Approaches that Convert CO_2 to Drop-In Jet Fuel

Gap / Problem Statement

Novel fuel development often requires feedstocks that present many technical and non-technical challenges from environmental, energy, political, and cost perspectives. Atmospheric, oceanic, and waste carbon dioxide (CO_2) offer an abundant sustainable resource that if properly exploited could be a feedstock to produce drop-in jet fuel while minimizing and potentially eliminating net life cycle greenhouse gas (GHG) emissions of fuel production and use. There are two fundamental challenges associated with such pathways:

(a) Capturing large quantities of CO_2 in an efficient and economic manner from the environment or waste streams, and

(b) Designing reliable, cost effective, and environmentally sound systems that chemically reduce, convert, and/or otherwise consume CO_2 feedstock to produce jet fuel and associated by-products.

Carbon dioxide capture is a large, complex subject addressed via a separate CAAFI R&D white paper. The focus of the current discussion is to identify and summarize various pathways, advantages, and challenges associated with part (b) above, namely photosynthetic, directly fed CO_2 and non-photosynthetic conversion of CO_2 to drop-in jet fuel in an indirect or direct manner. The more specific focus of this white paper is the subset of processes that utilize CO_2 at concentrations well above ambient.

Background

Carbon dioxide was one of the first gases described as a substance distinct from air. Its scientific history traces back to the 18th century, with advancing understanding of the basic physical and chemical properties of CO_2 occurring over time and into the early 19th century, at least at relatively low pressures. As it pertains to liquid hydrocarbon fuel production, we can classify the chemistry of CO_2 reduction and utilization broadly into two categories: photosynthetic and non-photosynthetic. We can organize the non-photosynthetic approaches also into two categories, biological and non-biological. Finally, we can categorize non-biological approaches into electrochemical, photo-catalytic, and thermochemical. In all cases, the target end product is a liquid hydrocarbon with physical and chemical properties identical or close to those of jet fuel, considered a higher value form of energy than the primary energy source because these properties make it suitable for use in aviation.

Photosynthetic Processes

As part of the carbon cycle, plants, algae, and cyanobacteria absorb carbon dioxide, light, and water to produce chemical energy. It takes a minimum of eight photons to fix a single molecule of CO_2, produce complex, reduced carbon containing molecules, and generate byproduct oxygen. Numerous companies, universities, and government agencies are developing and evaluating mechanisms that increase the efficiency and/or speed up this highly evolved process to produce, harvest, and sell substances of commercial value.

For instance, algae and other photosynthetic microbes are one of the most productive oil crops on a per-area basis. As a point of comparison, the Department of Energy (US DOE) estimates that soybean crops produce about 50 gallons of oil per acre per year, while algae have the quoted potential to produce 1,000-5,000 gallons per acre per year[1]. Although not all those developing algae cultivation ponds add CO_2 beyond what is absorbed from the atmosphere, some approaches attempt to improve yields and efficiencies by directly adding, to the ponds, carbon dioxide produced by a nearby coal fired plant, petroleum refinery, or other large-scale source in conjunction with a separate stream of nutrients. Reports suggest that bubbling CO_2 through algal cultivation systems can increase productivity, up to a saturation point. Algae will consume about 1.3-1.9 tons of CO_2 utilization per

---

[1] Sapphire recently publically released their commercial plans for 1.5 million gallons per year of crude oil equivalent from 300 acres of algae cultivation ponds and processing facilities in Columbus, New Mexico. This will be a 5000 gallons/acre/year commercial plant and 6250 gallons/acre/year if only 80% of the site is cultivation ponds. The capital expenditure is $135M. If we assume an 8%/year weighted cost of capital, this would imply ~$300/barrel of crude oil just from the capital cost. If we assume solar insolation similar to nearby El Paso Texas or an average 5.7 $kWh/m^2/day$ and 130000 BTU/gallon, this would imply a site efficiency of ~2.3%.

ton of algal biomass (dry) produced[2]; the range stemming from variation in algae species.

Non-photosynthetic

Even though in nature the great majority of CO_2 removal occurs through photosynthetic processes (> 100 Pg of carbon/year globally), there are a number of research efforts, in the US and around the world, into a rich variety of alternative non-photosynthetic approaches.

