CCEMC Project ID K131101

A Coupled CO_2 and Waste-Water Treatment Process to Create High Value Gas/Oil Field Chemicals

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Non-Confidential Report

1.0 Executive Summary

The University of British Columbia has developed a waste-to-value innovation that converts waste carbon dioxide and high salinity wastewater to value added oil and gas field chemicals and desalinated water for on-site utilization. The technology is highly suited for implementation in Alberta with potential for GHG reductions in excess of 1 Mtonnes of carbon dioxide every year. UBC has leveraged the CCEMC Grand Challenge Round 1 seed grant of $500,000 to raise an additional $600,000 to significantly advance commercialization of the technology by demonstrating a commercial scale pilot plant. An in-field pilot demonstration of the innovation is expected at a relevant site in Alberta by the summer of 2018. Round 1 of the CCEMC Grand Challenge was completed successfully resulting in:

1) <u>Validation of key performance targets and significant de-risking of the technology</u>

- Design and engineering of a prototype reactor
- Demonstration of the technology with economic performance
- Development of advanced anion exchange membranes in collaboration with Simon Fraser University with potential for durability improvements
- 1,500x scale up of the prototype reactor to a 5,000 cm^2 pilot plant capable of treating 25 barrels per day of wastewater and converting 100 kg of carbon dioxide per day
- Demonstration of the performance at the pilot scale
- Pilot plant fully capable of being converted to an in-field pilot

2) <u>Differentiated technology with powerful economics for implementation in Alberta</u>

- Innovation is highly suited for application within Alberta's O&G exploration and production sector
- NSERC supported market study identified alkaline surfactant polymer enhanced oil recovery (ASP-EOR) as a strong initial market
- Value creation of $35 per m^3 of wastewater treated when applied in the ASP-EOR sector
- Monte-Carlo risk analysis showing a strong value-proposition for the technology in the ASP-EOR market

3) <u>Partnerships within the value chain and a clear path to market</u>

- NORAM Engineering and Constructors a world leader in providing electrochemical-based plants will provide engineering design and integration expertise
- Questor Technologies Inc. will provide a site for an in-field pilot demonstration in Alberta where the UBC technology will be integrated with Questor's waste-gas to electricity system
- Saskatchewan Research Council will provide economic validation and front-end system design and engineering

4) **<u>Potential for GHG reductions in excess of 1 Mtonnes of carbon dioxide in Alberta</u>**

- At commercialization, an integrated UBC and Questor pilot system with 1,000 barrels per day wastewater capability is expected to reduce GHG emissions equivalent to 27,000 tonnes of carbon dioxide per year
- Successful commercial roll-out of the technology in 2020 has the potential to remove carbon dioxide in excess of 1.4 Mtonnes by 2022

5) <u>Significant fund raising for further commercialization of the technology</u>

- Matching funds from Western Economic Diversification ($450,000) and NSERC Innovation to Idea ($125,000) allowing for scale up efforts and for front-end engineering of the technology

2.0 Project Description

The UBC technology converts waste CO_2 and high salinity waste-water into value-added oil and gas (O&G) field chemicals and desalinated water for re-use. UBC's technology uses aspects of electrodialysis, ion-exchange membranes and fuel cell technology to electrochemically convert greenhouse or other gases into a mineralized form by combining with salts present in saline water to create new chemicals. The on-site generation of value-added chemicals and desalinated water, which can be used in O&G field operations, make the UBC technology a negative cost. This value proposition disrupts the traditional cost creating economic structure of incumbent desalination technologies.

On a wastewater throughput basis, ~25 kg_{CO2} can be removed per cubic meter of wastewater treated. CO_2 is mineralized in the form of product carbonate salts at ~0.5 kg_{CO2}/kg of carbonate salts, which can be used on-site. In addition, ~0.8 kg of hydrochloric acid is generated as a by-product per kg_{CO2} removed. Both carbonate/bicarbonate salts and hydrochloric acid are valuable compounds in the O&G exploration and production activities.

3.0 Project Goals

The overall goal of the project was to accelerate commercialization of the technology from a technology readiness level (TRL) of 2 to a TRL of 5 by: i) validating the key techno-economic assumptions of the value proposition of the technology, and ii) de-risking scale-up of the technology by demonstrating a scaled-up reactor. Four general tasks for the two year period of the project were proposed at the time of the grant agreement execution with CCEMC as summarized in Table 1. All tasks were successfully completed on-time and on-budget. The commercialization of the technology was significantly accelerated to a TRL of 6 by demonstration of a pilot plant capable of being converted to an in-field pilot.

Table 1: Summary of the milestones identified for the CCEMC project.

