UBC Social Ecological Economic Development Studies (SEEDS) Sustainability Program

Student Research Report

Carbon Capture and Storage

Robin Watts, Srikanth Narayan

University of British Columbia

VOL 500

Themes: Climate, Energy, Finance

Date: Aug 31, 2020

Carbon Capture and Storage

(Research on capturing carbon from emissions of UBC BRDF)

Robin Watts

Srikanth Narayan

Acknowledgements

Dr Vladan Prodanovic, Associate Professor of Teaching and Director MEL CEEN

Julie West, Sr. Energy Conservation Manager

James Montgomery, Energy Conservation Engineer

Joshua Wauthy, Utilities System Specialist

Dr Helen Atkinson, Business Development (C-capture)

Meryn Corkery, Project Coordinator

This report and research behind it would not have been possible without your support. We would like to express sincere gratitude for providing valuable guidance, comments and suggestions throughout the course of the project. Without your expert advice, persistent help, this project report would not have been realized. We are grateful for the insightful comments offered by everyone and constantly inspiring us.

Executive Summary

On December 12, 2015, Canada and 194 other countries signed the Paris accord, an ambitious agreement to fight climate change. This agreement called for a concerted effort to limit the global average temperature rise to well below 2°C and pursue further efforts to limit the increase to 1.5°C. (Canada, 2016) This implies that the remaining carbon budget available at our disposal is extremely limited, and that the world must reduce greenhouse gas emissions at a rapid pace. But even then, we may not meet the target without the aid of the so-called negative emissions.

Advanced technologies are being employed to reduce emissions in hard-to-abate sectors, such as cement and power, and also to sequester CO_2 already present in the atmosphere. High on the list is carbon capture, use, and storage (CCUS), the term for a family of technologies and techniques that capture CO_2 and use or store it to prevent its release into the atmosphere. Through direct air capture (DAC) or bioenergy with carbon capture and storage (BECCS), CCUS can effectively bring down CO_2 concentrations in the atmosphere, helping to achieve the need of the hour - negative emissions. In some cases, the captured CO_2 can be used to create products ranging from cement to synthetic fuels. (Biniek, Henderson, Rogers, & Santoni, 2020)

In their endeavour to meet the climate goals, the UBC Vancouver campus has achieved aggressive GHG reductions (38% from 2007 to 2018) and are committed to look for pathways to achieve zero and eventually negative emissions. However, UBC won't be able to completely reduce its reliance on fossil fuels due to research experiments and Bunsen burners. Also, to be noted is that the burning of purchased RNG (renewable

natural gas) also has a biogenic CO_2 component. Hence some sort of negative carbon accounting will be necessary if UBC is to fully reach its goal of zero GHG emissions by 2050.

A carbon capture and storage technology is likely to be deployed on UBC's Bioenergy Research and Demonstration Facility (BRDF) as this plant will be the main source of heat to UBC's buildings upon completion of its expansion in 2021. This research paper summarises the various potential CCUS technologies that could be deployed at the University biomass plant and provides a literature review on established carbon accounting frameworks to help inform the province on how to account for negative carbon sources. A financial assessment of the technologies available is carried out to arrive at the most feasible option for the BRDF plant at UBC. The paper also talks about the different pathways available for the utilisation of the captured carbon.

Table of Contents

List of Abbreviations

CCUS	Carbon capture utilisation and storage
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
DAC	Direct air capture
BECCS	Bioenergy with carbon capture and storage
UBC	University of British Columbia
BRDF	Bioenergy Research and Demonstration Facility
IPCC	Intergovernmental Panel on Climate Change
GHG	Greenhouse gas
BC	British Columbia
PCC	Precipitated calcium carbonate
HVAC	Heating ventilation and air conditioning
AI	Artificial Intelligence
TUM	Technical University of Munich
NOX	Nitrous oxides
SOX	Sulphur oxides

MEA	Monoethanolamine
PSA	Pressure swing adsorption
TSA	Temperature swing adsorption
EOR	Enhanced oil recovery
NETL	National Energy Technology Limited
LCA	Life cycle assessment
SMR	Steam methane reforming
PFD	Preliminary process flow diagram
NPV	Net present value

List of Appendices

1.0 Introduction

1.1 Carbon Capture and Storage

As per IPCC report, Carbon Dioxide Capture and Storage technology is a process consisting of the separation of CO_2 from industrial and energy related sources, transport to a storage location and long-term isolation from the atmosphere. In a nutshell, it is the process of capturing waste carbon dioxide (CO_2) usually from a point sources which maybe a power plant or a factory, transporting it to a predefined location and storing it in such a manner that it will be stored for long term duration usually a in an underground geological formation.

1.2 Special case of Capturing CO_2 from Biomass

The CO_2 released *to* the atmosphere during combustion of biomass is assumed to be the same quantity that had been absorbed from the atmosphere during plant growth. Because CO_2 absorption from plant growth and the emissions from combustion occur within a relatively short time frame of one another (typically 100-200 years), there is no long-term change in atmospheric CO_2 levels. For this reason, biomass is often considered "carbon neutral " and the Intergovernmental Panel on Climate Change (IPCC) *Guidelines for National Greenhouse Gas Inventories* specifies the separate reporting of CO_2 emissions from biomass combustion. It may be noted that when it is said that biomass is carbon neutral it means that, the emissions associated with burning of biomass are equal to the carbon sequestered by that biomass during its growth. However, there might be some emissions like transportation of biomass or processing etc. which are not entirely carbon neutral and should be accounted for in the relevant category or the economic sector.

Thus, the capturing of CO_2 from biomass forms a special basis for negative emissions accounting as described below (excerpts from Zakkour, Kemper & Dixon (2014) :-

- During the growth phase of biomass, it removes the carbon from the atmosphere (by photosynthesis) and converts it into organic matter. The mass of carbon removed by the biomass is recorded in an accounting scheme as CO_2 emissions removal.
- When biomass is harvested, its carbon content is released into the atmosphere by process of combustion, fermentation or natural decay process. For accounting purposes, the process is considered to be instantaneous (short term) which leads to full oxidation and results in release of CO_2 back to the atmosphere
- The emissions released offset the removal which happened during the growth and hence are considered as zero net sum when considered carbon stock changes in biogenic pools.
- But, when CO_2 is captured and stored for long-term which is usually done in underground geological formations, it is emission reduction.
- This captured and geologically stored CO_2 needs to be subtracted from the zero net emissions and the result is negative emissions.

1.3 UBC BRDF Facility

The BRDF at UBC Vancouver Campus is an energy generation facility which processes renewable biomass sourced from urban wood waste to generate thermal energy for heating campus buildings. The use of biomass to generate thermal energy in BRDF reduces campus emissions by 14% compared to 2007 levels. BRDF uses an average of 10,000 tons of wood waste every year.

Originally, the facility was designed with two systems - Biomass Heat Generation System and Biomass Cogeneration demonstration system.

The Biomass Heat generation system works by converting wood waste into syngas (methane, carbon monoxide and hydrogen) by gasification. This process converts organic solids into useful gas which can be used in place of fossil fuels. Then oxygen is added to the syngas to initiate the combustion process and produce flue gas. The flue gas is used to heat the boiler and produce steam. The steam is converted to hot water and distributed throughout the campus to heat the campus buildings.

The Cogeneration demonstration system was an experimental system in which gas was used to drive a cogeneration engine to produce both heat and electricity. It ran for 450 hours and thereafter it was stopped due to equipment failure in syngas conditioning. The equipment failures were not economical to repair or replace and thus currently, it is part of academic research. Currently, the cogeneration engine is fueled by a combination of renewable natural gas - bio methane and natural gas.

