Carbon Engineering – Direct Air Capture Pilot Plant Demonstration

Final Outcomes Report – PUBLIC VERSION

CCEMC Project ID:	C110149
Principal Investigator:	Adrian Corless
CCEMC Project Advisor:	Vicki Lightbown
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1. Executive Summary

CCEMC has supported Carbon Engineering in a multi-year process to design, build, and operate the world's first industrial direct air capture pilot plant. Carbon Engineering is a Canadian company founded in 2009 by leading environmental scientist David Keith and backed by investors Bill Gates (Microsoft) and Murray Edwards (CNRL). CE's mission has been to develop and commercialize technology to capture industrial scale quantities of CO2 from atmospheric air.

Direct air capture (DAC) has the ability to complement traditional flue gas CCS, renewables, and energy efficiency to help accelerate the deep GHG emissions cuts that are needed to avoid dangerous climate risk. DAC can capture CO_2 from the atmosphere at any location world-wide where demand or storage for the CO2 are available. Further, DAC can help us to manage emissions from the multitude of diffuse and mobile sources – such as transportation – that can often prove costly or challenging to control at source. The primary means of achieving this are to use CO_2 produced by DAC to manufacture "low carbon crude" via enhanced oil recovery, or "carbon neutral hydrocarbons" by direct fuel synthesis. In either case, DAC can enable production of global-scale quantities of transportation fuels that are compatible with today's infrastructure and engines, don't suffer the land use and food security issues of biofuels, and are ultra-low carbon intensity on a life-cycle basis.

Prior to this project, Carbon Engineering had conducted thorough R&D on direct air capture, had completed process engineering and equipment/technology selection for an overall DAC process, and had formed industrial partnerships with key equipment vendors and technology providers. Further, between Carbon Engineering and partners, each of the 4 "unit operations" that comprise CE's overall DAC process had been prototyped and tested individually or in conjunction with another unit operation. What remained – and what has now been addressed by this project – was to bring all unit operations together, and to operate a fully end-to-end pilot plant of CE's process with representative equipment and at representative scale.

Over the 4 phases of this project, CE has now conducted the preliminary testing to enable design of this pilot, the design and engineering itself, fabrication, installation, and finally operation of a 1 tonne-CO_2/day pilot plant. CE's project represents several "firsts": the first CO_2 scrubber manufactured from cooling tower components, the first "Crystalactor®" pellet reactor[1] running in the ~1 M OH regime, the first oxy-fired limestone kiln, and of course, the first industrial demo plant of direct air capture.

Over the latter half of 2015 and early months of 2016, CE's engineering and operations teams commissioned and operated the pilot plant. The original goals of the pilot project were to operate equipment and study overall integration risk, and to obtain real-world performance data from each unit operation to augment process simulation and "on paper" engineering designs for CE's commercial scale DAC technology. CE has now accomplished both.

Each of the major unit operations has now achieved the originally intended performance metrics, and CE has conducted a detailed investigation and sampling campaign to eliminate integration risk. CE is now

[1] Crystalactor® is a registered trademark of Royal HaskoningDHV, used with permission.

continuing operation of the pilot plant for further optimization and stress testing beyond the scope of this project.

CE has now achieved the original aims of this project and is now working with technology partners to update and revise the engineering design for CE's commercial scale DAC technology. CE now has a strengthened position in the DAC field and CE's DAC technology is ready for commercial deployment. However, CE's original target market is temporarily unattainable; energy companies are unwilling to engage in EOR projects due to low oil price. In response to this, CE is shifting strategies to commercialize the DAC technology in an "air to fuels" deployment. This new strategy, and the air to fuels concept, is highlighted in the "Next Steps" section below.

Overall, CE has appreciated CCEMC's support for this project, has accrued significant technological achievements over its course, and has also raised the public profile of direct air capture through demonstration with real-world industrial hardware. We are confident that this project has advanced the state of direct air capture technology such that DAC is available as a mega-tonne scale GHG mitigation option should Alberta choose to deploy it.

2. Project Description

a. Introduction and Background

Carbon Engineering (CE) will enable production of ultra-low carbon-intensity fuels by deploying our proprietary CO_2 Direct Air Capture (DAC) technology within a decade. These fuels have lower life-cycle carbon-intensity than biofuels with less environmental impact on land and water use, and may provide a cheaper pathway to low-carbon transportation for the 21st century than electric vehicles, biofuels or hydrogen. DAC provides a strategic economic and environmental benefit to Canada's energy industry by enabling the production of these low carbon-intensity fuels.

