Final Outcomes Report

Non-Confidential Version

Reporting Period: 1 Apr 2014 to 31 Dec 2015

Project Title:	Converting Carbon Dioxide into Chemicals and Fuels Using Clean, Domestic Sources of Energy in Alberta
Agreement Number:	K130079
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Lead Institution:	Liquid Light, Inc
Project Partners:	BP Canada, Getachew Assefa
Project Budget:	$9,953,600 (at April 2014 exchange rate)
CCEMC Funding:	$500,000
CCEMC Project Advisor:	Vicki Lightbown
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Executive Summary

Liquid Light's CCEMC supported project, "Converting Carbon Dioxide into Chemicals and Fuels Using Clean, Domestic Sources of Energy in Alberta" was successfully completed. The overall objective of the project was to demonstrate at small scale, the production of chemicals from carbon dioxide (CO_2) using Liquid Light's technology, and to provide proof that the system has the potential for broad adoption in Alberta. The basic process concepts and data necessary to develop a pilot facility were also successfully defined.

Liquid Light is a technology company developing a platform for carbon dioxide utilization in the production of chemicals. Through this project, the company has shown that a commercially viable path to GHG reductions by establishing CO_2 as a feedstock for the production of mono-ethylene glycol (MEG), a $27 billion industry. CO_2 is an ideal feedstock given its abundance and low cost. Liquid Light's technology is unique in that it can selectively produce multi-carbon chemicals like MEG with very high efficiency and a cost of production advantage vs. available chemical technologies.

The CCEMC supported project accomplished several key deliverables. First and foremost, the development of a full end-to-end process to produce MEG from CO_2 was accomplished. All process steps were demonstrated and gm or kg quantities of material were produced at each step. Key process data necessary for the design and construction of a pilot plant were derived. A full Life Cycle Analysis was completed for the production of MEG and other chemicals using the Liquid Light process, which showed the GHG reduction potential for each. It should be noted that process changes that occurred during the project affected the assumptions of the LCA. Using the correlations from the report, Liquid Light also developed an updated excel-based model to evaluate the GHG impact of the updated process. Overall the same conclusions were reached, irrespective of model or process. An important conclusion is that the CCEMC expectation of significant removal of CO_2 per year can be achieved when Liquid Light technologies are operated using 100% renewable power or a grid of a carbon intensity of ~ 100 kg CO_2 equivalents per MWh. Overall, over a ten-year period over one million tonnes of CO_2 would not be emitted into the atmosphere if Liquid Light technology was employed to produce MEG rather than conventional technology. Technology and process development continued at a rapid pace during the project, resulting in a total of 12 patents obtained, and 11 new patent applications filed. Finally, a complete techno-economic analysis of the process was performed which showed that the commercial adoption of this technology can be economically competitive with existing production technologies.

Over the course of the CCEMC project, the potential for Liquid Light's technology attracted the interest of several global companies and investor groups. Such interest has the potential to lead to an accelerated adoption and commercialization of this technology both in Alberta and globally. In July 2015 Liquid Light announced the signing of a technology development agreement with The Coca-Cola Company. The objective of the agreement is to accelerate the development of Liquid Light's technology which can make MEG from CO_2. Liquid Light's approach enables more efficient use of plant material to make MEG. For example, a bio-ethanol production facility could produce bio-MEG from the CO_2 byproduct that results from converting plant material into ethanol. The technology has the potential to reduce both the environmental footprint and the cost of producing MEG. MEG is one of the components used to make The Coca-Cola Company's plant-based PET plastic bottle. This agreement reflects the

growing importance that major consumer brands place on technologies which both lower costs and have environmental benefits.

Project Description

Introduction and Background

Liquid Light is a technology company developing a platform for carbon dioxide utilization for the production of chemicals. The company's technology will establish a commercially attractive path to GHG reductions by establishing CO_2 as a feedstock for the production of organic chemicals, a trillion-dollar industry. CO_2 is potentially an ideal feedstock given its abundance and low cost. Liquid Light's technology is unique in that it can selectively produce multi-carbon chemicals with very high efficiency and a significant cost of production advantage vs available chemical technologies.