The BRDF produces thermal energy at rate of 8.4 MW and electricity at rate of 2 MW. Currently, it is planned to add a new 12 MW boiler to the existing facility and thus heating capacity of the BRDF will increase to 20 MW. It is expected that this new addition of 12

MW boiler at BRDF will reduce 14,500 tonnes emissions CO2 equivalent annually and UBC will save more than $1M in annual operating costs.

1.4 Business Case for Carbon Capture in UBC BRDF

Before making any financial investment for any facility, it is important to ascertain the cost benefit analysis for the same. Thus, economic assessment of whether carbon capture makes sense at UBC or not is a must study. In order to understand that aspect, the current expenditure of UBC because of GHG emissions was studied.

Currently, the carbon tax of BC is 30$ / ton and the cost of carbon offset is 25 $ /ton. Thus, UBC pays 55 $/ton for the cost of GHG emissions. GHG emissions from natural gas at UBC Vancouver after the installation of a new 12MW boiler in a biomass power plant will be approx. 25,000 tons/yr. Considering the price of 55 $/ton, the annual expenditure because of GHG emissions after expansion of the biomass power plant facility will be around 1,375,000 $.

The biogenic carbon emissions considering the BRDF facility operates at full capacity are estimated to be 35,000 tons annually. As the emissions of BRDF are biogenic in nature, there is no additional expenditure in the form of carbon tax or carbon offset. However, capturing these emissions make a compelling case. IPCC guidelines clearly state that once the carbon is captured and stored permanently (geologically) or any other form, there is no distinction between whether the source of carbon was biogenic or from fossil sources. Typically, the capture fraction of carbon capture technology is 90% (C-Capture absorption technology). Thus, if the same 90% capture fraction is considered, it means that around 31,500 tons of CO2e from 35,000 tons of CO2e can be captured, which means UBC will have around 6,500 tons of carbon offsets to sell.

If the price of carbon offset is considered to be 11 $/ton of carbon, there is a potential of annual revenue generation of approx. 71,500 CAD. Further, since UBC will become carbon negative after the carbon capturing, there is a savings of 6,25,000 CAD expenditure (incurred in form of payment towards carbon offset - considering annual GHG emissions as 25000 tons CO2e and 25 $/ton of CO2e as payment towards carbon offset). Thus, the financials make a compelling case for motivating the UBC authorities towards carbon capture and storage facilities.

However, it may be noted that the capturing of carbon has certain costs associated with it. Though, capturing carbon and storing for long term or utilization in a manner which keeps the captured carbon out of atmosphere for longer duration is certainly beneficial for the environment, but financials need to make sense too. The information regarding requirement of initial investment for carbon capturing facility, the yearly operational expenses and the potential revenue generation need to be gathered to analyse the financial feasibility and is discussed further in the report.

2.0 Accounting Frameworks

Accounting framework is a published set of criteria used to measure, quantify and report the GHG emissions. The GHG Inventory report using an accounting framework forms the basis of different policies to mitigate the problem of climate change. This section of the report deals with the GHG accounting frameworks, guidelines regarding negative carbon accounting.

2.1 B.C. methodology for Quantifying GHG emission

Based on current international standards, British Columbia reports the CH_4 and N_2O portion of biomass as line items in the Province Inventory Report. Biogenic CO_2 – biomass emissions are currently reported as memo items. The emission factors of various fuels are available in **Appendix 1.**

The emission factor of wood fuel is considered majorly biogenic - 93.33 kg of biogenic CO_2-e/GJ of the energy as the carbon is part of the renewable carbon cycle. Only 2.24 kg of CO_2e emissions per GJ of energy are counted towards quantification of GHG emissions in case of industrial wood fuel. When the emission factor of wood fuel is compared with natural gas, wood fuel is very clean fuel. For each GJ of energy produced from natural gas, emissions of 49.87 kg CO_2e are counted in calculation of GHG emissions. Thus, it is better to use up the waste wood as part of the energy generation process as the carbon emitted from the same is part of the renewable carbon cycle.

B.C. methodology for Quantifying GHG emissions is silent regarding accounting framework related to capturing of carbon dioxide. As of today, there is no reference mentioned to any CCS technology in place or in the process of installation. If any such carbon capture facility is made operational in future, what changes should be incorporated in the accounting framework for quantifying the GHG emissions and captured emissions needs is an important aspect for policy making and is briefly discussed further in this report.

2.2 IPCC guidelines regarding Carbon Capture and Storage

IPCC - Intergovernmental Panel on Climate change is an intergovernmental body of the United Nations which is dedicated to provide the world with objective, scientific information relevant to understanding the scientific basis of the risk of climate change, its natural, political, and economic impacts and risks share knowledge related to possible response options. As per 2019 refinement to the 2006 IPCC guidelines for National Greenhouse Gas Inventories clearly states that “The capture of biogenic CO_2 emissions from biomass combustion, or other processes, should be treated consistently with CO_2 capture from fossil fuel combustion and reported in the Energy and/or IPPU sectors. Once captured and added to the carbon capture and storage processes there is no differentiated treatment between biogenic carbon and fossil carbon. Both captured biogenic and fossil CO_2 should not be added to the total emissions, i,e. net emissions should be reported.

IPCC special report on Carbon Dioxide Capture for greenhouse gas inventories and accounting discusses the implications of negative carbon accounting and possibility of possible frameworks regarding the same.

2.3 Accounting for Carbon Removals

The IPCC gives guidelines for reporting of annual emissions. The amount of CO_2 captured and stored can be measured and could be reflected in relevant categories. In order to account for the captured emissions there are two options. In the first option, Carbon capture and storage could be treated as a mitigation measure. Any source of carbon dioxide emission – for example power plants with CO_2 capture would have lower emission levels (kg CO_2/kg of fuel used) than the other conventional counterparts. Alternatively, the carbon dioxide captured, and stored amount could be reported as removals (sinks) for CO_2. Both the accounting options would definitely need to include the additional emissions which have occurred because of capturing, transportation and storage of carbon in the relevant categories. However, there are certain points to consider while evaluating both the options.

- In the first option, reduced emissions could be reported in the category where the capture takes place. For instance, if a power plant captures the CO_2, then the net emissions reported by the power plant could be reduced. However, it will reduce the transparency of reporting emissions. For instance, suppose there are two power plants of the same rated capacity, one without CCS and one with CCS technology. There would be a very large variation in the reporting of the emissions of both the power plants and thus accounting will be a much more complicated procedure.
- However, an alternative to this approach could be reporting detailed data – how much CO_2 was produced, how much was emitted to the atmosphere and how much was captured and how much was stored. This could be achieved by tracking the

flow of CO_2 through the entire capture and storage system. This is a transparent and consistent approach.

- The other option is to report the CCS as a sink. The amount of CO_2 stored could be reported as removal in the inventory. In order to achieve transparent reporting, the emissions/removals of CO_2 the emission related to capture, transportation and injection should be described clearly.
- An important consideration in both the cases is emissions such as physical leak – which can occur after a very long time period once the injection has been completed. A separate category under fugitive emissions – or a new category under capture, transportation and storage needs to be created.
- If the geological sites for long term storage are chosen carefully, the physical leakages are usually bound to be very small. However, for an accurate estimation, new methodologies need to be developed and continuous assessment by seismic measurements can be adopted.