Milestone	Task	Status
Parametric Study for Economic and Energy Analysis	Screening of commercial ion exchange membranes and operating conditions to provide parametric data for cell design, analysis and modeling	Successfully completed
Testing Results for Advanced Membranes (SFU)	Development (synthesis/characterization) of advanced cation and anion exchange membranes (SFU)	Successfully completed
Testing of Benchtop Electrodialysis Cell(s)	Experiments with existing (and modified) commercial electrodialysis cells; design and development of improved electrodialysis cell(s)	Successfully completed
Demonstration of Scaled-up Reactor	With our industrial collaborator we will design, implement and test a scaled-up reactor for demonstration of our approach	Successfully completed

The CCEMC project was focused on: 1) validating key techno-economic performance targets, 2) demonstrating a scaled-up pilot plant, and 3) developing key industry partnerships in preparation for in-field pilot demonstrations. The project has been successfully completed on budget and on time. This report presents the highlights of our achievements and the next steps towards a full scale commercialization of the technology.

4.0 Project Outcomes and Learnings

The first three milestones of the project led to development of several prototype reactors capable of removing a gas by electrochemical conversion at the electrode and desalinating wastewater with the use of ion-exchange membranes at UBC. Figure 1 shows a picture of the prototype reactor with an overall active area 3.24 cm^2. Extensive experimental testing and modelling, then allowed the UBC team to design a 1,500× pilot reactor, a scale up which far exceeded the initial expectations. The scale-up was implemented by NORAM Engineering, a world leader in manufacturing of turn-key chemical and electrochemical systems for industry.

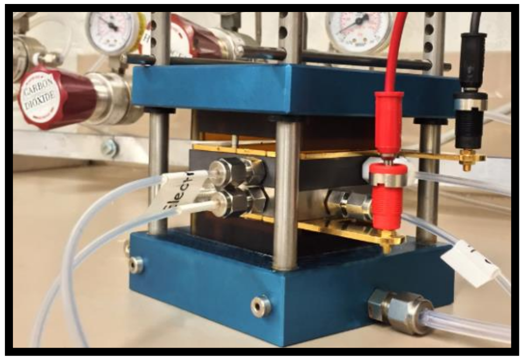

Figure 1: The 3.24 cm^2 proto-type reactor for electrochemical conversion of carbon dioxide and desalination of waste-water.

Figure 2 shows the pilot reactor with overall cell active area of 5,000 cm^2. The system, which has been used to demonstrate the scalability and the commercial viability of UBC's coupled removal of carbon dioxide and treatment of waste-water technology, has a wastewater treatment capability of 5 barrels per day and conversion of as much as 20 kg/day of carbon dioxide. The modular design of the electrochemical stack allows for simple and efficient expansion of treatment capability by increasing the number of reactors in the stack as shown in Figure 2. The balance of plant of this system has been sized to be able to treat 25 barrels per day of wastewater and remove 100 kg of carbon dioxide per day. Currently, the system is configured in such a way as to allow ease of access and ability to test a number of configurations. However, the actual required footprint of the technology is expected to be 60% of the footprint shown in Figure 2 and as such the system is mobile for application and can be easily transported to the field for demonstration. It is expected that this pilot plant will be demonstrated at a Questor site in Alberta within the next two years.

