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Carbon Engineering

Total anthropogenic emissions of one trillion tonnes of carbon (3.67 trillion tonnes of CO2), about half of which has already been emitted since industrialization began, results in a most likely peak carbon-dioxide-induced warming of 2 °C above pre-industrial temperatures, with a 5–95% confidence interval of 1.3–3.9 °C.

— Nature[1]

On a sunny Calgary morning in September 2013, Dr. David Keith was going into a conference room at the University of Calgary's Research Transition Facility, a commercialization hub for university technology where the Carbon Engineering (CE) offices were located. David was meeting with Arvinder Singh, the CTO, and Kenton Heidel, senior engineer, to understand how the negotiations were progressing with vendors commissioned to build components for the company's pilot plant for Direct Air Capture (DAC) of carbon dioxide. The pilot plant would deliver critical data regarding the cost and performance of CE's proposed technology to capture and process CO2 directly from the air. CE's partners and vendors would use this data to convince financiers to back a first-of-a-kind, industrial-scale plant capable of supporting Enhanced Oil Recovery for low-carbon transportation fuels.[a] **Exhibit 1** compares the fossil carbon intensity of different low-carbon transportation fuels refined from oil produced via Enhanced Oil Recovery (EOR) using different sources of CO2. Ultimately, CE planned to move beyond EOR using renewables or nuclear energy to produce synthetic fuels, where CO2 would be captured directly from the atmosphere and combined with hydrogen from water-splitting to produce specialty chemicals and ultra-low emissions hydrocarbon fuels that were fully compatible with today's transport infrastructure.

Earlier that morning Keith had gotten a string of disturbing emails. The preliminary construction bid for the CE prototype plant had come in at a stunning C$15M,[b] well in excess of the C$3M that Keith, his team and their outside experts had expected. Keith wondered what it meant. Was there some gross error in CE's thinking? Were CE's supply-chain partners pricing their bids on the expectation that there

[a] Enhanced Oil Recovery (EOR) referred to the process of oil extraction from a low productivity oil reservoir by flooding the reservoir with water, steam or highly-compressed gas such as CO2. Generally, there were three stages in oil production: (1) primary recovery where the reservoir produced oil driven by its own internal pressure, (2) secondary recovery where water was injected to maintain pressure and push out even more oil, and then (3) tertiary recovery where CO2 was injected both to maintain pressure and to act as a solvent stripping residual oil from the formation. The resulting CO2-oil mixture was then separated at the production site. That CO2 was recompressed for reinjection to produce yet more oil and was then recycled until production from the reservoir was no longer economic. The average mix of refined products from a barrel oil would release 0.35 tons of CO2 when burned. All the injected CO2 was geologically sequestered in the abandoned reservoir, lowering the net amount of fossil carbon introduced into the atmosphere by burning the produced oil.

[b] 1 Canadian Dollar was equivalent to 0.97 U.S. Dollar as of October 24, 2013, according to rates provided by Citibank N.A.

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was a low likelihood of follow-on business? Was there just something crazy in the construction market where everyone had too much work immediately available to be interested in offering their "best-and-final" price bids? Or maybe, everyone thought that CE's financial backers would just roll over and pay the price? Whatever it was, Keith knew it felt like a cloudy morning in Calgary, even if it was sunny outside.

Straddling Academia and Industry

Keith was Executive Chairman of Carbon Engineering, a company based in Calgary, Alberta working on the industrial-scale capture of CO2 from ambient air. He had built the company with the ambitious mission of mitigating climate change through the production of low carbon transportation fuels utilizing captured atmospheric CO2. In an environment with fledgling and uncertain policy support for solutions to climate change, Keith had brought together a team of committed scientists, private investors, and energy project developers to build CE's business.

CE had a major advantage in that Keith was a tenured faculty member at Harvard University with a joint appointment at the School of Engineering and Applied Sciences, and the Harvard Kennedy School. Owing to the nascent stage of development of the Direct Air Capture (DAC) field, Keith's international reputation and influence in the climate change policy sphere could play an important part in helping regulators and policymakers understand the potential impact of DAC in mitigating climate change.

Much of Keith's academic work in 2013 was on the controversial science and public policy of solar geoengineering, the possibility of artificially cooling the earth by methods such as injecting sulfuric acid into the stratosphere.[2] These technologies presented both opportunities and grave risks, and many people including Keith were outspoken about the need to establish strong new international controls on solar geoengineering development and to restrict the role of private industry in development of the technology. From time to time, Keith's prominent role in solar geoengineering had posed significant problems to CE because the two technologies—DAC and solar geoengineering—were sometimes conflated, bringing CE a level of scrutiny and hostility that it would not have otherwise received.

Besides Keith, many of the early team members at CE had either been graduate students who had worked with Keith at the University of Calgary, or had strong ties to the university. Maintaining close relations with the university, including strategically placing the firm's headquarters adjacent to the University of Calgary campus, provided CE with a sustainable advantage in recruiting talented engineers as the company looked to build a pilot plant and its first-of-a-kind (FOAK) plant. See **Exhibit 2a** for team photo, **Exhibit 2b** for a full-scale DAC plant view, and **Exhibit 3** for team biographies. In addition, Calgary was a hotbed of technological innovation as well as power and petroleum processing plant construction, supporting the development of Western Canada's massive petroleum resources from the Bakken shales near the U.S. border to the Athabasca oil sands near Canada's Northwest Territories.

In 2013, as CE geared towards a heightened pace of technology development, Keith brought in an energy-focused executive search firm to find a professional CEO. The new CEO was expected to bring renewed focus to the process of aligning partners to work with CE towards building the pilot plant and the FOAK. Keith said about the decision to bring in a new CEO, "I am reaching my level of incompetence in some ways... Some of my management weaknesses are things that I could get coaching for and fix, but I can't do that and do the Harvard job. It just isn't working."

Geoff Holmes, a senior business development executive and an early hire said about the decision to hire a new CEO given the progress CE had made over the past few years, "We've transitioned from being very investigative and R&D driven to being much more operational and execution driven and I don't think it's any mystery that [David's] strengths and what he really loves are in the former and not in the latter."

Financing CE

CE relied on a mix of private money, public money, and ultimately on project finance to achieve Keith's vision of making direct air capture a reality.

In 2009, CE raised a starting $3.5M in funding from Bill Gates, Murray Edwards, and others to conduct process design, R&D, and prototyping in Calgary, Alberta.[c] Gates had become aware of and had subsequently supported Keith's work on various academic projects involving climate science.[d] **Exhibit 4** contains the original business plan that Keith had sent to Gates in early 2009. In 2013, CE closed a $3M follow-on round from private investors to develop its first pilot-scale plant which would be used to predict the operating characteristics of CE's CO2 capture process at industrial-scale.[3]

In addition by 2013, CE had also raised $3M in non-dilutive funding from government sources, both provincial and national, such as Alberta Innovates Technology Futures (AITF), Carbon Management Canada (CMC), Scientific Research and Experimental Development (SR&ED) credits, Climate Change and Emissions Management Fund (CCEMC), and National Research Council Canada (NRCC) Industrial Research Assistance Program (IRAP). Arvinder Singh, the CTO, who also managed the grant writing process, said about CE's public fundraising strategy,

> Some Canadian startups have raised 3 times as much in non-dilutive funding as they have from dilutive sources. CE has only raised about half of its funding from non-dilutive sources. We should be able to raise a lot more from government sources than we have in the past.

The strategy for financing the first-of-a-kind (FOAK) industrial- scale plant was in the preliminary stages of development. The FOAK was expected to cost somewhere between $50M and $100M. See **Exhibit 5** for a timeline of CE's past and future milestones.

CE was considering the use of a highly novel financing structure for follow-on plants, once the FOAK risks had been eliminated. The proposed project finance structure segregated the project's revenue streams and corresponding financing into two tranches. The first tranche would use traditional oil & gas project financing instruments, being structured for repayment from sales of CO2 to EOR operators. The second would break new ground, being structured for repayment from the premium

[c] Bill Gates was the founder and Chairman of Microsoft. Murray Edwards was the founder and Chairman of Calgary-headquartered Canadian Natural Resources, Ltd. Edwards was a billionaire with extensive investments in Canadian oil sands, energy trusts, oil field services businesses, aerospace, destination resorts and the Calgary Flames hockey team.

[d] In addition to his role as the Executive Chairman of Carbon Engineering, Dr. David Keith had expertise in climate science, energy technology and public policy. He spent more than a decade working on Carbon Dioxide Capture and Storage (CCS) and through that work developed many contacts within the energy industry, environmental groups and regulators relevant to the work of CE. He was introduced to Microsoft-founder Bill Gates by Jabe Blumenthal, an early Microsoft employee, in December 2006, and since then Keith, Blumenthal and two others had served as informal advisors to Gates on energy and environmental topics. Gates provided more than $5M in funding for research work by Keith and others (See http://www.keith.seas.harvard.edu/ficer).

earned on low-carbon fuels sold to markets with direct mandates or regulated trading of carbon credits such as California and the European Union.

CE believed that this novel, tranched project financing structure would allow for many different and new types of investors to participate, those who wanted to profit from taking the yet-to-be established risks associated with political and regulatory uncertainty of low-carbon fuels, and those who simply wanted the relatively secure profits from assuming the well-defined risks of the traditional EOR business.

Managing Climate Change

In September 2013, the Intergovernmental Panel on Climate Change (IPCC) released their latest report, routinely referred to as the AR5. The report said: "Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions."[4]

Mitigating carbon emissions at the source was the primary strategy used by policy makers and regulators to prevent the more extreme climate change scenarios. However, efforts to reduce carbon dioxide emissions were meeting with varying degrees of success around the world. The political process attempting to create a global framework had met with severe roadblocks within the United States, political support weakening in some EU countries, and many large developing countries such as China and India unwilling to accept a cap on carbon emissions.