2.4 Things to consider in accounting framework

- One ton of the CO_2 stored permanently has the same benefit in terms of CO_2 concentrations as one ton of CO_2 emissions avoided. However, if the period of storage is temporary, the value is less than one ton of CO_2 emissions avoided. This important difference must be accurately reflected in the accounting system.
- Concern about displacement of emissions across provincial boundaries or a national boundary can make the accounting difficult.
- If we store the carbon dioxide away permanently, for how long it should be stored?
- Chomitz (2000) suggests that it should be acknowledged that storage of CO_2 is likely not permanent. Thus, it needs to be assessed what are the environmental and economic benefits of limited term storage and credits for the same should be allocated in the proportion.
- Herzog (2003) argues that the primary issue of stored CO_2 is a liability. He argues that if credit is given to CO_2 stored, there should be debits, if the CO_2 is subsequently released to the atmosphere.

2.5 Case of Canada National Inventory Report

In 2016, CO_2 Capture, Transport and Storage began in Alberta for the purpose of long-term geological storage, where the Quest project captures CO_2 from Shell's Scotford upgrader and transports it 65 kms north to a permanent storage site.

All other CO_2 Transport and Storage in Canada are associated with enhanced oil recovery operations at Weyburn, Saskatchewan. Beginning in 2014, most of the CO_2 captured at the Boundary Dam coal-fired power plant in Saskatchewan was also transported to Weyburn for enhanced oil recovery. Details of CO_2 capture volumes are presented in Table below. Consistent with the origin of the captured CO_2 (an upgrading facility and coal power plant), these volumes are subtracted from emissions reported under Mining and Upstream Oil and Gas Production, and Public Electricity and Heat Production, in Alberta and Saskatchewan, respectively. The snapshot of Canada's NIR (2017) of the Electricity sector with carbon captured incorporation is shown below in **Table 1.**

Economic Sector	Stationary Combustion	Industrial Cogeneration	Other Product Manufacture and Use	CO2 captured	Total (round off value)
Electricity	74.1	0.5	0.1	-0.5	74

Table 1 : Source : Adaptation from Canada National Inventory Report

Remarks

- The unit of GHG emissions is Mt CO_2 eq
- The captured carbon is displayed as a negative quantity. Though the CO_2 has been captured, it does not imply permanent storage, some portion may be re-emitted as fugitive emissions or in other sectors. Those emissions are recorded in the economic sectors where they occur.

2.6 Case of Finland Carbon Capturing and Storage Project

Currently, carbon capture and storage are practiced on a very small scale. In European Union, CO_2 capture and storage are not a key category. CCS projects are not usually described in national inventory reports of most of the countries. However, Sleipner CCS project, which is included in Norway's inventory report. Norway provides information on the annual captured and stored amounts. In addition, it also provides information on the amount of CO_2 which could escape to the atmosphere during the storage period or the injection period. As per Norway's report, roughly 0.8 % of the CO_2 is emitted during such a period which is quite small.

The amount of CO_2 captured reflects the CO_2 captured in pulp and paper mills in Finland, where PCC is formed and then used in the paper and paperboard industry. The final use of CO_2 captured is considered long-term storage except if the products are combusted which are then taken into account into corresponding categories. The snapshot of the Finland CO_2 capture is shown below in Table 2: -

Year	2011	2012	2013	2014	2015	2016	2017
Reported transferred CO2, kt	179.6	146.6	139.8	142.6	138.3	133.8	127.1

Table 2: Source: Adaptation from Finland National Inventory Report

Remarks

- The unit is Kilo tonnes CO2 (kt)
- The amount of CO2 captured is calculated on the basis of production of PCC

3.0 Carbon Capture Technologies

IPCC defines CCS as - "a process in which a pure stream of Carbon Dioxide (CO2) from industrial and energy related sources is separated (Captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere".

CCS technology differs from CCU technologies on aspects of what is done with the carbon once it is captured. IPCC defines CCU as "A process in CO2 is captured and then used to produce a new product. If CO2 is stored in the product for a climate-relevant time horizon only then it is considered to be a process of carbon dioxide removal.

Both Carbon Capture & storage and Carbon Capture and utilization are important technologies to mitigate the impending problem of climate change. On one hand, where carbon storage has the advantage of storing large amounts of carbon in geological formations but finding such suitable formations and life cycle assessment of the emissions associated with transportation and fugitive emissions during storage is a concern.

Carbon Capture and Utilization technologies offer advantages that carbon is utilized as a commodity and thus it offsets the cost of technology to a certain extent. However, large scale commercialization of such technologies is still under development but surely looks promising in the coming years.

Published literature on some of the technologies was reviewed, research on new technologies in the market was done and is discussed further in the report.

3.1 Direct Air Capture

DAC is a technology of capturing CO_2 directly from the atmosphere. The captured CO_2 can be permanently stored in the underground geological formations for a very long time or the captured CO_2 can be used in industries like producing synthetic fuels, food processing etc. As DAC plants capture CO_2 from the atmosphere, exactly what plants do, DAC plants are widely popularized as “artificial trees”.

Keith et al.,(2018) along with other employees from Carbon Engineering authored the article “ A process of capturing CO_2 from the atmosphere” describing the process in detail which is summarised below:-

Description – Depending on the physical state of the system components, this technology is categorized into two types. Aqueous solution or solid sorbents. In aqueous solution, the capturing medium is liquid. The air is passed through chemical aqueous basic solutions (example hydroxide solution) which captures the CO_2 and the rest of the air is released back to the atmosphere.

In solid DAC technology, the solid sorbent filters bind CO_2 particles from the air. When these CO_2 rich filters are heated, they release CO_2 which can be stored or transported for further use. The solid sorbents offer the possibility of low energy input, lower operating cost as compared to aqueous counter parts but has its own challenges of sealing requirement during regeneration, large structure, trade-off between sorbent performance and cost etc.

The schematic with the basic chemical equations of aqueous DAC is shown in **Fig 1**.

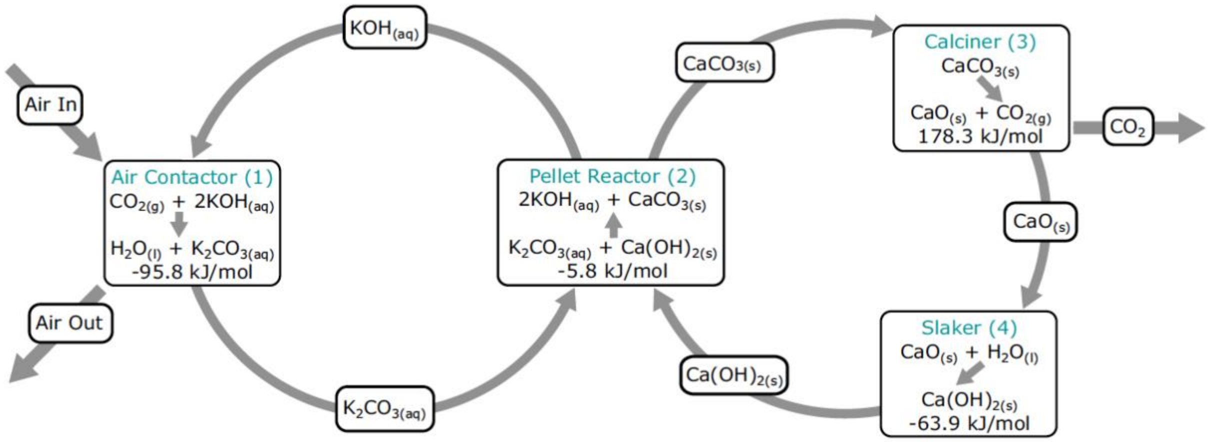

Fig 1: Source - Carbon Engineering

Process of Aqueous DAC

- Air is pulled from the atmosphere and passed through aqueous solution with ionic concentrations in Air contactor. CO_2 present in the air reacts with potassium ions and potassium carbonate (K_2CO_3) is formed.
- Potassium carbonate is further precipitated by Calcium ions in a pellet reactor to form Calcium Carbonate ($CaCO_3$).
- Calcium carbonate is heated to liberate CO_2 and CaO is produced as a by-product.
- CaO is hydrated to form Calcium hydroxide -$Ca(OH)_2$, which is utilized in reactors.

