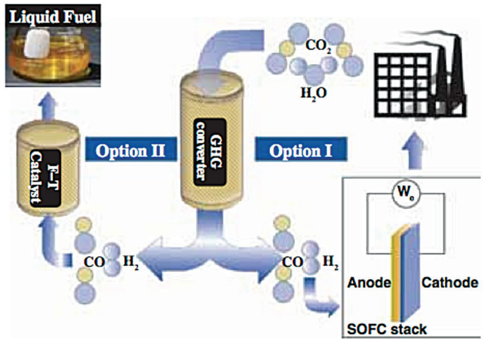
Partnerships & Demonstrations

None

Year Initiated: 2010
Level of Funding: $0
Weblink: eng.utoledo.edu/~aazad
Phone: 419.530.8103

Location: Toledo, OH
Number of Employees: 1
Project Leader(s): Abdul-Majeed Azad
E. abdul-majeed.azad@utoledo.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N



University of Toledo

The University has developed a technique that causes targeted and quantitative conversion of CO_2 and H_2O to CO and H_2, respectively, through a simple heterogeneous gas/solid redox process.

The technology uses a simple metal or metal oxide under very mild experimental conditions (580°C; 1 atmosphere). In laboratory work, CO_2 interacts with iron oxide (magnetite, Fe_3O_4) in one case, and with elemental iron in the other. The reduction of CO_2 to CO results in formation of Fe_2O_3 because of the oxidation of Fe_3O_4 and Fe.

The metal and metal oxide that mediate the conversion of CO_2 to CO, of water into hydrogen or the $CO_2 + H_2O$ mixture into syngas ($CO + H_2$), are, in turn, converted to an oxide with enhanced magnetic characteristics. The spent oxide could be either regenerated or used for manufacturing a variety of ceramic magnets. The regeneration of the spent oxide could be conducted either carbothermically or with gasified biomass that can serve as a low-quality substitute for conventional reductant under mild experimental conditions.

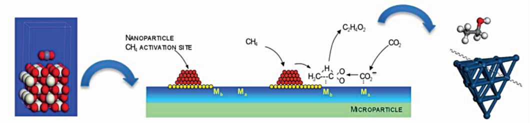
Partnerships & Demonstrations

The technology has been demonstrated at laboratory scale.

Year Initiated: 2008
Level of Funding: N/A
Weblink: cccu.wustl.edu/rprojects/lo1.php
Phone: 314.935.8055

Location: St. Louis, MO
Number of Employees: 7
Project Leader(s): Cynthia Lo
E. clo@wustl.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N



Washington University – Consortium for Clean Coal Utilization

Researchers at the University are studying mechanisms for converting carbon dioxide and methane to liquid fuels and other commodity chemicals, using both thermal and photochemical routes on multifunctional catalysts.

Heterogeneous nanoscale catalysts are being designed, synthesized, and characterized for their suitability in CO_2 conversion.

The catalyst design is guided by theoretical and computational studies. The theoretical studies will provide estimates of kinetic parameters for adsorption of CO_2 and CH_4 on different metal and metal oxide structures, which will then be tested and "tuned" in an iterative process based on experimental kinetic adsorption data on different nanoparticles, obtained via nonsteady-state experiments using the temporal analysis of products (TAP) approach.

The most promising catalyst configurations will be tested in microreactors at Technion and Washington University.

Partnerships & Demonstrations
This work is funded by the Consortium for Clean Coal Utilization, which is a center for research in advanced coal and carbon capture technologies. Peabody Energy, Arch Coal, and Ameren fund the consortium. Technion in Israel will partner with the University to test promising catalyst designs.

Year Initiated: N/A
Level of Funding: N/A
Weblink: westernresearch.org/management.aspx?id=576
Phone: 307.721.2376

Location: Laramie, WY
Number of Employees: 2
Project Leader(s): Vijay Sethi
E. vsethi@uwyo.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N

Western Research Institute

Western Research Institute (WRI) has developed a Fischer-Tropsch (F-T) process for converting carbonaceous feedstock to synthesis gas, which is then converted to ethanol and other higher alcohols using a proprietary WRI catalyst.

Catalysts used in the thermochemical process are tested in WRI's bench-scale fuel synthesis facility. Solid feedstocks are converted to synthesis gas in gasifiers; liquid or gaseous feedstocks are converted in reformers or partial oxidation reactors.

WRI states that its thermochemical processes can be used to produce ethanol from natural gas (GTL), coal (CTL) or biomass (BTL or cellulosic ethanol). It is suspected that the process can also process CO_2.

Partnerships & Demonstrations

WRI is partnering with Novus Energy to construct a 50-gallon-per-day pilot plant to demonstrate conversion of natural gas and anaerobic biodigester gas to mixed alcohols, predominantly ethanol. Synthesis gas is generated using a dual steam-methane/CO_2-methane reformer developed in collaboration with Novus Energy. The reformer uses a catalyst provided by Oxford Catalysts.

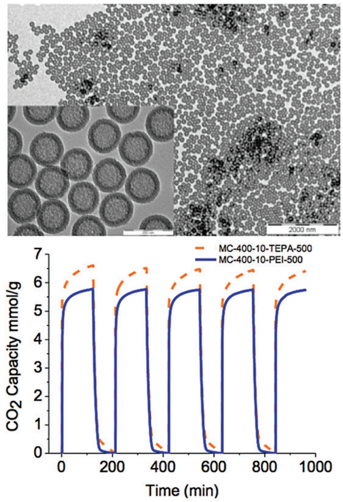
Mineralization »

Year Initiated: 2008
Level of Funding: $31.25M
Weblink: kaust-cu.cornell.edu
Phone: 607.255.9680

Location: Ithaca, NY
Number of Employees: 4
Project Leader(s): Emmanuel P. Giannelis
E. epg2@cornell.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

Center for Energy and Sustainability



KAUST – Cornell Center for Energy and Sustainability

This technology integrates Cornell's recently developed carbon capture platform involving mesoporous nanocomposite sorbents with conversion to single and multi-ion carbonates for use as cement/aggregate substitute or as chloride scavenger to mitigate against corrosion.

Specific research goals are to a) demonstrate a process to produce a series of low carbon emission cementitious materials combining carbon capture and sequestration; b) investigate the impact of crystalline and amorphous carbonates on the structure, flow and performance of cement pastes; c) optimize concrete mixtures that maximize incorporation of CO_2; and d) evaluate long-term performance.

Partnerships & Demonstrations

The KAUST-CU Center has a number of contacts with firms in construction and contracting who are potential partners for demonstrations of these novel low emission CO_2 concrete materials in roads, bridges, and buildings

Year Initiated: N/A
Level of Funding: N/A
Weblink: lbl.gov/msd/investigators/investigators_all/zuckermann_investigator.html
Phone: 510.486.7091

Location: Berkeley, CA
Number of Employees: N/A
Project Leader(s): Ronald Zuckerman
E. rnzuckermann@lbl.gov

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

Lawrence Berkeley National Laboratory

A team led by Ronald Zuckerman is attempting to mimic the natural process used by shellfish to mineralize CO_2 in a crystalline form called calcite and has found a method to accelerate this process up to 40 times.

The process uses a type of synthetic polymer called a peptoid as a catalyst to speed up the growth of calcite crystals. Peptoids, also known as poly-N-substituted glycines, mimic the shape and functionality of natural proteins and peptides, but are more stable and can be tailored for specific application, the team explained.

The peptoids are effective even at very low concentrations of CO_2 and are reusable, the team reports. While previous attempts to catalyze calcite could only achieve a 150 percent acceleration, the peptoids can accelerate the process 20 to 40 times, they claim.

Partnerships & Demonstrations

None

Year Initiated: 2010
Level of Funding: $499,890
Weblink: mcgill.ca/civil/faculty/shao/
Phone: 514.398.6674

Location: Montreal, QC, Canada
Number of Employees: 3
Project Leader(s): Yixin Shao
E. yixin.shao@mcgill.ca

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

McGill University – Department of Civil Engineering

Researchers, in collaboration with 3H Company, are working to develop a CO_2 curing process for the precast concrete industry that can utilize CO_2 as a reactant to accelerate strength gain, reduce energy consumption, and improve the durability of precast concrete products.

In this process, CO_2 is converted to thermodynamically stable calcium carbonate, which is embedded in calcium silicate hydrate. Concrete masonry blocks and fiber-cement panels are ideal candidate building products for carbon sequestration since they are mass-produced, and require steam curing.

The research will examine the possibility of achieving a cost-effective, high performance concrete manufacturing process through a prototype production using specially designed chambers, called CO_2 claves, to replace steam kilns and implement forced-diffusion technology to maximize carbon uptake at a minimal process cost.

The compact design of the CO_2 chamber and low cost carbon capture technology is predicted to result in a net process cost of less than $10 per ton of CO_2 sequestered.

In order to make the process economically feasible, the team is also focusing on developing a self-concentrating absorption technology to produce low cost CO_2 for concrete curing and to capture residual CO_2 after the curing process.

In July 2010, the team was awarded an approximately $400K award from NETL, bringing the total value of this project to approximately $500K.

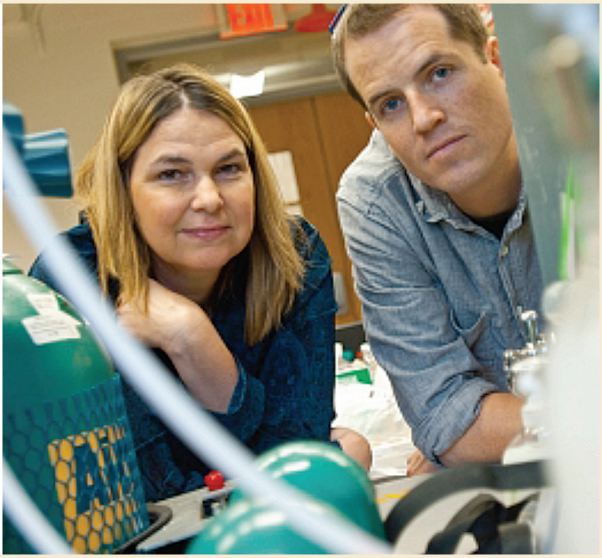
Partnerships & Demonstrations

The team is partnering with 3H Company. 3H Company specializes in research and development of clean coal technologies, with emphasis on CO_2 capture technologies. It is based in Lexington, KY.

Year Initiated: 2010
Level of Funding: N/A
Weblink: belcher10.mit.edu
Phone: 617.324.2800

Location: Cambridge, MA
Number of Employees: 3
Project Leader(s): Angela Belcher
E. belcher@mit.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A



Massachusetts Institute of Technology – Belcher Laboratory

W.M. Keck Professor of Energy Angela Belcher and two of her graduate students, Roberto Barbero and Elizabeth Wood, have created a process that can convert CO_2 into carbonates that could be used as building materials.

The process involves genetically engineering common strands of baker's yeast so that they facilitate the production of carbonates when CO_2 is added. Yeast don't normally do any of those reactions on their own, so Belcher and her students had to engineer them to express genes found in organisms such as the abalone. Those genes code for enzymes and other proteins that help move carbon dioxide through the mineralization process. The researchers also used computer modeling and other methods to identify novel proteins that can aid in the mineralization process.

The process requires capturing CO_2 in water and then combining the dissolved carbon dioxide with mineral ions to form solid carbonates. The biological system captures CO_2 at a higher rate, requiring no heating, cooling and use of toxic chemicals.

Their process, which has been tested in the lab, can produce about two pounds of carbonate for every pound of carbon dioxide captured.

Next, the team is focusing on scaling up the process so it could be used in a power plant or industrial factory.

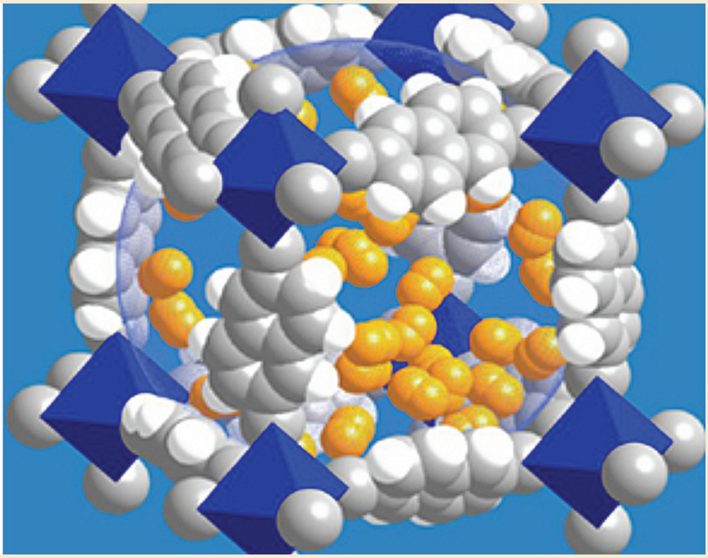
Partnerships & Demonstrations
The Italian energy company Eni funds the technology's development.

Year Initiated: 2010
Level of Funding: N/A
Weblink: yaghi.chem.ucla.edu
Phone: 310.206.0398

Location: Los Angeles, CA
Number of Employees: 8
Project Leader(s): Omar M. Yaghi
E. yaghi@chem.ucla.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: N/A

UCLA



University of California Los Angeles – Yaghi Laboratory

UCLA chemistry and biochemistry professor Omar M. Yaghi has created a synthetic "gene" that could capture carbon dioxide emissions.

The professor and his laboratory took organic and inorganic units and combined them into a synthetic crystal that codes information in three-dimensional DNA-like crystals. The material can be further developed to convert CO_2 into fuel.

The discovery results from an effort to assess the viability of MOFs in CO_2 storage. MOFs represent a class of porous materials that offer these advantages for CO_2 storage: ordered structures, high thermal stability, adjustable chemical functionality, extra-high porosity, and the availability of hundreds of crystalline, well-characterized porous structures yet to be tested.

The DOE's Office of Basic Energy Sciences federally funded the research. The research indicated that one member of a series of materials has 400 percent better performance in CO_2 capture than one that does not have the same code.

Partnerships & Demonstrations
Professor Yaghi has been collaborating with his former UCLA chemistry colleague and former CNSI director Sir J. Fraser Stoddart on how to take concepts from biology and incorporate them into a synthetic material.

Year Initiated: 2010
Level of Funding: N/A
Weblink: ims.ucsc.edu
Phone: 925.423.7990

Location: Santa Cruz, CA
Number of Employees: 1
Project Leader(s): Greg Rau
E. rau4@llnl.gov

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of CO_2 → ? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

University of California Santa Cruz – Rau Laboratory

Professor Greg Rau is working on a process to use seawater and calcium to remove CO_2 from power plants' flue stream to produce calcium bicarbonate. The vision is to then place the calcium carbonate in the sea to balance acidity and avert some of the consequences of global climate change.