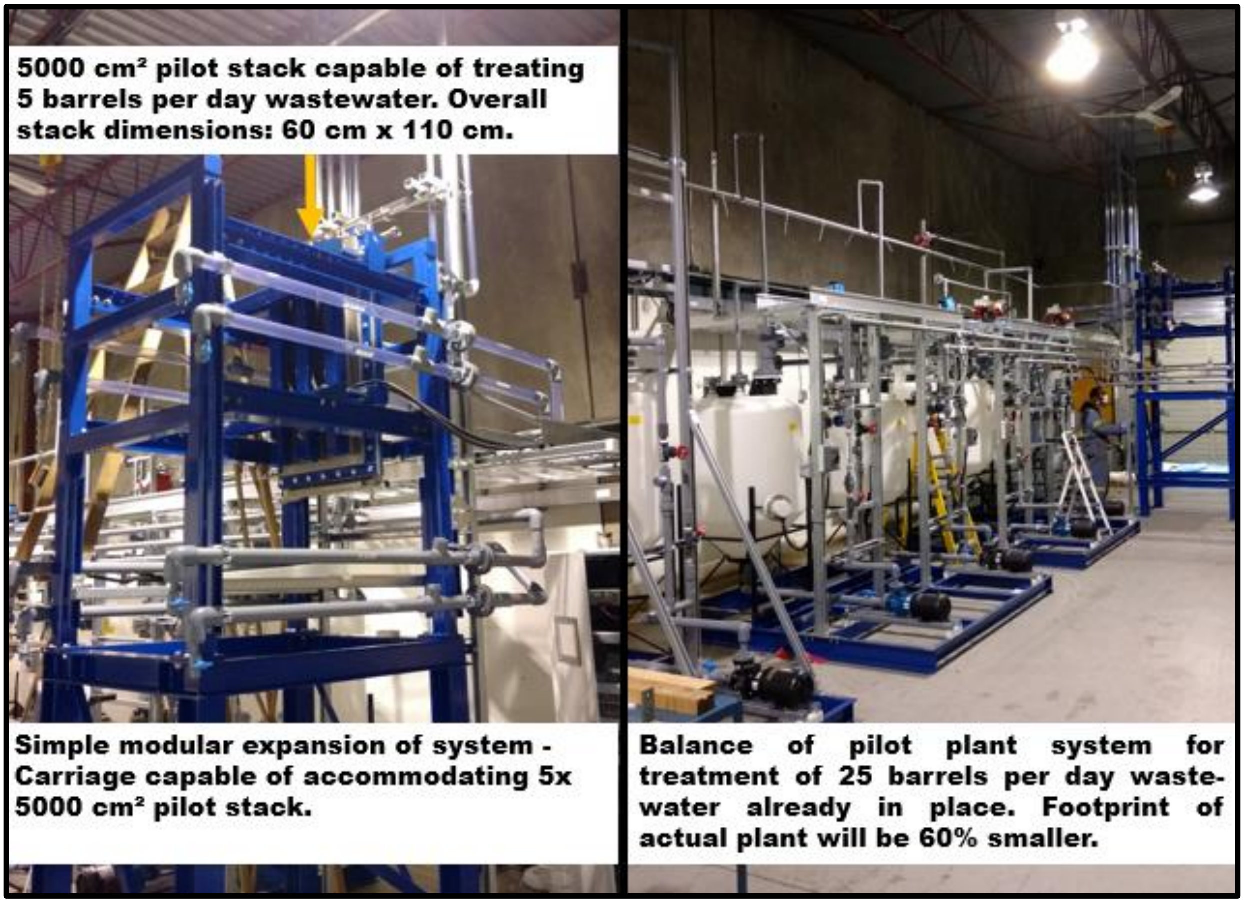

Figure 2: UBC's 25 BPD (5000 cm² active area) for conversion of high salinity waste-water and carbon dioxide to value-added chemicals and desalinated water.

5.0 Value proposition of the UBC Technology

While the UBC technology can be deployed in a number of unconventional O&G activities a market study of the UBC technology in 2015 identified the alkaline surfactant polymer enhanced oil recovery market as a particularly strong initial market.

ASP-EOR is a method of chemical EOR where an alkaline chemical such as sodium carbonate, sodium hydroxide or sodium bicarbonate is used in conjunction with a surfactant and polymer to reduce the interfacial tension and scrub the reservoir, releasing some of the oil and helping to extend well production period. Volumes of water required per well range from 4,000-30,000 m^3 per day. The amount of sodium carbonate in the injection fluid can be up to 1.5 wt%. Currently, sodium carbonate pricing and transportation can cost as much as $550/tonne. Typical polymer (e.g., hydrolyzed polyacrylamide, HPAM) amounts used in the extraction fluid increase with salinity of the water used for injection and range from 500 – 3000 ppm. Currently, HPAM polymer cost is $6,600 per tonne. LUX Research reports the growth in the ASP-EOR market is currently being driven largely by operations in Canada and the Middle East. In Canada, ASP-EOR is practiced mostly in Alberta and Saskatchewan. Globally, ASP-EOR is used as a technique for both on-shore and off-shore resource extraction.

Within this sector the UBC innovation provides an O&G producer (end-users) with the ability for desalination of their produced water to a desired level, on-site generation of alkaline chemicals from their waste gases and ensuring minimal usage of the very expensive polymer. Selectively tuning the salinity of the produced water to an optimal level can reduce polymer usage by 60%. Therefore, the UBC technology significantly reduces the need for water and produced water management, and eliminates the need to source and transport chemicals to a well site. The value proposition for UBC's technology when implemented in the ASP-EOR market is a net value creation of ~$35 per cubic meter of produced water treated as summarized in Figure 3.