With per capita energy use declining, most EU countries had pursued aggressive goals to mitigate GHGs, principally CO2, through energy efficiency regulations, heavy subsidy of renewables and purchase of international carbon market offsets over the past decade. With the enactment of new automobile mileage efficiency standards, most forecasts of United States' per capita energy use showed slow declines.[5] Due to the switch from traditional coal to less carbon-intensive natural gas as a fuel for electricity generation, the CO2 emissions from US electricity production were also falling as long as natural gas prices per BTU or EPA emission regulations kept utilities from switching back to coal.

While rich countries could afford to do whatever they wished to do, policymakers in poorer countries consistently made the trade-off in favor of the certain benefits of energy to their citizens today over the uncertain costs of global warming to their citizens in the future. Rising per capita consumer energy use of emerging economies contributed to a part of their growth in emissions, as did industrial and employment policies designed to encourage the relocation of energy-intensive industries from the West into the emerging economies. Emerging economies, particularly China and India, were carrying out their growth plans through ever expanding use of low-cost fossil fuel energy, primarily coal. From 2012 to 2016, China was expected to add 240GW, equivalent to 160 new coal-fired plants to its existing 620 coal-fired plants. During this time, India was expected to build over 46 new coal-fired plants.[6] As a result, Chinese and Indian CO2 emissions were rising rapidly and local air quality, particularly in Chinese population centers, was rapidly falling.

In response to ever growing citizen concerns about local air quality in major Chinese cities, 40 synthetic natural gas (SNG) plants were planned in China as of 2013 with a total capacity of 200 billion m^3 of SNG per year that exceeded China's total natural gas demand in 2012; the Chinese government had approved 9 of these plants with a total capacity of 37.1 billion m^3 per year.[7] SNG had life cycle GHG emissions of roughly 3-4 times that of conventional natural gas and once built the 9 Chinese SNG plants alone would contribute over 1% of global 2013 CO2 emissions every year.[8]

With a broader understanding of the multiple carbon cycles in the environment, the climate community now expected between 20% and 40% of annual CO2 emissions to have lifetimes in the atmosphere in the range of thousands of years before excess CO2 emissions were absorbed by the land and oceans.[9] **Exhibit 6** shows that at large concentrations of CO2 in the atmosphere, the mean lifetimes of CO2 are in the thousands of years with half-lives of about 1000 years.

Given the emerging appreciation of CO2 lifetimes and associated continuing impact on warming, climate scientists believed that it was for all practical purposes certain that sea level rise would continue centuries after 2100. Sea level rise was primarily affected by sea water volume expansion due to increases in global ocean heat content, and the new water created due to ice sheet melting. Studies had shown that reversing the thermal inertia behind the sea level rise due to the above factors took place at a centennial scale, requiring several decades to begin to register the effects even if world-wide carbon mitigation strategies could lower temperatures.[10]

A major study published by the Royal Society in 2009 concluded that "global efforts to reduce emissions have not yet been sufficiently successful to provide confidence that the reductions needed to avoid dangerous climate change will be achieved."[11] While the definition of "dangerous" was subject to much political and scientific debate, if the concentration of CO2 reached "dangerous" proportions, CO2 concentration remaining after mitigation efforts would remain high enough to negatively affect the climate patterns, weather extremes, ocean alkalinity and sea levels for centuries, if not millennia.

In all but the most rapid, world-wide carbon mitigation scenarios outlined in the IPCC report, mitigation alone would not be timely enough to prevent the global average temperatures from exceeding the 2 ºC limit, above which many scientists believed significant, irreversible effects from climate change would begin to occur. As MIT's Technology Review observed, "No one knows precisely how many tons of carbon will raise the temperature of the planet by 2 °C. And less warming than that could cause significant damage [to some eco-systems], while humans will probably survive higher levels."[12] Increasingly policymakers and scientists looked for ways to slow the growth of and eventually eliminate net CO2 emissions in order to contain the consequences of climate change, ocean acidification and sea-level rise.

Managing Net Carbon Dioxide Emissions

Given the difficulty of halting the accumulating CO2 emissions, several proposals for Carbon Dioxide Removal (CDR) were being considered by scientists and policymakers. Large-scale tree planting efforts or afforestation had many positive externalities in addition to removing atmospheric CO2, however, this offered a one-time benefit which more or less ended when the forest reached maturity after several decades, and required large areas of agriculturally productive land and water.[13] Other means of sequestering atmospheric CO2 into plant matter or biomass were possible with major land use commitments.

Agricultural or harvested biomass could be converted into biofuels and biochar, a form that could lock up carbon and prevent its return to the atmosphere. Other biomass related approaches focused on burning either plant material into biomass or growing biomass explicitly with the purpose of burning to generate energy and then capturing and storing the CO2 generated in the process to avoid introducing additional CO2 into the world's eco-system.

Oceanic approaches such as increasing ocean alkalinity and ocean fertilization also held promise. Ocean alkalinity could be increased by grinding large amounts of base ions that would react with acids to form neutral salts, thereby improving the ability of the oceans to absorb CO2 from the atmosphere.

Ocean fertilization involved increasing marine organism production in selected areas and drawing more CO2 away from the atmosphere in the process with subsequent deep sea sequestration when those organisms died and sank to the ocean abyss.

Geologic approaches mimicked weathering, injecting CO2 acidified waters that would react with subsurface minerals to capture and sequester the CO2. This was an anthropogenic variation of Mother Nature's tool of choice where mountain range weathering moved carbon through river run-off, then via shell-building organisms (largely plankton) settling to the deep ocean abyssal plain and inexorably down into the earth's mantle through subduction via plate tectonics.

The business case for Direct Air Capture (DAC) depended on a long-term need and society's willingness-to-pay for limiting atmospheric CO2.[e] DAC plants could be physically located far from the source of emissions, thus creating a path to capturing emissions using economically unproductive land for large-scale construction projects. However, few believed that mankind's problems from CO2 emissions would be solved by some futuristic fleet of DAC plants. The short and medium term business cases for most DAC technology ventures were focused on the economic value of producing industrial-grade CO2 on a capture site-specific, a market use-specific and regulatory regime-specific basis.

Evolving Regulatory Regime on Carbon Emissions

The important drivers of climate change policy were the United States, China, and the EU due to the magnitude of their CO2 emissions and the political power at their disposal to establish (or block) international agreements. Additionally, within the US, California had historically been the vanguard of environmental policy and, due to the purchasing power of the California consumer markets subject to California regulations, often set 'de facto' U.S. national standards which were often adopted by product manufacturers and public utilities serving other U.S. markets.

Global Warming Solutions Act of 2006

The California legislature enacted Assembly Bill 32 (AB32), the Global Warming Solutions Act of 2006, wherein the legislature found that "global warming poses a serious threat to the economic well-being, public health, natural resources, and the environment of California." New regulation adopted in California pursuant to AB32 began using a more comprehensive definition of carbon intensity of fuels. The life cycle carbon intensity measured the net flow of CO2 to the atmosphere over the production, refinement, and use phases of the fuel's life cycle. If CO2 were used to produce the fuel, for instance, by using enhanced oil recovery (EOR), the life cycle emissions of the fuel traced the origin of CO2 used to produce the fuel. If the CO2 were mined from the ground as was common, EOR would pump this mined CO2 back underground to produce oil, and the life cycle carbon intensity of the fuel remain unchanged. If however, the CO2 were captured from the air, EOR would remove this CO2 from the atmosphere in the process of extracting the oil, yielding a negative offset to the life cycle carbon

[e] Economists had many competing models to quantify the social cost of the damages caused by CO2 emissions. There was much debate on both the logic and the techniques for estimating these social costs. The U.S. Interagency Working Group on Social Cost of Carbon in May 2013 estimated that the average social cost of carbon due to climate change would be $12–65 per additional ton of CO2 emitted in 2020, and continue to increase in the future. Harvard economist Martin L. Weitzman discussed a conceptual method for evaluating the social cost of carbon depending on the uncertainty of damages caused by carbon and the ways in which one might value insuring against the costs of outlier climate change events with "incalculable" consequences and irreversible outcomes. Weitzman's method showed a social cost of carbon that ranged from $1-266 per ton. Costs in both papers are expressed in 2007 U.S. dollars per metric ton of CO2.

intensity of the fuels produced from the oil. See **Exhibit 7** for the life cycle fossil carbon intensity of different transportation fuels.

California Low Carbon Fuel Standard (LCFS)

A California Electric Transportation Coalition (CalETC) report stated, "Adopted in 2007, California's Low Carbon Fuel Standard requires a 10 percent reduction in the carbon intensity of transportation fuels by 2020, as measured on a lifecycle basis. The goals of the program are to reduce greenhouse gas emissions from the transportation sector, diversify the transportation fuels sector, and to spur investment and innovation in lower carbon fuels."[14]

Fuels that had lower carbon intensities than gasoline or diesel generated LCFS credits and the ceiling on maximum allowed carbon intensity would be progressively lowered through 2020. **Exhibit 8** shows that the LCFS credit surplus had dwindled, and the associated credit price had increased, as the carbon intensity ceiling was lowered over the past two years. The CalETC report described the manner in which regulated parties selling fuels with higher carbon intensities than the regulatory ceiling, such as refiners and distributors, had "the option of producing or blending low carbon fuels, or purchasing credits from other fuel providers, including, but not limited to biofuel producers, natural gas infrastructure providers, electric utilities, and hydrogen producers."[15]

While the California LCFS was already up and running, legal and political risks affected whether or not the program would survive, and whether or not it would maintain its current form.