Non-photosynthetic biological

Electrofuels is an approach that uses electricity as an energy source, carbon dioxide as the carbon source, and microorganisms as catalysts to generate liquid fuels. Electrofuels potentially enables using renewable electricity – becoming here the primary source – produced from wind and solar for fuels production (it is the equivalent of a chemical storage). The compelling reasons to use (renewable) electricity as a primary energy source to produce liquid fuels like jet fuel directly from CO_2 are in the high value of the end product and the de facto recycling of CO_2 generated by aircraft.

Chemoautotrophic microorganisms are those organisms that use electron donors (as opposed to phototrophs, which use solar energy) as their energy sources and can fix CO_2 into reduced carbon compounds. A number of researchers are developing two such biological non-photosynthetic approaches. They are looking into feeding electrons to these microorganisms directly from a cathode or indirectly from chemical electron donors like hydrogen, formic acid or ammonia produced by renewable electricity.

In the first approach, microorganisms directly "feed" on electricity as the energy source in conjunction with CO_2 as the carbon source and other nutrients necessary for metabolism. This novel approach relies on a property of some microorganisms known as electrogenicity, the ability of certain microbes to exchange electrons with an extracellular substrate. Two major types of bacteria appear to

---

[22] For example, 1.3 tons CO_2 per ton of algae, assumes an algae chemical composition $(CH_2O)_{106}(NH_4)_{16}PO_4$ whereas the multi-author harmonization report references 1.9 as being typical, e.g. with the chemical composition $C_{106}H_{181}O_{45}N_{15}P$

be electrogenic: *Shewanella* sp. and *Geobacter* sp., and a number of mixed microbial communities utilize or produce electricity in bio-electrochemical systems. After uptake of electricity, natural metabolic processes within the organism utilize the reducing power of the electrons to fix the carbon into fuel molecules such as methane, acetate, formate, or oils. No known naturally occurring microorganisms can both utilize electrons efficiently and fix CO_2. However, preliminary bioengineering efforts have focused on introducing one of these functionalities into a species containing the other. For example, researchers have exploited techniques from synthetic biology to create a strain of the non-electrogenic species *E. coli* that is capable of transferring electrons to extracellular iron oxide particles. Efforts are also underway to introduce fuel production pathways from other microbes and algae into *Geobacter* sp. Another promising bioengineering approach may be construction of artificial carbon fixation pathways that are more efficient than naturally occurring ones but based on extant enzymes.

A second approach uses electricity to generate a feedstock such as hydrogen, reduced nitrogen (ammonia), or reduced metal (ferrous iron) combined with CO_2 to power the growth of fuel-producing bacteria. In some cases researchers use formic acid obtained from catalytic hydrogenation of CO_2 as a feedstock, providing both electron donor and carbon source. The most commonly used organisms in this type of approach are methanogens, organisms that produce methane from CO_2, and acetogens, organisms that produce acetate from CO_2. Reduced carbon in the form of methane or acetate from these organisms can then pass to a second species for further processing into liquid fuels such as butanol or oils. This second approach has been demonstrated for a number of diverse metabolic pathways with a range of organisms including *Nitrosomonas europaea* (oxidation of ammonia to fix carbon), *Ralstonia eutropha* (oxidation of hydrogen to fix carbon), and *Acidithiolbacillus ferooxidans* (oxidation of ferrous iron to fix carbon). One interesting avenue is utilization of chemo-lithoautotrophic hyper-thermophilic bacteria, *i.e.* bacteria that grow at temperatures in excess of 60°C using inorganic energy sources and fixing carbon, such as *Metallosphaera sedula*. These bacteria offer the unique advantage of being utilizable in high temperature processes that can cut down on the number of processing steps required to harvest a liquid fuel.

For both of these approaches, there are significant hurdles left to overcome before achieving market ready status. Laboratory pilot-scale devices demonstrating the ability of microbes to use electricity as a primary source exist, but scale up and viable economics[3] remain a challenge. Furthermore, fundamental biochemical understanding of electrogenicity is in its infancy, severely restricting the number of species that can be utilized in direct contact with electrodes in microbial electro-synthetic processes.