Key features of DAC

- Capturing CO_2 using DAC is an energy intensive process. A design plant by Carbon Engineering captures 0.98 Mt-CO_2/year from the atmosphere and delivers around 1.46 Mt-CO_2/year. The additional 0.48 Mt-CO_2/year is due to combustion of natural gas required for energy requirement, which is also captured.
- The cost range of Carbon Engineering DAC is 94-232 USD \$/t-CO_2 captured.

Feasibility at UBC

Carbon Engineering installed a pilot project at Squamish, B.C just to test the technology and successfully demonstrated the same. Even though the pilot project just aimed to see the success of technology and the captured carbon was subsequently released in the atmosphere but the real question with DACs still remains the same. What to do with the captured carbon?

Thus, it can be said with confidence that DAC is a proven technology and can significantly play a significant role in combat with the crisis of climate change. Theoretically a direct air capture can be installed anywhere where an energy source is available and it is a positive step towards reducing carbon footprint. However, as DAC captures carbon directly from the atmosphere and not from point sources, it can be a carbon capture option for UBC but not specifically for BRDF.

3.2 Algae based Carbon Capture

The use of algae is often described as one of the efficient tools of carbon capture and sequestration. As per Hypergiant Industries, Algae based solution for carbon capturing is 400 times more effective as compared to trees. In order to give an overall picture, Hypergiant claims that one 3’ X 3’ cube of bioreactor prototypes can sequester as much carbon as one acre of trees.

Algae is a plant typically found in aquatic areas which uses photosynthesis similar to trees to absorb carbon. It potentially eliminates many of the challenges associated with other methods of carbon capture and utilization methods.

Facts about algae

a. Can survive in freshwater, saltwater, trunks, stones, soil, mud

b. Can exist in vast range of temperatures, acidity, turbidity

c. Occurs in a variety of forms, sizes, from single cell organism to multicellular

d. Algae are tiny plants which can be produced in seawater, they can be grown in significantly higher quantities per square foot than land crops.

Singh & Dhar (2019) argues that these microalgae are superperior to other feedstocks because of their ability to survive in harsh environments. Further, these do not require arable land and are capable of surviving in places where other crops/plants cannot inhabit such as alkaline water, land and waste water etc. A simple representation of micro algae based carbon capture and utilization is depicted below in **Fig 2**:-

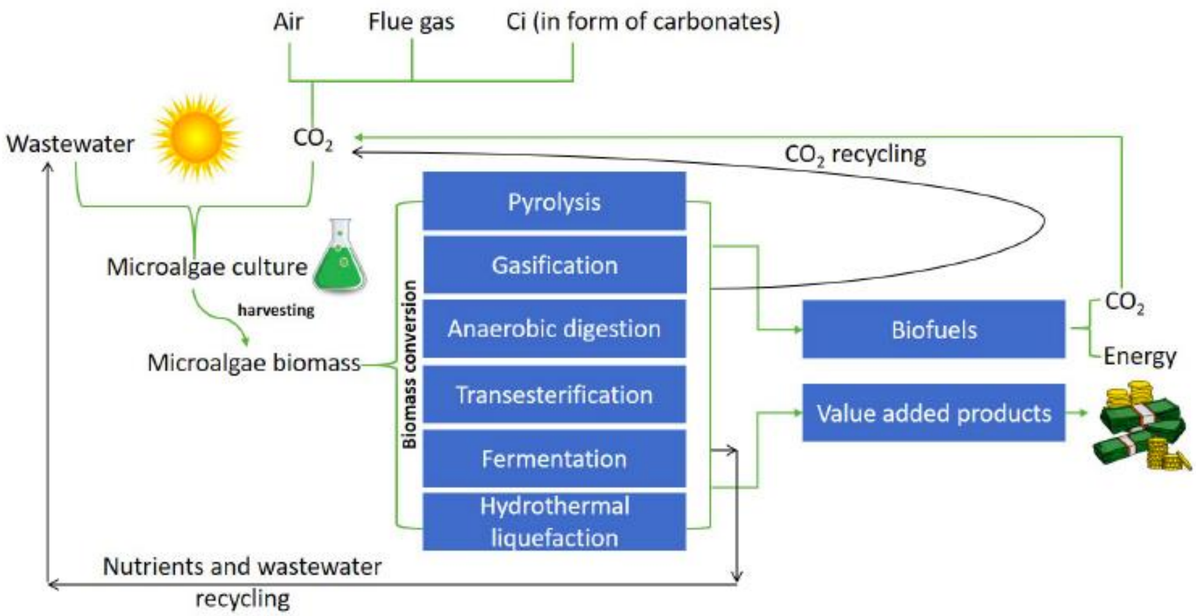

Fig 2 Source: - Singh and Dhar (2019)

Moreira and Pires (2016) studied the possibility of atmospheric capture of CO2 as a negative carbon dioxide emission path. Moreira and Pires (2016) argue that production of biofuels from microalgae produces several advantages compared with biofuels produced from other raw materials which include no requirement of arable land, usage of wastewater, co-production of other products etc. Further, micro algae are easy to grow, and growth rate is high.

The challenge which is associated with this technology is downstream process - manufacturing of biofuels. This technology gains more attention when a combined solution for wastewater treatment and CO2 atmospheric sequestration is looked at.

Bioreactor - Equipment of Hypergiant Technologies - Bioreactors are machines that process algae for carbon removal and create algae materials which can be used to make food, fuel, fertilizers, other uses. These bioreactors consist of interconnected closed tanks which hold water and since it is a closed system, it prevents pollutants from entering and limiting evaporation. Bioreactor can thus give two possible outputs. Algae oil can be put through different processes to make biofuels or plastics. The other possible use is algae itself which can be dried and converted into powder form. This powder form of algae can be used for nutrients or fibres. The process of carbon capture using algae of Hypergiant Technologies is described below: -

- Algae like any other plants require carbon dioxide, light and water. The air can be open air, or it can be exhaust of industrial pipes or HVAC systems.
- Now Algae needs carbon dioxide and light. CO2 is already present in the air and light can be provided via the sun or artificially.
- Algae and water is pumped through a series of tubes to increase surface area and hence maximizing the exposure to the light sources (which in case of artificial light is the lining of the reactor).
- Algae consumes CO2, it produces biomass. This biomass can be harvested & used in other industries to manufacture biofuels, animal feed, fertilizers, etc.
- Harvesting of Hypergiant Bioreactor is a separate system which is controlled by Artificial intelligence to maximize the CO2 capturing. Hypergiant's Bioreactor is a controlled system model, which uses AI to monitor the surroundings and accordingly control the process to maximize the CO2 production.

- Bioreactor captures 60-90% of the CO_2 and other nutrients in the air and clean air is released to the atmosphere.

A team of researchers at the TUM, led by Professor Thomas Bruck, have developed a methodology of efficient production of algae and exploration of economic models for scaling its utilization. The preliminary study showed that algae can be used to manufacture carbon fibres and such fibres have the same properties as conventional fibres. In fact solid carbon fibre is the second most stable form of carbon on the planet after diamonds.