Project Goals

The overall goal of the project was to complete the preliminary work necessary to design and build a tonne per day demonstration facility in Alberta during later stages of the CCEMC Grand Challenge. In order to develop the data needed to go to demonstration scale, Liquid Light researched, designed, and built a laboratory bench process capable of making 100's gram quantities of product per day from carbon dioxide. This work included all process steps from CO_2 input to product output. In conjunction with the laboratory work on the pilot, Liquid Light collaborated with Professor Getachew Assefa on a lifecycle analysis of the company's technology in the context of Alberta. The intention of the lifecycle analysis was to ensure the demonstration scale plant is built in a manner that is most appropriate for accomplishing the goals of the Grand Challenge. Laboratory results from the pilot and the results of the lifecycle analysis will be used to guide development of a basic engineering plan (BEP) for the tonne per day demonstration facility. There were three deliverables for the project:

1. g/d end to end production of mono-ethylene glycol (MEG) completed (12 months, Milestone 3). Liquid Light will provide CCEMC with data associated with MEG production from CO_2 that shows the results of MEG production.
2. kg/d end to end production of MEG with supporting data demonstrating commercial viability of technology (24 months, Milestone 8). Liquid Light will provide CCEMC with data and financial projections based on the data.
3. BEP for a t/d plant (24 months, Milestone 9). Liquid Light will provide CCEMC with a synopsis of the BEP.

There were a total of four tasks associated with this project. The tasks were:

Task 1 – Develop laboratory pilot making MEG from CO_2: Work on task 1 included the scale-up of all process steps from concept to grams per day to kilograms per day. It culminated in the production of monoethylene glycol (MEG) from CO_2 with all process steps demonstrated.

Task 2 – Draft BEP for integrated t/d unit: Task 2 principally involved the modeling and design of a demonstration plant that can be fielded in Alberta. The completion of Task 2 depended on data derived from Tasks 1 and 3.

Task 3 – Lifecycle analysis: Our team worked with Professor Getachew Assefa to complete a lifecycle analysis of the technology in the context of Alberta and CCEMC's goals. We used the results of the lifecycle analysis to guide the BEP design work such that the technology is configured to best meet goals appropriate to Alberta and CCEMC. It should be noted that process changes that occurred during the project affected the assumptions of the LCA. Using the correlations from the report, Liquid Light also developed an updated excel-based model to evaluate the GHG impact of the updated process.

Task 4 – Supporting activities: Task 4 included supporting activities for other tasks to include analytical chemistry support to R&D and G&A costs. Analytical chemistry lets us evaluate the results of experiments and is critical to technology scale-up. G&A includes project management, facilities, and administrative support to the project.

Work Scope Overview

We have completed the project and planned milestones on time and to the standards that were set above. The milestones and their status are shown in Table 1.

Table 1. List of Milestones and Their Status

Task	Planned Progress	Actual Progress	Comments on Variances
Milestone 1	Contract Signature	Completed	
Milestone 2, Tasks 1 and 4	All process steps operating individually at g/d scale as part of the overall plan to develop a laboratory pilot.	Completed	Completed on time. Process changes were made to ensure economic viability
Milestone 3, Tasks 1 and 4	1 g/d end-to-end MEG production using the process steps developed as part of Milestone 2.	Completed	Completed on time. Process changes were made to ensure economic viability
Milestone 4, Task 3	Complete lifecycle analysis to identify the best approaches to meet CCEMC goals.	Completed. Determined renewable power and low carbon hydrogen sources are the key to meeting CCEMC goals in Alberta.	N/A
Milestone 5	Submission of the interim report	Completed	N/A
Milestone 6 Task 1a	3 cell stack start-up	Postponed	Determined better focus for pilot scale

Task	Planned Progress	Actual Progress	Comments on Variances
Milestone 7, Tasks 1 and 4	kg/day end to end MEG production	Completed	The scale of this milestone was reduced to 100+g/day.
Milestone 8, Tasks 1 and 4	kg/day end to end MEG production at 100% of key performance indicators (KPIs): Purity, Energy, Rate, Yield	3 of the 4 initial KPIs have been achieved and exceeded at a 100 g/day scale	The scale of this milestone was reduced to 100 g/day and the energy KPI was recalculated but will not be focused on until pilot plant scale.
Milestone 9, Task 2	BEP for t/d system	Postponed until pilot plant scale	Initial process concept and simplified PFD were completed.

Greenhouse Gas and Non-GHG Impacts

A full life cycle analysis was completed for Milestone 4, Task 3, and the major conclusions and data are presented herein. The full report by Professor Getachew Assefa of the University of Calgary was submitted. Professor Assefa examined multiple products, including MEG, formic acid, oxalic acid, and glycolic acid. He also evaluated multiple sources of electricity and hydrogen. His general conclusions were that the source of electricity, the source of hydrogen, and the product chosen, all have a major impact on the ability of the technology to achieve CCEMC's goal of carbon negative utilization of CO_2. In the context of Alberta, it was determined that it is necessary for Liquid Light to utilize renewable electricity in order to be carbon negative. This is due to the carbon intensity of the grid, an average of 880 kg CO_2 equivalents per MWh (at the time of the life cycle analysis) compared to ~36 kg CO_2 equivalents per MWh for renewable power sources. The current carbon intensity of the Alberta grid is 650 kg CO_2 equivalents per MWh, however, 880 kg CO_2 equivalents per MWh was used in the LCA. It was also found to be very beneficial to use hydrogen sources from steam crackers, chlor-alkali, or renewable sources rather than steam methane reforming.