CE's Direct Air Capture (DAC) technology scrubs CO_2 directly from atmospheric air using a scalable technology that binds together a set of proven industrial processes in a novel configuration using our unique IP. Our process is "closed-loop" in that it does not require significant chemical inputs. In a first step, the air contactor - derived from cooling tower technology - cheaply ingests air and absorbs the CO_2 into a liquid solution. The second step—derived from a pulp and paper industry process–separates the CO_2 as a pure stream at high pressure and industrial pipeline grade, while also regenerating the original capture solution. CE has developed and incorporated proprietary technology into both steps of the process that has increased our CO_2 capture efficiency while also reducing energy use, capital and operational costs. Energy for our system is provided by natural gas with no significant requirement for grid power, the half ton of CO_2 from gas combustion is also captured, so that 1.5 tonnes of pipeline quality CO_2 are delivered for every 1 tonne of CO_2 captured from the air.

While superficially similar, CCS and DAC will compete in different markets. The capital and operating costs for DAC are significantly higher than for CCS because CO_2 from the atmosphere is so much more dilute than the industrial flue gas streams used for CCS. However, use of atmospheric CO_2 enables production of products with low or zero-carbon intensity, products that command price premiums and which cannot be produced with CCS. Use of DAC CO_2 in a petroleum reservoir during the EOR production phase, for example, results in lower life-cycle carbon intensity than is possible using CCS-EOR and in fuels that command a price premium over conventionally produced oil. Credit prices for low carbon fuels are over \$100 /tonne-$CO2_e$ under California's Low Carbon Fuel Standard (LCFS). DAC fuel competes with low-carbon transportation fuels such as biofuels or batteries but does not compete with CCS from large fixed sources such as upgraders or power plants.

The progressive adoption of a low carbon fuel standard across the US and in Europe poses a direct economic challenge to Canada's oil sands production. If low-carbon fuel regulations - currently enforced in California - are extended across the US, Canada's high-carbon oil exports will face substantial and permanent discounting. We believe the ability to produce large quantities of commercially viable low carbon intensity fuels will provide a strategic component to the efforts of Canadian producers to reduce life-cycle emissions of oil exports. Life-cycle based regulations – already in place in California, and potentially spreading much further – will create an immense demand for low-carbon fuels, which currently have very few technical pathways for production.

Prior to this project, CE completed a 3-year technology development phase, which included detailed process engineering, heat and mass balances, cost estimation—by external engineering firms—along with prototyping and component testing for all of the major equipment. This project encompasses a development stage to design and build a pilot plant to be commissioned and operational by Q4 2014. Our 1 t-CO_2/day capacity pilot plant will demonstrate the integration of all the process components, and will test major equipment at the scale required for the vendors to design and build at full-scale. This is the size required by our equipment vendors to provide performance guarantees for the full scale commercial plant. This first ever fully integrated DAC Pilot will embody the innovation and IP developed by CE to date; we anticipate significant arising IP from process integration and equipment design. This pilot is a technical risk reduction project, with the principle outcomes of the project being to obtain vendor performance guarantees for major component blocks and to successfully demonstrate the fully integrated CE DAC technology. These are both critical steps for the next stage development of a subsequent 30-100 kt-CO_2/year commercial plant.

CE's DAC technology is scalable, with commercial plant capacities of up to a million tonnes CO_2 per year. DAC can address the growing demand for industrial CO_2 in the fuel-energy sector, principally CO_2 EOR and can enable production of ultra-low carbon-intensity fuels. DAC has a key role to play in enabling low carbon intensity fuels in a range of fuel production industries.

Started in 2009, Carbon Engineering is a Calgary-based company led by David Keith (Professor, School of Engineering and Applied Sciences, Harvard University). CE has been very successful at raising private funds, including from private investors Murray Edwards of CNRL and Bill Gates of Microsoft. Carbon Engineering has developed partnerships with key equipment suppliers Technip and Procorp (CE has now shifted the partnership to Royal HaskoningDHV, as will be explained. CE refers to Procorp in several instances within this document, which are retained for retro-active accuracy of what work was done and who was engaged.). CE's competition consists of roughly 5 DAC developers world-wide, though we are seen as the most technically and commercially credible, and the closest to executing an industrial scale pilot. CE is the only Canadian company developing DAC, and the only Canadian finalist in the global $25M Virgin Earth Challenge.