The probable uses of utilization of Algae (Algae is the new green by HyperGiant) highlights the prominent uses of Algae where commercialization & utilization is likely on a rapid scale in the near future is depicted in **Fig 3**.

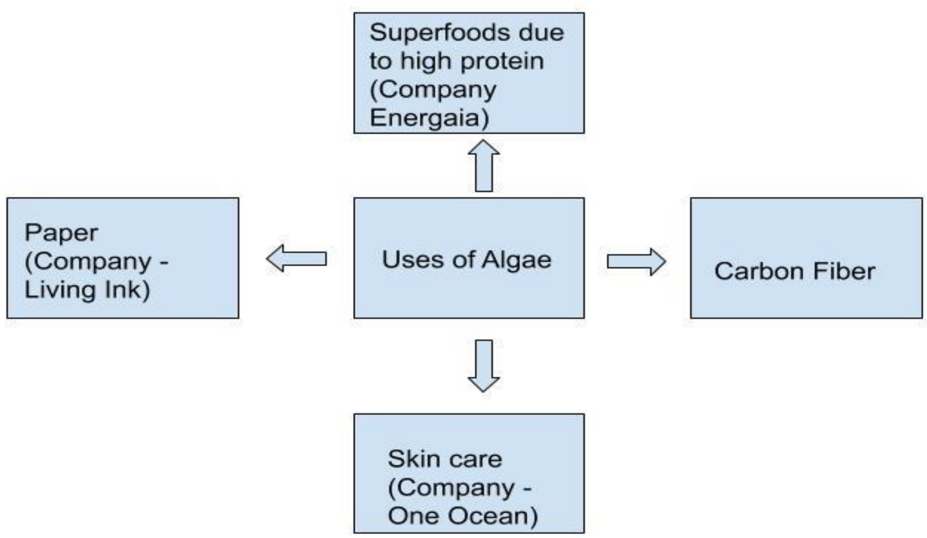

Fig 3: Uses of Algae

Feasibility of Carbon Capture via Algae at UBC BRDF

Though algae-based capture of CO_2 offers numerous advantages, however the installation of this technology on a commercial scale is still a distant dream. This type of technology is currently sufficient enough for installation in office buildings or exhaust of HVAC systems, but no potential source seems to present a reliable picture for operation of capturing CO_2 from a power plant. As of today, these bioreactors can serve a purpose for promotion or branding purposes for CO_2 capturing. Another important aspect of carbon capture using algae is the need to strengthen the downstream processes like association with the concerned industry. Though initiatives on a smaller scale or pilot projects have been taken by companies as mentioned above (Fig 3) but a wide scale development of such technology is a thing for the future and will take significant time to develop. Further, CO_2 utilization activities need to be strengthened in the local area where carbon capture is proposed, else the transportation of CO_2 will reduce the net reduction significantly. Thus, currently this technology cannot be utilized for BRDF facility at UBC but can make a promising case in the future.

3.3 Absorption

This is a post-combustion carbon capture technique which involves selective absorption. Here the capture units can be retrofitted into existing energy plants, by adding a CO_2 separation facility to remove CO_2 from the outlet flue gas stream. This involves only minimum modifications to the combustor compared to the set-up used for biomass combustion without capture. (Finney, Akram, Diego, Yang, & Pourkashanian, 2019)

Description - Absorption is a process where the gas captured enters in contact with a physical or chemical solvent in an absorption column. The solvent has specific characteristics that only absorb CO_2 and let the other gases pass. The CO_2-rich solution is usually transferred to a regeneration column, where the CO_2 is removed, and the solvent is recycled to be further reused. One of the most advanced processes for post-combustion CO_2 capture is wet solvent scrubbing —an absorption technology often using amine-based aqueous solvents. The process works on the temperature swing principle, where CO_2 is absorbed by the solvent at low temperatures and desorbed at higher temperatures. Absorber and desorber columns are essential components supported by a reboiler, condenser, coolers, pumps, and other ancillary equipment as illustrated in **figure 4**. (Santos, Goncalves, & Pires, 2019)

The Absorption process

- The solvent selectively absorbs CO_2 from the flue gas (Santos, Goncalves, & Pires, 2019)
- CO_2-rich solvent is then pumped to the desorber (Santos, Goncalves, & Pires, 2019)

- Flue gas leaving the absorber is passed through a water wash to remove entrained solvent droplets (Santos, Goncalves, & Pires, 2019)
- In the desorber the solvent is heated by the reboiler to release absorbed CO2(Santos, Goncalves, & Pires, 2019)
- After CO2 stripping, the 'lean' solvent is pumped through the cross-exchanger for heat recovery and then back to the absorber for the next cycle(Santos, Goncalves, & Pires, 2019)
- The high-purity CO2 stream leaving the desorber is cooled in the condenser to remove any water and solvent (Santos, Goncalves, & Pires, 2019)
- Condensed stream of liquid is sent back to the desorber (Santos, Goncalves, & Pires, 2019)

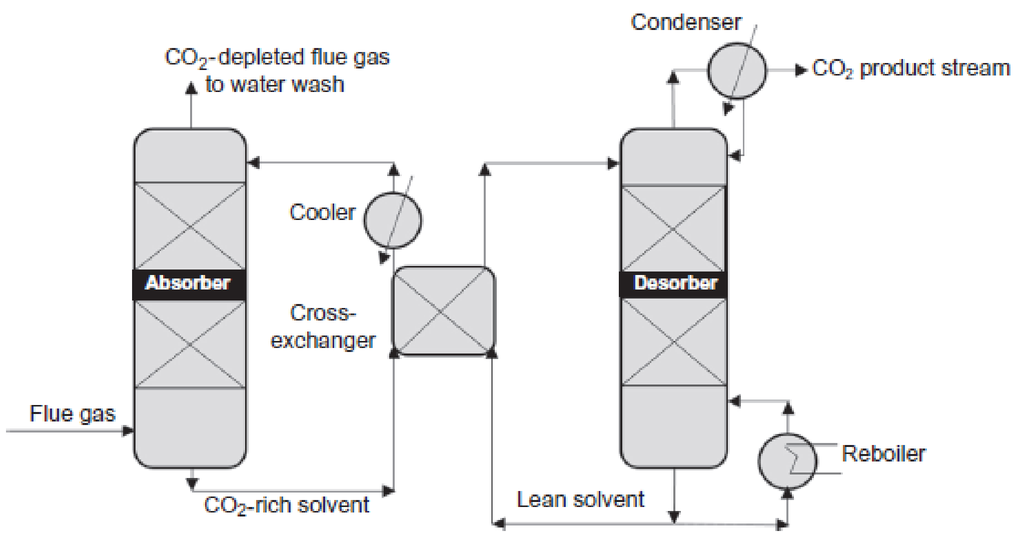

Figure 4 Simplified schematic of solvent-based absorption CO2 capture technique

Source: (Finney, Akram, Diego, Yang, & Pourkashanian, 2019)

Key features of the Absorption technique- Excerpts from (Santos, Goncalves, & Pires, 2019)

- Flue gas from biomass combustion is likely to need cleaning, including NOx, SOx, and particle removal, among others.
- Any heavy and transition metals present in the biomass flue gas can be absorbed by the solvent and may accumulate over time resulting in solvent degradation.
- Cyclic absorption and stripping processes results in the solvent being subjected to periodic heating and cooling which eventually causes it to degrade. To maintain capture performance, the degraded solvent must be periodically replaced. Some of the modern plants use reclaimers to recover active solvents.
- Both the absorber and desorber are normally packed columns. Random packing has traditionally been used due to the ease of installation and lower costs, but structured packing is becoming increasingly common owing to its enhanced performance and lower pressure drop.
- As biomass power plants are expected to operate on a smaller scale, a relatively smaller capture plant will make the installation of structured packing easier.
- This is an energy intensive technology. The majority of the energy is consumed in the stripping step, although different strategies are employed to reduce energy consumption, including flowsheet optimization, new solvents, process intensification, and parametric process optimization.
- The conventional solvents used are amines such as MEA.
- Alternatives are aqueous alkaline salts of amino acids, which are environmentally friendly, less volatile, and more resistant to oxidative degradation.