Legal Risks

In a recent opinion published on September 18, 2013, the U.S. Court of Appeals explained how California's LCFS regulation did not violate the U.S. Constitution's Commerce clause because the burden on out-of-state producers of ethanol was not "excessive" compared to the local benefit to California residents from strong climate change regulation.[16] Parties negatively affected by the LCFS were likely to continue submitting legal challenges to the regulators' interpretation of California legislation that enabled lower carbon fuels to compete in California. While LCFS proponents won the battle in court in San Francisco, it was not clear who would win the legal war that was likely to ensue.

Political Risks

The citizens of California had supported AB32 at the polls despite intense outside funding of political groups that opposed the bill. Proposition 23, an attempt to repeal AB32, was a California ballot proposition that was on the November 2, 2010 California statewide ballot. The attempt to repeal was defeated by California voters during the statewide election by a 23% margin. California had often led the nation in new initiatives. Many in the state, in particular the state's Northern California voters and world-leading Silicon Valley venture capital community believed that this first-mover tradition gave real impetus to the formation of new ventures and subsequently new industries headquartered in California. Other groups, particularly those in California's more traditional industries and its Southern California voters saw their views captured by KTTV Vice-President and General Manager Kevin Hale who took the view that this "well-intentioned Climate Change bill might damage our (California's) economy beyond repair."[17] As the costs of California's clean energy programs became obvious to California voters and bondholders, the AB32 would face on-going challenges from its political opponents.

Competition in the Low Carbon Transportation Fuels Space

Transportation fuels developed using EOR driven by CO_2 from carbon capture processes, such as CCS and DAC, carried much lower carbon intensities than EOR using geologic sources of CO_2 (**Exhibit 1**). In addition to EOR, some players intended to use the captured CO_2 towards production of low carbon algal biofuels.

Point Source Capture and Storage

Point source capture of CO_2 from industrial and power plant flue gases was more commonly referred to as Carbon Capture and Storage (CCS). **Exhibit 9** shows the scale of CO_2 emissions generated by top emitting U.S. coal power plants. CO_2 captured using CCS was used primarily for EOR, which involved pumping the captured CO_2 into a low productivity underground oil reservoir to improve the efficiency of petroleum extraction. While extracting CO_2 from a flue gas would likely continue to be cheaper than direct air capture (DAC), CCS required an active CO_2 emitting industrial process and could only be built in a few places near EOR-capable oil reservoirs or CO_2 pipeline networks before CO_2 transportation costs became prohibitive.

CCS integrated with coal-fired plants yielded a cost of CO_2 avoided ranging from an estimated \$23 to \$92 per ton, and CCS integrated with natural gas ranged from an estimated \$67 to \$106 per ton of CO_2 avoided (no plants had been built yet).[18] A 2007 report from the National Energy Technology Laboratory (NETL) estimated that North America had enough geologic storage for 900 years' worth of CO_2 at current emission levels.[19]

In 2012, 75 large-scale integrated projects (LSIPs) existed globally at different stages between project identification and operation, of which 8 were operating and storing 23 million tons of CO_2 each year. Summit Power planned to build a 400 MW clean coal project called the Texas Clean Energy Project (TCEP) that would require an investment of \$3 billion and generate 2.5 million tons of CO_2 annually for EOR customers in the West Texas Permian Basin. Construction on the TCEP was scheduled to begin in 2013.

Direct Air Capture and Storage

While CO_2 captured from Direct Air Capture (DAC) could be used in the same way as that from CCS, the main difference was that DAC captured CO_2 from the atmosphere instead of a point source. Due to the low concentration of CO_2 in the atmosphere relative to point sources, the cost of capturing CO_2 using DAC was likely higher than CCS. However, DAC did not require a point source of flue gas containing CO_2 emissions and plants could be built near an oil field, minimizing the need to convey the captured CO_2 over long distances. In addition to Carbon Engineering, several players had achieved varying degrees of success in achieving technical milestones but no player had yet achieved commercial scale.

ClimeWorks based in Zurich, Switzerland, had pursued a solid based adsorption/desorption process, which was attractive because much of the energy demand (roughly equal to CE's system) could be taken as low-grade heat. However, the ClimeWorks system suffered from lack of industrial precedent and experience, and there was currently no supply chain or industrial-scale manufacturing for their core adsorption material.

Global Thermostat (GT) was developing DAC technology that used low-cost industrial process heat to power CO_2 capture from the air. GT was founded by Graciela Chichilnisky, who created the Kyoto Protocol's carbon market, and Peter Eisenberger, who founded the Earth Institute at Columbia

University. GT had completed the development of a pilot plant in California, partnered with an algae producer that would use the captured CO2, and was reported as revenue positive. Emerging EU aviation fuel standards were establishing demand for algae-based aviation biofuels.[20]

Kilimanjaro Energy was founded in 2010 by two Columbia University scientists, Klaus Lackner and Allen Wright, to develop materials and prototypes for capturing atmospheric CO2.[21] Boeing Phantom Works were also developing DAC technologies but had recently decided to shift focus toward different objectives.

The Case for Carbon Engineering

While in the long run DAC could mitigate emissions "after-the-fact" regardless of source, the current market for the technology was in helping energy companies deliver much lower carbon intensity transportation fuels. CO2 emissions from transportation were difficult to capture as they were distributed across road vehicles, marine transport, and aircraft. While electric vehicles (EVs) were less carbon intensive than vehicles powered by traditional liquid fuels, CE did not expect that EVs would proliferate rapidly through the entire transportation ecosystem in the next decade. Keith spoke about why transportation would be a difficult part of the economy to decarbonize:

> Liquid fuels are 40 MJ/kg, a fancy expensive battery is not even 1 MJ/kg. Some parts of the transportation infrastructure—buses and some cars—can convert to electric but for other parts—airplanes, heavy freight modes—I think that's an all but unbridgeable gap. We can produce synthetic fuels in the long run that are hydrocarbons but carbon-neutral hydrocarbons. We're making these fuels from primary energy, just the way people make electricity from primary energy, and they'd be an energy carrier that when used provide no net carbon. And I think that's a big deal because it's one of the ways we could decarbonize the transportation system in the 21st century.

The California Low Carbon Fuel Standard (LCFS) primary pathway that CE was considering involved developing Enhanced Oil Recovery (EOR) projects in the Permian Basin in West Texas to extract crude oil from water-saturated oil deposits and where CO2 supplies for EOR had been historically constrained. In addition to conventional EOR, production from Residual Oil Zones (ROZs) had increased between 2005 and 2012 and it was estimated that ROZs could generate as much oil as the entire production from the Permian Basin region to date. Production from ROZs involved many of the same techniques as EOR including CO2 injection.[22] These unproductive oil reservoirs could be pumped with industrial-grade CO2 captured by DAC. The resulting fuel products from this petroleum would have a much lower fossil carbon footprint than the regulated maximum in California, and thus have the ability to capture a premium priced in the California fuels market. See **Exhibit 10** for an assessment of the potential market for CE under different levels of LCFS adoption in the U.S.

Carbon Engineering had partnered with Seattle-based Summit Power, a project developer with expertise in carbon capture to build the FOAK. Summit was an energy project developer that differentiated itself by pioneering new technologies and specialized in coal gasification, carbon capture, EOR, utility-scale solar, and large wind projects. As of 2013, Summit had managed over $9 billion in investments into 9,250 MW of power in operating or late-stage projects.[23]

Sasha Mackler, VP of Carbon Capture at Summit Power, said about the market opportunity:

> We see reducing emissions from distributed sources in the transport sector, and satisfying demand for CO2 in EOR operations as markets for air capture today. DAC can help us be

strategic about increasing CO2 supply options for EOR operations, developing low-carbon transportation fuels (oils, algal, etc.), and possibly lowering development hurdles compared to a CCS project.

CE's First Business Model

By design, CE's DAC system could be located anywhere in the world, possibly where construction cost and permitting were advantageous, as long as there were a nearby low-cost energy source and a nearby demand for the DAC's CO2 output. The first CE installations planned to use oil field-produced natural gas to power the DAC system and to deliver the resulting DAC CO2 output to CO2 carrying pipeline networks that served EOR operators.

EOR-LCFS Revenues

The combustion of natural gas to power the DAC system itself produced 0.5 ton of CO2 and powered the DAC system to capture an additional 1 ton of CO2, producing a total of 1.5 tons of pipeline quality CO2 for every ton of CO2 captured from the air. In the CE EOR-LCFS business model, these 1.5 tons of CO2 were valued at between $15 and $60 by a typical West Texas EOR operator[24]. This 1.5 tons of CO2 produced 3-6 barrels of tertiary recovery oil, depending on the geology of the reservoir and the characteristics of that reservoir's crude oil.

DAC fuels had lower life-cycle carbon intensities than CCS-EOR fuels. The economics of CE's business depended on whether DAC would be accepted as an approved "pathway," (**Exhibit 11**) specific regulations for calculating the credits given for any fuel under the LCFS, and whether California voters would uphold the LCFS enabling legislation in the future. In the second quarter of 2013, the carbon credit generated by 1 ton of CO2 captured from the air was valued at between $40 and $60 by a petroleum products distributor in the California LCFS market (**Exhibit 8**).

This gave CE an average revenue of between $55 and $120 per ton of CO2 captured directly from the air under 2013 market conditions, but that revenue could change rapidly as the California LCFS percentage ratcheted up or as the demand for EOR CO2 rose with oil prices.

Technology Strategy and Costs

One of the major differentiating elements of CE's technology against competitors was that the underlying components and processes had been used in industry for several decades and were largely well understood. Keith observed:

> Our current process has nothing that's super high tech and sexy that you publish articles in Science and Nature... It's classic chemical engineering which allows us to go big in scale quickly. We have called this our 'Russian Tractor' technology.