In summary, CE is a Canadian company developing homegrown IP and expertise that can be deployed globally to directly reduce emissions. CE has a unique proprietary direct air capture technology, and a commercialization pathway supported by strong consortia partners that leads to a viable business model in today's markets. We have had support for this project from CCEMC, SDTC, and IRAP, which greatly accelerated our deployment. Our direct air capture pilot plant has been a high profile project, and has generated significant media coverage. CE's direct air capture technology – now proven, can meet the demands of carbon-constrained fuels markets, and has the capacity to create millon-tonne-CO_2 per year emissions reductions in one of the more challenging and costly sectors of our economy.

b. Technology description

CE's "Pelletized Calcium" process is an adaptation of the Kraft caustic recovery process which is currently employed in most of the world's pulp & paper plants. The Kraft pulping process uses a hydroxide solution (commonly NaOH) to breakdown wood chips and form pulp. This reaction forms a carbonate solution (Na_2CO_3), which is then sent to the caustic recovery process, which uses calcium compounds in a 3-step cyclic loop to recover the original NaOH from Na_2CO_3 so the pulp mill operator doesn't have to purchase a continual supply of NaOH. The process is shown in Figure 1 below:

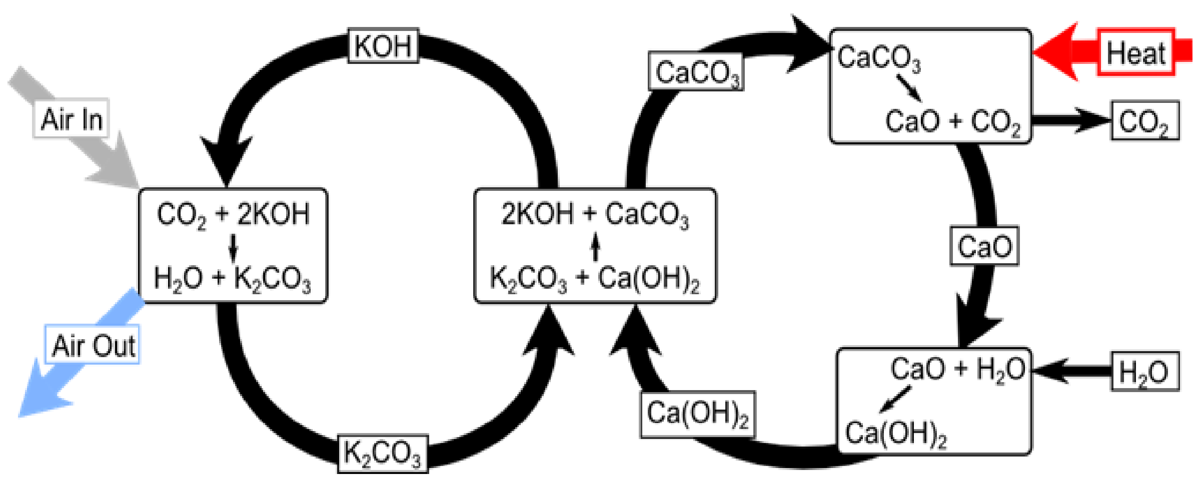

Figure 1: Chemical Loop of Kraft Caustic Recovery

The first step (called "causticization") uses hydrated lime, $Ca(OH)_2$), to convert the K_2CO_3 into KOH and forms a fine precipitate of limestone ($CaCO_3$) called lime mud. This lime mud must be separated from the liquid in large pressure filters. The liquid, which has been replenished in hydroxide, is sent to pulp more wood and the lime mud is sent to the second step ("calcination"). In calcination the lime mud is heated to above 900°C in an air-fired rotary kiln which releases CO_2 and forms lime (CaO). The final step in the loop ("slaking") submerges the lime in water where it reacts to form hydrated lime, which completes the loop.

c. Project Goals

CE's CCEMC project had one over-arching goal: to build the world's first direct air capture pilot plant, in order to reduce risk of the subsequent FOAK (First of a kind) commercial air capture plant. The size and configuration of the pilot Plant has been chosen to address the identified major risks at the lowest capital cost.

The pilot plant has several sub-goals:

- Test the cyclic closed-loop operation of our P-Ca process in order to identify operational issues and second-order risk factors that may arise from continuous operations, such as buildup of contaminants, and interactions between the major processing steps.
- Evaluate the three highest risk process components: the air contactor, the pellet reactor and the oxy-fired calciner, all under real process conditions.
- Demonstrate the technical feasibility and commercial viability of CE's DAC technology to potential end users and investors.

d. Work Scope Overview

Phase 1: Component Prototyping

Phase 1 focused on completing the engineering work and testing necessary to specify the process before detailed design and fabrication of the equipment could begin. Both the calciner and pellet reactor vendors needed to complete testing on our Process-specific feed streams before they can specify the design of equipment for the pilot. More detailed engineering of the commercial process was needed so that the pilot could be designed to adequately address the risks associated with a first of a kind commercial plant.