Process changes that occurred during the project affected the assumptions of the LCA. Using the correlations from the report, Liquid Light developed an updated excel-based model to evaluate the GHG impact of the updated process. This model was used for the calculations reported herein. Overall, the same conclusions in the LCA for the previous process were arrived at: for deployment of the process in Alberta and to have significant removal of carbon dioxide, renewable power must be employed. Current Alberta grid power is too carbon intensive for the Liquid Light process to compare favorably to conventional technology with respect to carbon emissions.

However, one important conclusion of the LCA study is that the CCEMC expectation of significant removal of carbon dioxide (CO_2) per year can be achieved when Liquid Light technologies are operated using 100% renewable power or a grid of a carbon intensity of ~ 100 kg CO_2 equivalents. For all comparisons herein, we considered ethanol-derived MEG as the main competing technology. This is due to the fact that corn-ethanol or plant-derived MEG is considered "green" and represents the highest growth market. Liquid Light's first process will provide new technology for "green" MEG, to replace the current ethanol-based route. As discussed, two cases showed large reductions in CO_2 emissions: the use of a grid of ~100 kg CO_2 equivalents per MWh or renewable power sources. When comparing the Liquid Light technology to conventional technology, it is important to note that only ~390 kWh/tonne MEG of electrical energy is required. The carbon emissions from the conventional process are primarily related to the chemical emissions and steam requirements. Therefore, the sensitivity of the conventional technology to the grid carbon intensity is minimal compared to Liquid Light. In addition, the same grid factor was applied to both the conventional and Liquid Light processes when possible.

Assuming H_2 from steam methane reforming, the current Liquid Light process carbon intensity is 400 kg CO_2 emitted per tonne MEG compared to 1,800 kg CO_2 emitted per tonne MEG for the conventional ethanol-based technology if a grid of ~100 kg CO_2 equivalents per MWh is used. Therefore, if this grid was employed, even with the highest emission source H_2, the Liquid Light technology represents a 78% reduction in emissions from conventional technology.

If renewable power is used (carbon intensity of 35.6 kg CO_2 per MWh) and renewable powered H_2 from water electrolysis, carbon dioxide is sequestered. A 175 kTa Liquid Light MEG plant would represent a sequestration of >35,000 tonnes per year of CO_2. If the replacement of conventional technology by Liquid Light technology is considered, >350,000 tonnes of CO_2 per year would be sequestered and reduced simply by employing Liquid Light technology rather than conventional. This is the equivalent of taking >70,000 cars off the road.

The expected annual GHG benefits projected over a ten-year period for the renewable power case are shown in Figure 1. The graph represents the annual reduction in emissions. By implementation of the project and development of a demo-plant operating at a tonne per day scale of 500 tonnes per year, an immediate benefit of 1,000 tonnes of CO_2 not being emitted would be achievable. As Liquid Light commercial facilities come on-line starting in 2020, benefits dramatically increase. Figure 1 represents a 175 kTa Liquid Light MEG plant coming on-line in 2020, with additional facilities starting up every three years. The benefits represent only the deployment of MEG facilities and do not represent additional plants making other products such as glycolic acid coming on-line.