Non-photosynthetic, non-biological

We can categorize other non-photosynthetic approaches as non-biological or industrial based. A three-step process describes an example of such approaches:

Step 1 – electrolysis, photo-catalytic, or thermochemical splitting of water to produce hydrogen and oxygen using either renewable electricity, photons from the sun, or concentrated solar energy (heat from the sun), respectively.

Step 2 – Production of carbon monoxide (CO) from CO_2 via one of a number of approaches, including but not limited to reverse water gas shift[4] (proven technology) or analogous processes to those that produced hydrogen in step 1.

Step 3 – Synthesis of long chain hydrocarbons from the carbon monoxide and hydrogen produced in step 1 and 2, in a Fischer Tropsch (FT) plant and upgrading the products to on-specification jet fuel, or oligomerization of olefins to finished jet fuel.

Such a three-step approach capitalizes on decades of synthetic fuel technology, in which synthesis gas, a mixture of hydrogen (H_2) and carbon monoxide (CO), is converted to hydrocarbons in a highly exothermic reaction: $nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O$[5]. The needed innovation thus focuses primarily on the difficult splitting reactions in which energetically spent carbon dioxide (CO_2) and water

---

[3] At 100% efficiency electricity to fuel and $0.06/kWh, the cost of electricity would be ~$100/barrel just for the cost of electricity. If the efficiency drops to 50% then the cost of electricity would increase to ~$200/barrel. This highlights the need to achieve very high efficiencies or to avoid using electricity all together.

[4] Reverse Water Gas Shift Reaction: $H_2+CO_2 \rightarrow CO+H_2O$, mildly endothermic 41.1kJ/mole.

[5] Approximately 25% of the chemical energy in the syngas converts to heat in the Fischer Tropsch reaction, providing an opportunity for heat integration in designing the system. Good system integration will also recycle the produced water and light tail gases from the reaction.

(H_2O) molecules are energized to CO and H_2: $2H_2O + \text{energy} \rightarrow 2H_2 + O_2$ and $CO_2 + \text{energy} \rightarrow CO + \frac{1}{2}O_2$ and also on system integration issues.

Electrochemical

It is certainly possible, using only mature technologies, to produce long chain hydrocarbons, following the above three-step process. Renewable electricity followed by (1) electrolysis to make hydrogen, followed by (2) reverse water gas shift to make CO from some of that hydrogen and a concentrated source of CO_2, (3) adjust the ratio of H_2:CO:CO_2 entering a FT reactor, and finally upgrading as needed to commercial grade jet fuel. One critical issue is the cost of the electricity needed and the relatively inefficient downstream processing: H_2 to finished product is on order 40% efficient. With relatively low cost 20% efficient solar electric and ~70% efficient commercial electrolyzers, the net efficiency is on order 6% sunlight to fuel efficiency and 30% electricity to fuel. At $0.06/kWh this equates to >$300/barrel. More importantly, as this approach relies on mature technologies, opportunities for substantial improvement seem unlikely.

Electrochemical reduction of CO_2 is receiving some attention; however, such technology development lags well behind the maturity of water electrolysis. The reduction of CO_2 by one electron to form $CO_2^{\bullet -}$, is highly unfavorable, having a formal reduction potential of -2.14 V vs SCE. Rapid reduction requires an overpotential of 0.1-0.6 V, due at least in part to the kinetic restrictions imposed by the structural difference between linear CO_2 and bent CO_2. An alternative and more favorable pathway is to reduce CO_2 though proton-assisted multiple-electron transfers. Hence, challenges include slow reaction rates (~20 per hour for CO, ~100 per hour for formate), low current densities, low stability of the catalyst (TN ~300 or less), controlling the selectivity (CO, formate, H2, etc.), finding inexpensive catalysts, and coupling the reductive and oxidative half reactions, *i e* eliminating the sacrificial electron donor.