The professor conducted a series of lab-scale experiments to find out if a seawater/mineral carbonate (limestone) gas scrubber would remove enough CO_2 to be effective, and whether the resulting substance—dissolved calcium bicarbonate—could then be stored in the ocean where it might also benefit marine life.

In his experiments, Rau found that the scrubber removed up to 97 percent of CO_2 in a simulated flue gas stream, with a large fraction of the carbon ultimately converted to dissolved calcium bicarbonate. At scale, the process would hydrate the CO_2 in flue gas with water to produce a carbonic acid solution. This solution would react with limestone, neutralizing the carbon dioxide by converting it to calcium bicarbonate—and then would be released into the ocean. While this process occurs naturally, it is much less efficient, and is too slow paced to be effective.

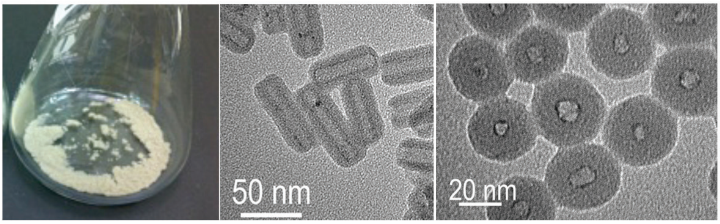
The Energy Innovations Small Grant Program of the California Energy Commission and Lawrence Livermore National Laboratory funded the work.

Partnerships & Demonstrations
None

Year Initiated: 2010
Level of Funding: $0
Weblink: engr2.pitt.edu/chemical/facstaff/enick.html
Phone: 412.624.9649

Location: Pittsburgh, PA
Number of Employees: 2
Project Leader(s): Robert M. Enick
E. rme@pitt.edu

Energy Efficiency (MWh/ton of converted CO_2): <0.20 MWh/tCO_2 (rough estimate)
Conversion Metric (Ton of CO_2 → ? quantity of product): 3-6 tons
Land Footprint (Tons/acre of capacity): ~200 m^2 for 10 tons CO_2/h
Water Footprint (Gal/ton of CO_2 recycled): 0
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y



Nano-encapsulated sorbents (Here: PEI inside of SiO_2) aggregate into micron-scale particles for CO_2 capture (left). The TEM images show examples of nanoparticles composed of ~50wt% porous, hollow nanoshells and 50wt% liquid or phase-change sorbents.

University of Pittsburgh – Veser and Enick CO_2 Capture Lab

The lab is working on encapsulation of liquid CO_2 sorbents within a porous, hollow, nanoscale shell of an inert material results in a dry powder containing ~50wt% of the pure liquid CO_2 sorbent. These powders are non-corrosive, enabling commercial-scale processing units to be manufactured from inexpensive carbon steel rather than stainless steel.

More importantly, the large energy penalty usually associated with evaporation of water from dilute sorbent mixtures (such as MEA + water) is avoided.

Further, the retention of the liquids within the nanoshell can enhance both the reaction kinetics and the CO_2-uptake capacity of these amine-based sorbents (e.g. MEA, PEI polyethyleneimine, etc.).

The energy for regeneration of the nanoencapsulated CO_2-rich solvent particles could be obtained from the off-steam from the power plant (turbine effluent).

Partnerships & Demonstrations

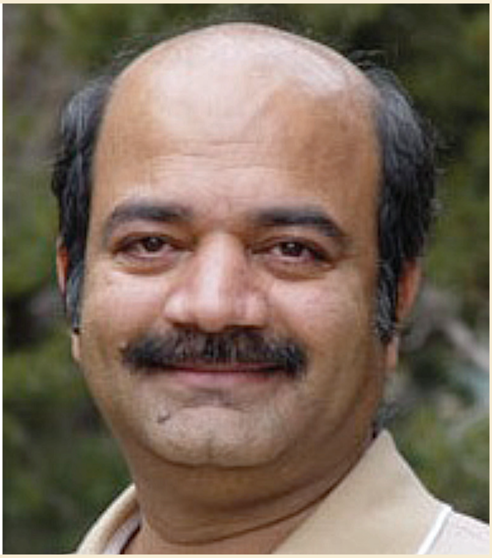
This is currently a lab-scale concept. The lab has demonstrated the ability to generate nanoshells, load these nanoparticles with liquid amines, and conduct cyclic CO_2 capture and release. The lab also has a suite of low viscosity liquids (e.g. MEA), viscous liquid (e.g. PEI), and liquid-to-solid phase-changing aminosilicone liquid solvents 1,3-bis(3-aminopropyl)tetramethyldisiloxane that can be encapsulated.

Year Initiated: 2004
Level of Funding: N/A
Weblink: uwadmnweb.uwyo.edu/UWRENEWABLE/Faculty/KJ_Reddy.asp
Phone: 307.766.6658

Location: Laramie, WY
Number of Employees: 10
Project Leader(s): KJ Reddy
E. katta@uwyo.edu

Energy Efficiency (MWh/ton of converted CO_2): N/A
Conversion Metric (Ton of $CO_2 \rightarrow$? quantity of product): N/A
Land Footprint (Tons/acre of capacity): N/A
Water Footprint (Gal/ton of CO_2 recycled): N/A
Raw Flue Gas (~12% CO_2) Instead of Pure CO_2?: Y

UNIVERSITY OF WYOMING



University of Wyoming: Reddy Laboratory

Professor KJ Reddy, who began testing a mineral carbonation process three decades ago, developed a "SequesTech" process that has demonstrated the simultaneous capture and conversion of carbon dioxide, sulfur dioxide and mercury from flue gas into solid minerals.

The process sequesters CO_2 emissions in fly ash in the smokestacks of coal-fired power plants, for use in applications such as gypsum.

The technology has run continuously for 7 years in a 2,120 MW coal plant, removing 25 to 30 percent of the CO_2 from 300 to 500 standard cubic feet per minute of flue gas with a concentration of 11 to 12.5 percent CO_2.

Reddy aims to commercialize the technology within the next couple of years.

Partnerships & Demonstrations

The pilot project utilized flue gas from a 2,120 MW coal fired power plant at PacifiCorp's Jim Bridger Power Station at Point of Rocks, Wyoming. It's been in operation for seven years.

Appendix A – Additional Non-Biological CCR Companies and Laboratories »

3M

Tom Hanschen
tphanschen1@mmm.com
www.3m.com
Minneapolis, MN

Alliant Tech-systems, Inc.

Vladimir Balepin
vladimir.balepin@atk.com
www.atk.com
Minneapolis, MN

American Science & Technology

AST has designed a novel catalyst that can crack CO_2 into carbon and oxygen. The carbon will in turn be used to produce platform chemicals.

Asok K. Raut
asok5a@gmail.com
San Diego, CA

Battelle Memorial Institute

Aaron Appel
aaron.appel@battelle.org
www.battelle.org
Columbus, OH

Exelus, Inc.

Exelus designs "engineered catalysts" with current focus on refining, monomer production, and biomass-to-gasoline. It is thought that these catalysts also have CO_2-reduction applications.

Mitrajit Mukherjee
mmukherjee@exelusinc.com
www.exelusinc. com
Livingston, NJ

GR Silicate Nano-Fibers & Carbonates

The company was awarded a ~$150K DOE grant in 2/2010 focused on carbon capture. It is thought that the company has a mineralization component to its work.

Vijay Mathur
griinc@hotmail.com
Federal Way, WA

Praxair

Jonathan Lane
Jonathan_Lane@praxair.com
www.praxair.com
Buffalo, NY

SRI International

Vladimir Balepin
vladimir.balepin@atk.com
www.atk.com
Minneapolis, MN

TDA Research

TDA Research pioneered an approach to utilize CO_2 in a "dry reforming" process. The process combines CO_2 with methane to reform CO_2 and CH_4 into carbon monoxide and hydrogen.

Steven Paglieri
spaglieri@tda.com
www.tda.com
Wheat Ridge, CO

Turchan Technologies

Jahr Turchan
jturchan@turchan.com
www.turchan.com
Dearborn, MI

Catholic Unknown University of America

Biprodas Dutta
duttab@cua.edu
physics.cua.edu
Washington, DC

Central Texas Dynamics Research

Brian Donald
bdonald@txdynamics.com
Austin, TX

Michigan Tech

Tim C. Eisele
tceisele@mtu.edu
www.chem.mtu.edu/chem_eng/faculty/tceisele.html
Houghton, MI

Michigan Tech

Research efforts in this laboratory are focused on (a) CO_2 conversion to novel solid materials and (b) synthesis of liquid fuels from CO_2.

Yun Hang Hu
yunhangh@mtu.edu
www.mse.mtu.edu/faculty/yunhangh.html
Houghton, MI

Northern Illinois University

Working on the conversion of CO_2 to useful materials including graphene.

Tao Xu
txu@niu.edu
www.chembio.niu.edu/xu/index.shtml
DeKalb, IL

Oxford University

Working on turning CO_2 into fuel.

Peter Edwards
peter.edwards@chem.ox.ac.uk
research.chem. ox.ac.uk/peter-edwards.aspx
Oxford, UK

Southern Illinois University

Tomasz Wiltowski
tomek@siu.edu
me.engr.siu.edu/faculty/wiltowski/index.htm
Carbondale, IL

University of Kansas Center for Research, Inc.

The Center for Environmentally Beneficial Catalysis focuses on the development of new technologies to sustainably produce chemicals and fuels. Current emphasis is on biomass conversion, yet catalysts are potentially applicable to CO_2 reduction.

Raghunath Chaudhari
rvc1948@ku.edu
www.cebc.ku.edu
Lawrence, KS

University of Massachusetts, Boston

The Rochford Research Group is primarily interested in artificial photosynthesis. The Group has a strong focus on the development of nanoparticle-molecule architectures for application in solar driven catalysis and dye-sensitized solar cells.

Jonathan Rochford
Jonathan.Rochford@umb.edu
alpha.chem.umb.edu/faculty/rochford/index.php
Boston, MA

University of Nevada

Manoranjan Misra
misra@unr.edu
www.unr.edu/mse/misra/index.html
Reno, NV

University of Utah

Zhigang Fang
zak.fang@utah.edu
powder.metallurgy.utah.edu
Salt Lake City, UT

Appendix B – Additional Biological CCR Companies and Laboratories »

70centsagallon .com

Biofuel technology company with a continuous harvesting photobioreactor.

Rich Fortun
info@70CentsaGallon.com
www.70centsagallon.com
Sarasota, FL

Accent Laboratories, LLC

Developing a low-cost, high efficiency algae harvesting and dewatering technology. Won an SBIR/STTR grant in 2008.

New York

AccuDx (Io- Mega)

At an envisioned pilot facility in Keokuk, Iowa, algae is grown in a 240,000 gallon tank using automated equipment for algae-based Omega 3-rich oil that would be a viable substitute for fish oils, and algae meal, a substitute for fish meal and/or soy concentrate in pet food.

Raveendran Pottathil
accudx@accudxtechnologie.com
La Jolla, California

Agrofuel

The company is focused on producing algae via outdoor ponds, shielded by mesh to control sun exposure. The system integrates carbonation, harvesting, water flow dynamics and nutrient/anitibiotic additives. Agrofuel projects a break-even point of around four years for this technology. Agrofuel is also researching photobioreactors. These PBRs will eventually be paired with industrially-based high CO_2 generators.

Colin Tebbett
colin@agrofuelco.com
www.agrofuelco.com
United Kingdom

Algae AquaCulture Technologies (AACT)

The company offers bioprocessors, photobioreactors, and other algae system components. AACT systems are ideally suited for the production of biodiesel, methane and hydrogen.

Michael Smith
michaels@dancehammer.com
www.algaeaqua.com
Montana

Algae Bioenergy Solutions

An algae development company. ABS determines site and economic feasibility of algae processing through joint ventures with wastewater treatment plants, municipal sites, industrial sites, and agricultural operations.

Chuck Pardue
chuckpardue3@gmail.com
www.absgreenfuels.com
Martinez, GA

Algae Biosciences Corp.

Holder of IP (39 patent claims) for algae-based technologies focused on nutraceutical, pharmaceutical, fuel, and other markets. The company produces algae in contaminant-free salt-water aquifers near Holbrook, AZ, where there's a pristine salt-water aquifer from a long-dried up sea.

Andrew Ayers
a.ayers@algaebio.com
www.algaebio.com
Holbrook, AZ

Algae Floating Systems

AFS Biofarm™ is a microalgae cultivation farm that consists of identical AFS Biounits™. AFS Biounits™ are made of identical AFS PBR Modules™ that in turn consist of proprietary photobioreactors. Production capacity of the farm ranges from 10 to 100 million gallons of algal oil per year. Current systems will be deployed on non-arable lands; the long-term strategy is to deploy AFS Biofarms™ offshore in the open sea.

Vadim O. Krifuks
v.krifuks@algaefloatingsystems.com
www.algaefloatingsystems.com
South San Francisco, CA

Algae Production Systems

The company focuses on the manufacture, sales and support of equipment for the production of algae, algae oil and algae biomass. The company sells equipment to grow (via photobioreactor) and harvest algae, as well as extract the algae's oil.

Richard Fortune
rfortune@algaeproductionsystems.com
www.algaeproductionsystems.com
Houston, TX

Algae Venture Systems

The company is developing a Rapid Algae Farming (RAF) System, which will serve as the platform for the creation of numerous products from algae, specifically biofuels and bioplastics. The RAF System is a fully automated network of enclosed photo-bioreactors that grows and processes algae. The design is fully adaptable, giving it the capability to utilize virtually any species of algae.

Ross O. Youngs
ryoungs@algaevs.com
www.algaevs.com
Marysville, OH

Algae World Wide, Inc.

The company will construct 1,400 algae ponds and a processing plant adjacent to the ponds on a designated, 1,200-acre site located in the Southwestern U.S. AWW has purchased the rights to the technology/know-how/formulas used to develop the first commercial algae farm over the last five years by a world-renowned, non-profit entity resulting from a $12.5 Million investment.

Larry W. Wiseman
larry@wiseman-associates.com
Silver Springs, FL

Algae.Tec

The Algae.Tec system combines closed control of algae production within an engineered modular environment and efficient downstream biofuel processing.

Peter Hatfull
phatfull@algaetec.com.au
algaetec.com.au
Subiaco, Perth, Australia

Algaecake Technologies Corporation

The company has a patent pending algae photo bioreactor and algae growth technology. Algae cake is a very valuable, hi-protein by-product of our system that will be allocated to the production of nutritional food additives, vitamin supplements, animal /fish feed and other valuable consumer products.