CE's core technology used to perform direct air capture contained two main elements—an air contactor and a regeneration or recovery process. The air contactor, derived from cooling tower technology, ingested air and absorbed the constituent CO2 into a liquid solution. The recovery step, derived from a pulp and paper industry process, took the liquid solution containing CO2 as an input, and separated the CO2 as a pure stream at high pressure and industrial pipeline grade, while also regenerating the original capture solution. CE had developed and incorporated proprietary technology into both steps of the process for the largest achievable scale while also reducing energy use, capital expenditures, maintenance costs, and input costs.[25] CE protected this knowhow using patents and trade secrets.

CE had developed a closed-loop CO_2 capture process which meant that most of the operating inputs to the process were continuously recycled and regenerated within the process. However, the availability of a low cost energy source was critical to the economic viability of CE's business model. In the US, the business model assumed that the newly discovered shale gas resources would keep natural gas prices low for the foreseeable future. Keith pointed out about the risk of natural gas prices going up, "High natural gas prices—or more accurately a high natural gas-to-oil price ratio—is a threat to our business model. I do expect prices to go up as LNG markets start coupling US natural gas prices to overseas markets."[f]

Keith said:

> There are lots of risks, but the fundamental opportunity is the following. People around the world are spending now about $300 billion a year on clean energy. If you look across that space and you say what fraction of that $300 billion is actually being spent on things where 'cost of carbon emissions avoided' is higher than $150 a ton. The answer is: Most of it! And we're cheaper.

Racing against the learning curves of competing teams and technologies, CE believed its DAC system could easily capture CO_2 for $200 per ton, and at full scale with disciplined construction management and process improvement, CE's average costs might approach or even fall beneath $100 per ton (**Exhibit 4,** see Economics section at top of page 16).

The Path Forward

In a few months, Keith would hand over operations to Adrian Corless, the new CEO tasked with the goals of building CE's pilot and FOAK plants. The entire CE team confronted the reality of competing in a rapidly evolving marketplace for low carbon transportation fuels where the policy and the politics of carbon remained extremely uncertain.

However, on that sunny Calgary morning, Keith's problem was much more pressing. He thought about his conversation with Summit Power a few weeks earlier, when Mackler had told him about the risks that the pilot plant would have to resolve for CE to build their FOAK.

Mackler had asked many questions:

- **Performance**—Will the process work as described and deliver CO_2 at the right concentrations reliably? Can this work in a commercial context in terms of on-line times, quality of CO_2, reliability?
- **Energy use and efficiency**—Can DAC be efficient enough to compete with other CO_2 capture processes?
- **Cost of the facility**—Will the plant be built within costs that are financeable? Will it be cost-effective to run in the market conditions many years from today? Who will finance the FOAK?
- **Supplier relationships**—Will the technology providers buy into the CE concept?
- **Regulation**—Will CE get a validated fuel pathway from the California regulators so that the LCFS recognizes DAC and the products from this technology under its regime?

As he entered the meeting, Keith thought, "How in the world are we going to get this pilot plant built?"

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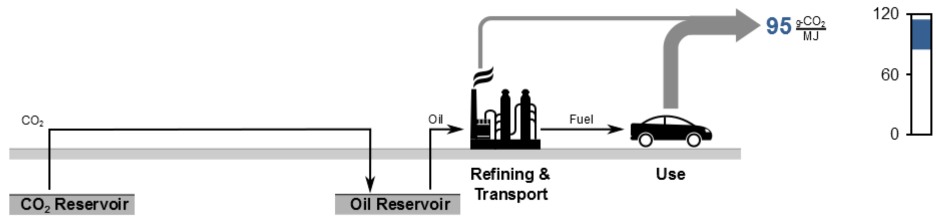
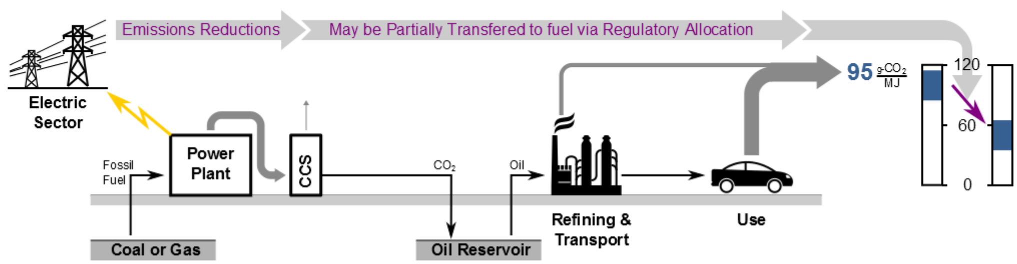
[f] The CE process consumed roughly 10 MMbtu (10 million BTUs) of natural gas for each ton of CO_2 captured. So a $1/MMbtu increase in gas price added $10/ton to the capture cost. In most oil & gas industry usage, M meant 1000, equivalent to the metric unit K.

Exhibit 1 Life Cycle Fossil Carbon Intensity of EOR-based Transportation Fuels

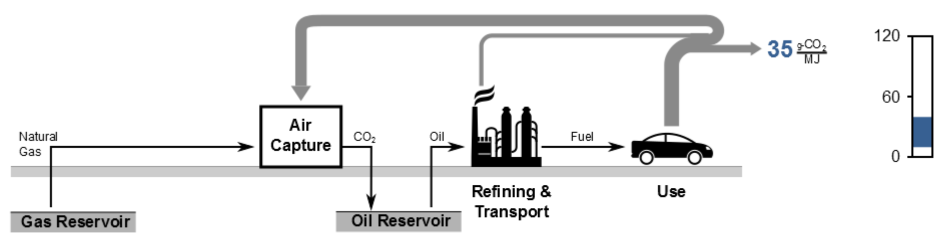
a. EOR using Geologic CO2 (Current Fuels - 95 gCO2/MJ)
CO2 is extracted from an underground source and sequestered again in an oil reservoir for no net CO2 offset for new fuel produced



b. EOR using Carbon Capture and Storage (CCS Fuels - 95 to 65 gCO2/MJ)
CO2 from fossil fuel burnt in a power plant is sequestered, and the benefits of the CO2 removed by injecting the CO2 underground using EOR are partially allocated to the electricity produced by power plant and to the transportation fuel produced



c. EOR using Direct Air Capture (DAC Fuels – 35 gCO2/MJ)
Sequesters CO2 emissions from transportation fuels produced using CO2-EOR oil



DAC economics depend on the market price of a carbon-offsetting fuel and the ratio of the oil price (output) to the natural gas price (input).

Methodology: When geologic CO2 is extracted and pumped back into an oil reservoir, no net CO2 is removed from the atmosphere. The fuels derived from coal-fired CCS allow a net quantity of CO2, and with natural-gas fired DAC an even larger net quantity of CO2, to be stored indefinitely in the oil reservoir from which the oil is extracted, thus removing CO2 from the atmosphere and lowering the carbon intensity of the oil output.

Source: Company documents.

Exhibit 2a Carbon Engineering Team in Mid-2011

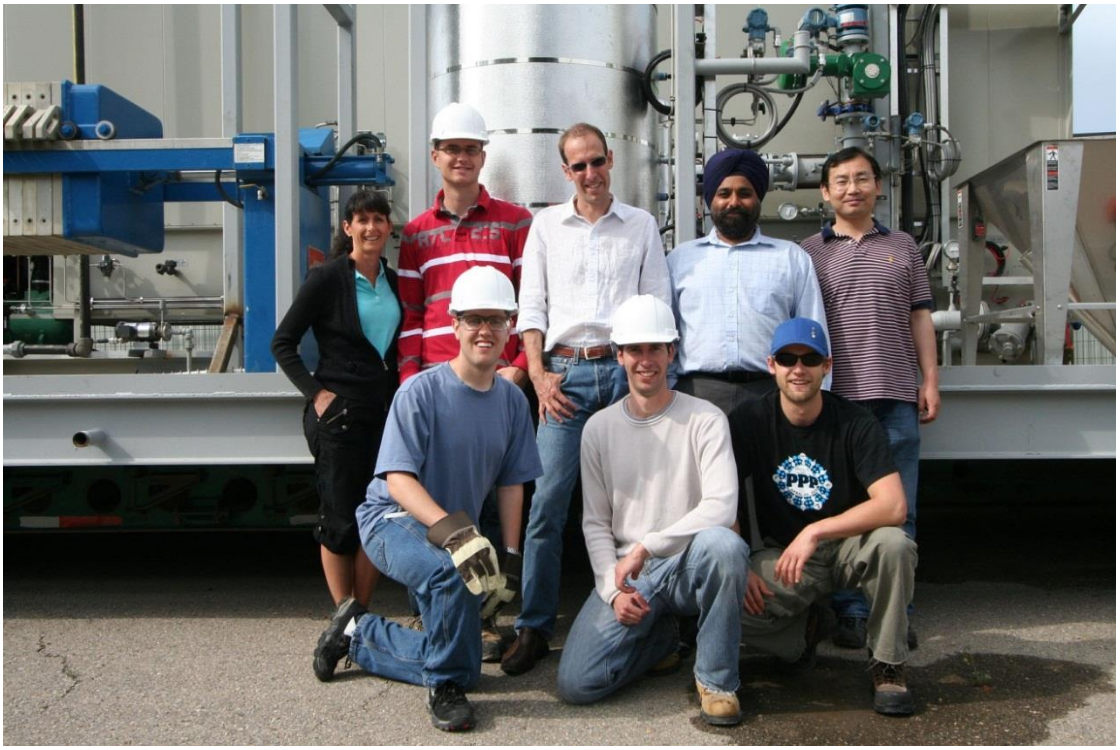


Exhibit 2b Computer-Generated View of an Industrial-Scale DAC Plant

This industrial-scale FOAK plant is 20m high, 200m long, and 7m deep, and has a capacity of 100,000 tons of CO2 per year (equivalent to annual CO2 emissions of approx. 20,000 average U.S. passenger vehicles)

Source: Company documents.