Milestone: Carbon Engineering has completed the requisite vendor testing and engineering to allow specification and design of each major pilot plant sub-system. CE has sub-system designs in hand, vendor support for the pilot built, and is ready to start detailed engineering and fabrication.

Phase 2: Pilot Engineering and Fabrication

This milestone included engineering the entire pilot. The process engineering for the pilot was conducted by the in-house engineering team. The pilot was designed such that each process step is a self-contained module such that connecting the utilities and process lines will make it fully operational. The air-contactor, pellet reactor, calciner and slaker were engineered and fabricated by their respective vendors and in some cases by CE. The washing, and make-up modules were engineered and fabricated by Carbon Engineering.

Milestone: Carbon Engineering has each pilot sub-system fabricated and skid-mounted at their respective locations of construction. CE is ready to ship the skids to the pilot facility location and begin integration.

Phase 3: Pilot Construction

This milestone included installation of the various process skids and ancillary buildings at the pilot site.

Milestone: Carbon Engineering has assembled the skids on the pilot plant site, and has obtained permission to begin start-up and operation.

Phase 4: Start-up and Operation

This milestone consisted of 3 tasks with the first two being preliminary testing and work before the pilot could be run continuously. The equipment was demonstrated to prove safe and adequate operation before integration with the system as a whole. Once fully operational the pilot ran to gather data with the aim of reducing the risk associated with building a commercial installation.

Milestone: Carbon Engineering has operated a fully-integrated direct air capture pilot facility, to produce and deliver pure CO_2 for 6 integrated months of run-time.

3. Outcomes and Learnings

a. Pilot Construction

Phase 3 of CE's project was the fabrication and install of CE's pilot plant equipment. The successes and achievements of this phase are best told in pictures. Refer to the panels below, which illustrate the construction and installation of CE's plant.


Figure 2: (clockwise from top left): Arrival of Pellet Reactor vessel. Early construction of the air contactor frame. Welding of the calciner vessel (seed addition and discharge area). And, first install of the PR vessel.

Figure 3 (clockwise from top left): Air contactor “substantial completion”. Early pellet reactor site assembly. Slaker install (there really is a slaker in there, you’ll just have to trust us). And calciner vessel fabrication progress.

Figure 4 (clockwise from top left): Air contactor completely installed. Pellet reactor and washer/dryer area. Calciner arrival. Calciner installed with cladding in place.

Figure 5: CE's air contactor and calciner module (with cladding) at the Squamish B.C. site.

b. Start-up and Operation

Phase 4 of CE's direct air capture project was defined as pilot plant operations and data acquisition with the goal to acquire performance data that allows CE's engineering team, in concert with key technology partners, to proceed with engineering of a commercial DAC plant. The work in Phase 4 consisted of pilot operations at CE's site in Squamish B.C. to bring each unit operation up to acceptable performance and to acquire real world operating data.

Other successes and highlights of Phase 4 include:

- Building out CE's site operations team and operating protocols. CE now has the capability to perform operations, maintenance, piping, and electrical on site with its own internal team. Significant expertise is being accumulated within the operational team that is leading to new equipment and operating concepts that targeted for testing over the next year.
- CE's DAC pilot has generated significant attention in the public media, among policy makers, and at the Federal and Provincial levels of government. Building on a call for more emphasis on carbon dioxide removal (CDR, of which DAC is a sub-part), appetite and interest in CE's technology has grown dramatically over the course of this project.
    - External to Canada, both the US DOE and ARPA-E issued specific funding opportunities

for dilute source CO_2 capture and fuel synthesis from atmospheric sources, respectively, within the last year. This has come after a prior history of skepticism on atmospheric CO_2 capture.

- Work on the Squamish air capture pilot plant has strengthened CE's relationships with industrial partners such as SPX Cooling Technologies and Technip.
    - Further, CE's demo project has achieved a fairly high profile within the BC Tech and Innovation communities, and has uncovered numerous connections with other tech entrepreneurs and local businesses that are proving valuable.