Ray O'Toole
o7oole@algaecake.com
www.algaecake.com
Tempe, AZ

Algaedyne Corporation

Licenses and constructs algal growth facilities focused on specific environmental and economic conditions. The plants will be located close to sources of CO_2, wastewater, nitrates, phosphates, and other nutrients.

Thomas Byrne
tbyrne@byrneltd.com
www.algaedyne.com
Preston, MN

AlgaeFuel

The company's AIPS (Advanced Integrated Pond System), uses a low cost, low-tech approach to treating municipal, industrial and agricultural waste resulting in a high yield, low maintenance cultivation system. Algae growth is fertilized in large-scale raceway ponds that use sewage treatment wastewater as a source of nutrients and are additionally supplemented with anaerobic bacterial byproducts. The company also sells a photobioreactor.

Alex Brendel
info@algaefuel.org
www.algaefuel.org
Concord, CA

AlgaeLink

The company's computer controlled, bioreactor technology nurtures the algae in a closed and controlled environment of clear tubes. The company also offers a feeding and control unit, central international monitoring room, computerized monitoring, and automatic cleaning system.

Peter van den Dorpel
info@algaelink.com
www.algaelink.com
The Netherlands

Algaen Corporation

Produces algae nutritional supplements.

www.algaen.com
Greensboro, North Carolina

Algaepower

The company has launched a pilot project to cultivate photobioreactor-based algae, and is testing the PBR at the Blue Spruce Farm in partnership with and receiving funding from Central Vermont Public Service, the state's largest utility. The unit recycles cow waste and the overall project goal is to produce biodiesel that can be used on Vermont farms for vehicles and equipment.

Gail Busch
gail@algepower.com
www.algepower.com
Vermont

Algaetech Sdn Bhd

This holding company's activities are in the field of micro algal research, development and consultancy as well as production and marketing of renewable energy and high value products such as anti-oxidants and other neutraceuticals.

Syed Isa Syed Alwi
info@algaetech.com.my
www.algaetech.com.my
Malaysia

Algaewheel

Algae paddlewheel technology.

Christopher A. Limcaco
info@algaewheel.com
www.algaewheel.com
Indianapolis, IN

Algal Integration Technologies, LLC

Seeking to use flue gas to grow algae for biofuels and other products.

South Boston, Virginia

Algasol Renewables

The company's technology is a flexible multi-compartment photobioreactor floating on water that can be deployed both on land in ponds or in the ocean. A patent pending in national phase in all relevant PCT countries covers all key aspects of the technology.

Miguel Verhein
info@algasolrenewables.com
www.algasolrenewables.com/en
Baleares, Spain

AlgaTechnologies Ltd

Founded to develop and commercialize Astaxanthin and other microalgae-derived products for the nutraceuticals and cosmeceuticals industry.

Hagay Tzur
hagay@algatech.com
www.algatech.com
Israel

Algenol Biofuels

Direct algae-to-ethanol process claims to yield 6-10K gallons of ethanol per acre per year. As the algae grow, Algenol taps into carbon dioxide from a nearby power plant and funnels it into the tanks. The algae takes the gas and converts it into oxygen and evaporated alcohol, which is then removed and concentrated for use as fuel.

Paul Woods
paul.woods@algenolbiofuels.com
www.algenolbiofuels.com
Bonita Springs, FL

Algoil Industries, Inc.

Working on various elements of algae biofuel production.

info@algoilindustries.com
www.algoilindustries.com
Taiwan

Alternative Energy Resources

Developed a process that will produce biodiesel from local species of algae.

John Travers
info@aer.ie
www.aer.ie
Dublin, Ireland

American Biofuels

Doing business as Community Fuels in Encinitas, owns one of California's largest biodiesel plants and has branched into algae development.

Lisa Mortenson
info@communityfuels.com
www.communityfuels.com
Encinitas, CA

Applied Research Associates, Inc.

Researching algae biofuel production.

www.ara.com
Panama City, Florida

Aquatic Energy

Development, construction, and operation of algae farms.

David Johnston
david.johnston@aquaticenergy.com
www.aquaticenergy.com
Lake Charles, LA

Aquentium

Developing green crude, and noted the potential of brackish or saltwater to host algae without disclosing the strains that it will focus on. Secured 475 acres in the State of New Mexico for the development of an algae biofuel production facility.

Mark Taggatz
mtaggatz@aquentium.com
www.aquentium.com
Perris, CA

Arizona Public Service

The US Department of Energy previously awarded a $70.5 million grant to capture the carbon dioxide emissions from the coal-fired Cholla Power Plant near Holbrook, AZ.

www.aps.com
Phoenix, AZ

Aurora Algae

Using saltwater, non-GM algae strains to produce algae for the omega-3, protein, feed, and fuel markets. It developed a method, derived from the wastewater treatment industry, for harvesting the algae without having to fully dry it out. Uses CO_2 rather than a paddlewheel to mix the algae.

Gregory L. Bafalis
info@aurorainc.com
www.aurorainc.com
Alameda, CA

AXI

University of Washington Professor Rose Ann Cattolico developed a fatty, fast-growing algae strain that might be able to produce a high-quality petroleum substitute faster and cheaper than other strains. She has been working with algae for 30 years. AXI isn't in the business of making fuel. Instead, it will work with biofuel producers to develop strains of algae that produce just the right lipids, or oils, for the fuel that the producer wants to make. The methods will not employ genetic modification.

Erick Rabins
erick.rabins@alliedminds.com
www.alliedminds.com
Boston, MA

Beckons Industries

The company is engaged in validation of microalgae for fuel and feed and has already developed a closed system photobioreactor for large-scale high density algae cultivation and is developing methods using green chemistry for energy efficient algae oil.

Dr. Chandra Prakash
md@beckons.org
www.beckons.org
Mohali, Chandigarh, India

Bio Architecture Lab (BAL)

Located in Berkeley, California and Santiago, Chile, Bio Architecture Lab (BAL) is dedicated to producing the world's lowest cost, most scalable, and sustainable source of sugars for biofuel and renewable chemical production. The feedstock source is aquafarmed, native macroalgae (seaweed), which can be grown globally. The company began cultivating 100 hectares of seaweed on the island of Chiloé, with the aim of producing biofuel.

Daniel Trunfio
contact@ba-lab.com
www.ba-lab.com
Berkeley, CA 94710

BiO_2 Solution

Algae production to treat wastewater.

Loren Josh
www.bio2solution.com
Strasburg, CO

Bioalgal Marine

Almeria University spin-off company specialized in cultivating and integral usage of microalgae. The company developed a new fertilizer manufactured from a microalga.

bioalgal@bioalgal.com
www.bioalgal.com
Almería, Spain

BioCee

In October 2009, the company received a $2.2 million from ARPA-E for biofuels from artificial symbiotic colony of photosynthetic cyanobacteria. BioCee also received a $150,000 Small Business Innovative Research grant through the NSF.

Luca Zullo
press@biocee.com
www.biocee.com
Minneapolis MN

BioCentric Energy Holdings, Inc.

BioCentric Energy, Inc. is primarily a research & development holding company, whose principals are involved in seeking innovative green energy solutions for the 21st Century. The company has a provisional patent pending invention of their closed loop Algae Pro Photobioreactor Solution.

Dennis Fisher
DennisFisher@biocentricenergy.com
www.biocentricenergy.com
San Juan Capistrano

Biofuel Advance Research and Development (BARD)

The company engages in the manufacture of biodiesel from soybean oil and algae oil in the United States. It also offers soybean meal; soybean hull; soybean oil to produce various non-food products, including inks, plasticizers, crayons, paints, and soy candles; glycerin for the cosmetic and pharmaceutical markets; algae oil and cakes for medicinal, human, and animal food chain uses; and oxygen to the health system for medically related uses.

Adrian E. Searight
contact@bardllc.com
www.bardllc.com
Philadelphia, PA

BioFuelBox

The company's technology directly converts wet algae paste into biodiesel, with a smaller amount of biomass as a byproduct.

Steven Perricone
sperricone@biofuelbox.com
www.biofuelbox.com/algae.html
San Jose, CA

BIOfuel From Algae Technologies (BIOFAT) project

Nine partners based in seven countries support the project and the goal is to show that ethanol, biodiesel and bioproducts call all be produced at large scale from algae. The European Commission's 7th Framework Program largely funds it.

Biolight Harvesting

Biolight Harvesting is working on a new technique for extracting oil from blue-green algae (also known as cyanobacteria) that would effectively allow Biolight (or another company that bought its tools) and turning into biodiesel in one step. If it works, it would cut the costs and likely the time required to produce industrial chemicals or fuel from algae.

Michael Melnick
michael@cmea.com
San Diego, CA

BioMara

A UK and Irish joint project that aims to demonstrate the feasibility and viability of producing third generation biofuels from marine biomass.

Ian Macfarlane
biomara@sams.ac.uk
www.biomara.org
United Kingdom

Bionavitas

Bionavitas has a proprietary patent pending technology - bringing light deeper below the surface for the high volume production growth of micro-algae.

Michael Weaver
michael@bionavitas.com
www.bionavitas.com
Redmond, WA

Blue Marble Biomaterials

The company focuses on encouraging wild algae growth in nutrient rich wastewater as well as converting environmental nuisance algae into reusable inputs. Uses anaerobic digestion to generate natural gas and other valuable bio-chemical streams.

Kelly Ogilvie
kelly.ogilvie@bluemarbleenergy.net
www.bluemarblebio.com
Seattle, WA

Blue Sun Biodiesel

The company is working on a project, funded by a federal grant, to find a way to turn the seaweed into a high quality jet biofuel.

Leigh Freeman
info@gobluesun.com
www.gobluesun.com
Golden, CO

Bodega Algae

The company is a developer of scalable algae photobioreactors. The closed continuous-flow reactors produce high-energy algal biomass for use in the production of biofuel.

Sam Hill
hill@bodegaalgae.com
www.bodegaalgae.com
Jamaica Plain, MA

BRAIN

A German biotech company that is developing a microorganism that digests CO_2 directly, without photosynthesis. It directly produces important components for the chemical industry, such as pyruvates, which can easily be converted into succinic acid, a potential platform chemical.

Jürgen Eck
je@brain-biotech.de
www.brain-biotech.de
Zwingenberg, Germany

BTR Labs

Private research facility focused on biotechnology, microorganisms and renewable raw materials to produce bio-energy, bio-fuels and value-added bio-chemicals.

erin@btrlab.com
www.btrlab.com
London, ON, Canada

Bye Energy

Working to develop bio-derived aviation fuels.

George Bye
Info@ByeEnergy.com
www.byeenergy.com
Englewood, CO

Caitilin

Offers a family of solid heterogeneous catalysts that claims to more easily and cheaply turn algae oil into certified biodiesel.

Larry Lenhart
llenhart@mdv.com
www.catilin.com
Ames, IA

Canadian Pacific Algae

Growing macroalgae.

www.canadianpacificalgae.com
Nanaimo, Canada

Canrex Biofuels Ltd

Working on various algae processes.

Nick Mashin

Carbon Capture Corporation

The company is developing new ways for using algae to absorb carbon dioxide emissions from electric power plants. The company operates a 160-acre site for a proposed 46-megawatt ultra-low emission natural gas power generation facility.

Bernard Raemy
braemy@carbcc.com
www.carbcc.com
La Jolla, CA

Cauffiel Technologies

$12.5 million project to develop aviation fuel from algae.

Ford B. Cauffiel
ford@cauffiel.com
www.cauffiel.com
Toledo, Ohio

CEHMM

This algae biofuel project is a research and development project investigating biodiesel production processes and the propagation, harvesting, and extraction of oil from both brine and fresh water algae.

Doug Lynn
dclynn@cehmm.org
www.cehmm.org
Carlsbad, NM

Cellana, Inc.

The company's technology is based on the coupling of enclosed photobioreactors, in which single strains of algae are grown continuously, with open ponds. It uses natural strains—without genetic modification.

Edward T. Shonsey
eshonsey@hrbp.com
www.hrbp.com
San Diego, CA

Cequesta Algae

Cequesta Algae is focusing on algae engineering, emphasizing fishmeal substitute.

David Waimann
david@cequesta.com
www.cequesta.com

Cereplast

The company makes bioplastics from algae. It intends to launch a new family of algae-based resins.

Frederic Scheer
fscheer@cereplast.com
www.cereplast.com
El Segundo, CA

Circle Biodiesel & Ethanol Corporation

Manufactures biodiesel plants and biodiesel processors, ethanol plants and stills, methane digester, a new algae photobioreactor for the production of algae (scalable and ready for commercialization), and a new algae harvesting system for the extraction of algae oil for algae biodiesel or algae biofuel. Algae harvesting system retails for $195,000 US dollars and can process one gallon of algae oil per minute from a fluid stream that is half algae and half water by mass.

Peter Schuh
peter@circlebio.com
www.circlebio.com
San Marcos, CA

Climos

Climos is exploring various processes for naturally removing large amounts of CO_2 from the atmosphere. Not currently focused on algae, but the company is known to be examining blue-green algae for its ability to sequester CO_2.

Dan Whaley
dwaley@climos.com
www.climos.com
San Francisco, CA

Compact Con-tractors for America

Aviation fuel from Algae.

Robert Fulton III
info@AlgaeAviationFuel.com
algaeaviationfuel.com
Cedar City, UT

Culturing Solutions

The company's Phyta-Platform PhotoBioreactor along with intensified Phyta Pond technology are used for the cultivation of monoculture algae. The company is also developing its process to hydrotreat and cavitate algae to release the lipids and separate the oil, water and biomass.

Dean Tsoupeis
dean@culturingsolutions.com
www.culturingsolutions.com
St. Petersburg, FL

Cyano Biofuels GmbH

Cyano Biofuels is an R&D company focused on the biology part of the biofuels and chemical feedstocks business. In 2010, Algenol acquired the company.

Dan Kramer
infocyano-biofuels.com
www.cyano-biofuels.com
Berlin, Germany

Cyanotech

Produces spirulina.

info@cyanotech.com
www.cyanotech.com
Kailua-Kona, HI

Desert Sweet Biofuels

The company originally focused on shrimp production, but has now utilizes its ponds for the production of algae. It has been involved in aquaculture for 14 years, managing fields in Ecuador. It switched to Arizona because of its warm dry climate, perfect for growing algae.

