CARBON UTILIZATION – EXPERIENCE AND LESSONS LEARNED FROM SUPPORTED PROJECTS

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Abstract

This paper shares the lessons learned from a portfolio of Alberta Innovates, InnoTech Alberta, C-FER and ERA supported projects related to CCUS, supplemented with experience gained from within the broader sector. This paper serves to summarize the body of knowledge developed and supported by these organizations regarding carbon utilization, and to recommend ways to help enable widespread use of CCUS both in Alberta and around the world. It is primarily focused on technology and knowledge development, identifying technology gaps, providing insights and recommends initiatives to develop CCUS technologies for widespread deployment to support emissions reductions targets. This paper also provides an overview of priority focus areas for future carbon utilization initiatives.

Purpose of This Paper

This paper has been published as part of a series of papers on work completed on various aspects of CCUS with recommendations regarding how to advance carbon capture in the future. This paper shares the lessons learned from a portfolio of Alberta Innovates, InnoTech Alberta, C-FER and ERA supported projects related specifically to CCUS completed over the past two decades. These organizations work very closely to ensure the most efficient development and deployment of promising solutions occurs within Alberta. This paper serves to summarize the body of knowledge developed and supported by these organizations, and to identify the remaining gaps that need to be addressed with recommendations regarding how to help enable widespread use of CCUS both in Alberta and around the world. This paper is not intended to be a policy position paper, but it may be used to inform policy decisions as required. It is primarily focused on technology and knowledge development, identifying technology gaps, insights and priority focus areas for further investment to de-risk CCUS technologies for widespread deployment to support emissions reductions targets.

1. Carbon Utilization

1.1. Introduction/Overview

In this paper we discuss carbon utilization pathways, as well as facilities and funding infrastructure within Alberta Innovates, InnoTech Alberta (InnoTech), and Emissions Reduction Alberta (ERA) for carbon utilization technology research, scale-up and commercial deployment.

Apart from storage and sequestration, captured CO_2 may also be utilized, or recycled. “Carbon utilization” is the term used to broadly describe the direct use of CO_2 or conversion of carbon input streams to valuable products. Carbon utilization is generally divided as follows:

- **Direct use** – for example, in enhanced oil recovery (EOR)
- **Mineralization** – carbon as an additive to mineral products, such as cement

- **Chemical conversion** – conversion of carbon to feedstock fuel, chemicals, and other novel materials, such as carbon nanotubes
- **Biological uptake**, via microalgae or microbes, for use in fuels, chemicals, food, fertilizer and other feedstocks.

Of note, almost all these applications currently require high purity CO_2, above 95 per cent. For comparison, flue gas from a typical natural gas power generation facility may contain 4-6 per cent CO_2. Therefore, concentration via CO_2 capture must be considered as part of the lifecycle of most conversion processes.

One of the key challenges for carbon utilization is that any utilization technology must consider the overall greenhouse gas (GHG) emissions from a life cycle analysis (LCA) perspective. Many carbon conversion applications require energy inputs to generate their end products, which in turn can lead to release of CO_2 and/or other more potent GHGs. CO_2 is a very stable molecule. Significant energy is required to break it apart to create other, more useful molecules. To make a material impact on GHG emissions, carbon utilization applications must not result in higher emissions than they are offsetting. Most carbon utilization technologies are still technologically immature from the standpoint of ensuring lifecycle “carbon negativity” or even “carbon neutrality”.

Certain applications, like mineralization in cement, are attractive because they have a large, existing markets. For other applications, like novel carbon-based materials, the market today is relatively small; however, there is significant potential when we imagine the future uses of carbon nanotubes to enhance the properties of everyday materials.

Sequestration, or geological storage, is currently a more straightforward, defined pathway for captured carbon compared to utilization within the Alberta context – so long as policies exist to enable the market. There are many commercial sequestration schemes in operation. Carbon storage is discussed in greater detail in the accompanying “Carbon Storage” paper (Chalaturnyk, 2022).

Beneficial reuse of carbon dioxide poses added economic as well as intangible benefits of converting what would otherwise be a waste product into a valuable commodity. Investment and commercialization of utilization technologies provides much greater potential for technology exports outside of Alberta compared to sequestration. Pure sequestration remains costly under current carbon tax regulations and will always depend on local geology and government policies. Utilization, on the other hand, has the potential to create self-sustaining markets almost anywhere in the world, especially as movement towards 2050 net zero targets gains momentum.

The following sections provide further background on carbon utilization LCA methodologies; the global and Alberta markets for carbon utilization technologies; and Alberta Innovates, InnoTech, and ERA’s role in supporting technology development in this field.

1.2. Life Cycle Analysis (LCA) of Carbon Utilization Technologies

LCA is an essential practice for evaluating the efficacy of carbon utilization technologies in reducing CO_2 emissions. The accepted standard is ISO 14044:2006, which specifies requirements and provides guidelines for LCA. Globally, work is underway to better apply these standards specifically to the nascent field of carbon utilization technologies. These efforts have been largely spearheaded by the Global Carbon Initiative (GCI) (Zimmermann, et al., 2020). Because carbon utilization is a relatively new application of LCA, protocols derived from the ISO standard did not exist until recently and have not yet reached general adoption.

One barrier to achieving standardization of carbon utilization LCA is that the outcome of any LCA depends on the boundary conditions of the assessment. For example, for carbon utilization technologies, this includes assumptions ranging from the source of the captured carbon, to where power and heat requirements are coming from, i.e. the carbon intensity of the grid; to the market conditions of a given technology at the time the LCA is undertaken. Even though standards exist, LCA is not straightforward, and should be considered a living assessment that must constantly be revisited and reconsidered in the context of ever-changing boundary conditions.

From 2017 – 2018, Alberta Innovates and ERA commissioned a team from the University of Calgary and University of Alberta to prepare an excel-based model framework and corresponding report, "Life Cycle Assessment of Carbon Conversion and Utilization Technologies" (Weldeyohannes, Ahmad, Islam, Bergerson, & Wolodko, 2018). The framework categorized utilization-conversion technologies and developed a standardized method for collecting data and performing LCAs across multiple technology pathways, including:

- **Mineralization**
  - Ex-situ only
- **Chemical Conversion - Feedstock/Novel Materials**
  - Reduction by chemical reaction other than hydrogen/hydrocarbons
  - Reduction involving electricity
  - Reduction by a hydrocarbon
  - Reduction by hydrogen
  - Reduction involving light (other than photosynthesis)
- **Biological Uptake**
  - Bioconversion (photosynthesis, fermentation)
- **Other CO_2 conversion methods** – i.e. thermal/plasma splitting processes.

This report did not assess the LCA for CO_2-EOR technologies, which has been studied elsewhere (Jaramillo, Griffin, & McCoy, 2009).

The Alberta Innovates/ERA-commissioned report used a set of specific boundary conditions relevant to the context in which the assessment was made. For example, the report assumed that all heat and electricity requirements would come from natural gas, leading to relatively unfavourable results for any technologies with high electricity requirements per kg of CO_2 utilized. The model also accounts for CO_2 emissions resulting from using the technologies, leading to negative results for any application involving a fuel that, when combusted, results in further emissions. Finally, the report assumes the market for all technologies remains static and does not consider new or emerging markets with the potential to grow.

Under these and other boundary conditions, the project assessed and compared CO_2 conversion pathways using the LCA model across four main metrics:

- Kg CO_2 equivalent per kg CO_2 converted
- Kg CO_2 equivalent per kg or MJ of product
- Avoided emissions compared to incumbent technology replaced; and

- Global emissions reduction potential.

Among all the pathways, according to this report, CO_2 mineralization, particularly in the concrete industry, shows the highest potential to reduce global GHG emissions. Compared to mineralization, other categories have no, little, or adverse net impact on global emissions reductions. This was the result for a few reasons. First, the concrete industry is massive, currently accounting for 8 per cent of global GHG emissions (Rodgers, 2018). Second, most CO_2 utilization-mineralization technologies are less GHG-intensive than current methods of concrete production. Finally, the use of concrete does not result in significant downstream emissions.

The report also included a sensitivity analysis. For example, the report explores the impact of heat/electricity sourced by means other than natural gas and provides an accompanying excel-based model so that boundary conditions can be adjusted to changing market or technological conditions. The positive results for the mineralization and other pathways all improve if low carbon sources of power are used for the conversion process. The model assumptions and inputs should be revisited to address specific situations over time, such as declining carbon intensity of Alberta's grid.

In parallel with Alberta Innovates' LCA activities, from 2016-present, other organizations such as the GCI have also assessed CO_2 utilization from an LCA and techno-economic assessment perspective (Zimmermann, et al., 2020) with alternate conclusions. This is discussed further in the technology and knowledge gaps section. More work is needed align Alberta Innovates/ERA's work with GCI's work in this area, as well as to complete next steps identified by the report. This is discussed in the technology and knowledge gaps section of this paper.

1.3. Global Market Landscape for Carbon Utilization

Globally, 35 GT of CO_2 are emitted each year (Lux Research, 2018). According to GCI's "Global Roadmap for Implementing CO_2 Utilization", CO_2 utilization mineralization and conversion technologies have the potential to reduce carbon emissions over 10 per cent and realize a global market of >$800B by 2030 (Lux Research, 2018). The CO_2-EOR market is also growing, as oil fields mature and lose primary productivity. The global EOR market is expected to reach $60B USD by 2025. CO_2 injection is considered one of the fastest-growing EOR applications worldwide, and accounts for approximately 60 per cent of all EOR projects in the US and Asia (Mordor Intelligence, 2021). The largest markets for carbon utilization technologies worldwide, for both EOR and conversion, are the US & China. It is not yet clear how all of these markets will be impacted by net-zero targets.