In conclusion, CE now has all data required to return to engineering of a full-scale commercial DAC plant. However, due to shifting market forces, particularly within the fossil fuel industry, CE has chosen to build out an "air to fuels" fuel synthesis platform around the DAC pilot, with a target of proving a process that could directly synthesize fuel production at 1000 bbl/day scale within the next several years. Further information on this is given in Chapter 7.

4. End of Project DAC Pilot Plant Characterization

The plant was partially characterized in the preceding section, on a Phase-by-Phase basis. This description gave an account of how the pilot plant progressed over the course of the project. In this section, we offer an "end of project" summary of the pilot plant capabilities and equipment.

a. Pilot Plant Capabilities

In developing Carbon Engineering's pilot carbon capture plant in Squamish, CE adopted an approach of first sourcing and identifying major equipment that would be required for a commercial-scale direct air capture plant, and then scaling each system down to the minimize size required to prove commercial feasibility based on key performance metrics.

The auxiliary equipment, which support the major equipment, include a scroll centrifuge, a vibrating screen washer and fluidized bed dryer, a pneumatic conveying system, several solids storage silos and various pumps and tanks for liquid storage and transfer. The wet lab equipment include basic lab equipment such as glassware and weigh scales, as well as an automatic titrator, automatic vibrating sieves, gas evolution apparatus, oven and fume hoods.

Taken all together, CE's equipment and facility forms the largest direct air capture plant built to scrub and purify CO_2 from atmospheric air. CE's pilot is equipped with all necessary design features, sensors, and controls to allow detailed experiments and testing plans to be run to support the engineering required to deploy commercial plants. CE's pilot allows industrially-relevant data to be acquired in order to greatly enhance the state of understanding of direct air capture of CO_2, and also testing and experiments that can be transferrable to make performance predictions about the deployment of CE's technology at Gigatonne per year removal scales.

b. Pilot Plant Equipment

The air contactor in place in the Squamish pilot plant, illustrated in Figure 6, is capable of delivering a range of air and liquid flow rates and is equipped with a full suite of sensors to assess CO_2 capture rate, water loss, pressure drops, and energy usage. CE's contactor is compatible with a wide range of chemical compositions, allowing study of a range of solution molarities and additives.

Figure 6 – Air Contactor at Squamish Pilot

The pellet reactor module installed at the Squamish pilot plant allows for testing and experimentation in relation to the causticization process, in addition to possessing the core operational capabilities required to form the calcium carbonate pellets. The core reactor vessel (at left of Figure 7) has a number of sample ports and sensors that allow detailed study of pellet bed development and performance. The supporting equipment (everything else seen in Figure 7) allows automated addition of seeds, extraction and processing of fines and washing/drying of mature pellets.

Figure 7 - Pellet reactor main vessel and seed feed system

CE's direct air capture research pilot platform utilizes a slaker to dissolve the decomposed solid pellets for re-use in the capture unit. The slaker used at CE's site is a standard industrial slaker of the type employed in pulp and paper plants around the world, where they are an important tool for converting calcium oxide (CaO) into a calcium hydroxide ($Ca(OH)_2$) slurry. An illustration of the slaker unit employed at CE's pilot plant is included below as Figure 8. The steam slaker envisioned for the commercial pilot plant would be entirely incorporated into the commercial calciner system.

Figure 8 - Slaker module

The Calciner for CE's pilot plant facility, illustrated in Figure 9, was installed and commissioned at site in August 2015. This calciner, like other units in CE's pilot plant, is centrally controlled and monitored by a full suite of sensors and instruments that allow control of gas fluidization rates, material addition, and detailed temperature monitoring and control. It is also designed to allow sampling and detailed study of the materials that are fed into, and extracted from, the calciner.

Figure 9: Calciner installed at Squamish pilot plant

5. Greenhouse Gas and Non-GHG Impacts

a. Contribution to Sustainability

CE's DAC technology enables capture of CO_2 directly from ambient air; it does not have any water or soil discharge streams, or any water or soil benefits. DAC does not apply directly to power plants or industrial facilities, so it does not reduce emissions of air pollutants, thus does not have any impact on "clean air".

When DAC CO_2 is used to produce liquid transportation fuels - via fuel synthesis, algal biofuels, or EOR - the resultant fuels have a much lower life-cycle carbon intensity (CI) than conventional fuels. Thus, marketing DAC to produce liquid fuels reduces GHG emissions from the transportation sector. Transportation is currently one of the niches of the economy with very few technical options to reduce emissions, and fewer still which are compatible with today's infrastructure.