Rick Thompson
info@desertsweetbiofuels.com
www.desertsweetbiofuels.com
Gila Bend, Arizona

Diversified Energy Corporation

The company's DEC Simgae™ system is an agriculture-based solution to large-scale algae production that has the benefits of both open and closed systems. The company has lipid extraction from algal biomass, electronic pulse technology that essentially ruptures algae cells via electronic pulsation or shockwaves. A North Carolina State process uses a catalyst to convert triglycerides (including those from algae oil) into petroleum (not biodiesel).

W. David Thompson
phillip.brown@diversified-energy.com
www.diversified-energy.com
Gilbert, AZ

Dr Reddy's Laboratories

Developing large scale algae production using the carbon dioxide from the company's boiler stacks.

GV Prasad
businessdevelopment@drreddys.com
www.drreddys.com
Hyderabad, India

DuPont

In early 2010, the Department of Energy awarded Dupont and partners funding for research into algae derived next-gen biofuels. The macroalgae-to-isobutanol project will focus on: improving domestic macroalgae aquaculture; converting macroalgae to bio-available sugars; converting those sugars to isobutanol; and economic and environmental optimization of the production process.

Wilmington, DE and Berkeley, CA

Earthrise Farms

The 108-acre facility near El Centro, CA, operated by Earthrise Nutritionals of Irvine, CA, grows Spirulina, a microalgae used in food, biochemistry, and pharmaceuticals.

Amha Belay
abelay@earthrise.com
www.earthrise.com
Irvine, CA

Eco-Solution

The company has developed a unique technology platform (O.N.E.) to help select and develop new microorganisms that give industry the ability to meet a range of environmental and regulatory requirements. The company's first applications include an innovative treatment of ammoniacal nitrogen contained in municipal and industrial wastewater as well as custom solutions to treat particularly recalcitrant industrial wastewater challenges.

Dominique Duvauchelle
infos@eco-solution.com
www.eco-solution.com
Paris, France

EcoSolids

The company's Cellruptor is a low-energy, algae oil extraction process.

Clive Rigden
clive.rigden@ecosolids.com
www.ecosolids.com
United Kingdom

Endicott Biofuels

Maker of second-generation biodiesel refinery equipment. The company is collaborating to develop renewable fuels from algae oil.

David M. Robinson
info@endicottbiofuels.com
www.endicottbiofuels.com
Houston, TX

Energae LP

The company uses algae to make waste-based ethanol for the nutraceutical industry.

Jerry Krause
www.energaecompany.com
Clear Lake, IA

Energy Derived

The company offers a technology that separates the algae out of a growth medium into concentrated algae biomass slurry, and outputs clean chemical free water that can be recycled back into the biomass growth process. The company also offers a harvesting technology.

Jeff Collier
jeff.collier@energyderived.com
www.energyderived.com
Scottsdale, AZ

Energy Farms, Inc.

The company has developed a commercialization plan that incorporates the sale of Energy Farm Franchise Units that will produce clean transportation fuels, biodiesel, electricity, and fresh water from otherwise unusable land, sunlight, and brackish water using patented and patent pending advanced materials and processes. These farms will be designed to convert low value resources into high value products using an environmentally conscious closed loop production system.

info@energyfarminc.com
www.efarm1.com
Santa Rosa Beach, FL

Enhanced Biofuels & Technologies

Open pond algae systems.

Ganapathy Arumugam
info@ebtplc.com
www.ebtiplc.com
London and India

ENN

Launched a pilot scale algal fuels project, gasifying coal underground for CO_2 capture and using the gas as feedstock for algal production. It utilizes a closed photobioreactor technology.

Gan Zhongxun
China

Ennesys

Ennesys is a French partnership of UK-based incubator PJC and algae oil services provider OriginOil. The joint venture will focus on urbanized markets, where high population densities and energy prices can give algae a major advantage for waste to energy generation.

Pierre Tauzinat
ptauzinat@pacificjunction.com
www.ennesys.com
France

Euglena

The company sells diet supplements made from a kind of algae called euglena. The company could also soon produce cosmetics, animal feed and even biofuel from these algae.

Tokyo, Japan

Ever Cat Fuels

The company employs a process to convert renewable feedstocks including algae into biofuel. Ever Cat Fuels is constructing a $5 million plant in Isanti, Minn., that will use this technology.

Clayton McNeff
support@evercatfuels.com
www.evercatfuels.com
Anoka, MN

Evodos

The company offers a centrifugal algae separation technology.

Mr. Marco Brocken
marco.brocken@evodos.eu
www.evodos.eu
The Netherlands

Femtobeam

The company's algae photobioreactor design does not require sunlight, relying on 100 percent photosynthetically active low-power light sources that emit light from the entire surface area, providing a uniform growth rate of single cells.

Robin L. Ore
www.femtobeam.com
Colorado

Fluid Imaging Technologies

The company is applying its FlowCAM technology to the task of algae classification and R&D, lipid analysis, algae growth concentration and growth rate monitoring, and bioreactor contamination monitoring.

Victoria Kurtz
info@fluidimaging.com
www.fluidimaging.com
Yarmouth, ME

Gas Technology Institute (GTI)

Partnering with Aquaflow Bionomic Corporation on an advanced biomass conversion technology program worth US$3.1 million that will be part funded by the US Department of Energy.

Terry Marker
terry.marker@gastechnology.org
www.gastechnology.org
Illinois

General Atomics

Algae derived jet fuel funded by a $43 million DARPA contract.

Carl Fisher
carl.fisher@ga.com
www.ga.com
San Diego, CA

Genesis Biofuel, Inc.

Grows algae in photobioreactors then transesterifies it into biodiesel.

Harvey Dorren
harveydorren@genesis-biofuel.com
genesis-biofuel.com
Boulder, CO

Genifuel

The company is applying its FlowCAM technology to the task of algae classification and R&D, lipid analysis, algae growth concentration and growth rate monitoring, and bioreactor contamination monitoring.

James R. Oyler
info@genifuel.com
www.genifuel.com
Salt Lake City, UT

Genomatica

The company developed a pioneering process that uses genetically modified bacteria to make a rubberized plastic known as 1,4-butanediol, or BDO, to replace petroleum-based feedstock used in chemical engineering and manufacturing.

Christophe Schilling
info@genomatica.com
www.genomatica.com
San Diego, CA

Global Green Solutions

The company offers vertical photobioreactors.

Doug Frater
info@sweetwatercapital.net
www.globalgreensolutionsinc.com
British Columbia, Canada

GO2WATER

Algae-based water purification technology.

Bailey Green
Bailey.Green@oswaldgreen.com
www.oswaldgreen.com
Berkeley, CA

Green Bios Technology

Has licensed a new type of algae bioreactor from Ohio University. The company plans to develop the reactor for customers interested in its diverse potential applications, which include curbing air pollution, treating municipal waste, carbon sequestration and growing feedstock for biofuel or pharmaceutical uses.

Joe Bajjani
info@greenbiostech.com
www.greenbiostechnologies.com
Austell, GA

Green Gold Algae and Seaweed Sciences

Produces bio-ethanol from macro-algae biomass.

Richard Serbin
Info@Gold-green.com
www.gold-green.com
Israel

Green Star Products, LLC

Uses a micronutrient to boost microalgae growth rate.

Joseph P. LaStella
info@GreenStarUSA.com
www.greenstarusa.com
San Diego, CA

Greener-BioEnergy

In the planned development stages of an algae bioreactor production facility to produce renewable biofuels.

Nick Rodrigues
info@greenerbioenergy.com
www.greenerbioenergy.com
Ripon, California

Greenshift

The company holds the exclusive rights to a patented process to grow thermophillic cyanobacteria - using a parabolic mirror to funnel sunlight into fiber-optic cables that carry it to acrylic glow plates inside the reactor - that fall to the bottom of the bioreactor once they've matured, where they can be harvested for extraction and conversion.

Kevin Kreisler
info@greenshift.com
www.greenshift.com
New York, NY

Harvel Plastics, Inc.

Produces a unique UV resistant clear PVC piping for use in photobioreactor systems.

harvel@harvel.com
www.envirokinguv.com
Easton, PA

Hawaii Bioenergy

Actively researching algae.

Paul Zorner
pzorner@hawaiibioenergy.com
www.hawaiibioenergy.com
Honolulu, HI

Heliae Development, LLC

Biofuel project uses technologies developed at Arizona State University. Focuses on algae used to produce to kerosene.

Daniel Simon
info@heliae.com
www.heliae.com
Gilbert, AZ

Hytek Bio Ltd.

Produces "bioreactors" to cultivate algae.

Robert Mroz
bob@hytekltd.com
www.hytekbio.com
Dayton, MD

Imperium Renewables

Converts feedstock oil, including that from algae, to biodiesel.

John Plaza
info@imperiumrenewables.com
www.imperiumrenewables.com
Seattle, WA

IngrePro B.V.

Focuses on the selection of the adequate algal strains, harvesting and extraction technologies. Operates the largest algae farms in Europe, producing 80 tons a year.

Carel Callenbach
c.callenbach@ingrepro.nl
www.ingrepro.nl
The Netherlands

International Energy, Inc.

Claims to have created a proprietary technology that harvests oil without killing the algae.

Charles Bell
Investors@InternationalEnergyInc.com
www.internationalenergyinc.com
Newark, NJ

Inventure Chemicals

Algae to biodiesel/ethanol conversion processes. Applying patent pending processes to develop and commercialize algae to biodiesel/ethanol conversion processes. Applying patent pending processes to develop and commercialize second-generation ethanol and biodiesel technology utilizing a variety of feedstocks, including algae. The company focuses on process conversion and plant design/construction.

Mark Tegen
mark.tegen@inventurechem.com
www.inventurechem.com/index.html
Seattle, WA

Kai BioEnergy Corp

The company has a proprietary, highly efficient, and fully integrated continuous production, harvesting, and extraction system. It's patented continuous, open system produces bio crude oil from microalgae.

Mario Larach
larach.m@kaibioenergy.com
www.kaibioenergy.com
San Diego, CA

Kalpa Energy

A modular, high-density, hybrid fermenter/photobioreactor design to produce algae in India.

Akash Shah
info@kalpaenergy.com
kalpaenergy.com
India

Kent BioEnergy

The company has developed systems for producing dense monoculture populations of microalgae in high-rate, constantly circulating ponds.

James Carlberg
jcarlberg@kentbioenergy.com
www.kentbioenergy.com
San Diego, CA

Kuehnle AgroSystems, Inc.

The company conducts biotech research and development of plant-based systems for production of biologically active compounds. Kuehnle received a Phase 1 SBIR award from the National Science Foundation to demonstrate the technical feasibility of producing dietary supplements and animal feed.

Gordon Wallace
gordow@aloha.net
www.kuehnleagro.com
Honolulu, HI

Kumho Petrochemical Co

Building an algae bioethanol plant in Korea.

www.kkpc.co.kr
Korea

Life Technologies

Investigating yeast and/or algal host systems, and the development of cloning, transformation, expression and genetic manipulation tools as part of a larger synthetic biology technology initiative.

Gregory T. Lucier
ir@lifetech.com
www.lifetechnologies.com
Carlsbad, CA

LiveFuels (Arare Ventures)

LiveFuels grows a robust mix of native algae species in low-cost, open-water systems.

Lissa Morgenthaler
Lissa@LiveFuels.com
www.livefuels.com
San Carlos, CA

Mighty Algae Biofuels

Closed photobioreactors to grow the algae.

Michael Fertik
fertik@post.harvard.edu
Redwood City, CA

MOR Technology

Algae oil extraction technology.

Curt Jones
curtj@mortechnology.com
www.reyntek.com/MOR/SC/index.php
Metropolis, IL

Neste Oil Corporation

Performing research into microbial and algae oil.

Jukka-pekka Nieminen
JukkaPekka.Nieminen@nesteoil.com
www.nesteoil.com
India

Northington Energy

Northington's biodiesel process converts virgin soybean and algae oil into biodiesel.

info@northingtonenergy.com
www.northingtonenergy.com
Cheyenne, WY

Novozymes

The company is a supplier and partner to many different consumer product value chains.

Peder Holk Nielsen
agmj@novozymes.com
www.novozymes.com
Denmark

Nualgi

The company uses diatom algae as a feedstock for Biodiesel.

M V Bhaskar
bhaskarmv.64@gmail.com
www.nualgi.com
Hyderabad, India

Ocean Nutrition Canada

Uses algae to supply omega-3 EPA and DHA fatty acid supplements. Looking at biofuel production as well.

Robert Orr
info@ocean-nutrition.com
www.ocean-nutrition.com
Halifax, Nova Scotia, Canada

OpenAlgae

The company is developing algae-specific processing technologies to enhance the economics of oil production from algae. Its algae concentration, electromechanical cell lysis, and solvent-less oil recovery technologies were developed in conjunction with UT Austin.

Hoyt Thomas
hhthomas@openalgae.com
www.openalgae.com
Austin, TX

Organic Fuels

The company has a proprietary oil extraction technology that removes the oil from the algae by destroying the cell wall electromechanically.

Hoyt Thomas
tgieskes@organicfuels.com
www.organicfuels.com
Houston, TX

OriginOil, Inc.

Developed an internally illuminated bioreactor, whose LED-lit bioreactors provide algae with only the wavelengths of light needed to stimulate growth. The company has also patented what it calls quantum fracturing - a system that creates micronized bubbles of carbon dioxide and nutrients that the company says are easier for algae to absorb. The system also combines quantum fracturing with tuned microwaves to burst the algae cells, releasing the oil inside and simplifying harvest.

Riggs Eckelberry
riggs@originoil.com
www.originoil.com
Los Angeles, CA

Origo Industries

Developing a variety of products, including algae.

origo@webershandwick.com
www.origo-industries.com
United Kingdom

Palmer Labs

The company is exploring algae and cyanobacteria production systems.

Miles Palmer
palmerlabs@palmerlabs.com
www.palmerlabs.com
Durham, NC

Palo Alto Research Center (PARC)

A technology being developed can potentially be used to separate algae from water using gravity's force on water, with very little external energy.

Meng Lean
mlean@parc.com
www.parc.com/about/people/113/meng-lean.html
Palo Alto, CA

Peterborough Renewable Energy Ltd

Its Algae Technology and Carbon Capture project is focused on capturing 10-20% of the energy-from-waste plant's emissions, with the algae making use of nutrients from the plant's potash.

Chris Williams
United Kingdom

PetroAlgae

The company is using 12 main, non-GM algae strains, some from Arizona State University, and none of them genetically modified. It has developed a continuous flow system to extract algae via pipeline and concentrate the algae down to 50 percent water content, or algae paste.

Fred Tennant
ftennant@petroalgae.com
www.petroalgae.com
Melbourne, FL

PetroSun

Open ponds to grow algae.