Direct CO_2 utilization via EOR is readily in use around the world today. Injection of CO_2 into mature oil formations has the potential to enhance oil recovery by reducing viscosity, swelling of the oil, vaporizing the oil, interfacial tension, and solution-gas (Moore, Mehta, Van Fraasen, Ursenbach, & Zalewski, 2005). All these factors reduce water requirements and increase the efficiency of oil production. Depending on the characteristics of the formation, the CO_2 used in EOR projects is permanently sequestered in the ground. Producers can therefore benefit from carbon credit policies in addition to the commercial benefits of CO_2-EOR.

Beyond EOR, conversion technologies offer a more diverse array of economic and technological possibility. GCI's Roadmap considers the global market for the following utilization technologies:

- **Mineralization**

    - Building materials – specifically concrete, carbonate aggregates
- **Chemical conversion - Feedstock**
    - Chemical intermediates – methanol, formic acid
    - Fuels – syngas, liquid fuels, and methane
    - Polymers

GCI's Roadmap does not examine novel materials or biological uptake technologies in detail due to the comparably small size of these markets, but acknowledges they exist (Lux Research, 2018).

According to GCI's Roadmap, of the utilization-conversion pathways, mineralization, and specifically concrete, provides the most immediate commercial opportunity; followed by fuels and chemical intermediates. Future opportunities for commercialization of novel materials are unclear, but there is high potential. According to this Roadmap, biological uptake technologies have less potential. This is in line with the market opportunities noted by the LCA model and report discussed above (2018). The GCI Roadmap acknowledges the limitations of their assessment: certain pathways such as novel materials cannot be compared on equal footing as the market was not well developed at the time of the study.

1.4. Alberta Market Landscape for Carbon Utilization

Alberta is the highest GHG-emitting province in Canada, emitting 267 MT CO_2eq in 2017 (Canada Energy Regulator, 2021). This is due primarily to its GHG-intensive oil and gas industry. To address this, the Alberta industry and government have initially focused on increasing CO_2-EOR implementation as a means to promote economic growth in parallel with sequestering large volumes of CO_2. Industry-led pilots of CO_2-EOR began in the early 2000s, some of which included government support (Gunter & Longworth, 2013). Today, the Alberta Carbon Trunk Line (ACTL) project provides the infrastructure for commercial-scale CO_2-EOR and sequestration. Enhance Energy's first-of-a-kind facility in Clive, Alberta receives CO_2 from the ACTL, floods the nearby reservoir to enable EOR and less GHG-intensive barrels of oil compared to barrels of oil produced by standard means. At the same time, the CO_2 is permanently sequestered in the ground.

The ACTL is only operating at 10% capacity, and opportunities exist for the industry to take greater advantage of this infrastructure. It has been estimated that across Alberta, deployment of CO_2-based EOR technologies could store 20-30 Mt CO_2/year, or the equivalent of removing 5-7.5 million cars from the road every year of operation (Alberta Economic Development Authority, 2009).

For carbon mineralization and chemical conversion pathways, Alberta's market landscape is immature. According to "CO_2 Conversion Landscape Analysis" by the Signals Intelligence Group commissioned by Alberta Innovates in 2014, 16 per cent of Alberta's industries are relevant to CO_2 conversion and utilization, and 70 per cent of these involve mineralization or chemical conversion (Signals Intelligence, 2014). A number of Alberta Innovates, InnoTech, and ERA-supported projects have partnered with industrial players in the concrete market, such as BURNCO and LafargeHolcim. Alberta Innovates, InnoTech and ERA's work via the Grand Challenge and NRG COSIA XPRIZE (discussed further below), particularly those hosted at InnoTech's ACCTC, have put Alberta on the global map for piloting and scaling up first-of-a-kind carbon utilization technologies. It remains to be seen which technologies will gain a permanent, commercial-scale foothold in the Alberta market.

1.5. Alberta Innovates, InnoTech, & ERA's Role in Carbon Utilization

Alberta Innovates supports carbon utilization innovations with funding on a competitive basis, and InnoTech has several testing facilities and capabilities to enable carbon utilization technology advancement in Alberta. InnoTech owns and operates the ACCTC and research facilities in Calgary focused on carbon utilization. ERA complements Alberta Innovates and Innotech by supporting mid to high technology readiness projects on a competitive basis through the call for proposals process. These funding & infrastructure resources are described in more detail below.

1.5.1. The Alberta Carbon Conversion Technology Centre (ACCTC)

Innotech operates the ACCTC, located in Calgary. The ACCTC captures CO_2 from the adjacent Shepard Energy Centre, Alberta's largest natural gas plant, and provides a steady supply of 25 tonnes of CO_2/day. The CO_2 can be concentrated if needed, enabling users to access CO_2 concentrations ranging from 4 to >99 per cent. The ACCTC has tie-ins and outdoor testing bays to host technology developers, focusing on pilot scale TRLs 6-9. The ACCTC has hosted XPRIZE and Grand Challenge finalists CarbonCure, C2CNT (now Carbon Corp), and Carbon Upcycling (CUT), all of whom were supported by both Alberta Innovates and ERA funding. The ACCTC has also hosted other technology developers including Air Co. and CERT, demonstrating the versatility of the facility to support a range of technologies. Through the commissioning and subsequent operation of the ACCTC and hosting the NRG-COSIA Carbon XPRIZE competition, InnoTech has also developed unique expertise related to carbon capture (amine-based systems) and carbon utilization (including conversion processes).

1.5.2. The Calgary Research Park facility

InnoTech has invested in research infrastructure for execution of bench-scale proof of concept R&D projects. This facility has laboratories available for testing lower-technology readiness projects in the areas of capture, conversion, and optimization, as an enabler for industry-funded commercial scale-up, including demonstration at the ACCTC. InnoTech is currently focused on (1) reducing the cost of carbon capture in novel ways, such as via cryogenics and plasma, that are more energetically and economically favorable than conventional methods; and (2) identification and optimization of CO_2 conversion and methane decarbonization technologies that are directly applicable to industrial processes in Alberta. This has the potential to drastically improve the economics of utilization technologies that rely on chemical conversion in the future.

1.5.3. ERA Support for Carbon Utilization

ERA provides funding for GHG-reducing technologies in the pre-commercial to commercial-scale stage of development (TRL 7-9). ERA has enabled carbon utilization technologies through several pathways:

- For the past decade, ERA has issued calls for proposals in areas including CCUS.
- From 2013-2021, ERA embarked on the "Grand Challenge" for carbon utilization technologies. This was a three-stage challenge across the scope of carbon utilization & conversion. It involved iterative funding: up to $500k/project for the first stage (24 projects), up to $3M/project for the second stage (4 projects), and up to $10M/project for the third stage (2 projects). The 2 finalists each received $5M and included CarbonCure, a concrete mineralization technology, and Mangrove Technologies, an electrochemical desalination and chemical production process. Further details about specific projects funded via the ERA Grand Challenge are provided in the following pages.

- ERA routinely accepts proposals via its partnership intake program (PIP), in collaboration with Carbon Upcycling Technologies (CUT) were both funded through PIP.

- ERA launched its Carbon Capture Kickstart CCUS FEED Study Competition in 2021 and anticipates future calls for proposals in the areas of CCUS and/or the hydrogen economy.

1.6. Carbon Utilization Pathways – Progress to Date

The following sections dive deeper into the carbon utilization pathways discussed in the previous section, and specific technologies that have been funded, developed and demonstrated by Alberta Innovates, InnoTech, and ERA across the pathways of direct utilization via CO_2-EOR, mineralization, chemical conversion, and biological uptake.

1.6.1. Direct Utilization

In this section, we discuss direct uses of CO_2, the largest and most established of these opportunities being CO_2-EOR; as well as novel and less developed applications, such as geothermal power, that have been supported by Alberta Innovates, InnoTech, and ERA over the years.

CO_2-based Enhanced Oil Recovery

CO_2-EOR is a compelling carbon utilization pathway in Western Canada due to the region's large and economically important oil and gas industry. There are estimated to be 1.5-2 billion incremental barrels of oil that may be recovered via injection of CO_2 in Alberta, presenting a significant economic driver to pursue CO_2-EOR, even without the sequestration aspect (Alberta Economic Development Authority, 2009). CO_2-EOR can effectively bring old reservoirs back to life by enabling recovery of an incremental 10-20% per cent of oil recovered from the reservoir by conventional means (Alberta Research Council; AERI, 2009).

Since Alberta has no natural CO_2 reservoirs, the challenge to deploying CO_2-EOR initially has historically been securing an economic source of high purity CO_2. Over time, however, interest around leveraging CO_2-EOR as a CO_2 sequestration pathway working towards a net zero future has increased. When combined with carbon capture technologies, CO_2-EOR has the potential to sequester 131Mt to 1.3 Gt of CO_2 in Alberta alone (Hares, 2020). Of note, since regulations only allow for sequestration at depths below 1000 feet, CO_2-EOR is not feasible in most of Alberta's oilsands (Government of Alberta, 2013). Therefore, while some work has been completed around CO_2-EOR in the oilsands, the major focus has been on conventional reservoirs.