- Ionic liquids have also been proposed due to their exceptional physicochemical properties, but they have drawbacks, including high viscosity and high costs. Mixing ionic liquids with amines can therefore provide the advantageous properties of both.
- Process intensification can also significantly drive costs down. RPB are used to reduce the size of the absorber and desorber, as it employs centrifugal force to improve mass transfer. The volume of packing required by a RPB absorber designed to capture 100 t/day of CO2 is six times smaller than that required for a conventional packed-bed absorber.
- The technology has been applied to gas sweetening plants for a while, but its application to biomass flue gases is new.

Feasibility at UBC

Scrubbing CO2 from process gases with liquid solvents such as MEA and related solvents has been the benchmark technology for over 60 years now (Webley, 2014). This is certainly a prospective technology for carbon capture at the BRDF plant in UBC. However, as mentioned above this is an energy intensive technology and the net carbon savings and the cost effectiveness of this technology can be arrived at only after a complete life cycle analysis, which should also take into consideration the potential utilisation options available for the captured carbon.

3.4 Adsorption

This is another post combustion carbon capture technique and it involves mixture separation. It works on the principle of differences in adsorption/desorption properties of the constituent of the mixture (flue gas). The technique also requires only minimum modifications to the existing plant set up. (Ben-Mansour, et al., 2016)

Description - The word adsorption is defined as the adhesion of ions, atoms or molecules from a liquid, gas or dissolved solid to a surface. The adhered ions, atoms or molecules form film on the surface of the materials to which they are attached and are called adsorbate while the material on which they are attached is called the adsorbent. Adsorption is different from absorption because in absorption, the fluid (absorbate) is dissolved by a solid or liquid (absorbent). Adsorption occurs on the surface while absorption entails the whole material volume. (Ben-Mansour, et al., 2016)

The Adsorption Process- Excerpts from (Ben-Mansour, et al., 2016)

- Flue gas is fed to a bed of a solid adsorbent.
- It fixes CO2 selectively until the equilibrium is reached.
- CO2 desorption is performed by swinging the pressure i.e PSA or swinging the temperature i.e TSA.
- In PSA the adsorption process occurs at high pressures and the swing for low pressures (generally atmospheric pressure) for the desorption process.
- In TSA, CO2 is desorbed from the solid adsorbent by raising the system temperature using hot air or steam injection.

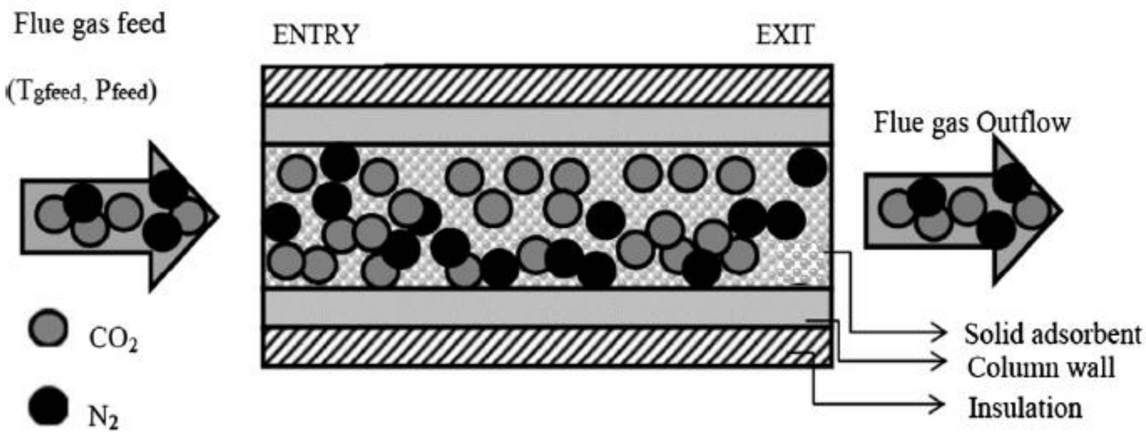

Figure 5 Schematics of adsorption carbon capture process in a cylindrical bed Source :(Ben-Mansour, et al., 2016)

Key features of the Adsorption technique

- To reduce the CO2 recovery cost, adsorbents must be regenerable, allowing their reuse for a large number of cycles.
- PSA has a simpler operation, low power consumption, and fast regeneration. However, the presence of water may lower the CO2 recovery.
- TSA has longer regeneration times than PSA but presents higher CO2 purity and recovery, avoiding the energy requirements to pressurize CO2.
- The selection of the adsorbents should take into account the specific surface area, the selectivity, and the regeneration ability.
- Typical adsorbents are zeolites and activated carbon.
- Amine-functionalized solids have higher selectivity at low concentrations, stability, and tolerance to moisture, due to the chemical character of the sorbent adsorbate interaction.

- This process has several advantages over the absorption process, such as (1) the low regeneration energy requirements, (2) the smaller environmental concern of the solid waste compared with the liquid waste, (3) resistance to corrosion, and (4) the broader range of operational temperatures.

Feasibility at UBC

This method is believed to be one of the most economic and least interfering ways for post-combustion carbon capture as it can accomplish the objective with small energy penalty and very few modifications to existing power plants. (Ben-Mansour, et al., 2016)

However, this is a fairly new technology and we do not have sufficient proven track records for reference. Further, in the context of CO2 capture from biomass, the major drawbacks of this technology are the sensitivity of the adsorbent materials to H2S and water. (Webley, 2014)

Therefore, this would not be a feasible solution for carbon capture at the BRDF plant.

3.5 Comparative Assessment of Carbon Capture technologies

The literature research of the technologies is summarized below: -

Technology and Company	Description	Advantages	Drawback
Algae based carbon capture **Hyper giant Technologies**	Bioconversion of CO_2 into fuels and other products via photosynthesis	Efficient in wide range of CO_2 concentration Faster growth rate of algae than plants Arable land not required Co-production of feed, biofuel and value-added products	Requires downstream processing like harvesting Makes the entire process cumbersome Sensitivity to other flue has components such as NO_x, SO_x, pH etc.
Post Combustion Absorption **C-Capture**	Selective absorption of CO_2 by chemical Solvents (Singh & Dhar, 2019)	High absorption efficiency (>90%) Sorbents can be regenerated by heating and/or depressurization. Most mature process for CO_2 separation. (Leung, Caramanna, & Maroto-Valer, 2014)	Absorption efficiency depends on CO_2 concentration Significant amounts of heat for adsorbent regeneration are required. Environmental impacts related to sorbent degradation have to be understood. (Leung, Caramanna, & Maroto-Valer, 2014)

Post Combustion Adsorption **Svante**	CO2 capture using solid adsorbent such as activated carbon, zeolite, Na2CO3, CaO, Etc. (Singh & Dhar, 2019)	Process is reversible and the absorbent can be recycled. High adsorption efficiency achievable (>85%). Low regeneration energy requirements (Leung, Caramanna, & Maroto-Valer, 2014)	Flue gas pretreatment necessary before channeling to adsorber due to high moisture content and presence of contaminants (e.g., SOx and NOx) Require high temperature adsorbent. High energy required for CO2 desorption. Relatively new technology with very few commercial installations (Leung, Caramanna, & Maroto-Valer, 2014)
Direct Air Capture **Carbon Engineering**	Air is pulled from the atmosphere and CO2 is separated by mean of chemical reaction in aqueous solution	Can be installed anywhere Carbon sequestered directly from atmosphere - point source not required	Energy Intensive Usually located away from residential places Requirement of open space

Table 3: Comparative assessment of carbon capture technologies

4.0 Carbon Storage

Once captured, CO_2 is compressed and shipped or pipelined to be stored either in the ground, ocean or as a mineral carbonate. These techniques are also known as geological storage, ocean storage and mineral carbonation. Sometimes the transported CO_2 is used in the Oil & gas sector for extracting oil from reservoirs and this process is called Enhanced Oil Recovery. In EOR, the carbon dioxide is stored underground, hence it is also viewed as a technique for carbon storage. Different storage technologies are discussed further in the report.