Gordon M. LeBlanc, Jr.
petrosun@cox.net
www.petrosuninc.com
Scottsdale, AZ

Photon8

The company employs genetically modified alga, closed photobioreactors, and a new dewatering process in its platform.

Brad Bartilson
bartilson@photon8.com
www.photon8.com
Brownsville, TX

Phyco Spectrum

Algae used to clean sewage.

V. Sivasubramanian
vavesu@gmail.com
www.phycospectrum.com
Chennai, India

PhycoSystems

Modular algae production systems for use in wet climates.

Anthony Michaels
tony@proteusenv.com
www.phycosystems.com
Los Angeles, CA

Plankton Power

Under the leadership of Plankton Power, the Regional Technology Development Corp. Massachusetts National Guard, Woods Hole Oceanographic Institution (WHOI), Marine Biological Laboratory (MBL), and Cape Cod Commission are joining forces to establish the Cape Cod Algae Biorefinery. The new facility will focus on pilot-and commercial-scale development of algae biodiesel that is cost-competitive with existing petroleum- and vegetable-based fuels, with improved performance characteristics.

Curtis S. Felix
cfelix@planktonpower.net
www.planktonpower.net
Cape Cod, MA

Plasma International Lighting Systems

Lighting systems to grow algae.

Don Cook
don.cook@plasma-i.com
www.plasma-i.com
Canada

Pond Biofuels

The algae are grown in sophisticated bioreactors. The company has filed patents for its technology, including the automated processes for growing and harvesting.

Terry Graham
info@pondbiofuels.com
www.pondbiofuels.com
Toronto, Ontario

Primafuel

Its Algae Biorefinery Program intended to combine upstream algae production and downstream biorefinery systems that will help commercialize algae technologies.

Rahul Iyer
solutions@primafuel.com
www.primafuel.com
New York City, NY

QuantumSphere, Inc.

A developer of advanced catalyst materials, high-performance electrode systems, and related process chemistries for turning algae to fuel.

Subra Iyer
siyer@qsinano.com
www.qsinano.com
Santa Ana, CA

Renewable Algal Energy

Developing a low-cost method for growing and harvesting algae.

jsk@renewablealgalenergy.com
www.renewablealgalenergy.com
Kingsport, TN

Renewable Energy Group

The company has adapted its multi-feedstock technology to refine oil from a variety of algae strains and produce biodiesel. Company working with several groups to commercialize algae production, but it is not producing algae itself.

Jeffrey Stroburg
Jeffrey.Stroburg@regfuel.com
www.regfuel.com
Ames, IA

Renewable Fuel Products Incorporated

Distributed, portable renewable diesel production from algae.

Peterson Conway
peterson@renewablefuelproducts.com
www.renewablefuelproducts.com
San Francisco, CA

Renewed World Energies

The company created a closed system and automated microalgae production facility. It's pilot facility is near Georgetown, SC.

Kevin McLemore
kevinm@rwenergies.com
www.rwenergies.com
Georgetown, SC

Renewergy

A unique system for the cultivation of algae.

Luke McConnell
info@renewergy.biz
www.renewergy.biz
Pennsylvania

Replenish Energy

A process that cultures and harvests microalgae in saltwater ponds for the production of pure vegetable oil.

Jorge Gaskins Alcott
gaskins@8thsea.ne
www.replenishenergy.org
San Juan, Puerto Rico

Rosetta Genomics

Working with Seambiotic to develop strains for algal biofuel.

Amir Avniel
amir@rosettagenomics.com
www.rosettagenomics.com
Israel

Russell Industries, Inc.

Building an algae farm in Houston, TX.

Rick Berman
InvestorRelations@ru308.com
www.russind.com
Houston, TX

SAIC

Developing algae based jet fuels with General Atomics; funded by a $25 million DARPA contract.

www.saic.com
McLEan, VA

SBAE Industries

Produces algae for aquaculture, energy, and other markets.

Marc Van Aken
Marc.Van.Aken@sbae-industries.com
www.sbae-industries.com
Belgium

Scipio Biofuels

The company is developing a closed photobioreactor system for algae to be used in large-scale plants and in smaller systems for specific industries such as trucking or airports.

Matt Snyder
contact@scipiobiofuels.com
www.scipiobiofuels.com
Aliso Viejo, CA

Scottish Bioenergy Cooperative Ventures

Builds, sells and operates photobioreactors for capturing carbon dioxide emissions to grow algae feedstock for biodiesel production.

David Van Alstyne
dc@scottishbioenergy.com
www.scottishbioenergy.com
St. Cyrus, Scotland

See-O-Two

Developing and deploying a closed pond system.

Joachim Grill
office@seegroup.com
www.see-o-2.com
Vienna, Austria

Sequest, LLC

The company has plans for a wastewater to algae facility in Michigan that diverts CO_2 from a local coal plant.

Bob Truxell
info@sequestllc.com
sequestllc.com
Bloomfield Hills, MI

Smith Algae BioFeeds

The company is taking CO_2 from power plants and ethanol plants to grow algae. Algae fed beef from this program will be tested for healthy fat compositions and for delivering healthy DHA and EPA into consumers of algae fed beef.

Donald Smith
dsmith@smithcogen.com

Smorgon Fuels

Working on biodiesel production from algae.

www.biomaxfuels.com.au
Melbourne, Australia

Solar Biofuels Consortium

An international team experimenting with a new genetically modified algal strain that appears able to make significant amounts of 90 percent pure hydrogen, while also producing oil for biofuel or other purposes.

Ben Hankamer
b.hankamer@imb.uq.edu.au
www.solarbiofuels.org
Queensland, Australia

Solarvest Bioenergy

Solarvest's intellectual property is a biologically based hydrogen producing technology, which provides a method for controlling key genes in algae resulting in the continuous production of hydrogen gas.

Gerri Greenham
ggreenham@solarvest.ca
www.solarvest.ca
Canada

Solazyme

Solazyme grows algae heterotrophi-cally – without any light in metal tanks, while being fed sugar.

Matthew Frome
mfrome@solazyme.com
www.solazyme.com
S. San Francisco, CA

Solena

Solena uses high temperatures to gasify algae and other organic substances with high-energy outputs.

Robert T. Do
abranch@solenagroup.com
www.solenagroup.com
Washington, DC

Solix Biofuels

Produces an integrated, flexible algae growth system utilizing Solix's proprietary, floating photobioreactor panels.

Bryan Willson
Bryan.Willson@colostate.edu
www.solixbiofuels.com
Fort Collins, CO

Solray Energy, Ltd.

Plant converts algae to fuel.

Chris Bathurst
chris@solrayenergy.co.nz
www.solrayenergy.com
Christchurch, New Zealand

Star Energy

Provides the answers on how to convert algae feedstocks into energy efficient, environmentally friendly revenue streams.

Ken Salyards
kjs@starenergyco.com
www.starenergyco.com
Maryland

Stellarwind Bio Energy

Algae production technology.

William R. Kassebaum
Will.Kassebaum@ieee.org
www.stellarwindbioenergy.com
Indianapolis, IN

Subitec

Focuses on algae cultivation and photobioreactors.

Peter Ripplinger
p.ripplinger@subitec.com
en.subitec.com
Stuttgart, Germany

SunEco Energy

The company uses a blended hetero and phototrophic system. The initial commercial product to be produced by SunEco is dewatered, de-gummed biocrude algal oil. This product is suitable to be refined into biodiesel.

Keith Mayer
keith@sunecoenergy.com
www.sunecoenergy.com
Imperial Valley, CA

Sunlight Direct

Produces photobioreactors that use sunlight-induced photosynthesis to grow algae.

John D. Morris
morrisjd@sunlight-direct.com
www.sunlight-direct.com
Oak Ridge, TN

Sunrise Ridge Algae, Inc.

Engaged in research, development and commercialization of aquatic biomass technology.

Norman Whitton
norm.whitton@sunrise-ridge.com
www.sunrise-ridge.com
Houston, TX

Sustainable Green Technologies

Claims to have uncovered the elusive and long sought after lipid trigger in green algae to create obese algae. Also, SGT's microbes can convert a variety of feedstock into biohydrogen energy.

James Gibson
contactus@sgth2.com
www.sgth2.com
Escondido, California

Synthetic Genomics

The company's scientists have genetically engineered algae not just to turn CO_2 into oil, but also to continuously excrete that oil directly into the surrounding water.

J. Craig Venter
collaborations@syntheticgenomics.com
www.syntheticgenomics.com
La Jolla, CA

Targeted Growth

Focuses on breeding and biological modification of algae and other crops.

Thomas Todaro
main@targetedgrowth.com
www.targetedgrowth.com
Seattle, WA

Tecnalia

The Energy Unit at the company is researching the potential of mass production of microalgae as a crop, working on the selection of stocks, the optimization of crop production systems (open, closed and mixed), as well as the optimization of various operation variables in the harvesting and final treatment of the microalgae for their transformation into energy.

Rogelio Pozo
info@tecnalia.info
www.tecnalia.com
Spain

Ternion Bio Industries

Manufacturers a distinct, patent-pending photobioreactor system.

Chris Schuring
chris.schuring@ternionbio.com
www.ternionbio.com
San Jose, CA

Texas Clean Fuels

The company's Algae Growth Unit, or AGU, a specialized, patent-pending clear, plastic tank product , which is intended for mass cultivation of algae biomass as a feedstock for biodiesel and other alternative fuels processes.

Jonathan L. Gal
jlgtcf@live.com
www.texascleanfuels.com
Rockwall, TX

Touchstone Research Laboratory, Ltd.

Developing a closed algae cultivation system that controls seasonal temperature fluctuations at a competitive cost.

info@trl.com
www.trl.com
Triadelphia, WV

Transalgae

The company uses genetic engineering combined with practical agricultural, industrial and economic approaches to grow algae.

Noam Gressel
info@transalgae.com
www.transalgae.com
Israel

Trident Exploration Corp.

The company is a natural gas exploration company that is working with Menova to find ways to reduce its CO_2 emissions by growing algae in photobioreactors.

Dave Gerwing
dgerwing@tridentexploration.ca
www.tridentexploration.ca
Calgary, Alberta, Canada

U.S. Biofuels

Closed photobioreactor algae production in central California.

California

United Environment & Energy

The company uses a mixed metal oxide catalyst to come up with an algae-to-biodiesel conversion process. The process involves pumping the algae oil plus methanol through a solid catalyst at high pressure.

Ben Wen
b-wen@unitedee.com
www.unitedee.com
Horseheads, NY

University of North Dakota - Energy & Environmental Research Center (EERC)

In 2009, the company was awarded a subcontract by SAIC to use its proprietary technology to produce jet fuel from algal oils.

Peter A. Letvin
pletvin@undeerc.org
www.undeerc.org
North Dakota

Valcent Products Inc.

High density vertical bioreactor and vertical growth system.

Stephen Fane
info@valcent.net
www.valcent.net/s/Home.asp
Vancouver, B.C., Canada

Varicon Aqua Solutions

The company specializes in the production of algae and aquaculture.

aqua-solutions@varicon.co.uk
www.variconaqua.com/United Kingdom

Virtuoso Biofuels

Offering an algae oil extraction technology.

Anthony C Prehm
tprehm@virtuosobiofuels.com
www.virtuosobiofuels.com
Council Bluffs, Iowa

W2 Energy

The company produces and offers a photobioreactor.

Michael McLaren
info@w2energy.com
www.w2energy.com
Carson City, NV

WaterWheel Factory

The company produces metal waterwheels for algae ponds.

Bob Vitale
vitale@waterwheelfactory.com
www.waterwheelfactory.com
North Carolina

Wesley Holdings, Ltd.

Building and operating an algae facility to be used initially as organic fertilizer.

John M. Dutton
j.dutton@comcast.net
El Dorado Hills, CA

World Health Energy Holdings Inc.

A public holding company that aims to develop joint venture partnerships for algae production—for both biodiesel and commercial fish food purposes. Its algae production technology relies on tubular photobioreactor systems.

David Lieberman
info@worldhealthenergy.com
www.worldhealthenergy.com
Washington, D.C.

XL Renewables

Lined trough algae production systems.

Ben Cloud
ben@xlrenewables.com
www.xldairygroup.com
Phoenix, AZ

Ames Laboratory

In 2008, the DOE awarded $885,000 to its Ames Laboratory to research using nanoscale particles to harvest chemical compounds—such as triglycerides, neutral lipids, and fatty acids—from microalgae for biodiesel production.

George Kraus
gakraus@iastate.edu
www.ameslab.gov/cbs/fwp/nanorefinery
Ames, IA

Arizona State University

A long time algae development leader. Focused on the production of aviation biofuel from algae, among other products.

Qiang Hu
huqiang@asu.edu
biofuels.asu.edu/biomaterials.shtml
Tempe, AZ

Ateneo de Manila University, Philippines

Producing biofuel from algae, using a local species of algae.

Teresita R. Perez
tperez@ateneo.edu
www.ateneo.edu
Manila, Philippines

Auburn University

Working on algae to biofuel.

Ron Putt
ronputt@auburn.edu
www.nrmdi.auburn.edu/bio/experts.php
Auburn, Alabama

Austin Peay State University

Lead researcher is the author of more than 70 research publications on biofuels and a patent for hydrogen production by cyanobacteria.

Sergei Markov
Sergei Markov
www.apsu.edu
Clarksville, TN

Ben Gurion University of the Negev

The school's Microalgae Biotechnology Lab is recognized internationally as experts in strain selection, genetic engineering and aquaculture.

Sammy Boussiba
sammy@bgumail.bgu.ac.il
www.bgu.ac.il/bidr/bic/researchers/Boussiba_Sammy.htm
Midreshet Ben-Gurion, Israel

Brooklyn College

Research focuses on photosynthesis, secondary carotenoid biosynthesis and biofuels production from microalgae.

Juergen Polle
jpolle@brooklyn.cuny.edu
www.brooklyn.cuny.edu/pub/Faculty_Details5.jsp?faculty=599
Brooklyn, NY

Brunswick Community College

Teachers and students in the biotechnology program are growing enough algae to produce around 75 pounds of oil each month. That oil will fuel tractors and utility vehicles on campus. They are exploring ways to extract oil from algae with ultrasonic waves.

Michelle Sabaoun
sabaounm@brunswickcc.edu
www.brunswickcc.edu
Bolivia, NC

California Polytechnic State University (Cal Poly)

The university is focused on algae-based wastewater treatment, biofuels production, bioreactor design, and other aspects.

Tryg Lundquist
tlundqui@calpoly.edu
ceenve.calpoly.edu/faculty/tlundqui/
San Luis Obispo, CA

Carbon Trust, The

Operates the Algae Biofuels Challenge, which incubates promising technologies and companies.