CO_2-EOR has been limited in Alberta to date. In addition to CO_2 supply cost, the barriers for CO_2-EOR in Alberta include unitization and long-investment cycle compared to quick return, high yield projects (Gunter & Longworth, 2013). CO_2-EOR development in Alberta was also hindered by the US shale gas revolution and crash in the price of oil in 2015.

Despite these challenges, today, CO_2-EOR has reached commercial scale in Alberta, and is well-advanced in neighboring Saskatchewan, thanks in part to early work performed by Alberta Innovates and InnoTech. In Saskatchewan, the Weyburn Project, which began using CO_2-EOR in 2000, is now recognized as the largest underground geologic storage project in the world. To date, Weyburn has safely sequestered more than 31 million tonnes of CO_2 sourced from the coal-fired Boundary Dam Power Station and a coal gasification plant in North Dakota (Whitecap Resources Inc., 2021). Experience from the Weyburn project indicates that about 190 kg of CO_2 is sequestered for every barrel oil produced (IEA, 2004).

In Alberta, while the industry has not yet reached its full potential, promising commercial-scale work is underway. Enhance Energy is now performing simultaneous CO_2-EOR and sequestration using CO_2 sourced from the ACTL that originates from emitters in the Alberta industrial heartland. In March 2021, Enhance announced the milestone of sequestering 1 million tonnes of CO_2 to date (Enhance Energy, 2021). The ACTL is only 10% full now so there is significant capacity to add more CO_2-EOR projects in the region. At full capacity, the ACTL could transport up to 14.6 million tonnes of CO_2 per year, which represents approximately 20 per cent of all current oil sands emissions or the equivalent of capturing CO_2 from more than 2.6 million cars in Alberta (Enhance, 2021).

CO_2 EOR – Progress to date

CO_2-EOR projects in Western Canada began in the early 2000s at the Weyburn field in Saskatchewan and the following large-scale pilots in Alberta: Swan Hills, South Swan Hills, Judy Creek, Redwater, Enchant Arcs, Zama and the Pembina Cardium; as well as a number of small-scale pilots that happened to be located near a CO_2 source (Gunter & Longworth, 2013). Alberta Innovates and InnoTech, in partnership with the University of Calgary and industry partners, supported experiments at several of these pilots. Additionally, Alberta Innovates and InnoTech have commissioned comprehensive reports that span assessments of techno-economic potential of CO_2-EOR in Alberta, barriers to CO_2-EOR commercialization, and transitioning CO_2-EOR projects to long-term sequestration projects. All these projects and reports have paved the way for commercial-scale CO_2-EOR deployment in Western Canada that is in turn having a meaningful impact on reducing CO_2 emissions today, in addition to being a significant source of economic growth. A summary of these reports and their major findings are provided below.

EOR- CO_2 Pilot Projects at the Weyburn Field in Saskatchewan

The Weyburn field, one of the largest medium-gravity crude oil fields in Canada, was discovered in 1955. The field covers approximately 180 km^2 in the southeastern corner of Saskatchewan and produces oil from the Midale Beds of the Mississippian Charles Formation (Elsayed, Baker, Churcher, & Edmunds, 1993). The field was operated by Cenovus until 2017 and then sold to Whitecap Resources.

This field has benefitted from numerous innovations, including the start of CO_2 enhanced oil recovery in 2000. At that time, the field was also the focus of a major international research initiative to monitor CO_2 storage, called the "IEA GHG Weyburn-Midale CO_2 Monitoring & Storage Project". This Project, which began in 2008, is recognized as the largest underground geological CO_2 storage project in the world (Whitecap Resources Inc., 2021). It was designed to study methods for monitoring CO_2 movement in the subsurface and determine the security of storing CO_2 for hundreds to thousands of years.

In 2013, as part of this larger effort, InnoTech completed two studies. The first entailed a mechanistic modelling approach to determine the long-term fate of CO_2 in a 2.15 km^2 area, to draw broader conclusions around CO_2 sequestration potential across the entire field. In collaboration with Cenovus and the Petroleum Technology Research Centre (PTRC), InnoTech completed predictive simulations showing an additional oil recovery of 19 per cent due to miscible CO_2 flood. Total CO_2 stored in the simulated area at the end of the operation was projected to be 2.48 million tonnes within the 2.15 km^2 area. The study determined that mechanical dispersion plays a critical role in the performance of CO_2-EOR and geologic storage and recommended several improvements in mechanical dispersion strategies for enhanced long-term recovery and sequestration (Uddin, Jafari, & Perkins, 2013).

In addition to the mechanistic modelling study, InnoTech completed a project that entailed use of geochemical tracers into a model of fluid flow and phase behavior. The researchers used a reservoir model to obtain flow patterns and phase behaviors, which were history matched to oil & water production rates. This project enabled the partners to establish the baseline (pre- CO_2 EOR) chemical and isotopic conditions of the Weyburn Reservoir; monitor changes in the chemical and isotopic composition of produced aqueous fluids and gases at the wellheads and establish the position of the CO_2 front through chemical monitoring at the producing wells; and assess the gas distribution within reservoir fluids and its interaction with reservoir rock under subsurface conditions (Talman, Perkins, Jafari, & Shevalier, 2013).

CO_2-EOR Pilot Projects in Alberta

In the early 2000s, building on some of the early work at the Weyburn field, Alberta Innovates and InnoTech also supported pilots in Alberta; namely the small-scale Medicine Hat Glauconitic Pool as well as the large, industry-led pilots at Swan Hills and Penn West (Pembina).

In 2002, Alberta Innovates commissioned a study by Vikor Energy at Medicine Hat to assess the feasibility of CO_2 flood to enhance oil recovery over time. The Medicine Hat Glauconitic Pool is a small pool that was discovered in 1981 and heavily drilled until the mid-1990s, prior to being subject to waterflood starting in 2001. Modelling predicted that at the end of the waterflood, significant oil would remain in the reservoir. There also happened to be a relatively inexpensive CO_2 source nearby from a previous CO_2-EOR pilot, making this reservoir an obvious candidate for a small-scale CO_2-EOR pilot (Vikor Energy, 2002).

The Alberta Innovates study found that CO_2 causes viscosity reduction and increased oil swelling, in turn causing injected water to displace CO_2-saturated oil more effectively than without CO_2. The study evaluated different combinations of CO_2 and water, concluding that simultaneous injection (a water-alternating-gas scheme) was most effective at increasing production, with a high water-to-CO_2 ratio (Vikor Energy, 2002).

Alberta Innovates and InnoTech also supported work at some of the Alberta industry's early large-scale pilot fields; namely the Swan Hills Reservoirs (Moore, Mehta, Van Fraasen, Ursenbach, & Zalewski, 2005) and Penn-West (Lawton, Coueslan, Bland, & Chen, 2005), located in the Pembina field.

Swan Hills Reservoirs, part of Beaverhill Lake and owned by Devon Oil Corporation, was among the early large-scale CO_2-EOR pilots in Alberta. Swan Hills was discovered in the 1950s and heavily drilled until the end of the 1960s. The field began to decline and was then tested for waterflood in the 1980s. In 2005, Alberta Innovates worked with University of Calgary researchers to assess the Swan Hills reservoirs for CO_2-EOR potential. The larger goal of this project was to evaluate the effect of oxygen as an impurity in the CO_2 stream. Injection of CO_2 into this type of reservoir showed similar effects to Medicine Hat of reducing oil viscosity, among other effects to enhance recovery. The report observed and recorded phase changes at different purities of oxygen in the injected CO_2 (Moore, Mehta, Van Fraasen, Ursenbach, & Zalewski, 2005).

Subsequently, Alberta Innovates commissioned researchers from the University of Calgary to assess another depleted reservoir, the Penn West Pilot, located in the Pembina Oil Field, for efficacy of CO_2-

EOR and geological storage of CO_2. They developed a baseline seismic program to determine how securely the CO_2 was staying in the ground (Lawton, Coueslan, Bland, & Chen, 2005).

CO2 EOR in the Oil Sands

Beyond looking at conventional reservoirs, which have the most potential for CO_2-EOR both from a recovery and sequestration perspective, Alberta Innovates has also completed work assessing CO_2 injection in oil sands using the VAPEX process. While this work has not directly led to commercial-scale projects for CO_2-EOR, it has improved the province's comprehensive understanding of CO_2 recovery and sequestration potential.

From 2003 – 2008, Alberta Innovates worked with the University of Calgary to evaluate a CO_2-based VAPEX process for in-situ recovery of bitumen from oil sands reservoirs, with the potential side benefit of permanent CO_2 sequestration. Thermal methods such as steam assisted gravity drainage (SAGD) are most common for extracting bitumen in Alberta and in the heavy oil industry around the world. These methods can be uneconomic in smaller or more difficult to extract oil due to the high heat requirements. In these cases, VAPEX may prove more economic. Testing for this project included an experimental program for CO_2-heavy oil systems and semi-scaled physical model tests of the CO_2-based VAPEX process. The results showed that displacing methane with CO_2 is effective at high pressures (Maini & Yarranton, 2008).

While the VAPEX process itself has continued to gain traction for use in the oil sands, including a large-scale project recently completed by MEG Energy (ERA, 2020a), there has been less focus on developing this for CO_2-EOR specifically because of the limited potential for CO_2 sequestration.