Exhibit 3 Carbon Engineering Management and Directors' Bios

David Keith, PhD *Executive Chairman*	David, who has led Carbon Engineering since 2009, has worked at the interface of climate science, energy technology and public policy for 20 years. As a technology developer and innovator, he built a high-accuracy infrared spectrometer for NASA's ER-2 and developed new methods for reservoir engineering to increase the safety of stored CO2. David took first prize in Canada's national physics prize exam, won MIT's prize for excellence in experimental physics, was listed as one of TIME magazine's Heroes of the Environment 2009.
Adrian Corless *CEO*	Adrian had most recently served as CTO at Plug Power and at Cellex, where he led technology development of commercial-scale fuel cell products. He holds a Masters of Applied Science degree in Mechanical Engineering from the University of Victoria.
Arvinder Singh, PhD *CTO*	Arvinder has more than 13 years of corporate R&D experience with an emphasis on technology development and commercialization. He has a PhD in Chemical Engineering from McGill University in Montreal, Canada, and an MBA in International Business from Marquette University in Milwaukee, USA. Arvinder has four patents issued, and over a dozen in application. At CE, he manages technology development and directs operations.
Kenton Heidel *R&D Engineer*	Kenton worked as an engineer-in-training at both oil-and-gas EPC firms and manufacturers, in both cases assisting in new product development. After graduating in 2008 from the University of Calgary with a BSc in Mechanical Engineering, he was hired by David Keith to assist with the air capture project that was presented on the Discovery Channel program, Project Earth. At CE, he advises on the design of experiments, equipment and processes.
Geoffrey Holmes *Research Scientist & PR Manager*	Geoff has won research awards for arctic field work in auroral physics and for analysis of energy system economics. He held NSERC's top-tier Canada Graduate Scholarship for his MSc, and received an Innovation Challenge Prize for applying his research to the commercialization of air capture. Geoff's previous work in outdoor leadership led him to four continents before he was drawn to CE by the chance to work on this unique environmental technology. He now designs and tests CE's air contacting systems, and manages CE's PR efforts.
Kevin Nold *Process Engineer*	Kevin recently graduated from a cooperative education program at the University of Waterloo, where he obtained a Bachelors of Applied Science in Chemical Engineering with an Option in Management Sciences. At CE, he performs process modeling and design for different stages of development.
Jane Ritchie *Process Development Engineer*	Jane received her M.Sc. and B.Sc. in Chemical Engineering from the Schulich School of Engineering in Calgary, Alberta. Jane graduated with Distinction, held NSERC's Post-Graduate Scholarship for her M.Sc. work, and has over five years of experience in the engineering, procurement, and construction field. Jane's valuable experience in both "front end" and "detailed" design stages of petroleum facilities, as well as her strong research background, help her excel as CE's lead process development engineer.
Hollie Roberts *Office Manager*	Hollie has worked with David Keith since 2007, as his Executive Assistant at the University of Calgary. She manages the day-to-day office operations of CE, including human resources, purchasing and accounting.
Jabe Blumenthal *Board Member*	A Seattle native and resident, Jabe graduated from Yale in 1982 with a degree in Applied Mathematics and went to work for Microsoft, designing the first version of Excel and becoming the company's first Program Manager. In 1994 he left Microsoft to teach mathematics and physics at his alma-mater, Lakeside High School in Seattle, where he was the Head of the Science Department until the end of the 2003 school year. Since then he has since focused on climate and energy policy advocacy work, in the Pacific Northwest and nationally, and is the board co-chair of Climate Solutions.
Denis Connor *Board Member*	Denis is an electrical engineer who started his career at Bell Labs and then moved on to MDA. He was President of the Science Council of BC from 1988 to 1990. He was the founding Chief Executive Officer and President of QuestAir, which merged with Xebec in early 2009. He has been a leader in numerous Canadian green-tech start-ups, including General Fusion, and advises the Canadian Department of Foreign Affairs and International Trade on their support of renewable energy technology companies.
Laurie Pare *Board Member*	Laurie Pare is a chartered accountant and a former partner of Price Waterhouse Coopers LLP. He is a director of Jovian Capital Corporation and is a financial consultant for one of CE's largest investors.

Source: Company website.

Exhibit 4 A Proposal to Bill Gates (Early 2009)

Carbon Engineering: Developing Air Capture Technology

Large-scale technologies for capturing CO_2 directly from the air would fill a crucial hole in the toolbox of carbon-climate technologies. Air capture breaks the link between emission source and capture technology; it enables carbon-neutral hydrocarbon fuels, and in the long-run, it enables negative emissions as a tool to manage global climate risks.

Capturing CO_2 from the air at a concentration of 0.04% might seem absurd when it is hard to finance capture from power plants where CO_2 concentrations are greater than 10%. But physics and thermodynamics tells us that air capture should be feasible; and, economics tells us that there is surprising value in the freedom to build a capture plant where it's cheapest—rather than retrofitting existing facilities—and near the best sequestration sites. Air capture also opens the option to apply industrial economies of scale to a myriad small and hard-to-control CO_2 emitters such as vehicles and home furnaces.

We are working to turn theory into engineering reality using a conservative design built on a novel application of commercial gas scrubbing technology and a low-energy chemical process derived from the pulp and paper industry.

This business plan provides a pathway for developing an air capture technology based around a scalable low-risk process-chemistry. The next major development step is a 4-5 $m CDN three-year research and development effort that grows from its university-based roots to encompass work by contract engineering firms (for cost estimation) and the construction of a research-scale pilot plant (to test the end-to-end process).

The path to commercializing novel large-scale energy technologies is very long, and even under the most optimistic scenario, commercialization would only begin in earnest at the end of this three-year R&D phase. The work is therefore structured around a new low-overhead company called *Carbon Engineering* that will focus on directed research with little of the outreach and marketing associated with a typical startup. This structure will (a) facilitate collaborative technology development agreements with suppliers, (b) incent employees via ownership, (c) enable us to tap government funds aimed a green-tech startups, (d) consolidate IP for further development; and finally (e) enable us to blend financing from philanthropic sources, patient Angel investors and governments.

Air capture has been largely ignored by the mainstream energy engineering community, in part due to over-hype by some early innovators and because developers have ignored the power of carbon arbitrage: an air capture plant build in China where costs are low might—by legal agreement—scrub CO_2 from the most regulated hard-to-manage emitters where carbon costs are highest.

Our work is, in part, driven by the idealistic conviction that the best way to accelerate innovation on advanced climate technologies, such as air capture, is to design a system which is widely seen to be credible. Even if it is not economic today, a credible benchmark design will drive innovation by others. We want our technology to win, but we know we can also win by encouraging smart engineers to look at our design and say, "I can do better."

Our goal is to design industrial plants that can capture megatons a year of CO_2 out of the air for less than $100 per ton CO_2. Our three-year development pathway will take us a huge step closer to understanding the costs and technical risks of our process. If we can meet this goal, both the environmental and financial rewards may be very large.

Technology

We are designing air capture systems using low-cost conventional materials and chemical-processes in order to *maximize scalability* and *minimize technical risk*.

CORE TECHNOLOGY: Our technology captures CO_2 from air using strong NaOH solutions in a *contactor* and then recovers CO_2 and regenerates fresh NaOH from the CO_2-rich solution in the *caustic recovery* process.

- Our contactor design is an intermittently-wetted (to cut fluid pumping costs) structured packing housed in novel cross-flow contactor geometry (to minimize capital cost).
- The titanate caustic recovery process is adapted from technology developed for the paper industry. The titanate process uses half the energy of calcium-based process previously considered for air capture. Amazingly, the heat requirement is roughly equal to that for the Amine processes now used for capture from power plants (although we required much higher temperatures).
- Rather than designing exotic capture materials that promise low-energy capture, our designs aim to minimize capital costs which tend to drive overall capture cost.

- CO_2 capture from air with NaOH was commercialized in the 1950's. While energy costs are high, it is very low risk, highly scalable and enables the design of large-scale contactors with low capital and operating costs.
- The lower technical risk of capture and titanate-based NaOH recovery helps assure operation at or near design rates, spreading the fixed costs over a larger "product" volume.

ECONOMICS: A serious end-to-end cost estimate requires an integrated process model and a suite of process unit studies subcontracted to engineering design firms. While we are about 18 months from a full cost estimate, early scaling studies suggest we have a chance to get under 100 \$/ton-CO_2.

- Results from a 5m-tall prototype contactor shows energy cost <100 kWhr/ton-CO2 at capture rates >20 ton-CO2/year, and initial costing suggest that capital, energy and O&M costs for the capture step could be <30 \$/ton-CO2.
- Heat inputs for the titanate process are about 5-8 GJ/ton-CO2 so operating costs could be under 30 \$/ton-CO2 for natural gas which is the most expensive fuel. Developing capital costs estimates will be a focus of Phase 2 development.