Ben Graziano
Ben.Graziano@CarbonTrust.co.uk
www.carbontrust.co.uk
London, UK

Clemson University

Focusing on a method of algae harvesting and oil extraction using brine shrimp.

David Brune
debrune@clemson.edu
www.clemson.edu/cafls/departments/biosystemseng/faculty_staff/brune.html
Clemson, SC

Cleveland State University

The university is developing methods for separation of the algae from the perfusion fluid and extraction of the oil from the algae that are low in energy use and manufacturing cost.

Joanne M Belovich
J.BELOVICH@csuohio.edu
facultyprofile.csuohio.edu/csufacultyprofile/detail.cfm?FacultyID=J_BELOVICH
Cleveland, OH

Colorado School of Mines

Laboratory projects include the study of (a) hydrogenase enzymes and the production of hydrogen from phototrophic micro-organisms, (b) starch and lipid metabolisms in algae, (c) 'omics' based approaches applied to defining whole cell metabolic and regulatory pathways, (d) the diversity of water-oxidizing phototrophs that are adapted to saline ecosystems, and (e) the enzymatic control of metabolic flux in algae.

Matthew Posewitz
mposewit@mines.edu
chemistry.mines.edu/faculty_bio_posewitz.shtml
Golden, CO

Colorado State University

Working closely with algae startup Solix.

Bryan Willson
Bryan.Willson@colostate.edu
www.colostate.edu/features/biofuels-from-algae.aspx
Fort Collins, CO

Columbia University

Using genetic engineering to incorporate a new metabolic pathway into an organism that is currently used for wastewater treatment. The bacterium, N. europaea, has the ability to grow on ammonia and CO_2 and produce butanol. The cells will fix CO_2 from the atmosphere, and the ammonia will either be generated electro-chemically, or it will be obtained during wastewater treatment. Funded by ARPA-E.

Scott Banta
sbanta@cheme.columbia.edu
openwetware.org/wiki/Banta
New York, NY

The Donald Danforth Plant Science Center (The Center for Advanced Biofuels Systems)

In 2007 the Taylor family, owners of Enterprise Rent-A-Car, joined forces with the Donald Danforth Plant Science Center, the largest independent plant research center in the world, to establish the Enterprise Rent-A-Car Institute for Renewable Fuels. The institute's aim is to create the next generation of alternative fuel technologies from environmentally sound plant sources, thus reducing our greenhouse gas emissions and our dependence on non-renewable resources.

Richard Sayre
rsayre@danforthcenter.org
www.danforthcenter.org/cabs
St. Louis, MO

Imperial College

Part of the Algal Bioenergy Consortium (ABC), which involves a large multidisciplinary group of scientists who aim to use algae for a number of different applications in the bioenergy industry.

Peter Nixon
p.nixon@ic.ac.uk
www.bio.ic.ac.uk/research/pnixon/
London, UK

Iowa State University

Leading a $5.3 million study of biodiesel production from algae using silica nanoparticles.

Victor Lin
vsylin@iastate.edu
www.news.iastate.edu/news/2010/jan/biofuels
Ames, IA

Israel Oceanographic and Limnological

Looking at the production of biochemicals from marine algae and their medical applications.

Amir Neori
neori@ocean.org.il
www.ocean.org.il/eng/researchinstitutesandinfrastructure/oceannationalinstitute.asp
Haifa, Israel

James Cook University

Developed and operates a pilot algae to biofuel project.

Kirsten Heimann
kirsten.heimann@jcu.edu.au
www.jcu.edu.au/mtb/staff/academic/JCUDEV_014315.html
Townsville, Australia

Kansas State University

Focused on growing algae in the ocean on very large, supporting platforms. The National Science Foundation awarded them a Small Grant for Exploratory Research in 2009 for their work.

Wenqiao Yuan and Zhijian Pei
wyuan@ksu.edu; zpei@ksu.edu
www.kstate.edu/media/newsreleases/nov09/algae110309.html
Manhattan, KS

Khon Kaen University

Researchers have discovered a new species of algae, which could be used for the commercial production of biodiesel.

Ratanaporn Leesing
ratlee@kku.ac.th
www.kku.ac.th
Khon Kaen, Thailand

Los Alamos National Lab

Undertaking applied research in the algal biofuels area and assist several companies in the private sector (CEHMM; General Atomics).

Greg Goddard
ggoddard@lanl.gov
nfcr.lanl.gov/personalprofiles/goddard.html
Los Alamos, NM

Massachusetts Institute of Technology

The laboratory has bioengineered an enzyme that can increase the hydrogen production capacity of algae.

Shuguang Zhang
Shuguang@mit.edu
www.web.mit.edu/lms/www
Boston, MA

Massey School of Engineering

Producing algal broth from marine algae in tubular photo-bioreactors.

Yusuf Chisti
Y.Chisti@massey.ac.nz
www.massey.ac.nz/~ychisti/~yc.html
Palmerston North, New Zealand

Michigan State University

Current areas of focus are:
1. Regulation of photosynthetic membrane lipid assembly; 2. Lipid trafficking between the endoplasmic reticulum (ER) and the plastid; and 3. Regulation of storage lipid biosynthesis in plants and algae.

Christoph Benning
benning@cns.msu.edu
bioenergy.msu.edu/feedstocks/algae.shtml
East Lansing, MI

Mississippi State University

Working with General Atomics to demonstrate the feasibility of large-scale biofuels production from military and municipal wastewater treatment facilities.

Jim.Elliott@ga.com
www.msstate.edu
Mississippi State, MS

Montana State University

Received a US DOE grant to study algae oil.

Brent Peyton
bpeyton@coe.montana.edu
www.chbe.montana.edu/BPeyton/
Bozeman, MT

Murdoch University

The principal research concerns the commercial-scale production of fine chemicals such as carotenoids, fatty acids and bioactive molecules by large-scale algal culture.

Michael Borowitzka
m.borowitzka@murdoch.edu.au
www.bsb.murdoch.edu.au/groups/asrg/MABResearch1.html
Murdoch, Australia

Myongji University

Focused on various nutrients that influence algae growth.

www.mju.ac.kr
Yongin, Korea

National Institute of Water and Atmospheric Research

Wastewater treatment and algal production in high rate algal ponds with carbon dioxide addition.

Jason Park
j.park@niwa.co.nz
www.niwa.co.nz
Auckland, NZ

National Renewable Energy Laboratory

Lead the 15 year program to investigate algae, and has recently invested more than $1 million of internal funds to restart its algal biofuels program.

Al Darzins
al_darzins@nrel.gov
www.nrel.gov/biomass/national_bioenergy.html
Golden, CO

New Mexico State University

The US Air Force has granted New Mexico State University $2.364 million towards algal research to study better ways to grow algae and refine its oil.

Peter Lammers
plammers@nmsu.edu
www.chemistry.nmsu.edu/Dr.%20LAMMERS%20FACULTY%20PAGE.html
Las Cruces, NM

NRC Institute for Marine Biosciences

The project's aim is photosynthetic fuel production on a large scale, mostly from algae growing in eastern Canada.

John R. McDougall
info@nrc-cnrc.gc.ca
www.nrc-cnrc.gc.ca/eng/projects/nbp/biofuels.html
Ottawa, Ontario, Canada

Oak Ridge National Lab

Cooperative research with Utah State University on discrete challenges in the production process (e.g., photosynthetic saturation, minimizing surface shading, hydrophobic materials to prevent biofouling in photobioreactors, and scalable photobioreactor design).

Miguel Rodriguez Jr.
rodriguezmjr@ornl.gov
www.ornl.gov/sci/ees/bsd/bst/people/m_rodriguez.shtml
Oak Ridge, TN

Old Dominion University

Performing algal-biodiesel research.

Gary C. Schafran
gschafra@odu.edu
www.eng.odu.edu/cee/directory/schafran.shtml
Norfolk, VA

Oregon State University

Growing algae in photobioreactors for biofuel use.

Ganti Murthy
murthy@engr.orst.edu
bee.oregonstate.edu
Corvallis, OR

Pacific Northwest National Laboratory

Performs basic and applied research in the area of microalgal biofuels.

Mark Wigmosta
mark.wigmosta@pnnl.gov
hydrology.pnnl.gov/staff/staff_info.asp?staff_num=818
Richland, WA

Pittsburg State

Received $2 million in federal money to fund the university's Kansas Polymer Research Center, investigating polymer production via algae.

Andrew Myers
amyers@pittstate.edu
www.btikansas.com/home/KPRC/
Pittsburg, KS

Princeton University

The group seeks to improve the oil yield and production rate of a single species of microalgae through directed evolution. They utilize microfabrication technology to create microhabitats to control the nutrient environment of the species, monitor oil production through Raman Spectroscopy, and punish colonies of algae that have low oil yield.

Robert H. Austin
austin@princeton.edu
austingroup.princeton.edu/research/biofuel-algae
Princeton, NJ

San Diego Center for Algae Biotechnology

A consortium of researchers from The Scripps Research Institute (TSRI), the University of California, San Diego (UCSD), and Scripps Institution of Oceanography (SIO), in partnership with private industry.

The center collaborates with the private sector to apply lab discoveries to the industrial world through robust research and development in biology, chemistry, and engineering.

Stephen Mayfield
sdcab@ucsd.edu
algae.ucsd.edu
San Diego, CA

Sandia National Laboratory

Has received approximately $5 million from various governmental sources to conduct a research program relating to algal-based production of biofuels and co-products with an emphasis on water resources and utilization. Has a cooperative agreement with LiveFuels, Inc.

Ron Pate
rcpate@sandia.gov
www.sandia.gov
Albuquerque NM

Sardar Vallabh Bhai Patel University of Agriculture and Technology

Nitin Naresh
svbpuat_meerut@indiatimes.com
www.svbpmeerut.ac.in
Meerut, India

Seawater Foundation, The

Pursuing algae to biofuels in the Middle East.

Carl Hodges
carl@seawaterfoundation.org
www.seawaterfoundation.org/
Phoenix, AZ

Syracuse University

The university has a patented method for converting lipids (from soy, algae, rapeseed, etc.) to biodiesel fuel using a 96%-efficient supercritical process.

Larry Tavlarides
lltavlar@syr.edu
lcs.syr.edu/facultyandstaff/research.aspx?id=1956
Syracuse, NY

Tamil Nadu Agricultural University

Developed a pilot plant technology for bio-diesel production from micro-algae from petroleum industrial wastes.

C. Ramasamy
vc@tnau.ac.in
www.tnau.ac.in
Coimbatore, India

Texas A&M

In addition to optimizing biofuels production, research and development efforts are focused on the potential for utilizing byproducts as primary components of livestock and mariculture feeds.

Bob Avant
bavant@tamu.edu
www.tamu.edu
College Station, TX

University of Arizona

Focused on the biology, culture and ecology of algae.

Kevin Fitzsimmons
kevfitz@ag.arizona.edu
cals.arizona.edu
Tucson, AZ

University of Bari

Focused on issues such as the production of biodiesel from macroalgae by supercritical CO_2 extraction and thermochemical liquefaction.

Michele Aresta
m.aresta@chimica.uniba.it
www.circc.uniba.it
Bari, Italy

University of California Berkeley

Pioneered a process to divert the natural flow of photosynthesis in green microalgae and to sustainably generate hydrogen gas.

Anastasios Melis
melis@berkeley.edu
pmb.berkeley.edu/newpmb/index.shtml
Berkeley, CA

University of Florence

Focusing on marine and micro algae.

Mario R. Tredici
mario.tredici@unifi.it
www.diba.unifi.it/CMpro-v-p-158.html
Florence, Italy

University of Georgia Biorefining and Carbon Cycling Program

Examining whether wastewater from the carpet manufacturing industry can be leveraged to grow oil-producing algae. Researchers have isolated natural strains of microalgae from the wastewater that may be good candidates for use in biodiesel production.

Ryan Adolphson
ryan@engr.uga.edu
biorefinery.uga.edu/biomassdevelopment.html
Athens, GA

University of Hawaii

Home to one of the largest collection of algae in the world.

Alison Sherwood
asherwoo@hawaii.edu
sites.google.com/site/sherwoodlabwebsite/
Honolulu, HI

University of Hull

Working on various aspects of algae.

Michelle Tobin
m.l.tobin@hull.ac.uk
hypercontent.hull.ac.uk/cems/Meet_the_Staff/Academics/Tobin_Michelle/index.html
Scarborough, UK

University of Kentucky

Focused on genetically creating a replacement for oil and coal shale deposits.

Joe Chappell
chappell@uky.edu
http://www.uky.edu/Ag/Agronomy/Chappell
Lexington, KY

University of Louisiana

Focused on growth of microalgae and light dynamics in photo-bioreactors.

Barbara Benson
barbarabenson@louisiana.edu
rres.louisiana.edu/research.htm
Lafayette, LA

University of Maryland

Focused on algae for water purification and biofuel production.

Patrick Kangas
pkangas@umd.edu
www.nrmt.umd.edu/kangas.htm
College Park, MD

University of Massachusetts

Working on various aspects of algae.

Ed Klekowski
edk@bio.umass.edu
www.bio.umass.edu/biology/conn.river/spiro.html
Amherst, MA

University of Michigan

Developing a heating/cooking process to expedite the production of algae based green crude oil. Researchers are also developing a two-step, catalyst-free algal biodiesel production process, using wet algal biomass and bypassing the drying and solvent extraction steps.

Phillip Savage
psavage@umich.edu
che.engin.umich.edu/people/savage.html
Ann Arbor, MI

University of Minnesota

Researchers at the Metropolitan Council and the University of Minnesota's Initiative for Renewable Energy and the Environment (IREE) have teamed up to investigate the potential for algae-to-fuel technology.

Dick Hemmingsen
hemmings@umn.edu
environment.umn.edu/iree
St. Paul, MN

University of Nevada

Studying the green algae Dunaliella.

John Cushman
jcushman@unr.edu
www.ag.unr.edu/cushman
Reno, NV

University of New Hampshire

Group in the school's Biodiesel Lab have been looking into effectively growing algae in wastewater or seawater.

Ihab Farag
ihab.farag@unh.edu
www.unh.edu/p2/ihf
Durham, NH

University of New Haven

Recently landed a $135,276 grant from the Connecticut Center for Advanced Technology to research the possibility of using algae in Long Island Sound as a fuel source.

Carmela Cuomo
ccuomo@newhaven.edu
www.newhaven.edu/cdc/55001
West Haven, CT

University of North Dakota

In 2009, was awarded a subcontract by Science Applications International Corporation to develop jet fuel from algae.