Photo-catalytic

Artificial photosynthetic systems (photo-catalytic) inspired by the blueprint of photosynthesis but built from synthetic organic or inorganic components may also prove a useful approach for producing reduced carbon fuels, although practical systems do not yet exist. These approaches directly convert solar photons, CO_2, and water to fuels such as hydrogen, carbon monoxide, alcohols, and small hydrocarbons. It was the pioneering work on photo-electrochemical splitting of water to hydrogen and oxygen by n-type TiO_2 using ultraviolet light back 1972 that marked the beginning of the research field. Since then, researchers have made significant progress in new semiconductor photo-catalysts, molecular photo-catalysts for hydrogen production and water oxidation, dye-sensitized photo-electrochemical cells, and electrochemical reduction of carbon dioxide. Researchers have advanced the design of artificial reaction centers, donor-chromophore-acceptor triads are typical designs. In these molecules, a light harvesting chromophore is sandwiched between a source of electrons, *i.e.* the donor, and an electron sink, *i.e.* the acceptor. Researchers have explored a number of types of molecules for each functional fragment, such as carotenoid-porphyrin-fullerene triads, and they have been able to observe relatively long-lived charge-separated excited states. In essence, these molecules are molecular photovoltaic devices. There are claims of observations for quantum yields as high as 0.95 for the formation of the charge-separated state and lifetimes on order 100's of nanoseconds at room temperature. The critical challenge is to develop catalysts that perform CO_2 reduction as well as electron source oxidation and efficiently couple them to artificial photosynthetic systems. Water is probably the most desirable electron source, but development of water oxidation catalysts has proved especially difficult. Successful examples typically rely on precious metals such as iridium and not at a sufficiently low enough level to permit scaling to a commodity level.

It is feasible photo-chemically to reduce CO_2 at select semiconductor surfaces or at catalyst-coated electrodes. Semiconductors utilized for this purpose include TiO_2, p-GaP, p-GaAs, n-GaAs, p-InP, and iron pyrite. However, four main challenges remain: (1) high overpotentials (-1.7 to -2.5 vs. SCE depending on solvent; kinetic limitations), (2) low current (Faradaic, <20%) efficiency, (3) poor electrode stability, and (4) thermodynamic non-selectivity (i.e. a formation of a mixture of product species including CO, formic acid, formaldehyde, methanol and methane).

Solar thermochemical

The water and carbon dioxide splitting reactions are made feasible using a two-step, concentrated solar driven, high-temperature, metal oxide based thermochemical cycle (TCC). A TCC divides thermodynamically unfavorable reactions into two or more favorable reactions. Generically, the first half of a cycle is an endothermic reduction driven by concentrated sunlight:

$$\frac{1}{\delta}MO_{x,solid} \xrightarrow{heat} \frac{1}{\delta}MO_{x-\delta} + \text{½}O_{2,gas}$$

followed by the mildly exothermic re-oxidation step to close the cycle using either carbon dioxide or water as the oxidant:

$$\tfrac{1}{\delta}MO_{x-\delta} + CO_2 \rightarrow \tfrac{1}{\delta}MO_x + CO$$

or

$$\tfrac{1}{\delta}MO_{x-\delta} + H_2O \rightarrow \tfrac{1}{\delta}MO_x + H_2.$$

The metal oxide MO_x can either completely volatize on reduction, for example

$$ZnO_{solid} \xrightarrow{heat} Zn_{gas} + \text{½}O_{2,gas}$$

or remain solid, for example:

$$\tfrac{1}{\delta}CeO_{2,solid} \xrightarrow{heat} \tfrac{1}{\delta}CeO_{2-\delta} + \text{½}O_{2,gas}$$

Other reducible oxides are certainly possible as long as they have some redox active sites, e.g. $Ce^{+4} \rightarrow Ce^{+3}$ or $Fe^{+3} \rightarrow Fe^{+2}$ and bind the oxygen ion tightly enough to overcome the binding energy in carbon dioxide or water.

In essence, a TCC is a heat engine that uses heat to do chemical work of breaking bonds; hence, it converts heat energy into chemical energy. High efficiency is theoretically possible at these high temperatures for such thermally driven processes, especially when compared to approaches that are more conventional, e.g. biofuels or electrolysis. Sunlight to hydrogen or to CO at 20% or better efficiency appears feasible. However, no one has yet demonstrated such efficiencies.