Competitors

- *Lackner/GRT, www.grestech.com*. Klaus Lackner pioneered modern work on air capture. GRT technology was funded by Gary Comer (Land's End) to develop Klaus' technology. They have pursued many different pathways including a solid sodium carbonate system, electrochemical methods and, most recently, an ion exchange membrane with humidity swing absorption. It is very hard to judge the technology status [redacted] Because current technology produces CO_2 enriched air rather than pure CO_2, it seems most likely to succeed in small-scale applications like greenhouses or as a pretreatment algae biofuel production.
- *Eisenberger/Global Thermostat*. Peter Eisenberger is using solid amine technologies that are being developed by the US Department of Energy for CO_2 capture from power plants. The air capture application depends on the use of low-cost heat within industrial facilities. Peter's competitive advantage derives from his former senior role at Exxon Research and his leveraging of people and research there. [redacted] it's hard to assess how good the underlying technology is. Success will depend on the ability to manufacture the very high technology coatings at low capital cost and to have them operate for long durations in air without contamination.
- *Trachtenberg/Carbozyme, www.carbozyme.us*. Trachtenberg has focused on the application of carbonic anhydrase, the natural enzyme that speeds the reaction of CO_2 with water, to develop CO_2 selective membranes. They worked on air capture but now seem to be focusing on power plant capture and do not seem to have a clear competitive route to air capture because of the very high capital cost of the membrane/enzyme systems.
- *Livermore*. A group at Livermore National Lab is developing nonbiological catalysts that mimic the effect of carbonic anhydrase. The clever trick is that these catalysts offer much greater stability and tolerance for harsh chemical environments than carbonic anhydrase and they can afford to be less effective. Summary: a promising idea in its early stages. Livermore is not developing contactor designs and we have discussed applying our contactor design technology to their chemistry if their chemistry can be commercialized.

SWOT Analysis

Strengths

- Strong and motivated team.
- "Russian tractor" technology that is built on conventional chemical processes without exotic materials and is highly scalable. No unobtainium required!
- Technology can be more quickly proved out at scale than is possible with competing methods.

Weaknesses

- Complex technology with many process steps that will only be cost-effective at large scales (> 100 kt-CO_2/year).
- Technology can only be economic at relatively large scale making entry into markets harder than for competitors since first commercial plants would cost more than \$100 million.

Opportunities

- Air capture enables a plant built in China with Chinese construction cost to effectively remove CO_2 from smokestacks or tailpipe in the most expensive and regulated markets in the world. Because carbon is evenly mixed in the world's atmosphere, air capture enables a form of arbitrage to take advantage of the enormous differences in capital costs and carbon prices around the world.
- Effective carbon prices over 100 $/ton are developing in tightly regulated markets that do not allow conventional offsets such as the emerging Low Carbon Fuel Standard or the European aviation regulations.
- At oil prices of 100 $/bbl, CO_2 can have a direct market value of 30-50 $/ton for use in Enhanced Oil Recovery (EOR). An air capture facility built to provide CO_2 to a high-value remote EOR opportunity could make revenue simultaneously from the CO_2 supply and from the production of carbon credits.

Threats

- Technical fixes required to make the titanate process work might add so much complexity that the whole process becomes uneconomic.
- Current CO_2 "offset" market prices are very low. While the carbon reductions associated with these offsets are largely fictional, they nevertheless are a threat to the market for "gold standard" CO_2 offsets based on the physical removal of carbon from the atmosphere and transfer to geologic storage.
- This technology will only be useful if carbon sequestration is accepted by the public and regulators; sequestration sites are actually developed and licensed and the regulatory structure allows financial credits for air capture systems perhaps located in countries other than the credit buyer's.

Technology Development Pathway

PHASE 1: CONCEPTUAL DESIGN: COMPLETED FALL 2008

Lab and small prototype scale experiments in an academic environment. Work began at Carnegie Mellon University in 2004. We constructed two prototype contactors (each 6-8 m tall) using different designs in 2005 and 2008.

- Results from the 2008 prototype and from laboratory and chemical process modeling on the titanate process suggest that costs under 100 $/ton are possible motivating the transition to Phase 2.
- Provisional patents filed on the contactor design and on the specific pathway for applying the titanate chemistry to air capture.
- Costs to date: ~0.7 $m.

PHASE 2: PROCESS DESIGN AND TESTING: STARTING DECEMBER 2008

This phase goes from the current conceptual design to a full end-to-end chemical process design and a small-scale pilot plant. The overall goals for of the 3-year work plan are:

- An end-to-end process design.
    - A thoroughly documented and tested chemical process model, including sensitivity studies on the major variables.
    - Design studies for each process unit with major assumptions and uncertainties clearly documented.
- Overall process CO_2 capture cost estimated to ± 50%.
    - Note: while ± 50% might seem a wide margin, it is surprisingly hard to hit given uncertainties in process design, construction costs and fuel prices.
    - Capital cost estimate for the proposed plant.
    - Operating cost breakdown.
    - Major cost drivers and their uncertainties clearly identified.
- Major technical risks identified and assessed.

- An operating pilot plant
  - Capture rate 20-30 tons-CO_2/yr
  - Continuous testing of full caustic recovery cycle.

Projected Cost for Phase 2 are 5-7 $m (CDN) over three years starting July 2009.

- Work based at U-Calgary with funding flowing through a simple low-overhead company structure in order to facilitate subcontracting, incent employees via ownership and to consolidate IP for further development.
  - U-Calgary office space, lab space and analytical equipment used wherever possible; engineering student labor used for pilot plant construction.
- Cost breakdown:
  - Salaries, benefits and U-Calgary overhead: 50%.
  - Travel, equipment and supplies (except pilot plant): 5%
  - Contract engineering: 15%
  - Pilot plant: 20%
  - Business costs including management and IP protection: 10%
- Funding plan
  - We have 1 $m (CDN) in hand from a philanthropic source. If we raise 2-3 $m of Angel funding we expect to get a ~50% match from the Alberta government to bring total funds to the required 5-7 $m (CDN).

THREE SCENARIOS AT END OF PHASE 2

1. Failure

- Example: fatal flaw in the titanate process & no path to market for contactor.
- Path forward: dissolve company for negligible salvage value.

2. Partial Success

- Example 1: fatal flaw in the titanate process & successful development of a contactor design of significant value to competitors developing air capture with alternate chemistry.
- Example 2: titanate process technology valuable for to pulp and paper.
- Path forward: reorganize company around most successful option and license IP or sell company.
- Even partial success will drive attention and funding for air capture research.

3. Success

- Process design study and pilot plant experience suggest that commercial facility could be designed at costs under $100 per ton CO_2.
- Path forward: Move to Phase 3.

Note: there are many pathways forward beyond a successful Phase 2. The example here serves to illustrate one pathway and to suggest that a licensing route is a more likely route for this kind of large energy technology than direct construction of facilities by an expanded technology development company.

PHASE 3-A

Develop a commercial plant design for licensing.

- Technology development within a free-standing company.
- Funds needed of order 15 to 30 $m over about three years.
- Market and regulatory development.

PHASE 3-B

Construction and long-duration operation of a 100 kt-CO_2/yr (one-tenth scale) pilot plant. At this scale, a pilot plant is built to limit the fiscal and operation risk involved in constructing a full scale plant. Cost would be of order 50 $m over 2-4 years.

PHASE 4

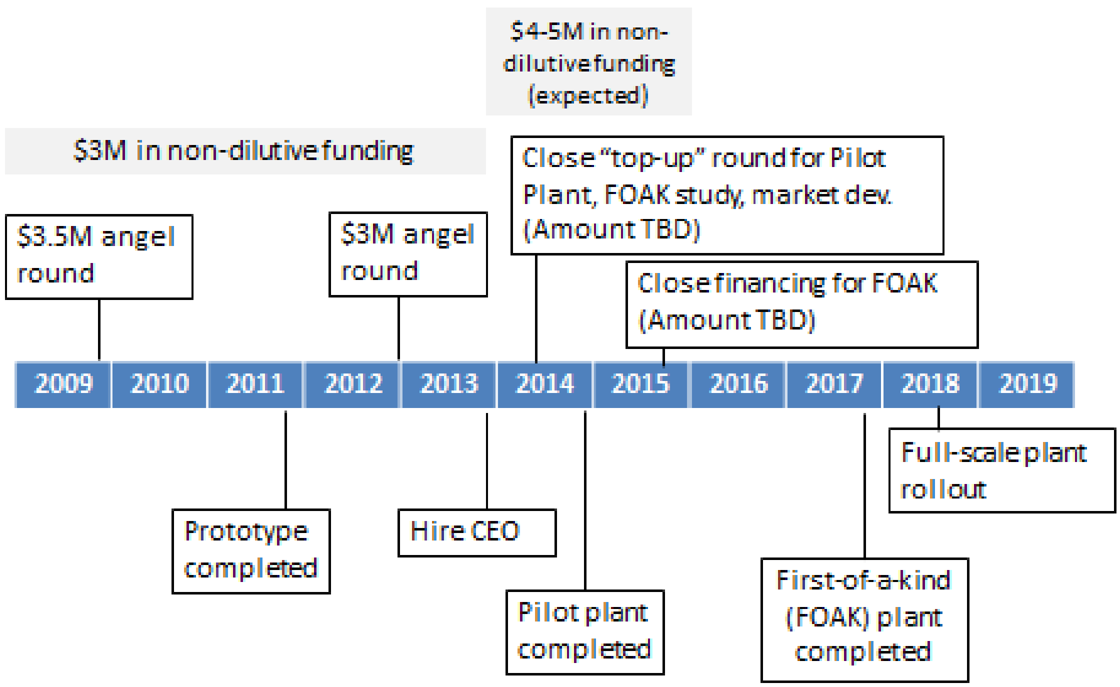
Commercial plants built under license to a major Engineering Procurement and Construction (EPC) firm.