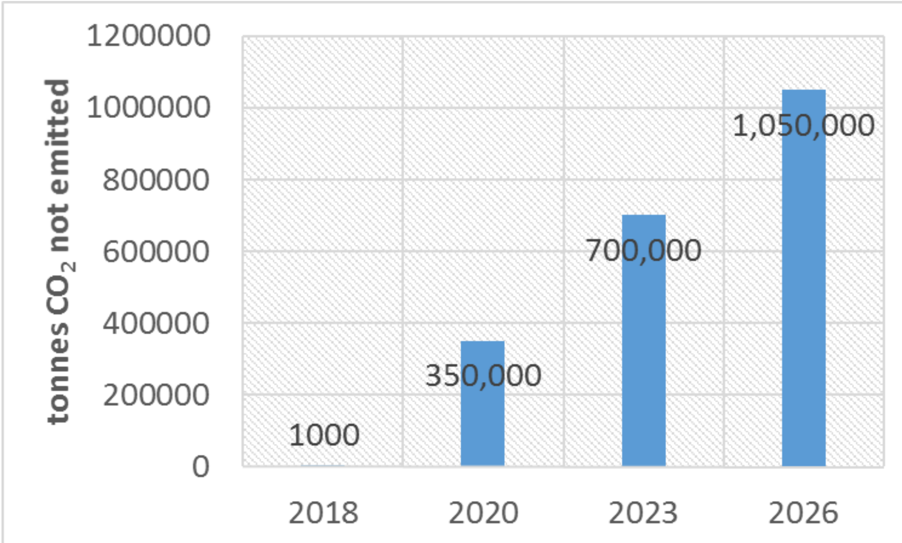

Figure 1. Ten-year projected reduction in CO_2 emissions on an annual basis by deployment of Liquid Light MEG plants vs. conventional ethanol-based MEG plants. The first demo-scale plant of 500 tonnes per year MEG will be constructed in 2018, followed by the deployment of commercial facilities starting in 2020, with additional plants built every three years. The scale of each plant is 175 kTa.

Overall, over a ten-year period over one million tonnes of CO_2 would not be emitted into the atmosphere if Liquid Light technology was employed to produce MEG rather than conventional technology. This represents a large reduction in CO_2 emissions consistent with the goal of the CCEMC objectives.

Outcomes and Learnings

Task 1:

A lab scale demonstration of Liquid Light's process was completed and achieved and exceeded the set KPI's: the MEG purity reached above 99.9%; and every process step had over 80% yield. Supporting analytical development work helped achieve these targets.

Task 2:

The pilot plant daily capacity target was modified to 100 kg/d due the infrastructure limitations at the future pilot location. Due to project delays, the BEP is not submitted with this report

Task 3:

Professor Getachew Assefa of the University of Calgary examined multiple products, He also evaluated multiple sources of electricity and hydrogen. His general conclusions were that the source of electricity, the source of hydrogen, and the product chosen, all have a major impact on the ability of the technology to achieve CCEMC's goal of carbon negative utilization of CO_2. The LCA study concluded that the CCEMC expectation of significant removal of carbon dioxide (CO_2) per year can be achieved when Liquid Light technologies are operated using 100% renewable power or a grid of a carbon intensity of ~100 kg CO_2 equivalents.

It should be noted that process changes that occurred during the project affected the assumptions of the LCA. Using the correlations from the report, Liquid Light developed an updated excel-based model to evaluate the GHG impact of the updated process. Overall, the same conclusions in the report for the previous process were arrived at: for deployment of the process in Alberta and to have significant removal of carbon dioxide, renewable power must be employed.

Scientific Achievements

Numerous, high-impact publications and patents were reported and applied for during the project. A bibliography is listed below. Unpublished provisional patent applications are removed from the list for this non-confidential report.

New Patent Application filings

Electrochemical Production of Synthesis Gas from Carbon Dioxide
US 14/253,964
April 16, 2014

Electrochemical Co-Production of Products with Carbon-Based Reactant Feed to Anode
US 14/463,430
August 19, 2014

Electrochemical Reduction of CO2 with Co-oxidation of an Alcohol
US 14/470,700
August 27, 2014

Process and High Surface Area Electrodes for the Electrochemical Reduction of Carbon Dioxide
US 14/471152
August 28, 2014

Heterocycle Catalyzed Electrochemical Process
US 14/488,848
September 17, 2014

Obtained Patents

US 8,663,447 March 4, 2014	Conversion of Carbon Dioxide to Organic Products LL 09-2496-D3
US 8,691,069 April 8, 2014	Method and System for the Electrochemical So-Production of Halogen and Carbon Monoxide for Carbonylated Products LL 0027
US 8,692,019 April 8, 2014	Electrochemical Co-Production of Chemicals Utilizing a Halide Salt LL 0026
US 8,721,866 May 13, 2014	Electrochemical Production of Synthesis Gas from Carbon Dioxide LL 0004
US 8,821,709 September 2, 2014	System and Method for Oxidizing Organic Compounds While Reducing Carbon Dioxide LL 0029
US 8,845,877 September 30, 2014	Heterocycle Catalyzed Electrochemical Process LL 0003
US 8,845,876 September 30, 2014	Electrochemical Co-Production of Products with Carbon-Based Reactant Feed to Anode LL 0024
US 8,845,875 September 30, 2014	Electrochemical Reduction of CO2 with Co-Oxidation of an Alcohol LL 0025
US 8,845,878 September 30, 2014	Reducing Carbon Dioxide to Products LL 0016A
US 8,858,777 October 14, 2014	Process and High Surface Area Electrodes for the Electrochemical Reduction of Carbon Dioxide LL 0017A
US 8,961,774 February 24, 2015	Electrochemical Production of Butanol from Carbon Dioxide and Water LL 0008A
US 8,986,533 March 24, 2015	Conversion of Carbon Dioxide to Organic Products 09-2496 D1