Enhanced Gas Recovery

Alberta Innovates has also performed some limited laboratory-scale work on enhanced gas recovery (EGR). In 2004, Alberta Innovates investigated EGR and CO_2 storage for Alberta gas pools, using 1D laboratory tests on gas/gas displacement. The tests demonstrated that EGR is technically feasible and most effective with mixtures of gases. The study also included a preliminary economic assessment for 13 depleted Alberta gas pools selected. Previously, very little work had been done in this area; and only by the US and Hungary. The test results were promising and suggested additional testing was warranted. Follow on work has been limited, however, due to greater focus being placed on EOR (Turta, Sim, Singhal, & Goldman, 2004).

CO_2-EOR Feasibility Analyses

The early pilot work discussed above was for the most part successful and indicated tremendous potential for CO_2-EOR in Alberta, as well as enabling improvements in CO_2-EOR technology; however, there remained a need for a more comprehensive understanding of CO_2-EOR potential, barriers, and long-term strategies for CO_2 sequestration. Subsequent work by Alberta Innovates and InnoTech in the 2010s transitioned into more strategic reports for assessing the broader Alberta CO_2 EOR landscape. This includes "CO_2 Potential in Alberta" (Alberta Research Council and AERI, 2009), "Overcoming Barriers to Commercial EOR" (Gunter & Longworth, 2013), "Identification of Oil Reservoirs in Alberta Suitable for CO_2-EOR" (Bachu & Jafari, 2016), and "Transitioning of Existing CO_2-EOR Projects to Pure CO_2 Storage Projects" (Jafari & Faltinson, 2013), discussed below.

In 2009, Alberta Innovates (then-Alberta Research Council) completed a report, "CO_2 EOR Potential in Alberta", in partnership with AERI (Alberta Research Council and AERI, 2009). This report was commissioned because Albertans needed a better understanding of the potential CO_2-EOR opportunities and limitations, and to collect data that would enable the acceleration of CO_2-EOR projects. The project included a detailed reservoir development analysis and quantification of the potential for incremental oil recovery and associated CO_2 capture results from five prototype pools, which were subsequently extrapolated to 35 analogue pools to provide an estimate of total CO_2 EOR potential in the province.

This study improved upon earlier work by providing detailed, technical reservoir evaluation, although it did not include a detailed economic assessment. The study did also not take into account the cost of CO_2 delivery to the site. The study concluded that based on CO_2-EOR predicted incremental recovery, the development of Beaverhill Lake (BHL) hills should take priority over Pembina pools (Alberta Research Council and AERI, 2009). This was mainly due to BHL's higher processing rate; and its better position to permanently contain the CO_2 flood. The total potential CO_2-EOR for all the prototypes and analogues studied was predicted to be 171.4M m^3 and would require 253 million tonnes of CO_2 – the majority of which would be stored permanently in the target reservoirs (Alberta Research Council and AERI, 2009).

Subsequently, in 2013, Alberta Innovates commissioned Bach Enterprises and Amulet Solutions to write a report (Gunter & Longworth, 2013) identifying commercial barriers and making recommendations to overcome them. The report assessed ideal technical features for CO_2-EOR fields in Alberta, but also the carbon price at which CO_2-EOR becomes economic in competition with other oil and gas projects. The report was commissioned at the time of the US shale revolution, however; with quick return, high yield projects posing a source of competition to longer term, high capital CO_2-EOR investments. This was a significant barrier to economically deploying CO_2-EOR in Alberta.

In 2016, Alberta Innovates took on a second comprehensive assessment of CO_2-EOR in Alberta. While CO_2-EOR posed an attractive option for Alberta oil and gas companies to simultaneously enhance oil production and be part of a green energy future, most studies to date had focused on company-specific reserves, and the results were proprietary. This study was commissioned to amend that gap. This project entailed a province-wide assessment for miscible CO_2-EOR, based on information found in the Alberta Energy Regulator's databases using a set of 14 screening criteria. Incremental oil production was estimated for various combinations of injection CO_2 and water volumes.

The study concluded that of the approximately 13,000 reserves in Alberta, 264 reservoirs met the criteria set for CO_2-EOR; with Pembina and Redwater D3 being the largest by far (Bachu & Jafari, 2016). Incremental oil recovery ranged 10-12 per cent, producing 260,000 – 306,000 incremental m^3 oil, storing 902-945 Mt CO_2 if miscible CO_2-EOR was implemented (Bachu & Jafari, 2016). This represents about 9 years of CO_2 emissions from Alberta's largest emitters (over >500 kt CO2/year) (Bachu & Jafari, 2016).

Recognizing a gap between existing CO_2-EOR projects focused solely on production vs long term sequestration, in 2013, Alberta Innovates commissioned a project to develop a transition scheme between "CO_2-EOR" projects and "carbon capture and storage (CCS)" projects. The objective of the transition hybrid scheme was to maximize CO_2 storage while continuing oil production which otherwise would have been uneconomic. This would create additional storage space in the reservoir by producing incremental oil, with the reservoir produced water being disposed of in another formation.

A hypothetical reservoir simulation model was used to illustrate the shift over time from a conventional CO_2-EOR project to a hybrid CO_2-EOR/CO_2 storage scheme, and then to a pure CO_2 storage scheme. The project concluded that insertion of a hybrid transition phase between the end of the CO_2-EOR operation and the initiation of a pure CO_2 storage operation leads to an incremental oil recovery factor of approximately 9 per cent (Jafari & Faltinson, 2013). More importantly, the report showed that the implementation of a hybrid scheme significantly increases the amount of CO_2 storage in the reservoir, by up to 67 per cent (Jafari & Faltinson, 2013).

Thanks in part to the foundational work of Alberta Innovates and InnoTech, CO_2-EOR is now in commercial scale operations in Alberta and Saskatchewan, despite not having reached its full potential. Importantly, the regulatory structure for CO_2-EOR is now in place, and the ACTL, completed in mid-2020, is now directly connecting CO_2 sources at refineries in the Alberta Industrial Heartland with EOR fields in central Alberta. For prospective users of CO_2 EOR, it is primarily a matter of receiving approvals to operate and securing a source of CO_2. They will either co-locate with facilities that generate and capture CO_2, or within a certain proximity to the ACTL, which is currently only operating at partial capacity.

As part of increased support for rapid adoption of CCUS, the Government of Alberta is also currently exploring a "hub" approach to carbon sequestration, including CO_2-EOR, to increase equitable access across the industry. There are also several large-scale projects underway to increase CO_2 capture and thus the capacity and thus utilization of the ACTL.

CO_2 Direct Utilization – Novel Applications

Beyond CO_2-EOR, CO_2 may be directly used in several other comparatively small-scale applications, ranging from carbonated beverages to producing geothermal power. While Alberta Innovates, InnoTech, and ERA's work in this area has been limited, we note two projects below.

In 2012, Alberta Innovates (then Alberta Innovates-Technology Futures) worked with Canmet Energy to evaluate the technical possibility of using supercritical CO_2 ($ScCO_2$) as working fluid to extract heat from geothermal reservoirs. The numerical modelling study explored some of uncertainties associated with this application, such as the rate of thermal drawdown and recharge of the reservoir; the corrosive nature of $scCO_2$-water mixture and its impact on equipment design and cost; the impact of formation mineralogy and $scCO_2$ interactions at elevated temperatures; the rate of CO_2 sequestration and its ultimate fate; and the realistic modelling of phase change characteristics. The results demonstrated that despite the lower heat capacity of $scCO_2$ compared with that of water, the lower viscosity of CO_2 results in a higher mass flow rate for similar operating conditions, and therefore higher energy extraction rates from reservoirs (Jafari & Mannan, 2012).

In another novel application, ERA is currently supporting a brewery in central Alberta, Blindman Brewing, to capture and recycle a portion of the CO_2 produced by the brewing process. The brewery normally spends thousands of dollars per year purchasing CO_2 to inject into their beer, while also producing CO_2 waste as part of the process. Under this project, the brewery will be capturing the CO_2 that would have other been waste, scrubbing it and compressing it to carbonate their beers and run canning lines — reducing their emissions, and need to purchase CO_2 nearly to zero. This is accomplished using a device about the size of a refrigerator. Blindman is the first small brewery in Canada to capture and recycle their CO_2. With thousands of breweries across Canada, the US, and the world, they hope to pave the way for broader market adoption (Rieger, 2021).

1.6.2. Mineralization, Chemical Conversion, & Biological Uptake

Beyond direct utilization, CO_2 may also be converted to carbon-based materials as a means of enhancing their properties and/or permanently sequestering CO_2. These technology pathways are typically divided into (1) mineralization, (2) chemical conversion, which includes feedstock chemicals, fuels, & novel materials, and (3) biological uptake. In Alberta, all these pathways are considerably less developed than CO_2-EOR. ERA, Alberta Innovates, and InnoTech have all performed significant work to advance all these pathways; particularly via ERA's Grand Challenge from 2013-2021, as well as support for recipients of the NRG-COSIA XPRIZE from 2015-2021. Funded projects, outcomes, and the current status of these technology applications in Alberta, are discussed in the following sections.

It is worth noting that the goal of these projects was not only to scale up and advance the technologies, but to open up meaningful economic opportunities in Alberta. In some cases, while commercialization was not achieved in Alberta, the companies nonetheless leveraged Alberta Innovates, InnoTech and ERA support as a stepping-stone to enable technology transfer across Canada and in some cases, worldwide. In other cases, lack of follow-on progress illustrates the fundamental techno-economic and LCA barriers that remain to widespread commercialization of these technologies.