People

- David Keith. A hands-on experimental physicist from an early age, David talked his way into Canada's major laser lab in Grade 11. As an undergraduate, he won Canada's national physics prize exam. As a graduate student at MIT he built the first interferometer for atoms and won MIT's biennial departmental prize for excellence. David gained experience with large-scale engineering projects working for Jim Anderson at Harvard, where he lead the development of a small satellite proposal and of a new high-accuracy radiometer that flew on the NASA ER-2 high-altitude aircraft, an engineering effort that entailed about 15 scientists and engineers along with many contractors, NASA pilots and engineers.
- Bob Cherry (PhD), Idaho National Laboratory. His thirty years of experience covers research, design, and startup of new energy and commodity chemical technologies for world-scale applications. He has worked for Exxon Research and Engineering, ARCO Chemical Co., Duke University, and now the Idaho National Laboratory, a US Department of Energy lab. Bob spent three months with our group in summer 2009 and continues to provide active technical and organizational leadership. We may recruit him to Calgary if Phase 2 is funded.
- The full-time air capture engineering team currently includes:
    - Maryam Mahmoudkhani PhD, a chemical engineer who comes from one of the top groups doing research for the pulp and paper industry.
    - Kenton Heidel, a mechanical engineer who worked as an undergraduate on the contactor experiments in 2005.
    - Jianjun Dai, a chemical engineer with a PhD from one of the world's best groups working on fluidized bed combustion at University of British Columbia and with extensive industrial experience with Sinopec in China.
    - Doug Brown, who graduated with top honors in chemistry from McGill.
- Mike Andrews, Formerly a senior partner at Ernst & Young, Mike now serves as a business manager and advisor to a number of Alberta based companies.
- Alessandro Biglioli, with 20 years of experience in technical startups from electronics to biomed to aerospace. An aerospace engineer by training he has experience in management, fund raising and University-based ventures.
- Oleh Hnatiuk, Connect Capital Corporation. Oleh was trained as a metallurgical engineer, became involved in business and ended up helping to create and lead Vencap an Alberta-based venture capital firm which managed almost $300 million of investment capital in the 1980's and 1990's, before serving as CEO of University Technologies International. He has also been President of an environmental technology company focused on the hydrocarbon energy industry.

Source: Company documents.

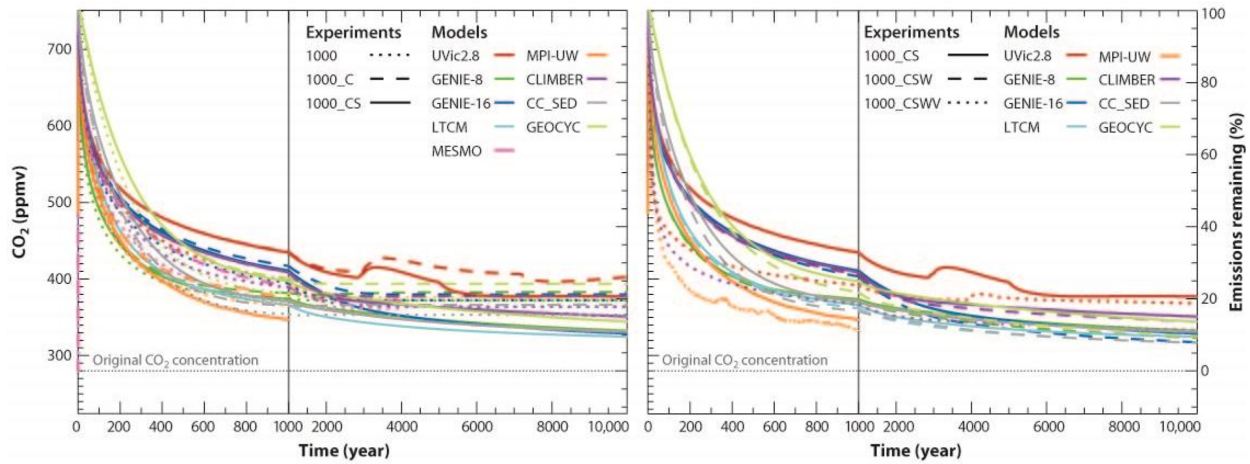
Exhibit 5 CE Timeline (as of September 2013)



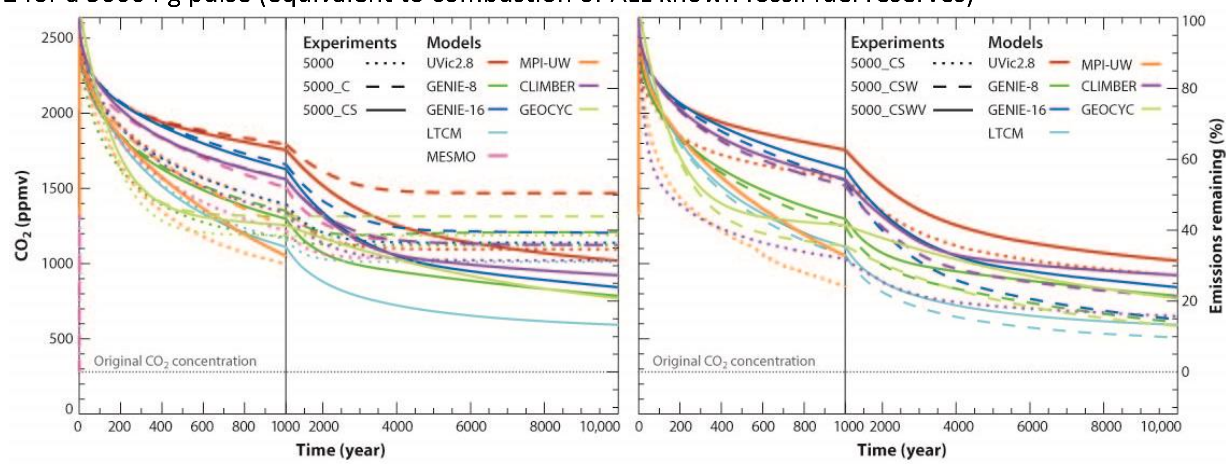
Source: Casewriter, company interviews.

Exhibit 6 Lifetime of Atmospheric CO2

a. Atmospheric CO2 for a 1000 Pg pulse (equivalent to cumulative carbon emissions within IPCC 1 trillion tons budget)



b. Atmospheric CO2 for a 5000 Pg pulse (equivalent to combustion of ALL known fossil fuel reserves)



Source: David Archer et al., "Atmospheric Lifetime of Fossil Fuel Carbon Dioxide," Annu. Rev. Earth Planet. Sci. 2009.37:117–134.

Exhibit 7 Comparison of Life Cycle Fossil Carbon Intensity of Fuels

Process	Life-cycle Fossil Carbon Intensity (gCO2e/ MJ)	Fuel cost ($/ Gasoline Gallon-equivalent)
Regular gasoline (contains 10% ethanol)	**~93-98[a]**	**$3.65[a]**
Ethanol from Corn	73 to 121	$4.57[f]
Algal Biodiesel	55 to 351	N/A
CCS-EOR	~72[b,c]	N/A
Compressed Natural Gas	68	$2.14
Ethanol from Brazilian Sugarcane	58	N/A
DAC-EOR	**35[c]**	**In Lab**
Biodiesel from corn oil, waste greases, and animal fats Renewable diesel from tallow Ethanol from molasses	< 35	$4.13
Electric Vehicles	~30[d]	$3.34-6.68 [g]
Cellulosic ethanol from farmed trees, forest waste	20-22	N/A
DAC-Hydrogenation	**0[e]**	**In Lab**

Source: Adapted from company documents, company interviews, California Air Resources Board, Energy & Environmental Science, California Energy Commission, U.S. Department of Energy, and Argonne National Laboratory data.

Notes:

[a] Assuming 10% ethanol blend, with carbon intensity of ethanol referring to "ethanol from corn." Price of gasoline refers to average retail price on July 29, 2013 according to EIA survey.

[b] Assuming the carbon sequestration benefits of CCS are allocated to electricity production (from where CO2 is captured) and to transportation fuel, proportional to the financial value of the energy products. Also, assumes that 90% of the CO2 emitted during electricity production is captured.

[c] Both CCS and DAC EOR carbon intensities are highly sensitive to the "lift ratio" i.e. the amount of oil produced per ton of CO2 injected into the oil reservoir.

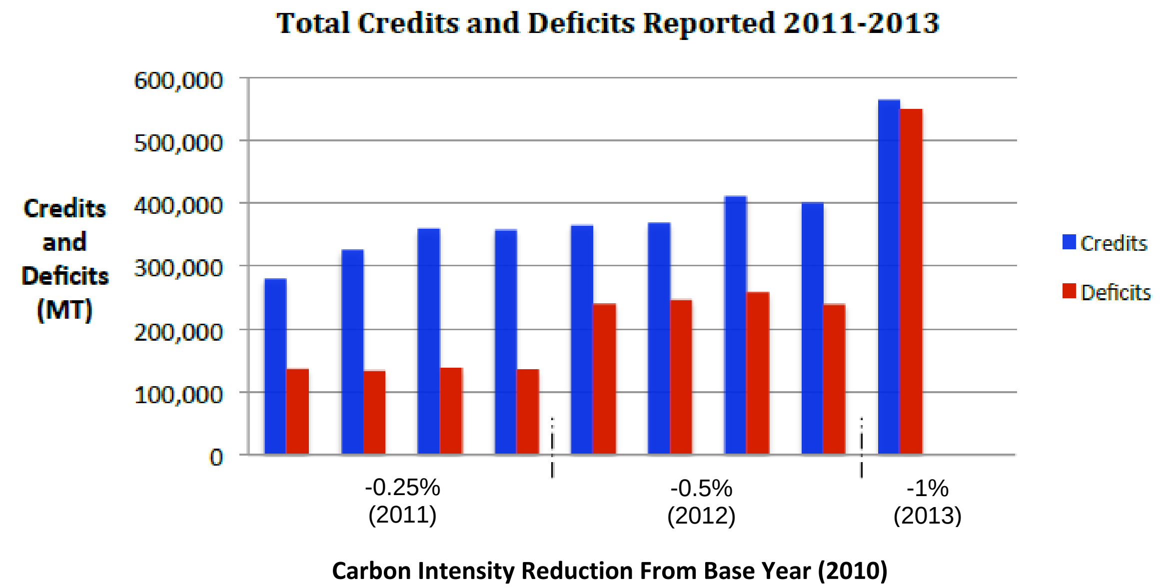
[d] Accounts for the increased energy efficiency of electric vehicles compared to gasoline-powered vehicles. Assumes carbon intensity of electricity in California, which may be higher or lower in other states.