While solar thermal technologies require a particular quality of sunlight that only exists in the southwest of the US and other desert environments around world, this is not necessarily a severe limitation. Instead of ubiquity, the most relevant metric is the potential of any approach to have the potential to scale to a size that matters relative to the fuel demand given the resource that exists. In evaluating the scalability and the available resource, one can see that the potential impact is significantly larger than many imagine. Briefly, analysis shows that seven southwestern states have land appropriate for this and similar applications (1.5% of the total US land area, after filtering for high quality sunlight, unencumbered or environmentally sensitive land, large contiguous areas, and low slope) wherein the resource conservatively totals 9.4 terawatts. Utilizing this resource to produce fuel with a lifecycle efficiency of 12.5% would provide 80% of US total petroleum demand (2007 basis). Alternatively, utilizing only 12.5% of the resource could meet 10% of US petroleum demand. Therefore, one can conclude that solar thermal technologies more than meet the criteria of potential significant national impact, despite their regional applicability.

Challenges specific to solar thermochemical come in three broad categories: the reactor, the working redox active materials, and systems-related considerations. Researchers are addressing each of these challenges, but achieving commercial viability in a reasonable timeframe will require rapid and continuous advances to improve on the efficiency and durability and drive down anticipated cost and resource intensity.

Thermodynamics dictates that the two reactions of a TCC are favorable at two different temperatures. Preserving the sensible heat of the metal oxide as it cycles between high and low temperatures (recuperation) is crucial to achieve high efficiency. Other vital reactor attributes, in addition to recuperation, include: (1) inherent separation of the two products, CO or H_2 from O_2, (2) continuous utilization of incident solar energy, (3) direct illumination of the reactive metal-oxide during thermal reduction, and (4) an independent (partial) pressure control for each half-cycle. The challenge is to design for these attributes, for desired radiative absorption and emission properties, for the gas flows and gas/surface interactions, and for durability.

The redox active materials forming the heart of the TCC must perform predictably and reliably over many thousands of cycles in an extreme non-steady-state environment. To achieve maximum efficiency, the material must meet not only thermodynamic and physical criteria, but also be designed to function in a manner that balances and maximizes incident solar flux, redox chemical kinetics (limited by thermodynamics), reactant/product species transport, and heat recuperation to maximize efficiency and chemical flux. The challenge is to design for all the vital attributes: thermodynamics, kinetics, ion transport, sufficient surface area, and long-term chemical and physical stability.

A key challenge at the systems level is to preserve the energy of the energized reactor products into the final fuel product, which includes optimizing separations, gas handling, intermediate storage, and heat integration. Nevertheless, lifecycle end-to-end energy efficiency of sunlight to fuel of 12.5% seems feasible.

Solar Reforming

Here we introduce a lower risk approach to reduced carbon fuels that also has attractive economics. This technology hybridizes concentrated solar with natural gas, while consuming CO_2 to produce syngas for further processing to jet fuel. The natural gas is used as a carbon and hydrogen source, but not as an energy source to drive the endothermic reactions.

$$CH_4 + CO_2 \rightarrow 2H_2 + 2CO \quad \Delta H_{298} = +247 \text{ kJ/mol (dry reforming)}$$

$$CH_4 + H_2O \rightarrow 3H_2 + CO \quad \Delta H_{298} = +206 \text{ kJ/mol (steam reforming)}$$

A number of prototype solar receivers and catalysts exist in the US, Australia, Germany, and Israel. At temperatures in the vicinity of 800 to 900°C, and a 1:1:2 CH_4:CO_2:H_2O results in the desired 2:1 H2:CO syngas.

$$\text{e.g. } 0.725\ CH_4\ (582\text{ kJ}) + 0.725\ CO_2 + 1.45\ H_2O + \text{heat (189 kJ)} \rightarrow$$

$$CO\ (283\text{ kJ}) + 2H_2\ (488\text{ kJ}) + 0.45\ CO_2 + 0.9\ H_2O \text{ at } {\sim}800\text{-}900^\circ C.$$

The reaction consumes CO_2 (nearly 0.4 moles of CO_2 per mole of CH_4) as opposed to generating CO_2 in a gas to liquids plant.

Related technologies can solar reform other sources of hydrocarbons, including waste biomass, algae, and coal.

Current Status

The above discussion of various process options to utilize CO_2 is an illustrative but NOT complete survey of the many approaches to using carbon dioxide as a feedstock in the production of drop-in jet fuel.