Mineralization

CO_2 mineralization is a process in which CO_2 reacts with metal (hydro)oxides or metal (hydro)silicates in cement, concretes, fly ash, furnace slugs, mafic rocks (e.g., basalt), and mafic rock mining tailings to form carbonate minerals. In CO_2 mineralization, the carbon ion remains at an oxidated state and the mineralization process is energetically favorable. Material properties may be enhanced when CO_2 mineralization occurs. Mineralization presents the second largest volume CO_2 utilization opportunity after CO_2-EOR.

The largest and most developed mineralization pathway by far is in the concrete industry. Concrete is the world's most abundant man-made material, and its production is responsible for 8 per cent of global GHG emissions. Cement, the binding material used to make concrete, is the most carbon-intensive ingredient, and is combined with aggregates to form concrete. Cement and concrete production offer promising avenues for commercial-scale CO_2 utilization and sequestration.

The mineralization pathway is compelling from a lifecycle analysis perspective because: (1) the mineralization process generally captures more CO_2 than it emits, and (2) no further emissions result during the use of the mineralization end-products. Moreover, in the case of concrete, CO_2 mineralization products can avoid CO_2 by being less CO_2-intensive than the incumbent products they replace (i.e. cement). As a result, mineralization technologies may be carbon negative from a lifecycle perspective through both CO_2 utilization (uptake), modest CO_2 emissions resulting from the process, and potential CO_2 avoidance downstream (Weldeyohannes, Ahmad, Islam, Bergerson, & Wolodko, 2018).

ERA supported eight mineralization technologies through its Grand Challenge launched in 2013. InnoTech hosted XPRIZE finalists CarbonCure and Carbon Upcycling Technologies (CUT) at the ACCTC, both of whom were supported by ERA and Alberta Innovates funding. Key learnings from these successful projects are summarized below.

CarbonCure

One of ERA's most successful carbon utilization technologies funded to date is CarbonCure, whose technology involves injection of CO_2 into concrete during mixing to form calcium carbonate ($CaCO_3$), permanently storing the CO_2. In masonry and ready-mix applications, CO_2 reacts with freshly hydrated cement; whereas in wash water and recycled concrete applications, CO_2 reacts with hydrated cement. Mineralized CO_2 improves the concrete's compressive strength, which in turn reduces overall cement requirements, resulting in CO_2 avoidance.

With this CO_2 mineralization method, a relatively modest quantity of CO_2 is utilized. The larger CO_2 reduction opportunity results from CO_2 avoidance, due to reduced cement usage in the concrete. CarbonCure's project in Round 2 of the Grand Challenge indicated that approximately 0.3 tonnes CO_2 can be utilized and 2.5 tonnes cement avoided (or 2 tonnes of CO_2) per 1,000 tonnes concrete (Lehigh Heidelberg Cement Group, 2020). Of note, the process uses relatively little energy, approximately 62 kWh/tonne CO_2 utilized (LeBlanc, 2022), making it easily carbon-negative, even under today's grid conditions.

The technology is now considered commercial and CarbonCure has agreements and contracts in place with several concrete suppliers in Alberta to implement their technology and to supply low carbon concrete. In 2019, Calgary International Airport built a new centralized deicing pad, the East Deicing Apron, using low-carbon concrete made with CarbonCure processes. The East Deicing Apron project saved 160 tonnes of CO_2. How much GHG emissions reductions this technology can realistically bring to Alberta has yet to be quantified.

Carbon Upcycling Technologies

Alberta Innovates, InnoTech, and ERA have each contributed to the scale up of Carbon Upcycling Technologies (CUT), another successful mineralization technology. Similar to CarbonCure, CUT's technology utilizes CO_2 by injecting it into fly ash, an ingredient of concrete, and also avoids CO_2 by reducing cement requirements for concrete production. Fly ash is first chemically activated to absorb CO_2. Then CO_2 is injected into a 'reactor', or a pressurized ball mill assisted by the presence of catalyst. The CO_2-treated fly ash can improve concrete compressive strength at lower cement mixtures.

In Alberta, CUT operates out of the ACCTC and uses concentrated CO_2 from the flue stream at the Shepard Energy Centre, a natural gas power plant. Their facility was scaled up to 20 tpd of CO_2-embedded fly ash materials over the course of 2021. CUT has several partnerships with concrete producers in Alberta, including Lafarge, Burnco, and CEMEX.

Based on production rates at the ACCTC over the past year, CUT utilizes approximately 10 tonnes of CO_2 in 200 tonnes of fly ash for every 1,000 tonnes of concrete, displacing 10-15 tonnes of cement (Thomas, 2007), resulting in 8-12 tonnes of CO_2 emissions avoided (Carbon Upcycling Technologies, 2021) (Lehigh Heidelberg Cement Group, 2020). At commercial scale, the power requirements and resulting emissions have not been quantified; but based on the information available, this technology would lead to CO_2 reduction by reducing cement content in concrete.

Other Mineralization Work

The above projects are nearing completion of their government-supported work and have achieved commercial scale. Additional mineralization projects funded by the ERA Grand Challenge or other means are described in Appendix 1.

In terms of other ongoing work, InnoTech is now conducting a series of R&D initiatives for developing a new CO_2 mineralization concept. The concept is for reuse of finely crushed construction waste concrete and a CO_2-activated bonding agent for producing construction masonry blocks. This has been designed based on a circular economy way of thinking: to make meaningful impact on carbon footprint by reducing the CO_2 production by reducing cement production (scope 3, or downstream emissions), as well as sequestrating CO_2 in the structure of the produced concrete blocks (scope 1, or at-source emissions).

Chemical Conversion

The second major pathway for CO_2 utilization outside of EOR is chemical conversion. Chemical conversion of CO_2 is a process in which either CO_2 or carbon ion in CO_2 is converted into materials, chemicals, and fuels. In this process, the cationic carbon ion (C^{4+}) in CO_2 molecules is chemically reduced to elemental carbon (C) or anionic carbon (C^{4-}). This conversion process requires significant energy input. The GHG reduction potential of a CO_2 chemical conversion process depends on the nature of the input energy. If fossil fuel is used as input energy, the process will release more CO_2 than the amount of CO_2 converted. The products from chemical conversion processes may bring further GHG reduction benefits during their use, however. Therefore, there may be overall GHG reduction benefits although the actual conversion process is often GHG positive (CO_2 released is more than CO_2 converted in the conventional process). For example, if CO_2 from a fossil-fuels power plant is captured and on-site electricity is used to make carbon nanotubes, there will likely be net positive on-site GHG emissions. But when the carbon nanotubes are used to reduce cement use in concrete, there will be downstream GHG benefits that may result in a net GHG benefit across the value chain.

ERA has funded 16 chemical conversion projects via the Grand Challenge. A number of representative projects are summarized here to illustrate the potential of chemical conversion for CO_2 utilization, with additional projects noted in Appendix 1.

CarbonCorp (formerly C2CNT)

Alberta Innovates and ERA have jointly supported scaleup of Carbon Corp (formerly C2CNT). Carbon Corp (formerly C2CNT)'s technology, called "Genesis Device™", produces carbon nanotubes (CNTs) via molten electrolysis. CNTs have excellent thermal and electrical conductivity and can be used as composites in a variety of materials to increase strength and reduce overall material requirements. Carbon Corp recently completed work at the ACCTC utilizing concentrated CO_2 from the flue stream of the Shepard Energy Centre. The process utilizes 3.7 tonnes CO_2 and 7 MWh per tonne of CNTs produced (Carbon Corp, 2022). Thus approximately 4 tonnes CO_2 will be released under current grid conditions (0.57 tonnes CO_2eq/MWh), but 2.5 tonnes CO_2 will be released if the electricity is from natural gas combined cycle (0.35 tonnes CO_2eq/MWh).

Going forward, Carbon Corp has partnered with Capital Power, who is in the early stages of constructing a facility at their Genesee Generating Station based on Carbon Corp's technology to produce 2500 tonnes of carbon nanotubes per year in its first phase Station (Genessee Carbon Conversion Centre (Phase 1), 2021). Capital Power's estimates show that one tonne of CNTs has the potential to displace up to 940 tonnes of cement, which equates to 770 tonnes CO_2 avoided, assuming general-use Portland Cement (Deeg, 2022) (Lehigh Heidelberg Cement Group, 2020). This has yet to be confirmed by the market due to the emergent nature of CNTs.

Carbonova

Carbonova's technology uses a patented catalyst and converts CO_2 and natural gas into carbon nanofibres (CNFs). CNFs can reduce cement loading in concrete or resin loading in polymer composite materials. Carbonova' CNFs will likely have lower GHG intensity than incumbent products which amount to 20 tonnes of CO_2 per tonne of CNF produced (Toray, 2022). Similar to Carbon Corp's technology described above, CNF can enable Scope 3 emission reductions; but the full potential magnitude of this impact is not yet understood due to the emergent nature of the CNF market. The technology is at an early stage, and a full life cycle analysis of the CO_2 emission reductions is yet to be performed.