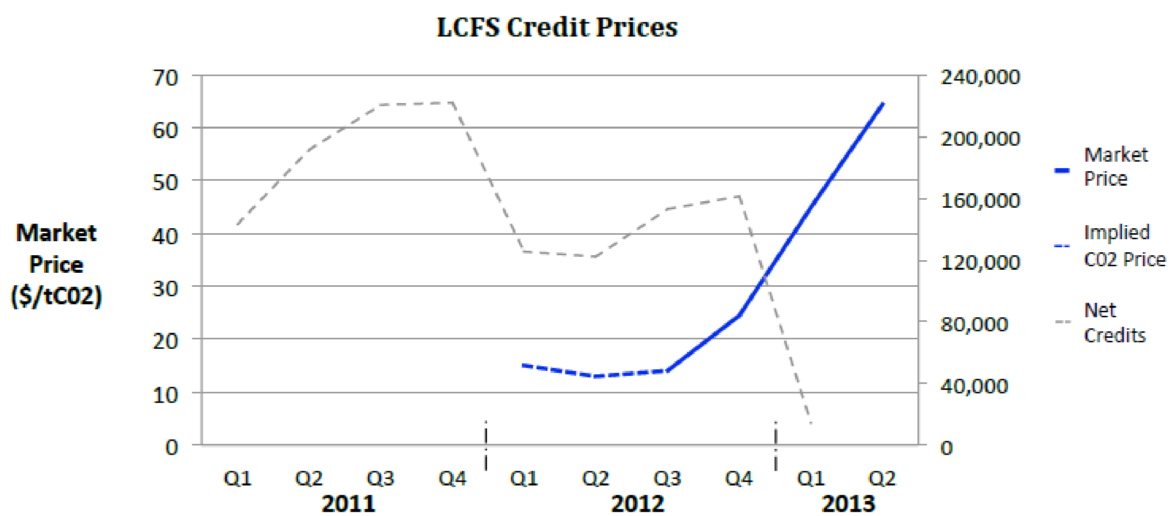
[e] DAC-Hydrogenation refers to combining CO2 obtained from DAC with hydrogen obtained from electrolysis, steam reforming even thermochemical cracking to produce a hydrocarbon fuel for transportation. If powered by carbon-neutral electricity, this process can produce a carbon-neutral fuel.

[f] Corn ethanol cost refers to national average of E85 fuel, a blend of 85% ethanol and 15% gasoline. Ethanol (E85) contains about 30% less energy (BTUs) per volume than gasoline. Flexible fuel vehicles (FFVs) operating on E85 do not experience a loss in operational performance, but may experience a 25-30% decrease in miles driven per gallon compared to operation on gasoline.

[g] 1 Gasoline Gallon Equivalent = 33.40 kWh of Electricity. Variation is due to range of electricity prices of $0.10-0.20 per kWh across geographies.

Exhibit 8 Market Structure and Pricing of California LCFS Credits





Source: Adapted from California Air Resources Board (CARB) data and Company documents.

Note: In the top chart, quarterly LCFS credits and deficits (generated when fuels lower or higher than the carbon intensity ceiling, respectively, are imported or produced) are shown. Reduction in the regulated carbon intensity ceiling below initial baseline is annotated on the x-axis. As the carbon intensity ceiling was further reduced each year, the surplus of credits over deficits was seen to dwindle. This credits surplus is plotted as a dashed line on the lower graph, and as supply dwindled, the price of credits in the LCFS market has risen. LCFS credit prices were not reported in 2011, were only back-calculated as an "implied CO2 price" from individual fuel trades in early 2012, and began to be explicitly reported in Q3 2012.

Exhibit 9 Emissions Equivalencies for Top U.S. Emitters of GHGs

	Total 2011 Emissions (million metric tons of CO2)	Percent of Total U.S. CO2 Emissions	Percent of Global CO2 Emissions from Energy Use	These Plants Produce CO2 Greater Than or Equivalent To . . .
Top Emitting Plant (Scherer Power Plant, GA)	21	0.4%	0.1%	• The total energy related emissions of Maine • The pollution produced by electricity use in all New England homes in a year
Top 10 Emitting Power Plants	179	3.4%	0.5%	• Total emissions of all the passenger vehicles in New York and California • The total energy-related emissions of Venezuela
Top 50 Emitting Power Plants	656	12.4%	2.0%	• Half the emissions of all passenger vehicles in the United States • The total energy-related emissions of Texas
Top 100 Emitting Power Plants	1,052	19.9%	3.2%	• The emissions of all passenger vehicles in the United States • The emissions produced by electricity use in all U.S. homes in a year

Source: Adapted from Environment America Research & Policy Center, *America's Dirtiest Power Plants* (September 2013).

Exhibit 10 Market Size

Scenario A:

- California LCFS Only. Petroleum Demand (D_O) = 957 M bbl/yr.
- Biofuels, electric vehicles, and DAC each take one-third of the market for emissions reductions in transportation sector, CE takes the entire DAC share. MS_{CE} = 33%.

Scenario B:

- US Nation-wide LCFS. Petroleum Demand (D_O) = 7300 M bbl/yr.
- Biofuels take half, electric vehicles and DAC each take a quarter of the market for emissions reductions in transportation sector, CE takes a third of the DAC share due to other competitors entering this large market. MS_{CE} = 8%.

Scenario	Total Petroleum Demand (D_O)	Fraction Reduction Sought in Carbon Intensity	Percent Market Share for CE DAC (MS_{CE})	Volume of CO_2	Total Addressable Market Size
A	957 M bbl/yr	10%	33%	15 Mt/yr	$2.2 B/yr
B	7300 M bbl/yr	10%	8%	28 Mt/yr	$4.1 B/yr

Rationale: The market for DAC, much like the technology itself, is nascent and evolving. There was not yet a standard method to calculate the total addressable market for DAC facilities. Assessing the size of demand for low-carbon fuels – the first target market for DAC – and then estimating market share scenarios for DAC meeting part of that demand, two scenarios were developed, where a low-carbon fuels regulation (California only in the scenario A and Nation-wide in scenario B) seeks to reduce aggregate emissions from fuels by 10%. Market share for CE-DAC fuels was estimated to meet this demand. From this market share, the total amount of CO2 that CE-DAC facilities would have to supply was calculated, and multiplied by the revenue per ton-CO2 to estimate the value of the total addressable market.

Source: Company documents.

Exhibit 11 Approved LCFS Fuel Pathways with the Assessed Fossil Carbon Intensity

FACILITY NAME	FACILITY ADDRESS	COMPANY ID	FACILITY ID	FUEL PATHWAY CODE	CARBON INTENSITY (CI) VALUE (gCO2e/MJ)	FUEL PATHWAY DESCRIPTION	PHYSICAL PATHWAY CODE	PHYSICAL PATHWAY DESCRIPTION
Corn Ethanol								
Agri-Energy LLC	502 S. Walnut Avenue Luverne, MN 56156	4824	70086	ETHC004	98.40	Corn Ethanol - Midwest; Dry Mill; Dry DGS, NG	PHY02	By rail from U.S. to CA
Brazilian Sugarcane Ethanol								
Copersucar S.A. - Usina Barra Grande de Lençóis S.A.	Rod Marechal Rondon s/n, Km 289, Lençóis Paulista, SP, 18680-900 Brazil	3702	70412	ETHS002	58.40	Sugarcane Ethanol - Brazilian sugarcane with average production process, mechanized harvesting and electricity co-product credit	PHY13	By ocean tanker from Brazil through the Panama Canal to a port in California
				ETHS003	66.40	Sugarcane Ethanol - Brazilian sugarcane with average production process and electricity co-product credit		
Biodiesel								
Biodiesel of Las Vegas	5233 E El Campo Grande Ave N Las Vegas, NV 89115	5648	81267	BIOD004	18.72	Biodiesel - Conversion of waste oils (Used Cooking Oil) to biodiesel (fatty acid methyl esters - FAME) where "cooking" is required. Fuel produced in the Midwest	PHY08	By truck from U.S. to CA

The California Air Resources Board (CARB) provided steps to calculate the carbon intensity of a fuel:

Step 1: Calculate the number of megajoules (MJ) of energy in the fuel sold. *Gallons of fuel (gallon) X energy density (MJ/gallon) = Number of MJ (MJ)*

Step 2: Account for energy economy ratios (EER), if necessary. For example: EER for Electric Vehicles = 3. *Number of MJ from Step 1 (MJ) X EER value from table = Adjusted number of MJ (MJ)*

Step 3: Calculate the difference in the carbon intensity between the low carbon fuel standard and the fuel sold. *CI of standard (gCO2e/MJ) – CI of fuel sold (gCO2e/MJ) = CI difference (gCO2e/MJ)*

Step 4: Calculate the credits/deficits in grams of CO2 equivalent. *Number of MJ (MJ) X CI difference (gCO2e/MJ) = number of grams CO2e (gCO2e)*

Source: California Air Resources Board.

Endnotes

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