Direct air capture (DAC) combined with EOR can produce hydrocarbon fuels with a life-cycle carbon emissions intensity (CI) that can be less than a third that of conventional fuel. DAC therefore develops a more efficient exploitation of non-renewable resources and by providing CO_2 to locations not served by pipelines it "increases access or availability of energy". Enabling production of low carbon-intensity fuels is of strategic importance to the Canadian oil and gas industry. Emerging regulations on lifecycle carbon fuel intensity in the US and the European Union pose substantial economic risks to Canadian oil sands producers whose fuels have relatively high carbon intensity. Not all fuel needs to be produced with the DAC EOR method to meet these emerging regulations, only a small amount of this low carbon-intensity fuel is needed to blend with the conventional streams to reach compliance.

CO_2 from DAC can also be used as a feedstock for bio-algae fuel production, or for the direct synthesis of carbon neutral hydrocarbon fuels (from CO_2 and H_2) using renewable energy sources such as wind, solar or nuclear power. Using either of these routes allows the primary energy source to be stored, transported, and consumed in high energy-density liquid format that is perfectly compatible with existing transportation infrastructure. Both methods can be made truly carbon neutral. Due to this enabling role in synthetic fuel production, DAC increases access or availability of renewable fuels.

Production of Algal biofuels needs CO_2 enriched air in order to be cost competitive. The most commonly discussed option is to supply CO_2-enriched air from coal or gas power plants, but this has two significant limitations. First, while producing algal biofuels from power plant exhaust does produce an overall emissions benefit, the net emissions of the system are exactly the same as the original power plant. When considering the lifecycle analysis, one can either claim that power plant emissions are eliminated or that the fuel emissions are zero. Second, there are serious siting constraints when a location must be suitable for large-scale bio-algal cultivation (cheap land, high sunlight, access to plentiful water) and have a nearby power plant. DAC removes both limitations, and lowers the CI for the whole system to nearly zero.

b. GHG Benefits from the Project

Current: None.
Future: None.

CE's DAC pilot was designed to capture CO_2 from atmospheric air, to process it through all major unit operations required for future commercial scale plants, and then to vent the CO_2 back to the air. The only output from this pilot is data and knowledge. As such, CE's pilot does not directly create GHG benefits.

Thus far, pilot data suggests that at commercial scale, CE's DAC process will require an energy input of 8.7 GJth/t-CO_2-captured. CE's process is designed to utilize natural gas to meet this energy demand when deployed in an injection scenario (either for pure sequestration or enhanced oil recovery) and to collect and compress all combustion CO_2 as well as the stream captured from air. For fuel synthesis deployments, CE is currently engineering process variants which cut the use of Natural Gas and instead utilize renewable electricity and/or bio-gas.

c. GHG Benefits from Market Adoption of the Technology

Current: None.
Future: ~1,000,000 tonnes-CO_2/yr per installed plant.

Carbon Engineering's chief commercialization strategy is to use DAC to supply atmospheric CO_2 for direct fuel synthesis and enhanced oil recovery (EOR). These applications result in fuels with very low life-cycle carbon intensity (CI). When sold into a market that has a regulatory constraint on CI, these fuels command a financial premium or generate a credit which can be financially monetized. This premium and the commodity value of the synthesized fuel form an aggregate revenue stream that enables viable project economics. Based on CE's expected market entry through B.C. and California, GHG quantification will be based on pre-existing performance standards for California's Low Carbon Fuel Standard (LCFS) for the "rest of the world" and B.C.'s Fuel Standard for "Canada". The Baseline GHG emissions for Canada are taken as 91.56 gCO2e/MJ. Baseline GHG emissions for the Rest of the World are taken from the California LCFS for CARBOB and are deemed to be 99.18 g CO2e/MJ.

CE is pursuing opportunities to deploy direct air capture in both enhanced oil recovery and fuel synthesis scenarios. Here, we present the case of how emissions reductions are quantified, and the amount of emissions that may be generated during technology roll-out, for the EOR case. The same logic and methodology apply to fuel synthesis, which generally results in fuels with even lower carbon-intensity than the CI value calculated here for DAC-EOR. It should also be noted that DAC can play a stand alone role, to capture atmospheric CO2 and sequester it in, for example, a saline aquifer. Markets do not yet exist to support this "pure sequestration" deployment, but this approach may one day be used to negate emissions from locations where they are too difficult or costly to manage at source. Overall, air capture is immensely scaleable, and in any of the above deployment configurations, can offer high volumes of emissions reductions.