The approaches to energy conversion highlighted above offer key advantages including compatibility with current infrastructure, production of a high energy density fuel that is simple to transport and distribute, and minimal or reduced life cycle GHG emissions. Notably, algae farms can be set up on marginal lands and have significantly reduced footprints versus today's more conventional oil seed options. A great many microorganisms –at face value- appear physiologically well poised for such production. However, only a few microorganisms may be sufficiently active and suitably compliant to maintain commercially relevant productivity. The fundamental biology and chemistry is indisputable; nevertheless, the non-photosynthetic processes appear hindered by low production volumes or are at a relatively low on the technology readiness scale (TRL) level and hence predominantly focused on early proof–of-concept experiments.

Whereas open ponds have been used for algae production for many decades, these come with major crop protection challenges, and a number of commercial, university, and government research teams pursuing algae, CO_2, and nutrient streams as a source of biofuels are investigating how to improve enclosed photobioreactors. These photo bioreactors will need further development and improvement to be commercially viable for routine biofuel applications.

Genetically modified microorganisms may further improve the efficiency and rate of energy conversion to liquid fuels and product processing. A genetically engineered approach provides both promise and peril: increased rates of production and novel organism capabilities (such as product excretion) versus increased regulatory barriers. However, regulatory processes and rules are still evolving.

Direct (non FT) conversion of CO_2 to hydrocarbons is in its infancy and all the possible reactions and processes not predominantly involved with reverse water gas shift are yet to be explored in depth.

Splitting water electrochemically is a mature technology; however splitting water photo-catalytically is not. Being able to do significantly better than commercially available PV+electrolysis is a significant challenge. Solar thermochemical has received much less attention, but does show promise for higher sunlight to hydrogen efficiency. Reducing CO_2 either electrochemically or photo-catalytically also has received much less attention and finally splitting CO_2 in a solar thermochemical cycle is a relatively recent quest.

Solvability and Approaches

All large-scale renewable energy technologies face the challenge of capturing and converting a low-density energy source into a more concentrated and usable form. For solar technologies (including biofuels), this translates to costs and resource limitations arising from the collection of sunlight, which makes high efficiency especially important. New energy technologies must also offer clear advantages in efficiency, cost, and/or scalability over currently available alternatives. For synthetic fuels from the sun, the only known and proven pathway as stated above would use solar-generated electricity (PV or CSP) to drive water electrolysis to produce H_2 with downstream processing to the liquid hydrocarbon.

As stated above, a limitation that will need to be overcome before any of these pathways can be considered a successful commercial technology is identifying a steady and reliable source of carbon dioxide at levels of purity that are acceptable to the underlying microbial or industrial process. This topic is addressed in a separate CAAFI R&D white paper, and the discussion below assumes this barrier has been addressed.

Finding more efficient methods and processes associated with every aspect of production is essential. Energy conversion projects are characteristically capital intensive and mostly this appears to be the case with CO_2 conversion technologies. There are fixed costs from a project's inception as well as ongoing operational costs of CO_2 purchase or production, providing nutrient or energy inputs, isolating the bio oil or syngas, and the conversion to a usable liquid fuel. However, a source of hydrogen and intermediate reduced carbon species and its production remain the largest hurdle to overcome.

Whereas biological processes to convert CO_2 to fuel are complicated by microbial robustness, industrial processes to convert CO_2 and hydrogen with no biological intermediary to fuel are promising but appear limited by questions around a thermodynamically efficient reactions to produce hydrogen and reduce CO_2.

For non-photosynthetic processes, materials research, computational modeling, and catalytic or solar reactor design would reduce energy consumption to make a hydrocarbons production process from carbon dioxide potentially feasible; limited reports of techno-economics exist in the literature. More such analyses would help identify the critical economic barriers.

For electrofuels, the cost of the raw electric power also appears to be a challenge. It is reasonable to assume that bulk wholesale electricity prices will average out around \$0.06 per kilowatt-hour over time. This translates at claims of 88% efficiency to about \$2.50 per gallon of fuel just for the energy, leaving very modest headroom for all other expenses including bioreactors (expected major expense) and profit, let alone metabolic health of the organism. Cheaper sources of renewable energy or higher costs of conventional Jet-A will be critical for this pathway to succeed.

All other pathways depend on achieving high efficiency and fast kinetics, reactor or electrochemical cell designs, and system integration.