Mangrove Technologies

Mangrove was an overall winner of ERA's Grand Challenge. Their process converts waste gases and saline water to desalinated water, hydrochloric acid, and sodium hydroxide using electric power. The sodium hydroxide can be used to convert CO_2 and other GHGs to carbonate or bicarbonate salts, which can be used in oil and gas operations. From a lifecycle perspective, Mangrove estimates that GHG reductions from a desalination facility of 1000 m^3/day capacity would be 30,660 tonne CO_2eq/year, inclusive of CO_2 utilized and avoided. Mangrove is now finalizing the design of a system that will ultimately be demonstrated at Canadian Natural Resources Limited (CRNL) mining site in Alberta. Successful commercial rollout of Mangrove's technology could result in an estimated 265 kt CO_2 emissions reductions/year in Alberta (Mangrove Water Technologies, 2019).

McGill University Artificial Photosynthesis

In the artificial synthesis process, a semiconductor acts like a kind of artificial leaf. Solar energy is captured by the semiconductor, which leads to the generation of electron/hole pairs. The energetic photogenerated electrons can reduce input CO_2 to higher energy carbon-based compounds such as CO and CH_4, if the conduction band minimum is more negative than the reduction potential of CO_2. McGill's process uses type III-nitride semiconductor materials, which have large absorption coefficients in the visible range, excellent charge carrier properties, a tunable band via slight variations in the alloy content, all while being able to encompass the redox potentials of water splitting and CO_2 reduction (Mi, 2020). The process is still at laboratory scale; and no system engineering work has been completed to date. But remains a potential avenue to a fully circular CO_2 ecosystem. McGill researchers are not currently performing any work in Alberta, and CO_2 utilization/avoidance at this stage is negligible.

CO_2 to Fuels Example

The area of CO_2 to fuels, in which the CO_2-produced fuels are combusted downstream, is a particularly challenging case of carbon utilization from a lifecycle perspective. In many of the previously discussed examples, regardless of whether the core processes themselves are CO_2 positive or negative, the resulting CO_2-derived products do not emit CO_2 themselves and also tend to avoid CO_2 by displacing more GHG-intensive incumbents at end use. In the case of CO_2-to-fuels, not only is the conversion process energy-intensive and often carbon-positive, the products themselves will result in additional emissions reductions as identified in IEA (2019) and Weldeyohannes et. al. (2018).

Chemical Conversion- Innotech Work

Notably, through the past five years of commissioning and subsequent operation of the ACCTC, InnoTech has advanced in developing unique expertise related to carbon capture (amine-based systems) and conversion, particularly in feedstock technologies. This learning has the potential to greatly improve the economics and thermodynamics of conversion-feedstock technologies in the future. InnoTech is now investing in research infrastructure to enable bench-scale, proof of concept and lab-scale pilot plant projects to advance technology solutions geared towards implementation in Alberta. InnoTech is currently at various stages of technology evaluation for a range of technologies including plasma methane pyrolysis, metal oxide CO_2/methane conversion, CO_2 to synthetic diesel/alcohol/syngas, induction heating-assisted dry reforming of CO_2/CH_4, and CO_2 to polymer conversion.

InnoTech is establishing a plasma methane pyrolysis processing laboratory specializing in GHG abatement. The laboratory is equipped with several different types of plasma equipment and is focused on converting methane to hydrogen, hydrogen to ammonia, CO_2 to CO and any other potential options using a cost and energy-effective energy delivery mechanism. This process is intended for producing hydrogen from natural gas without producing CO_2. It is applicable for all hydrogen consuming, gas producing companies, refineries and up grading processes. The technology is currently at technology readiness level (TRL) 3.

The metal oxide CO_2/methane conversion concept has global applications and the potential to make a step change in GHG reduction. This concept was developed in-house to convert CO_2 to added value elemental carbon and is currently at TRL 3. It is a chemical looping process where the active agent circulates in a looping process and converts CO_2 to elemental carbon. InnoTech is currently working on combining this with a University of Calgary technology for direct air capture. This was recently included in the AVATAR accelerator program for submission into the XPRIZE for Carbon Removal competition.

The CO_2 to Synthetic Diesel/Alcohol/Syngas technology converts a mixture of CO_2 and hydrogen to alcohols (methanol or ethanol) and is at TRL 3. In this concept, the intention is to use methane as a direct source of hydrogen and drive the reaction forward by adjusting the process conditions such as pressure, temperature, or mixture ratio. This technology is applicable to the oil and gas industry. The energy inputs to generating fuels from CO_2 have inherent thermodynamic challenges that often result in net increases in CO_2 emissions, however.

The induction heating assisted dry reforming of CO_2/CH_4 technology has been studied for the last few decades, but there is no commercial deployment. This initiative evaluates the potential use of induction heating applications for dry reforming purposes by implementing a better energy delivery mechanism. This technology is applicable to the oil and gas industry.

The CO_2 to polymer conversion technology concept is designed to convert CO_2 to a polymer or surfactant via a chemical reaction. The intent is to produce a material that has a wide range of applications, such as servicing water treatment and tailings. It is currently at a TRL 2.

Biological Uptake

Beyond direct utilization, mineralization, and chemical conversion, CO_2 can also be converted to fuels through biological processes based on photosynthesis. Natural photosynthesis by sunlight is responsible for plant growth on the Earth and is responsible for almost all of the approximately 160 billion liters of biofuels predicted to be produced globally in 2021 (IEA, 2020). There have been also many technology developments to use CO_2 to algae conversion. In this process, CO_2 is used to grow algae, which stores the chemical energy. Many algae-to-CO_2 conversion technologies are also based on using natural sunlight. Even large global oil companies such as ExxonMobil invested in algae growth in early 2010s. But most algae players exited from the market, and investment began to decline before 2016 (Global CO2 Initiative, 2016). The main challenge is economical, but water use intensity is also a concern. Lifecycle analysis for bioconversion technologies faces issues not so much on the core process but on logistics and scalability issues, according to Weldeyohannes et. al. (2018).

Alberta Innovates, InnoTech, and ERA's work in this area has been limited, but ERA funded three bioconversion projects involving microbes and microalgae via the Grand Challenge Round 1. This work is described in Appendix 1. These projects did not proceed in part due to the scalability issues discussed above. None of Alberta Innovates, InnoTech or ERA have ongoing work in this area, apart from some work looking at natural CO_2 sequestration.

In addition to the biological uptake projects funded through the Grand Challenge, Alberta Innovates and InnoTech performed several years of bio-char research in partnership with the University of Alberta. While not technically a 'biological uptake' carbon utilization technology by the conventional definition, this project involved conversion of CO_2 already stored in biomass waste to a more permanent form. This is also discussed in Appendix 1.

1.7. Insights, Remaining Gaps and Recommendations - Utilization

Collectively, Alberta Innovates, InnoTech and ERA have spent more than $50M on carbon utilization technologies over the past 20 years. This support has ranged from early seed funding to co-funding commercial-scale, first-of-a-kind pilots across the full spectrum of carbon utilization pathways. In some cases, Alberta Innovates, InnoTech and ERA have supported companies through early development all the way up to commercialization in Alberta.

CO_2-EOR is now advancing commercially and is expected to be the largest volume near-term opportunity in Alberta. Mineralization also continues to have significant potential. Key mineralization technologies such as CarbonCure and CUT have successfully completed first commercial production and sale in Alberta, facilitated by the support of Alberta Innovate, ERA, and Innotech. CarbonCure and CUT technologies provide a good benchmark for new mineralization technologies going forward.

Chemical conversion is more energetically challenging than mineralization, but government support in this area has resulted in some promising technologies with the potential to promote new industries and result in net CO_2 benefit. This includes tailored oilsands applications like Mangrove Technologies, and technologies that could result in significant downstream CO_2 avoidance by displacing CO_2 intensive incumbents. An example technology is CarbonCorp's Genesis Device™ that produces CNTs from captured flue gas streams. This technology will enter commercial scale production at Capital Power's Genesee Carbon Conversion Centre over the next few years.

Biological uptake as a utilization pathway looks less promising in Alberta in the near term, due mainly to logistical and scaling challenges of microalgae production.

Going forward, strategic gaps remain to achieving Alberta's full potential. These gaps & recommendations to addressed them are discussed below.

Gap: Revising Lifecycle Assessments

Gaps remain in revising our understanding of LCA across each of the major carbon utilization pathways. Alberta Innovates and ERA, in collaboration with the University of Calgary and University of Alberta, produced a comprehensive LCA report on carbon utilization. The report had some limitations, however, which the authors identified, and laid out the following next steps to address:

- Expand LCA cases by engaging more technology developers;
- Expand LCA results from literature;

- Assess economic facility/TRL, explore range of scale up technologies;
- Host an expert workshop to discuss results from Phase 1 to get input into breadth of study;
- Develop an open-source tool to facilitate consistent assessment by all stakeholders; and
- Collaborate/coordinate with other global initiatives.

While some of these next steps are in the preliminary stages, most have not been completed and more work is needed. For example, the LCA methodology should be revisited under the boundary conditions of today, as well as 2030 and 2050 energy mix scenarios. The model should also be revisited to account for recent technological advances; for example, improvements in conversion economics and thermodynamics, and global market changes in the field of novel carbon nanomaterials. The results could feed into the technology roadmap discussed below.