4.1 Enhanced Oil Recovery

In order to understand the importance of CO_2 in Enhanced Oil recovery, it's important to have a basic understanding of how oil production takes place. During production of oil, usually there are three phases. The first one is when a company digs wells, the underground reservoirs push the oil to the surface. But only about 10% of the oil can be recovered in this fashion. During secondary production, a fluid usually water or gas is pumped in the reservoir and oil is pushed to the surface. The general range from 20-40% of oil can be recovered in this secondary production.

Any other production after the secondary phase, comes under tertiary production which includes injection of any fluid which is originally not found in the reservoir. The most common method of tertiary production of oil is EOR in which CO_2 sometimes alternated with pulses of water is injected in the well (injection well) and thus oil is extracted from the production well. Enhanced Oil Recovery (EOR) by injection of CO_2 can recover up to 60%

of the oil in the reservoir. A schematic of Enhanced Oil Recovery (EOR) from National Energy Technology Limited, US department of Energy regarding is depicted in the figure 6 below:

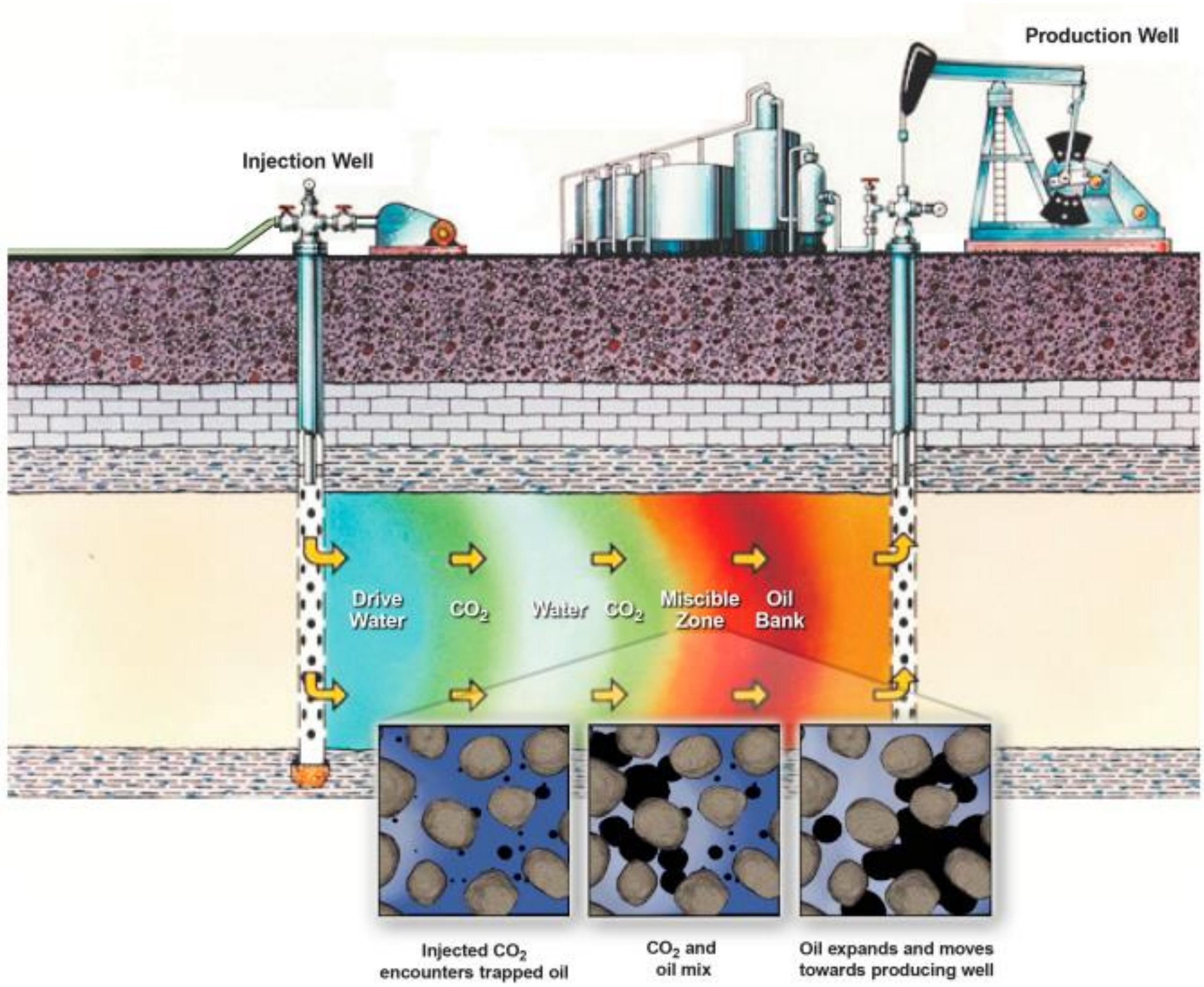

Figure 6 - Source : NETL

Debate around EOR

There is a strong argument for EOR as ways to reduce the carbon intensity of oil and sequester large quantities of carbon. However, an equally opposite case makes an argument that there should be lesser production of oil and gas to reduce the emissions.

Further Núñez-López (Frontiers papers) did a dynamic LCA on Enhanced Oil Recovery (EOR) projects and concluded that EOR projects are carbon negative during early phase (usually 6-18years) because during that time period oil production is significant and hence carbon dioxide requirement iis high and that carbon dioxide is permanently stored underground. However, after a certain time period, oil production diminishes and the EOR project is no longer carbon negative.

Feasibility of EOR as a storage option for UBC

The CO2 which can be captured from UBC BRDF facility is around 100 tons/day. When this figure is compared to the requirement for the EOR process (which is substantially high), the UBC captured carbon seems to be marginally low. Further, B.C. production of oil is relatively low as compared to other provinces. Though Alberta is dominant, B.C oil production falls behind Newfoundland & Labrador, Saskatchewan and Manitoba also. Further, tie up with the Oil industry, transportation of CO2 to the oil extraction site and not to mention the life cycle assessment of the entire EOR process complicates this option of storage of CO2 for UBC.

4.2 Geological Storage

Geological storage involves injecting CO2 into geological formations such as depleted oil and gas reservoirs, deep saline aquifers and coal bed formations, at depths between 800 and 1000 m. Depending on the characteristics of the site, CO2 can be stored through different trap mechanisms, including impermeable layers known as ‘‘caprock’’ (e.g. mudstones, clays, and shales) which trap CO2 underneath as well as in situ fluids and organic matter where CO2 is dissolved or adsorbed. Subject to the reservoir pressure and temperature, CO2 can be stored as compressed gas, liquid, or in a supercritical condition. The latter (@31.1 8C and 73.8 bar) makes it denser, increasing the pore space utilisation and making it more difficult to leak.