Gerald H. Groenewold
ghg@undeerc.org
www.undeerc.org
Grand Forks, ND

University of Queensland

Established the Solar Bio-fuels Consortium that is engineering green algal cells and advanced bioreactor systems to produce biofuels such as hydrogen in a CO_2-neutral process. Working with Clemson University on algae to biodiesel for military use.

Ben Hankamer
b.hankamer@imb.uq.edu.au
www.solarbiofuels.org
Queensland, Australia

University of Southern California

Researching various aspects of micro and macro algae.

Karla Heidelberg
Kheidelb@usc.edu
college.usc.edu/faculty/faculty1012507.html
Los Angeles, CA

University of Texas Austin

Home to one of the largest collection of algae in the world.

Jerry Brand
jbrand@mail.utexas.edu
www.biosci.utexas.edu
Austin, TX

University of Tulsa – Tulsa Alternative Energy Institute

In partnership with Sapphire Energy to produce renewable 91-octane gasoline made from algae based green crude.

Daniel Crunkleton
daniel-crunkleton@utulsa.edu
www.orgs.utulsa.edu/altenergy/Site/Welcome.html
Tulsa, OK

University of Virginia

Commenced three projects to improve yields from algae-to-fuel production. The first project will test for optimal levels of solid waste and carbon dioxide fed to the algae, with a target of improving yields by 40 percent. A second project will compare the economic and environmental benefits of algae biodiesel to soy. A third project will optimize oil extraction by testing different algae processing techniques, including grinding up of solid waste before feeding it to algae.

Lisa Colosi
lmc6b@virginia.edu
people.virginia.edu/~lmc6b/LisaColosi/Home.html
Charlottesville, VA

University of Washington

Research includes chloroplast genome architecture and gene function in non-chlorophyll b containing algae and functional genetic diversity within stramenopile population. Professor Cattolico has discovered a unique patented technology, she calls Algae X.

Rose Ann Cattolico
racat@u.washington.edu
www.faculty.washington.edu/racat
Seattle, WA

Utah State University

Developing commercial scale systems to grow algae to produce biofuel.

Jeff Muhs
jeff.muhs@usu.edu
www.innovationutah.com/biofuels.html
Salt Lake City, UT

Virginia State University

Working with VirginiaTech to develop biofuel from algae.

Louis Landesman
landesman49@yahoo.com
pubs.ext.vt.edu/442/442-886/442-886.html
Blacksburg, VA

Wageningen University and Research Center

The objective of AlgaePARC (Algae Production And Research Centre) is to develop knowledge, technology and process strategies for sustainable production of microalgae as feedstock for fuel, chemicals, food and feed at industrial scale. AlgaePARC is the first research centre in the world that allows comparison of different outdoor photobioreactor designs.

René H. Wijffels
rene.wijffels@wur.nl
Wageningen, Netherlands

Washington State University

A $2 million partnership with Targeted Growth, focused on biofuel production.

Ralph Cavalieri
cavalieri@wsu.edu
Pullman, WA

Washington University

Received DOE support to delve into the science of photosynthesis and how light energy is harvested using algae as the model.

Robert Blankenship
blankenship@wustl.edu
biology4.wustl.edu/faculty/blankenship/index.html
St. Louis, MO

Wayne State University

Biofuels Energy Laboratory focuses on many issues, including algae.

K.Y. Simon Ng
NBEL@wayne.edu
www.eng.wayne.edu/page.php?id=4765
Detroit, MI

Appendix C – Additional Discussion of Biological CCR »

Decades of development experience and recent years of high-level algae funding indicate significant interest in algae technologies. Therefore, in addition to the main body content, further discussion on algae is provided. This discussion focuses on algae productivity as well as the production of transportation fuel, currently the most talked about end algae end use.

Algae Productivity

Algae grow very rapidly. Cellular division can lead to between one and four doublings in cell count per day for fast growing algae strains. Slow growers like the high oil content botryococcus braunii double every seven days.

Algae thrive in warmer climates, particularly tropical and equatorial. With the assistance of (often expensive) technology, such as photobioreactors (PBRs) that provided added warmth and nutrients, algae can be grown virtually anywhere.

Various sources speculate on the current productivity level of algae oil production. Estimates vary from 10,000 to 100,000 or more gallons per acre per year (g/acre-yr) of potential yield. Yet deciphering fact from fiction is straightforward.

Algae production deals with two laws of thermodynamics: the law of conservation and the law of suboptimal efficiency (i.e. energy into a system exceeds energy out).

On average, an acre of land in Southwest America can provide approximately 5 to 6 kWh/m^2/day of solar radiation.[98] Yet not all of that energy is converted by the algae into oil. Energy is lost through non-PAR solar energy, light transmission loss, reduced photon absorption, inherent photosynthetic loss, cellular energy use, and the creation of non-oil biomass.

The combination of perfectly clear equatorial skies, maximum efficient photosynthesis, and high oil yield algae would yield a theoretical maximum of 53,000 g/acre-yr of algae oil. Yet in the real world, incorporating site-specific solar data, moderate oil yielding algae, and other realistic efficiency assumptions would yield maximum levels between 4,900 and 6,500 g/acre-yr of purely photosynthetic algae oil.[99]

Assuming the low-end level of productivity, approximately 29 million acres of land – slightly less than the size of Arkansas – would need to be occupied in order to produce from algae the 142 billion gallons of gasoline that the United States consumed in 2007.[100]

Algae Fuel Costs

Once the algae are produced, if fuel is the desired end product, there are three primary techniques to produce fuel from algae:

Technique	Characteristics	Pros	Cons
Oil Extraction	After being removed from water, algae are "dewatered" and dried, oil molecules extracted from algae cells, then refined into fuel.	Produces liquid transportation fuel that can go into existing vehicular fuel tanks.	Many steps in the process present several technical challenges. Dewatering is a particular challenge. Drying can be energy intensive.
Gasification	After being removed from water, algae are placed in an anaerobic digester where they produce a methane and carbon dioxide rich biogas.	Simple – wet algae can be placed in digester. Proven – digester technology is well established and deployed at different levels around the world.	Finished product is a gas, which is less suitable for transportation fuel than liquids.
Oil/Fuel Self-Excretion	Remaining in water, engineered algae excrete oil or finished fuel from their cellular walls. The fuel rises to the surface of water where it is harvested.	Potential to produce liquid fuel without undertaking dewater, drying, extraction, and other phases.	New technology - not proven outside the laboratory. Genetic modification may encounter local resistance, and questions about physiological robustness remain.

The cost of algae fuel is primarily a function of capital costs, input costs, and labor.

Many experts state that capital costs (i.e. racetrack ponds or PBR machinery, grading costs, etc.) typically account for 75 percent of overall costs, with the rest attributed to input costs (e.g. energy and nutrients) and labor. Many experts also state that 30 acres is the minimum cost effective commercial size.

There is typically a 3:1 relationship between capital costs and the cost of finished fuel. In other words, in order to yield fuel at $1 per gallon, capital has to be at a cost of $3 per gallon capacity.

However, PBRs are in a league of their own when it comes to costs due to the complexity of the technology. One large cost for PBRs is the pump energy consumed to move water vertically into hanging bags. Another cost is associated with the materials used to make the PBRs. This cost comes either upfront in the purchase of durable material, or during operation as less durable material is replaced. For instance, polyethylene is cheap, but lasts only three months or so before replacement is required. Plastic tubes can last two years, but are moderately more expensive. Polycarbonate tubes can last ten years, but are significantly more expensive. The price per acre of PBRs can be approximately 10 times the price per acre of open ponds.

The price for inputs to algae fuel varies. If CO_2 has to be purchased rather than donated, producers will spend between $5 and $100 per ton, resulting in costs between $10 and $200 per ton of algae produced. Commercial fertilizer, comprised of 25-40 percent nitrogen, is $300-500 per ton, resulting in costs between $35 and $200 per ton of the cost of algae.

These numbers translate into fuel prices of approximately $500-1,500 per dry ton of algae (i.e. ~$30 per gallon) for the most economical systems. However, the nutraceutical markets into which algae has traditionally been sold are limited in scale and can bear prices in excess of $5,000 per ton.

In order to drive the price of algae fuel down to the $1-3 per gallon range, extracted algae must be produced at about $50-150 per dry ton. In order to produce and sell algae into commodity energy and protein markets at prices below $300/t, productivity of algae must be at least 60 grams per square meter per day and total cultivation, drying, and processing capital costs must be no more than $150,000/hectare.[101]

Appendix D – Brief Overview of Biochar CCR »

Indigenous Amazonian populations produced Terra Preta – a super-fertile soil, some of which are thought to be 7,000 years old,[102] which are also known as "Dark Earths" – using slash-and-char methods (instead of slash-and-burn).[103] Slash-and-char uses low-intensity smoldering fires covered with dirt and straw, for example, which partially exclude oxygen.[104] While carbon-depleted soils tend to be dry and prone to erosion, carbon-rich soil is dark, crumbly, fertile, and moist.[105]

Terra Preta has a very high content of biochar, which is similar to charcoal and is what is responsible for Terra Preta's high carbon content.[106] Terra Preta contains up to 64 times more biochar than surrounding red earth.[107] It acts to hold the nutrients in the soil and sustain its fertility from year to year.[108]

Biochar is created when organic matter is heated without oxygen (i.e. "slash-and-char"). Heating the plant biomass without oxygen is a process known as low-temperature pyrolysis.[109] The pyrolysis of wood starts at 200–300 °C (390–570 °F).

Pyrolysis converts trees, grasses or crop residues into biochar, with twofold higher carbon content than ordinary biomass.[110] Moreover, biochar locks up rapidly decomposing carbon in plant biomass in a much more durable form.[111]

Pyrolysis can be tailored to produce biochar, biofuels (such as methanol), or a combination of both. When plants and trees are "only" reduced to charcoal, the carbon remains in the charcoal, apparently for periods up to 50,000 years, according to research by Makoto Ogawa.[112]

Evidence is mounting that biochar's highly porous structure helps retain valuable nutrients and provides huge surface area and a protective structure that encourages beneficial microfungi to grow.[113] These microfungi may be a key to biochar's power to lock in carbon for sustained timeframes.

Biochar has been shown to improve the structure and fertility of soils, thereby improving biomass production.[114]

Productivity of crops in Terra Preta is twice that of crops grown in nearby soils.[115] In experimental plots, adding a combination of charcoal and fertilizer into the rainforest soil boosted yields by 880% compared with fertilizer alone.[116] Lukas Van Zwieten, a scientist working for the New South Wales government, found that adding four tons of biochar per acre tripled the mass of wheat crops and doubled that of soybeans.[117]

Biochar enhances retention and therefore efficiency of fertilizers. By the same mechanism, it may also decrease fertilizer run-off.[118] Thus, biochar has the potential to reduce pollution of surface or groundwaters and reduce methane and nitrous oxide emissions.[119] In the dry tropics, biochar helps the soil retain water and therefore helps crops grow, particularly in times of drought.[120] Some of the greatest opportunities for soil carbon sequestration lie in the world's most depleted and eroded soils, such as those in sub-Saharan Africa, south and central Asia, and Central America.[121]

As a rule, Terra Preta has more plant-available phosphorus, calcium, sulfur, and nitrogen than is common in the rain forest. In fact, it has as much as three times as much phosphorous (reaching 200-400 mg P/kg) and nitrogen. The soil is specifically well suited for "tropical fruits". Corn, papaya, mango and many other foods grow at three times the rate than in the "normal" tropical soil.

Fallows on the Amazonian Dark Earths can be as short as six months, whereas fallow periods on traditional tropical soils (so-called oxisols) are usually eight to ten years long.[122] Amazonian Dark Earths in Açutuba had been under continuous cultivation without fertilization for over forty years.[123] Furthermore, carbon-enriched soil does not become depleted after repeated use, as do other soils.[124]

Biochar has the potential to be augmented by the carbon present in industrial flue gas, thus presenting an opportunity to capture and recycle carbon emissions. The level of this potential is unclear, as is the approach's commercial feasibility.

Appendix E – Government Funding Announcements for CCR »

Release Date: July 06, 2010

Research Projects to Convert Captured CO_2 Emissions to Useful Products

Six Projects Selected by DOE Will Further Important Technologies for Helping Reduce CO_2 Emissions and Mitigate Climate Change.

• Washington, D.C. — Research to help find ways of converting into useful products CO_2 captured from emissions of power plants and industrial facilities will be conducted by six projects announced today by the U.S. Department of Energy (DOE).

The projects are located in North Carolina, New Jersey, Massachusetts, Rhode Island, Georgia, and Quebec, Canada (through collaboration with a company based in Lexington, Ky.) and have a total value of approximately $5.9 million over two-to-three years, with $4.4 million of DOE funding and $1.5 million of non-Federal cost sharing. The Office of Fossil Energy's National Energy Technology Laboratory will manage the work.

Converting captured CO_2 into products such as chemicals, fuels, building materials, and other commodities is an important aspect of carbon capture and storage technology, viewed by many experts as part of a solution for reducing CO_2 emissions and helping mitigate climate change.

It is anticipated that large volumes of CO_2 will be available as fossil fuel–based power plants and other CO_2-emitting industries are equipped with CO_2 emissions control technologies to comply with regulatory requirements. While DOE efforts are underway to demonstrate the permanent storage of captured CO_2 through geologic sequestration, there is also a potential opportunity to use CO_2 as an inexpensive raw material and convert it to beneficial use.
The selected projects will develop or improve scalable processes with the potential to use significant amounts of CO_2.

The selected projects are described below:

• Research Triangle Institute (Durham, NC.)—RTI will assess the feasibility of producing valuable chemicals, such as carbon monoxide, by reducing CO_2 using abundant low-value carbon sources, such as petcoke, sub-bituminous coal, lignite, and biomass, as the reductant. The team will then evaluate whether additional processes can be added that use the carbon monoxide to produce other marketable chemicals, such as aldehydes, ketones, carboxylic acids, anhydrides, esters, amides, imides, carbonates, and ureas. (DOE share: $800,000; recipient share: $200,000; duration: 24 months).

• CCS Materials, Inc. (Piscataway, NJ.)—Investigators will attempt to create an energy efficient, CO_2-consuming inorganic binding phase to serve as a high-performing substitute for Portland cement (PC) in concrete. The project team will use a novel near-net-shape forming process that uses a binding phase based on carbonation chemistry instead of the hydration chemistry used in PC concrete. (DOE share: $794,000; recipient share: $545,100; duration: 36 months).

• Massachusetts Institute of Technology (Cambridge, MA.)—In this project, researchers will investigate a novel electrochemical technology that uses CO_2 from dilute gas streams generated at industrial carbon emitters, including power plants, as a raw material to produce useful commodity chemicals. This integrated capture and conversion process will be used to produce a number of different chemicals that could replace petroleum-derived products. (DOE share: $1,000,000; recipient share: $250,067; duration: 24 months).