There are also gaps in aligning the previous LCA work with other global initiatives. In parallel with Alberta Innovates' LCA activities, from 2016 - present, the GCI, in partnership with international industry experts, conducted an even broader activity around CO_2 utilization LCA, focused on standardization and alignment with techno-economic assessments (TEAs) (Zimmermann, et al., 2020). They developed a preliminary set of guidelines for performing LCA specific to CO_2 utilization technologies, in answer to the lack of generally accepted application of the ISO standard. Version 1.0 of these Guidelines was published in 2018 and Version 2.0 was recently published in 2020. Their categorization divided up utilization technologies in a very different manner than the Alberta Innovates/ERA LCA report. Any follow up work on the Alberta Innovates-sponsored carbon utilization study should be reconciled with the GCI project approach to align on methodologies and accelerate standardization.

Gap: Understanding the Alberta Market for Carbon Utilization Technologies

There are gaps in understanding the market for carbon utilization in Alberta across all carbon utilization pathways.

In the area of CO_2-EOR, little to no work has been performed by Alberta Innovates or InnoTech in the past 10 years. The global oil and gas industry has undergone many changes since these reports were written; namely the US shale gas revolution in the early 2010s and the crash in oil prices, negatively impacting Alberta's economy, in late 2014 and early 2015. Oil prices have since partially recovered, but as global pressures and support for climate change has intensified, prices are unlikely to recover to the high levels seen in the early 2000s. On the other hand, interest in CO_2 sequestration and introduction of aggressive carbon pricing has improved the economics of CO_2-EOR. While the technical conclusions of these reports remain relevant, from an economic perspective, gaps remain in assessing CO_2-EOR in the context of today's political and economic climate.

Furthermore, while Alberta has a clear niche for CO_2-EOR, market opportunities for carbon conversion technologies are not well understood. Mineralization and conversion pathways require further analysis to determine which are the most promising for Alberta, and which have industry advocates to enable large-scale commercial adoption. Examples of gaps to be addressed include:

- Understanding the Alberta-specific drivers and constraints for large-scale industrial players in the concrete industry to maximize adoption of mineralization technologies
- Improving the economics & lifecycle CO_2 balance of carbon conversion technologies, in coordination with carbon capture technologies

- Determining which conversion technologies are best suited for a changing energy landscape – for example integration into an envisioned future hydrogen economy
- Capitalizing on Alberta's first-mover progress in globally emergent areas, like CO_2 conversion to CNTs and CNF, and demonstrating meaningful, significant end-uses for novel materials that result in material downstream emissions reductions
- Aligning with industry on the current status and future plans of biological uptake technologies

Gap: Need for an Alberta-Focused Carbon Utilization Technology Roadmap

Building the above-mentioned gaps in LCA, technoeconomics, and market intelligence, there is a need to leverage all the knowledge that has been gained in a succinct and useful way in the form of a multi-sectoral CCUS roadmap, specific to Alberta, and working backwards from a future net zero economy. The roadmap should consider technology readiness, market opportunities, LCA, and GHG reduction targets; as well as identify areas where government support is needed to accelerate technology transfer. For example, this roadmap could address questions such as:

- What is the timeframe for reaching Alberta's full potential of CO_2-EOR and ultimately transitioning these to CO_2 sequestration projects, where appropriate?
- What is a realistic timeframe and steps towards large-scale commercialization of carbon conversion technologies in Alberta, across each of the relevant major pathways?
- What are the gaps to integration of carbon conversion and capture technologies to accelerate commercial adoption of carbon conversion technologies?
- How does CCUS fit in with a future envisioned hydrogen economy? Of note, this is discussed at a high level in Alberta's Hydrogen Roadmap (Government of Alberta, 2021).
- What is the impact, if any, of carbon pricing and policies now, in 2030, and in 2050 on adoption of carbon utilization technologies?

The Government of Alberta, leveraging the historical work funded by Alberta Innovates and ERA, should partner with the industry to develop this roadmap.

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Appendix 1 – Additional ERA Grand Challenge Projects

The following additional technologies were funded either through ERA's Grand Challenge (2013-2021) or hosted at the ACCTC via the NRG COSIA Carbon XPRIZE:

Mineralization

- **Solidia Cement & Concrete (2016)**: Solidia is a New Jersey-based company that ERA supported through Rounds 1&2 of the Grand Challenge. The technology involves two parts: (1) Solidia cement manufacturing, which has 30% reduced CO2 requirements compared to conventional cement; and (2) Solidia concrete using Solidia cement, which can set via reaction with CO2 on industrial scale. Solidia has established operations at 8 industry sites across Canada, including a partnership with LafargeHolcim. ERA's support to Solidia has enabled them to have continued Canadian and international success today. In May 2021, they announced they had secured $78M in funding to further advance deployment of their technology at commercial scale in Canada and the US (Global Cement, 2021).
- **Skyonic SkyCycle/CarbonFree (2016):** Skyonic SkyCycle, now renamed CarbonFree, developed a thermolytic process using CO2 from a confined source that produces calcium carbonate or magnesium carbonate as the CO2 mineralization product. From 2014-2016, ERA supported SkyCycle to install a pilot facility near its home base in Texas and explore potential commercial applications in Alberta. While the company has not gone on to deploy their technology in Alberta at-scale, they recently partnered with Fluor to bring their technology to market, which will be focused mainly in the US (CarbonFree, 2021).
- **New Sky (2016):** ERA supported New Sky, based out of Boulder Colorado, through Round 1 of the Grand Challenge. New Sky Energy's CarbonCycle technology uses caustic soda (NaOH) to capture and mineralize CO2 into soda ash (Na2CO3) and sodium bicarbonate (NaHCO3) as part of the acid gas upgrading process. CarbonCycle also produces sulfuric acid, carbonates and hydrogen as co-products. New Sky also has two technologies that pair with CarbonCycle to remove H2S from sour gas. New Sky piloted their technology at an Oklahoma natural gas field and brewery in Colorado and deployed a commercial system in Wyoming. They established an office in Alberta and expressed a strong interest in commercial deployment, but were not awarded Round 2 funding, as they were not able to secure a commercial partner in time for the competition.
- **McGill University (2016):** ERA supported McGill University's concrete mineralization technology through Round 1 of the Grand Challenge. This project entailed examining a cement matrix and aggregates for reactivity with CO2, and long-term CO2 storage capacities. The manufactured aggregates were fabricate using calcium-rich waste products, combined with CO2; replacing natural sand and stones for concrete production. McGill partnered with Lehigh Hanson of Edmonton for this project. While the McGill research group did not pursue further opportunities in Alberta, they went on to form a start-up, CarbiCrete, in 2016. CarbiCrete focuses on replacing cement as the binder in concrete, as well as injecting CO2 for sequestration while enhancing the concrete product's strength. In early 2021, CarbiCrete launched an industrial-scale pilot project in partnership with Patio Drummond, a Quebec maker of paving

stones and other concrete products. Production at their Drummondville plant began on January 29 of this year 2021 (Chipello, 2021).

- **Blue Planet (2016):** ERA supported California-based Blue Planet's CCUS concrete technology through Round 1 of the Grand Challenge. This technology platform permanently converts CO2 to carbonate mineral products that potentially include all the ingredients of concrete. Specifically, the technology uses established water process membrane operations to combine inputs of various natural and wastewaters with CO2 to produce solutions that are rich in bicarbonate (HCO3) ion that, when combined with hard water, result in the direct mineralization of calcium carbonate (CaCO3). While Blue Planet was ultimately unable to deploy a pilot in Alberta as part of the Grand Challenge, they have since been successful elsewhere. In 2020 they announced raising of $10M of additional capital. Knife River, based out of Montana, announced an investment partnership with Blue Sky to create and market synthetic limestone, manufactured using Blue Planet's technology. More recently, Blue Planet announced a partnership with Mitsubishi, who will be supporting Blue Planet as part of its corporate decarbonization efforts (Blue Planet, 2021).
- **CCm (2016):** Unlike other recipients, CCm, based in the UK and funded through Round 1 of the ERA Grand Challenge, did not focus on the concrete industry; rather, their process incorporates CO2 into a range of new materials, the most advanced of which is a compound fertilizer. Similar to concrete, the fertilizer is actually enhanced by the presence of the CO2. Over the course of the project, CCm demonstrated the validity of this approach, but also expanded its scope to improve the GHG and product benefits of its process beyond the original expectations. By the end of the project, CCm was in the advanced stages of negotiations with two UK operators, and in initial discussions with operators in Alberta. While CCm ultimately did not end up commercializing in Alberta, they have had continued success in raising funds in the UK and continues to be involved in waste-to-product technologies in the agriculture industry.

Chemical Conversion

Reduction of CO_2 using hydrocarbons (dry methane reforming, bi-reforming, tri-reforming)

- **Enerkem (2016):** Based in Montreal, Enerkem developed a dry methane reforming technology that uses CO_2 and methane to produce CO and hydrogen, and uses these as raw materials to produce a variety of industrial chemicals. ERA funded Enerkem through Rounds 1&2 of the Grand Challenge. Today, Enerkem is still active and working in partnership with oilsands companies. They are focused on conversion of biomass to synthetic fuels and chemicals, rather than strict CO_2 utilization; but benefitted from the early ERA work optimizing their catalysts.
- **Gas Tech Inc. (2016):** This is one of two technologies developed by Gas Tech. This involved production of acetic acid from CO_2 and methane, via dry reforming of methane with CO_2 to produce syngas, which is a precursor to methanol, formic acid, and acetic acid. They used a nickel-based catalyst and recommended further testing as next steps. Gas Tech Inc. appears to no longer be active and did not apply for Round 2 funding.
- **Robert Gordon University (2017):** This University project based out of the UK entailed "tri-reforming" of CO_2 and methane as feedstock via a bolt on system to flue gas emissions at a facility. The process removes CO_2 for onward processing into chemicals. They developed a

miniature prototype, but their technology was not sufficiently advanced and they did not have enough local commitment to advance towards commercialization in Alberta. The carbon management program is still active at the University in the UK.