The carbon intensity of fuels produced by DAC-EOR is dependant on the specifics of refining and transport used downstream of the petroleum production, and chiefly, it depends on the EOR "lift ratio". Lift ratio is a reservoir and production specific metric that describes how much oil is produced for each unit of CO_2 injected. CE has assumed a representative lift ratio of 2 bbl/tonne-CO_2, and once refined to a fuel, this yields a life-cycle carbon intensity (well to wheel) of 45.55 g-CO_2-e/MJ-fuel. CE has also used the assumption that the oil produced gets refined to fuels with average Lower Heating Value (LHV) of crude energy content of 5746 MJ/bbl.

CO_2 reductions are incurred during upstream EOR crude production, when DAC-EOR sequesters atmospheric CO_2 in an oil reservoir as part of crude production and are considered in-direct reductions. This draw-down of CO_2 to the upstream production phase partially compensates for the emissions from combustion, and results in the low life-cycle emission intensity of the fuel. There are no "co-benefits" that have been identified by CE for this technology, and the emissions reductions have been are calculated for a scenario of DAC-EOR penetration into the North American market.

For CE's intended fuel synthesis application, emissions reductions are incurred by exactly the same method as above; fuels with very low carbon intensity are produced, and are assumed to displace fuels with conventional carbon intensity. Carbon Engineering has conducted preliminary carbon balances for several fuel synthesis applications, and carbon intensities are in the range of 30 g/MJ for the simulations calculated thus far.

6. Overall Conclusions

CCEMC has supported Carbon Engineering in a multi-year process to design, build, and operate the world's first industrial direct air capture pilot plant. Carbon Engineering is a Canadian company founded in 2009 by leading environmental scientist David Keith and backed by investors Bill Gates (Microsoft) and Murray Edwards (CNRL). CE's mission has been to develop and commercialize technology to capture industrial scale quantities of CO_2 from atmospheric air.

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7. Next Steps

The commercialization plan in CE's original project proposal involved using atmospheric CO_2 supplied by DAC to conduct enhanced oil recovery (EOR) which would result in "low carbon crude". This low carbon crude would in turn be sold into a market such as that created under California's or BC's low carbon fuels standard. By monetizing both the value of CO_2 to the EOR producer, and the value of the LCFS credits that would be generated, a revenue-positive DAC-EOR operation was predicted.

Since time of proposal, the oil and gas market has shifted dramatically on us. Changes in crude oil price since Fall 2014 will be familiar to all readers and do not bear repeating here. However, a few thoughts on the impact to CE's proposed business plan are indeed worth presenting. CE's business plan presented in the proposal, rests upon supplying atmospheric CO_2 to conduct enhanced oil recovery in order to produce premium value "low carbon crude". With oil prices at current lows, producers are unwilling and unable to take on new ventures like atmospheric-EOR, and CE is facing a lack of demand and stasis in this market.

CE remains very interested in acting upon DAC-EOR opportunities should they arise. The majority of CE's previous market entry plan and market impact assessment are still relevant. If anything, CE is in a stronger position with respect to its DAC competitors than at time of project proposal, and there is a stronger realization in the policy and academic communities that DAC has a significant role to play in mitigating emissions. However, the class of companies that would be sought to act as CE's end-user or partner are not in a position to do so in a time of low oil prices.

However, in addition to DAC-EOR, CE has also put effort into developing the direct fuel synthesis concept. This involves using renewable electricity to produce Hydrogen, then reacting that with atmospheric CO_2 to make octane or diesel that are fully renewable and have no fossil carbon content. Direct fuel synthesis has been a long-term ambition of CE for years; it stands out as one of the very few ways by which we might power the global transportation market with zero carbon emissions. CE had traditionally seen this market as a distant long-term driver for development of DAC, but several things have shifted in recent years.

First, evolution of systems like California's LCFS have started to place life-cycle carbon intensity regulations (and incentives) on fuels. Advanced fuels, such as those made by direct synthesis, would generate significant credits under LCFS-style systems.

Second, the cost of solar PV power and the cost of electrolysers have both seen dramatic cost reductions over the previous several years. CE has been accumulating data from experts in these fields to build preliminary cost assessments of synthetic fuel production. These analyses are indicating that production costs seem reasonable with which to enter fully renewable, ultra low-carbon, cleaner burning fuels into the market space.

CE is turning focus to act upon an alternate business model that utilizes DAC CO_2 and renewable electricity to directly synthesize gasoline or diesel. This is often called fuel synthesis or "air to fuels" and the resultant products are often termed synfuels. CE is now in the midst of a project to build out, integrate, and test fuel synthesis equipment at CE's existing DAC facility in Squamish, BC.