Journal Articles

Barton Cole, E.; Baruch, M. F.; L'Esperance, R. P.; Kelly, M. T.; Lakkaraju, P. S.; Zeitler, E. L.; Bocarsly, A. B. "Substituent Effects in the Pyridinium Catalyzed Reduction of CO2 to Methanol: Further Mechanistic Insights," Top. In Cat., **2014**, in press.

Parajuli, R., Gerken J. B., Keyshar K., Sullivan, I., Sivasankar, N., Teamey K., Shannon S. Stahl, S. S., Barton Cole, E. "Integration of Anodic and Cathodic Catalysts of Earth-Abundant Materials for Efficient, Scalable CO_2 Reduction," *Top. in Cat.*, **2014**, in press, invited paper.

White, J. L.; Herb, J. T.; Kaczur, J. J.; Majsztrik, P. W.; Bocarsly, A. B. "Photons to Formate: Efficient Electrochemical Solar Energy Conversion Via Reduction of Carbon Dioxide," *J. CO_2 Util.* **2014**, *7*, 1-5.

Conference Presentations

Cole, E. B.; et al. “Electrochemical and Photoelectrochemical Conversion of Carbon Dioxide to Chemicals” MRS Spring Meeting, San Francisco, CA, 2014, *invited talk*.

Cole, E. B. “CO_2 to Polymers, Plastics, and Pop Bottles” 4th Carbon Dioxide Utilization Conference, San Antonio, TX, 2015, *invited talk.*

Parajuli, R. “Electrochemical Production of Multi-Carbon Chemicals from CO2” CO2Forum, Lyon, France, 2014.

Law, D. “Harnessing CO_2: A Market-Focused Perspective” ABLC, Washington, D.C., 2015.

Law, D. “Harnessing Bio-CO_2 as a Low Cost Feedstock to Make More Sustainable Chemicals” BIO World Congress, Montreal, Canada, 2015.

Rice, A. “From Catalyst Discovery to Commercialization: Scaling CO_2 Utilization Technologies” Third Biennial CO2 Workshop, Princeton University, Princeton, NJ, 2015.

Next Steps

Liquid Light intends to further develop and optimize the CO_2 to MEG process at the lab scale in preparation for the design and construction of a pilot plant in 2017. A specific focus on achieving lower cell energy and increased rates of reaction through improved design is in place. To accelerate and assist in this process, several technology development agreements have recently been put in place with global electrochemical technology providers including a recently announced partnership with De Nora. Additional partnerships with brand owners and the respective supply chain are in discussion. The first large scale CO_2 to MEG commercial plant is anticipated to be under construction in 2020.

Additional efforts are underway to research and then license electrochemical approaches for the production of other CO_2 based chemicals.

Based on results achieved to date at Liquid Light and its partners, we are confident that Liquid Light has identified a robust and simple path to overcoming the critical energy-carbon hurdle that is both technically and commercially viable.

Communications Plan

Liquid Light will communicate the achievement of the CCEMC project and the CO_2 to MEG process viability to a broad range of potential strategic investors, peer groups and licensees. Liquid Light is focused on developing compelling and competitive process technologies. It will license these technologies to major chemical producers with a combination of fees paid on signing, milestone payments and production based royalties, while the partner builds and operates the production plants. In order to be successful, a comprehensive communication plan including targeted business development activities, publications, conference presentations, media relations, website presence and the achievement of public recognition is essential. In addition to the recognition gained by being a CCEMC Grand Challenge award winner, Liquid Light has gained multiple other awards. Biofuels Digest named Liquid Light the #1 Hottest Small company in the Advanced BioEconomy in 2014, followed by a #5 finish in 2015. The CleanTech group named Liquid Light the Rising Star of the Year in the CleanTech 100. ICIS named Liquid Light a finalist for the Innovation Award. Dr. Emily Cole, co-founder and CSO, was named one of the top innovators under 35 by the MIT Technology Review and as one of the top ten Next Wave Energy professionals under 35 by LinkedIn. Liquid Light and Dr. Cole were also one of six companies spotlighted in the CNN series “2020 Visionaries”, airing on CNN international.