- **University of California (2016):** This technology involved "bi-reforming"– combined steam and dry-reforming of CO_2 and methane to make methanol. They employed a pyrochlores-based catalyst. The project entailed experimental and modelling work to evaluate the catalyst. They used the "GHGenius" model LCA and explored the potential for Alberta deployment. While they did not deploy in Alberta, the University program is still active.
- **University of Alberta (2016):** This is a CO_2/methane dry reforming process to co-produce electricity and syngas. The process involves selective oxidation of H_2 in novel solid oxide fuel cells. ITA was also involved in this work. While six patents have been filed, the technology has not progressed significantly towards commercial adoption.

Reduction of CO_2 using heat:

- **E3Tec (2016):** E3Tec is a spinoff from Argonne National Laboratory and is based in Illinois, US. Their technology uses CO_2 combined with heat, to manufacture dimethyl carbonate (DMC). The process uses "heat-integrated reactive distillation" and proceeds as follows: (1) reaction of CO_2 with ammonia to form urea; (2) reaction of urea with methanol for DMC synthesis. DMC is used to make polycarbonates, solvents, and fuel additives. The project's outcome was optimization of processes, developing databases and a test plan, and designing a pilot plant in Alberta. While they did not apply for Round 2 funding or proceed with the pilot, the company is still active and has completed other research projects over the past several years.

Reduction of CO_2 using light:

- **McGill University (2019):** ERA supported this project through Rounds 1&2 of the Grand Challenge. Conventional processes using CO_2 to make hydrocarbons are endothermic. McGill's process uses CO_2 + water to mimic natural photosynthesis and make chemical products including methane, hydrogen, oxygen, and methanol. It employs an efficient photocatalyst – metal nitride – readily used in semiconductor industry. The photocatalyst is customizable to different operations depending on the metals used. This project entailed a small field demonstration in Alberta, but the technology was not sufficiently advanced to perform an LCA.

Reduction of CO_2 using direct catalytic conversion

- **Air Co. (2021):** Air Co.'s patented technology transforms CO_2 captured from the air into impurity-free alcohols that can be used in spirits, fragrances, sanitizers, and a variety of consumer industries. In the long-term, it is intended to be used as a carbon-negative fuel. Air Co. demonstrated their fixed bed flow reactor system technology at ITA's ACCTC for the NRG COSIA XPRIZE competition and remained at the site to continue to optimize their technology at pre-commercial scale and will be implementing commercial scale at various locations in the US. Air Co.'s multitude of consumer products are available in the US and Ontario and will eventually be available in Alberta (alcoholic spirits, sanitizer products, etc.).
- **RTI International (2016):** RTI is a multinational non-profit research group. ERA supported them via Round 1 of the Grand Challenge, but they were declined for Round 2 funding. Their

technology uses CO_2 to produce ethylene oxide by reacting CO_2 with novel catalysts to produce CO. They focused on catalysts that select oxygen and optimized these catalysts via bench-scale tests and completed a preliminary pilot facility design. While the technology did not progress in Alberta, RTI continues to be active in this area and was awarded $10M in U.S. DOE ARPA-E funding earlier this year to pursue ammonia production.

- **Gas Tech Inc. (2016):** As part of their ERA Grand Challenge project, Gas Tech Inc. Investigated a second method of CO_2 utilization: production of acetic acid from CO_2 and methane using direct catalytic reaction of methane with CO_2. This involved an isothermal reaction with a palladium/cobalt catalyst. They recommended further testing as next steps. Gas Tech Inc appears to no longer be active and did not apply for Round 2 funding.

Reduction of CO_2 using hydrogen:

- **Pioneer Energy (2016):** Pioneer Energy is based out of Colorado and is a sister company to Pioneer Aeronautics and the Mars Society. They were supported through Round 1 of the ERA Grand Challenge but denied Round 2 funding. Their process converts methane and CO_2 to butanol using a "reverse water gas shift reaction". It was demonstrated at the lab scale and showed a CO_2 intensity reduction compared to conventional gasoline production, depending on the source of methane. While the project did not proceed in Alberta, they went on to demonstrate CO_2 utilization as part of micro-brewery operations in Colorado.
- **Liquid Light Chemicals (2016):** ERA supported Liquid Light through Round 1 of the Grand Challenge. The project considered end-to-end production of mono-ethylene glycol at varying scales via a process that requires hydrogen, CO_2, and power as inputs. They performed the groundwork to design and build a 1 tonne/day demonstration facility in Alberta, and built a laboratory process to make 100s of g quantities of product per day. They also performed an LCA as part of the project that concluded a need to be powered by 100% renewables. Liquid Light had some success after the ERA project, including receipt of $15M in funding and signing a deal with Coca-Cola. They have not made any announcements in the past five years, however.
- **Quantium (2016):** Funded through Grand Challenge Round 1 and based out of Edmonton, Quantium boasted a carbon *negative* solution. Their process uses CO_2 emissions and hydrogen produced via green electrolysis to make methanol. They claimed to use a milder process than conventional syngas to menthol catalyst and performed experiments at the bench-scale. While Quantium did not proceed via the Grand Challenge Round 2, they were subsequently awarded funding from NRCan in partnership with the University of Alberta, in 2016 and 2018. They have also had success in other applications such as novel materials for the oil and gas industry.

- **CERT Systems Inc. (2021):** As one of the finalists in the $20M NRG COSIA Carbon XPRIZE, CERT demonstrated their technology that converts CO_2 emissions into renewable fuels and chemical feedstocks using water and electricity at the ACCTC. CERT's technology uses a membrane electrode assembly (MEA) of electrochemical cells to reduce CO_2 into renewable fuels and chemical feedstocks. Since the XPRIZE, CERT vacated the ACCTC and is operating out of Ontario.

Biological Uptake

- **Industrial Microbes (2016)**: Industrial Microbes is a California-based company with a yeast fermentation process that uses CO_2 and methane as feedstock to produce malate, a substance that can be used to make biodegradable plastics, synthetic fibers for clothing, synthetic rubber, and more. Because of the province's significant sources of CO_2 and methane, Industrial Microbes identified that Alberta would be an ideal candidate for deployment, and were awarded funding as part of ERA's Grand Challenge Round 1. The project was successful in further advancing the malate-production technology at bench-scale, and they identified a need for two commercial partners to scale up and commercialize in Alberta; specifically, to bridge the gap between large emitters and chemical manufacturing facilities. While scale-up has not yet occurred in Alberta, Industrial Microbes has continued to have success elsewhere. ERA funding enabled them to raise seed funding with additional partners. Recently, the company received $5M from the U.S. Department of Energy to collaborate with a U.S. national laboratory to further advance their fermentation technology.
- **Oakbio (2015)**: Oakbio is another California-based company that was funded via ERA's Grand Challenge Round 1. Their technology also uses an algal based fermentation technology to capture CO_2 at point source and convert to biofuels and chemicals – namely *n* butanol. This can be used as a replacement for gasoline. Unlike other algal-based methods, Oakbio's process uses hydrogen, rather than light; making this technology compatible with a hydrogen-based economy. Oakbio partnered with an Alberta cement plant and refinery to receive flue gas samples for testing, but did not apply for Grand Challenge Round 2 funding, and therefore has not advanced their technology in Alberta since this time.
- **University of Maryland (2016)** The University of Maryland received ERA Grand Challenge Round 1 funding to further develop their algal-based carbon sequestration technology. The main goal was to remove at least 50 tons per year of CO_2 using four full-scale HY-TEK Bio photobioreactors (6,800 L each). They succeeded at installing bioreactors at their Baltimore Research Plant, but the algae growth itself was not successful. In addition, a secondary goal was to establish the technology to produce 1,000 liters of biofuel intermediate and 10 kg of lutein per year by 2016, and this was achieved at a much smaller scale than intended. Like the others, they did not apply for Grand Challenge Round 2 funding. While the ERA-funded project itself did not achieve all of its goals, work at the University of Maryland has continued, and in 2020 the U.S. DOE awarded the researchers $3M in funding to scale up the technology. Work to date has been performed mainly in collaboration with the U.S. Argonne National Laboratory, located near Chicago IL (University of Maryland, 2020).
- **Innotech BioChar Research (2009):** Bio-char is charcoal made from biomass, which can in turn be used or simply stored as a means of CO_2sequestration. Use of the bio-char would of course result in re-release of the CO_2 into the atmosphere. Sequestration would not result in re-release of CO_2, but adds cost to the process. This work involved a conceptual techno-economic study to estimate the cost of production of biomass-based charcoal in a centralized plant and its storage in a landfill to sequester CO_2. The project evaluated and compared conversion processes and biomass feedstocks, including whole forest biomass; forest harvest residues; and municipal solid waste (MSW). Among the three feedstocks examined, the cost of production of bio-char was found to be cheapest from MSW, at $75/tonne in production costs and $26/tonne of CO_2 sequestered (Kumar & Sarkar, 2009).