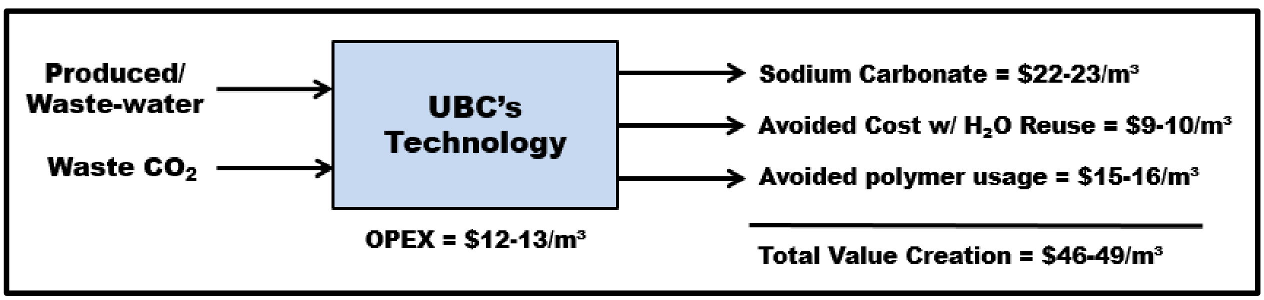

Figure 3: Value proposition of the UBC technology when applied to the ASP-EOR sector. Assumptions: Electricity price = $0.10/kWh; HCl Price = $90/tonne; Sodium carbonate Price = $550/tonne; Avoided H_2O cost 4; Membrane cost = $300/$m^2$ and replaced every 18 months; 95% Uptime; TDS Removed/m^3 = 40,000 mg/L

6.0 Reduction of Greenhouse Gases

The UBC technology is expected to be integrated with a Questor Technology Inc.'s waste-gas (primarily methane) to power system which will provide both electricity and a source of carbon dioxide. An integrated UBC-Questor system is anticipated to remove GHG emissions equivalent to approximately 81.6 kg_{CO2E}/barrel of wastewater treated. At this rate a proposed integrated UBC-Questor pilot system with a wastewater treatment capability of 25 barrels per day would remove GHG equivalent to 745 tonnes of carbon dioxide per year. In addition the system would produce 96 kg of hydrochloric acid and 154 kg of sodium carbonate per day. Table 2 summarizes the greenhouse gas emissions reductions from the implementation of a 1,000 barrel per day wastewater treatment capability integrated UBC and Questor system.

Table 2: Summary of amount of carbon dioxide removed by a commercial roll-out of a 1,000 barrel per day wastewater treatment capability integrated UBC and Questor system. Assumptions: 1,000 barrel per day system treats 330,000 barrels per year.

	2017	2018	2019	2020	2021
Technology development stage	Pilot Demonstration		Commercial Roll-out		
Commercial units introduced to market			1	10	30
Cumulative units in operation			1	11	41
Barrels of wastewater treated per year			330,000	3,630,000	13,530,000
GHG emissions reduced (tonnes CO2E)			26,923	296,158	1,103,862
Cumulative GHG emissions reduced (tonnes CO2E)			26,923	323,081	1,426,943

7.0 Overall Conclusions and Next Steps

Seed funding of $500,000 from the CCEMC was used to accelerate the commercialization of a modular and mobile waste-to-value innovation that accepts waste carbon dioxide and high salinity wastewater and converts them into value added chemicals and desalinated water for on-site utilization in O&G operations. The project was successfully completed on-time and on-budget with the technology being taken from a concept being demonstrated at the lab scale to a fully functioning 5,000 cm^2 pilot plant capable of desalinating 25 barrels of high salinity wastewater and converting 100 kg of carbon dioxide per day. The pilot plant is capable of being converted to a fully integrated field pilot.

The technology has been significantly de-risked through validation of key techno-economic assumptions and demonstration of the scaled-up pilot. The innovation addresses a significant market wide pain of water and wastewater management, and greenhouse gas emissions in the unconventional O&G exploration and production sector, and is highly suitable for implementation in Alberta. For an end-user in the O&G sector the ability for on-site generation of chemicals, desalination of wastewater to a desired salinity and conversion of carbon dioxide provides a highly attractive value proposition of approximately $6-7 of value created per barrel of wastewater treated.

Key partnerships within the value chain with NORAM Engineering and Constructors, and Questor Technologies Inc. have been made. It is expected that NORAM will provide engineering services for integration of UBC's pilot plant to Questor's waste-gas to electricity system at a Questor site in Alberta. An in-field demonstration of this integrated system is expected within the next two years. In addition, we have engaged with the Saskatchewan Research Council (SRC) for application of the system in Saskatchewan. The pilot system is capable of treating as much as 25 barrels per day of wastewater and enabling the removal of GHG equivalent to 745 tonnes of carbon dioxide every year. At commercialization, each 1,000 barrel per day treatment capability UBC/Questor system is expected to remove GHG emissions equivalent to approximately 27,000 tonnes of carbon dioxide.