• Brown University (Providence, RI.)—Researchers will demonstrate the viability of a bench-scale reaction using CO2 and ethylene as reactants to produce valuable acrylate compounds with low-valent molybdenum catalysts. Exploratory experiments will be conducted to identify the factors that control the current catalyst-limiting step in acrylic acid formation. (DOE share: $417,155; recipient share: $107,460; duration: 24 months).

• McGill University (Quebec, Canada)—In collaboration with 3H Company (Lexington, K.Y.), researchers aim to develop a curing process for the precast concrete industry that uses CO_2 as a reactant. To make the process economically feasible, a self-concentrating absorption technology will be studied to produce low-cost CO_2 for concrete curing and to capture residual carbon after the process. (DOE share: $399,960; recipient share: $100,000; duration: 24 months).

• PhosphorTech Corporation (Lithia Springs, GA.)—Investigators will develop and demonstrate an electrochemical process using a light-harvesting CO_2 catalyst to reform CO_2 into products such as methane gas. Researchers hope to achieve a commercially feasible CO_2 reforming process that will produce useful commodities using the entire solar spectrum. (DOE share: $998,661; recipient share: $249,847; duration: 36 months).

www.netl.doe.gov/publications/press/2010/100706-Research_Projects_To_Convert.html

Webpage Date: July 22, 2010

Innovative Concepts for Beneficial Reuse of Carbon Dioxide

Funding for 12 projects to test innovative concepts for the beneficial use of carbon dioxide (CO_2) was announced by the U.S. Department of Energy. The awards are part of $1.4 billion in funding from the American Recovery and Reinvestment Act (ARRA) for projects that will capture carbon dioxide from industrial sources.

These 12 projects will engage in a first phase feasibility study that will examine beneficial uses in a variety of ways, including mineralization to carbonates directly through conversion of CO_2 in flue gas; the use of CO_2 from power plants or industrial applications to grow algae/biomass; and conversion of CO_2 to fuels and chemicals. Each project will be subject to further competitive evaluation in 2010 to determine a portfolio of projects that will be funded for design, construction, and testing.

The initial phase of these 12 projects includes $17.4 million in ARRA funding and $7.7 million in private funding for a total investment of $25.1 million. During a competitive Phase Two process, approximately $82.6 million in Recovery Act money will be awarded to the most promising of these projects to complete design, construction and testing of pilot systems.

Innovative concepts for beneficial CO_2 use awards include:

• Alcoa, Inc. (Alcoa, PA.)—Alcoa, Inc., and its partners, U.S. Nels, CO_2 Solutions Inc., and Strategic Solutions Inc., will capture and convert CO_2 into mineral carbonates for reuse. Flue gas will be treated in a sodium alkali scrubber design, coupled with a carbonic anhydrase-based enzyme catalyst, to convert alkaline clay to carbonate-enhanced clay for soil remediation. (DOE share: $999,451)

• Calera Corporation (Los Gatos, CA.)—Calera will demonstrate an innovative process to directly mineralize CO_2 in flue gas to carbonates and convert them to materials directly usable in the construction industry. Calera, along with Bechtel, EPRI, U.S. Concrete, and Khosla Ventures, will use a novel membrane electrolysis process to produce sodium hydroxide for use in a CO_2 absorber. Intermediate slurry from the absorber will be converted to aggregates and cementitious substitutes. (DOE share: $1,681,377)

• Gas Technology Institute (GTI) (Des Plaines, IL.)—GTI and partners University of California San Diego, the University of Connecticut, San Diego Gas and Electric Company, and Southern California Gas Company propose to capture power plant flue gas CO_2 using macroalgae (seaweeds) cultivated in non-submerged greenhouses. The macroalgae will be harvested and processed via anaerobic digestion into methane for fuel to the power plant. (DOE share: $993,284)

• Novomer Inc. (Ithica, NY.)—Researchers from Novomer plan to develop polycarbonates from a petrochemical, CO_2, and a proprietary catalyst. The system will permanently store CO_2 in new chemical structures that are up to 50% by weight CO_2. (DOE share: $2,107,900)

• Phycal LLC (Highland Heights, OH.)—The project objective is to capture CO_2 gas and recycle it in an algal oil production process in an open raceway pond using partially processed wastewater. Phycal, along with SSOE Engineering; GE Global Research; Aqua Engineers; Seambiotic; Kuehnle AgroSystems, Inc.; Group 70; and the NASA Glenn Research Center, will use two patented technologies, Heteroboost™ and Olexal™, to cultivate the microalgae and produce algal oil. (DOE share: $3,000,000)

• Renewable Energy Institute International (REII) (McClellan, CA.)—REII will process CO_2 and natural gas in a solar reformer to produce syngas suitable for a Fischer-Tropsch process for making liquid fuels. REII will collaborate with Desert Research Institute, Pacific Renewable Fuels, and Clean Energy Systems Inc. (DOE share: $1,358,920)

• Research Triangle Institute (RTI) (Durham, NC.)—RTI, along with Kellogg, Brown and Root (KBR) and Süd Chemie, will use CO_2 and waste fuel gas stream in existing ethylene production facilities to produce pipeline-quality synthetic natural gas. The process will leverage commercial reactor technology used in fluid catalytic crackers in petroleum refining and a novel nickel-based catalyst developed by RTI. (DOE share: $1,065,743)

• Skyonic Corporation (Austin, TX)—Skyonic will demonstrate its patented SkyMine® process to remove CO_2 from industrial waste streams and generate saleable carbonate and/or bicarbonate materials. Skyonic will collaborate with Capitol Aggregates; Ford, Bacon and Davis LLC; Skadden, Arps, Slate, Meagher and Flom; RDB Environmental Consulting; and Wm Smith and Co. (DOE share: $3,000,000)

• Sunrise Ridge Algae (SRA) (Houston, TX)—This project will involve the cultivation of algae using CO_2 from cement plant waste stack gas. The harvested algae will be converted into liquid fuel and carbonaceous char using catalyzed thermochemical conversion technology. The liquid fuel may serve as a diesel fuel replacement or extender, while the char can be burned as fuel instead of coal in the cement factory kilns. SRA will collaborate with URS Group, Texas Lehigh Cement Company, UOP LLC, and the Houston Technology Center. (DOE share: $511,327)

• Touchstone Research Laboratory (Triadelphia, WV.)—Touchstone will use a novel phase change material to enclose raceway ponds where they will cultivate algae using CO_2 from combustor flue gas. The algal lipids will be recovered to produce biofuel and the algae biomass will be used in an anaerobic digestion process to produce electricity and recover nutrients.

Partners with Touchstone include The Ohio State University Ohio Agricultural Research and Development Center and GZA GeoEnvironmental, Inc. (DOE share: $517,818)

• University of Massachusetts, Lowell (Lowell, MA.)-The University of Massachusetts, Lowell, along with Jordan Development Company and Core Energy, will use CO_2 to investigate permanent storage via mineralization in Otsego County, Mich., by injecting the CO_2, water, and black carbon as an emulsion into a nearby semi-depleted oil reservoir. (DOE share: $572,891)

• UOP LLC (Des Plaines, IL.)—UOP and partners Honeywell-Resins and Chemicals, Honeywell-Process Solutions, Envergent, Aquaflow, Vaperma, and International Alliance Group will use a Vaperma membrane to capture exhaust stack CO_2 from the Hopewell, Va., caprolactum (used to make nylon) plant. The CO_2 will be used to grow microalgae for eventual processing to biofuel and fertilizer. (DOE share: $1,522,149)

In July 2010, U.S. Energy Secretary Steven Chu selected six projects to continue into Phase II that aim to find ways of converting captured carbon dioxide (CO_2) emissions from industrial sources into useful products such as fuel, plastics, cement, and fertilizers. These include:

• Alcoa, Inc. (Alcoa Center, PA.) - Alcoa's pilot-scale process will demonstrate the high efficiency conversion of flue gas CO_2 into soluble bicarbonate and carbonate using an in-duct scrubber system featuring an enzyme catalyst. The bicarbonate/carbonate scrubber blow down can be sequestered as solid mineral carbonates after reacting with alkaline clay, a by-product of aluminum refining. The carbonate product can be utilized as construction fill material, soil amendments, and green fertilizer. Alcoa will demonstrate and optimize the process at their Point Comfort, Texas aluminum refining plant. (DOE Share: $11,999,359)

• Novomer Inc. (Ithaca, NY.) - Teaming with Albemarle Corporation and the Eastman Kodak Co., Novomer will develop a process for converting waste CO_2 into a number of polycarbonate products (plastics) for use in the packaging industry. Novomer's novel catalyst technology enables CO_2 to react with petrochemical epoxides to create a family of thermoplastic polymers that are up to 50 percent by weight CO_2. The project has the potential to convert CO_2 from an industrial waste stream into a lasting material that can be used in the manufacture of bottles, films, laminates, coatings on food and beverage cans, and in other wood and metal surface applications. Novomer has secured site commitments in Rochester, NY, Baton Rouge, Louisiana, and Orangeburg, SC where Phase 2 work will be performed. (DOE Share: $18,417,989)

• Touchstone Research Laboratory Ltd. (Triadelphia, WV.) - This project will pilot-test an open-pond algae production technology that can capture at least 60 percent of flue gas CO_2 from an industrial coal-fired source to produce biofuel and other high value co-products. A novel phase change material incorporated in Touchstone's technology will cover the algae pond surface to regulate daily temperature, reduce evaporation, and control the infiltration of invasive species. Lipids extracted from harvested algae will be converted to a bio-fuel, and an anaerobic digestion process will be developed and tested for converting residual biomass into methane. The host site for the pilot project is Cedar Lane Farms in Wooster, Ohio. (DOE Share: $6,239,542)

• Phycal, LLC (Highland Heights, OH.) - Phycal will complete development of an integrated system designed to produce liquid biocrude fuel from microalgae cultivated with captured CO_2. The algal biocrude can be blended with other fuels for power generation or processed into a variety of renewable drop-in replacement fuels such as jet fuel and biodiesel. Phycal will design, build, and operate a CO_2-to-algae-to-biofuels facility at a nominal thirty-acre site in Central

Oahu (near Wahiawa and Kapolei), Hawaii. Hawaii Electric Company will qualify the biocrude for boiler use, and Tesoro will supply CO_2 and evaluate fuel products. (DOE Share: $24,243,509)

• Skyonic Corporation (Austin, TX) - Skyonic Corporation will continue the development of SkyMine® mineralization technology--a potential replacement for existing scrubber technology. The SkyMine process transforms CO_2 into solid carbonate and/or bicarbonate materials while also removing sulfur oxides, nitrogen dioxide, mercury and other heavy metals from flue gas streams of industrial processes. Solid carbonates are ideal for long-term, safe aboveground storage without pipelines, subterranean injection, or concern about CO_2 re-release to the atmosphere. The project team plans to process CO_2-laden flue gas from a Capital Aggregates, Ltd. cement manufacturing plant in San Antonio, Texas. (DOE Share: $25,000,000)

• Calera Corporation (Los Gatos, CA.) - Calera Corporation is developing a process that directly mineralizes CO_2 in flue gas to carbonates that can be converted into useful construction materials. An existing CO_2 absorption facility for the project is operational at Moss Landing, Calif., for capture and mineralization. The project team will complete the detailed design, construction, and operation of a building material production system that at smaller scales has produced carbonate-containing aggregates suitable as construction fill or partial feedstock for use at cement production facilities. The building material production system will ultimately be integrated with the absorption facility to demonstrate viable process operation at a significant scale. (DOE Share: $19,895,553)

www.fossil.energy.gov/recovery/projects/beneficial_reuse.html

ARPA-E Project Selections

April 29, 2010

University of Massachusetts Amherst
(University of California San Diego, Genomatica)
$1,000,000
Amherst, MA

Electron Source – Electric Current: This project will develop a "microbial electrosynthesis" process in which microorganisms use electric current to convert water and carbon dioxide into butanol at much higher efficiency than traditional photosynthesis and without need for arable land.

Pennsylvania State University
(University of Kentucky)
$1,500,000
University Park, PA

Electron Source – Solar Hydrogen: Hydrogen consuming bacteria that usually derives its energy from residual light and organic waste at the bottom of ponds will be "rewired" to use electricity. The organism will be able to convert hydrogen and carbon dioxide into a bio-oil that can be refined into gasoline.

The Ohio State University
(Battelle Memorial Institute)
$3,977,349
Columbus, OH

Electron Source – Hydrogen: An industrially scalable bioreactor approach to incorporate genetically engineered bacteria that metabolize carbon dioxide, oxygen, and hydrogen to produce butanol. The team anticipates at least a twofold productivity improvement over current levels and a cost that can be competitive with gasoline.

Massachusetts Institute of Technology
(Michigan State University)
$1,771,404
Cambridge, MA

Electron Source – Hydrogen: A bacterium capable of consuming hydrogen and carbon dioxide will be engineered to produce butanol, which could be used as a motor fuel.

Ginkgo BioWorks
(University of California Berkeley, University of Washington)
$6,000,000
Boston, MA

Electron Source – Electric Current: The project will engineer a well- studied bacterium, E. coli, to harness electric current to convert carbon dioxide and water into isooctane, an important component of gasoline.

Harvard Medical School- Wyss Institute
$4,194,125
Boston, MA

Electron Source – Electric Current: This project will engineer a bacterium to be able to use electricity (which could come from renewable sources like solar or wind) to convert carbon dioxide into octanol, an energy-dense liquid fuel.

Massachusetts Institute of Technology
(Harvard University, University of Delaware)
$3,195,563
Cambridge, MA

Electron Source – Hydrogen and/or Direct Current: This project will engineer two microbes, working together, to convert carbon dioxide and hydrogen into oil, which could be refined into biodiesel.

North Carolina State University
(University of Georgia)
$2,729,976
Raleigh, NC

Electron Source – Hydrogen: The project will engineer a novel pathway into a high-temperature organism to use hydrogen gas to convert carbon dioxide into precursor compounds that can be used to produce biofuels such as butanol.

OPX Biotechnologies Inc.
(National Renewable Energy Laboratory, Johnson Matthey Catalysts Inc.)
$6,000,000
Boulder, CO

Electron Source – Hydrogen: Microorganisms will be engineered to use renewable hydrogen and carbon dioxide inputs to produce a biodiesel-equivalent fuel at low cost. Catalysts will be explored to convert the microbial fuel into jet fuel.

www.arpa-e.energy.gov/LinkClick.aspx?fileticket=mK6vhQztzb4%3d&tabid=83

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