Both "low carbon crude" and synfuels address the same ultimate market: the increasing fraction of the world's $3 trillion/yr transportation fuels that must be delivered at lower carbon intensity or with carbon neutrality. The market potential remains the same.

The shift towards synfuels will allow CE to act independently of oil field operators to potentially even finance/own/operate a small first commercial plant to sell synfuels directly to an end user. An ideal customer would be an entity such as BC Transit or UPS, which operate large vehicle fleets and who are likely willing to pay premium value for low carbon-intensity fuels as they are committed to aggressive emissions reductions. For these end users, synfuels may be a very competitive approach to meeting emissions targets, as they involve no new technology or infrastructure turn-over on the part of the end-user, and they offer verifiable fool-proof emissions reductions.

b. "Air to Fuels" Demonstration Plant

Carbon Engineering has moved on to the design, construction, and operation a state of the art synthetic fuels plant which incorporates the direct air capture pilot plant previously installed at Squamish, BC with additional fuels processing equipment. This project will deliver the world's first air to fuels (A2F) plant that demonstrates low or zero carbon intensity liquid fuel production by a process that is technically and economically feasible at commercial scale.

CE's current DAC plant is able to capture ~1 tonne of CO_2 per day from the atmosphere, and currently releases that CO2 in a hot CO_2/H_2O stream. In this project, CE will make the modifications necessary to this plant to provide atmospheric CO_2 as a feedstock to the down-stream fuel synthesis equipment.

The primary motivation for the development of A2F technology is allow for the mass production of low-carbon fuels in order to displace those made from crude oil. Fuel synthesis has been conducted from coal in the past, and from natural gas in limited markets today, but the resulting products are still inherently fossil fuels. Synthesis from atmospheric CO_2 allows production of a fuel that is ultra low-carbon on life-cycle basis and can reach near carbon-neutrality. Further, these fuels have other attractive characteristics: 30x higher energy density than batteries, ~100x lower land-use than biofuels, domestically producible, and drop-in compatibility with current infrastructure and engines.

Significant technical work will be required to integrate equipment to synthesize fuel from atmospheric CO_2. CE has identified many opportunities for innovation that can occur when well known chemical synthesis processes are integrated with our existing DAC technology. This project will allow for this development and for the demonstration that synthetic fuels can enter the market place and deliver GHG benefits.

As CE executes this project, it will be the first company to deliver a full A2F process that is commercially scaleable. Significant integration and technology risks will be addressed, and detailed performance and cost estimation data will be produced. It is expected that a heavy emphasis will be put on co-optimization of the systems and IP generation in that area is highly likely. CE aims to guide demo efforts based on what equipment and approaches show commercial promise, so that the outcome of this project will ideally be a market-ready technology to synthesize liquid fuel from atmospheric air at industrial scale.

8. Communications Plan

a. Public Media Coverage

Two specific high-profile articles are found at the following hyperlinks:

- http://www.canadianbusiness.com/lists-and-rankings/most-innovative-companies/carbon-engineering/
- http://www.theglobeandmail.com/technology/science/a-canadian-companys-attempt-to-get-a-grip-on-the-carbon-emissionsproblem/article27970800/

CE also continues to participate in the growing momentum in the Squamish region to fund and host a UBC-led clean fuels research and innovation hub.

- http://www.squamishchief.com/news/local-news/ubc-clean-energy-research-centre-in-the-works-for-squamish-1.2185476

b. Go-Forward Communications Plan

CE's Communications Plan rests on the following venues, for each of which, CE's approach is briefly defined.

1. Conferences.
    a. CE regularly gives policy and technical talks at industry and academic conferences.
    b. In 2016, CE will present pilot plant data at
        i. CCUS Conference, Tysons Virginia, June 14-16, 2016
        ii. GHGT 13, Lausanne Switzerland, Nov 14-18, 2016
2. Journal publications
    a. CE has periodically published in high-profile journals such as *Science* and *Philosophical Transactions of the Royal Society*, and is planning to produce one summary paper for recent DAC research and development for a top-calibre academic journal in 2016.
3. Public Media
    a. CE continues to be actively engaged with the public media as a technical voice that is often sought out on innovation or clean-tech topics.
4. Targeted One-on-One Engagement
    a. CE actively seeks out technology partners, end-users, project financiers, and government policy makers for targeted discussions relevant to CE's commercialization trajectory.