A solar hybrid approach with natural gas could provide a robust bridge. The challenges are less substantial, but still include catalyst design, solar reactor design, and issues of system integration.

Benefits to Industry as a Whole

Natural, unaltered photosynthetic process is about 0.1% to 2% efficient depending on the plant species. Utilization of concentrated CO_2 as a feedstock provides an opportunity to improve productivity and recycle / sequester an important greenhouse gas at or near the source.

Either electrofuels produced by a biological or a non-biological route provide an interesting systemic benefit and risk in that they can tie their predominant energy source to the grid. By its very nature, the electric grid can deliver power from numerous renewable and non-renewable sources, which creates a resiliency to unforeseen events as only one of many benefits. Market based pricing provides both a technical challenge and a further opportunity to greatly reduce the cost of electricity as off peak rates can be extremely low (under today’s market conditions) and have even been known to occasionally go negative. However, taking advantage of only off-peak rates would lower the capacity factor, reduce productivity, and increase the cost of capital. Nevertheless, wide scale adoption of electrofuels would mean that the grid would indirectly power aircraft.

The non-photosynthetic pathways also provide the potential to reduce substantially the land area required to produce fuels compared to algae or traditional agricultural approaches, if they can achieve a reasonable fraction of their theoretical efficiency. This reduces and can eliminate conflicts over land use for food and animal feed or conservation, and other potential impacts such as introduction of non-native species into the environment.

Potential Timeline and Costs

Daniel Yergin, in his latest book, “The Quest” points out that energy transitions have historically taken a century to complete. To make this point, he highlights the movement from wood to coal, and then coal to oil some years later. Because energy systems are inherently capital intensive, it would be unrealistic to expect a complete transition time to sustainable option on a time scale of a few years or even a decade.

Many of these technologies are not market ready today. Several have reached prototype stage, but realistically need close to a decade to mature. Fuels from algae production are reaching demonstration stage. Solar reforming of natural gas could be demonstration ready in a couple of years, with adequate resources.

As with these historical references, it will be necessary for entrepreneurial companies and individuals to find niche applications, which can provide revenue for additional research.

Algae Reference

Ryan Davis, et al, Technical Report ANL/ESD/12-4; NREL/TP-5100-55431; PNNL-21437, June 2012 “Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost Emissions, and Resource Potential from a Harmonized Model.

Some Electrofuels References

El-Naggar M. et al., Proc. Natl. Acad. Sci, **2010**, 107, 18127.

Nevin, K. P. et al., Environ. Microbio., **2011**, 77(9), 2882-2886.

Jensen, H. M. et al., Proc. Natl. Acad. Sci., **2010**, 107(45), 19213-19218.

Bar-Even, A. et al. Proc. Natl. Acad. Sci., **2010**, 107(19), 8889-8894.

Some Artificial Photosynthesis References

Barton, E. E. et al., J. Am. Chem. Soc., **2008**, 130(20), 6342-6344.

Munoz-Garcia, A. B. and Carter, E. A. J. Am. Chem. Soc., **2012**, 134(33), 13600-13603.

Yui, T. et al. ACS Appl. Mater. Interfaces, **2011**, 3(7), 2594-2600.

Gust, D.; Moore, T. A.; Moore, A. L. Acc. Chem. Res. **2009**, 42(12), 1891-1898.

Akira Fujishima and Kenichi Honda, Nature **1972**, 238, 37-38.

Etsuko Fujita, James Muckerman, and Kazunari Domen, ChemSusChem **2011**, 4, 155-157.

Some Solar Thermochemical References

James E Miller, et al, in Energy Technology 2010, Edited by: Neale R. Neelameggham, et al TMS (The Minerals, Metals & Materials Society), **2010**

Robert Service, “Sunlight in your tank”, Science Magazine, **2009**, volume 326, 1472-1475.

William C Chueh, et al, Science, **2010**: Vol. 330, 1797-1801.

J. Kim, et al “Fuel production from CO_2 using solar-thermal energy: system level analysis” Energy Environ. Sci., **2012**, 5, 8417.

Dennis Schuetzle and Robert Schuetzle, Final Technical Report, NETL, **2010,** “Solar Reforming of Carbon Dioxide to Produce Diesel Fuel”.