CO2 storage in geological formations is at present probably one of the most promising options owing to the previous experience by the oil and gas industry. For example, the industry has a good understanding of the structural characteristics and behaviour of depleted oil and gas reservoirs and the existing well-drilling and injection techniques can be adapted for carbon storage applications. Deep saline aquifer formations are also a possibility for storage with a large storage capacity estimated at 700–900 Gt CO2. However, very little is known about coal bed formations and further explorations are required before they can be considered a safe storage option.

4.3 Ocean Storage

Ocean storage relies on the principle that the ocean bed has a huge capacity to store injected CO_2 at great depths. Yet, ocean storage has never been tested on a large scale even though it has been studied for over 25 years.

4.4 Mineral Carbonation

Mineral carbonation involves reacting CO_2 with metal oxides such as magnesium and calcium oxides, to form carbonates. Carbonation, also known as 'mineral sequestration', can be considered as both storage and utilisation option. The latter applies if the intended application of the carbonates goes beyond storing CO_2 to be used as a material; for example, in the construction industry.

4.5 Challenges of storing Carbon Dioxide

The challenges for CO_2 storage are primarily a function of economic, legal, and regulatory challenges. For instance, Geological Storage of CO_2 poses a set of challenges. First and the foremost is finding the suitable geological formation where the carbon dioxide can be stored. Another concern is potential leakage of CO_2 from the site. Further, accurate quantification of storage potential and constant monitoring of the trapped CO_2 is another concern for the accounting framework.

In Spite of some challenges, the driving force is that by some estimates, the United States could geologically store 500 years of its current rate of CO emissions; globally, the number is around 300 years. This potential is constrained by the fact that carbon storage (without use) is largely a cost and thus attracts relatively little project investment and innovation, particularly in the absence of regulatory support or incentives. Moreover, there are also complex legal issues that must be resolved, such as liability for potential leaks, as well as the jurisdictional complexities associated with underground property ownership and use.(Mckinsey) The annual leakage rates reported in the literature range from 0.00001% to 1%, depending on the permeability of the geological structure and its faults or defects.(Rosa, Adisa)

Still, by 2030 it is estimated that storage could account for 200 Mtpa of CO abatement—a small but meaningful slice of the full potential for storage. (Mckinsey)

4.6 Current Carbon storage Projects

There are several ongoing CCS projects around the world, ranging from the pilot to commercial scale. The latter include the Sleipner and Snøhvit projects in Norway, the Weyburn-Midale in Canada, the In Salah in Algeria and the Salt Creek project in the USA. These projects have been operating in saline aquifer formations (Norway) and depleted oils and gas reservoirs (Canada, Algeria and USA) for more than 10 years. (Rosa, Adisa)

4.7 Carbon Storage options comparison

Option	Storage locations	Cost (US$/tonne CO2 stored)	Feasibility at UBC
Geological storage	Depleted oil and gas reservoirs Deep saline aquifers coal bed formations	0.5 to 8	Low
Ocean (pipeline)	Ocean bed	6-31	Very low
Mineral carbonation	As carbonates by reacting with metal oxides	50-100	Medium

Table 4: Estimates of CO2 storage costs (Dadhich, Dooley, Fujii, Hohmeyer, & Riahi)

Notes:

1. The cost mentioned for geological storage does not include monitoring costs
2. Ocean storage includes offshore transportation costs: range represents 100 to 500 Km distance offshore and 3000 m depth
3. Unlike geological and ocean storage, mineral carbonation requires significant energy inputs equivalent to approximately 40% of the power plant output

5.0 Carbon Utilisation

To secure a stable climate for future generations, humanity will need to permanently bury gigatons of carbon dioxide. According to studies, 350 ppm (Hansen et al., 2008) of CO2 in the atmosphere is the upper bound of safety which we have already surpassed, and we emit more and more each year. Building a carbon capture and storage industry of sufficient size would mean starting immediately, but at least for now, there is little financial incentive to do so. Companies can't make money burying carbon, so they mostly don't. One way to scale up the carbon-capture side of the industry would be to boost demand for captured CO2, which can be used as an input or feedstock in various other industrial processes. Capturing carbon (either from industrial waste streams or from the ambient air) and using it in industry is known as carbon capture and utilization (CCU). (David Roberts)

Utilisation Pathways

The term carbon utilisation refers to the different avenues or pathways where captured CO2 can be put to use or "recycled" to produce economically valuable products or services. The various available carbon utilization options are illustrated in Figure 8. It is to be noted that each carbon utilization pathway has specific characteristics in terms of technical maturity, market potential, economics, and CO2 reduction impact. (Bobeck, Peace, & Ahmad, 2019)

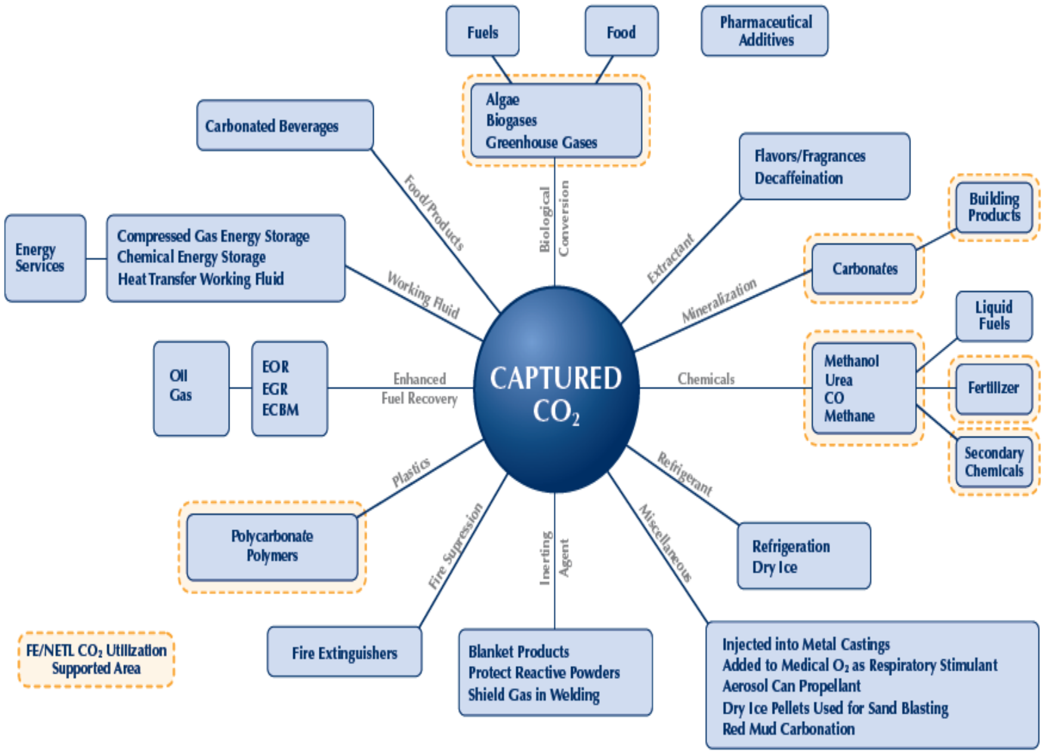

Figure 8 : CO2 utilisation pathways

Source: National Energy Technology Laboratory www.netl.doe.gov

The utilisation approaches depicted above can be clubbed into seven general categories as illustrated in figure 9

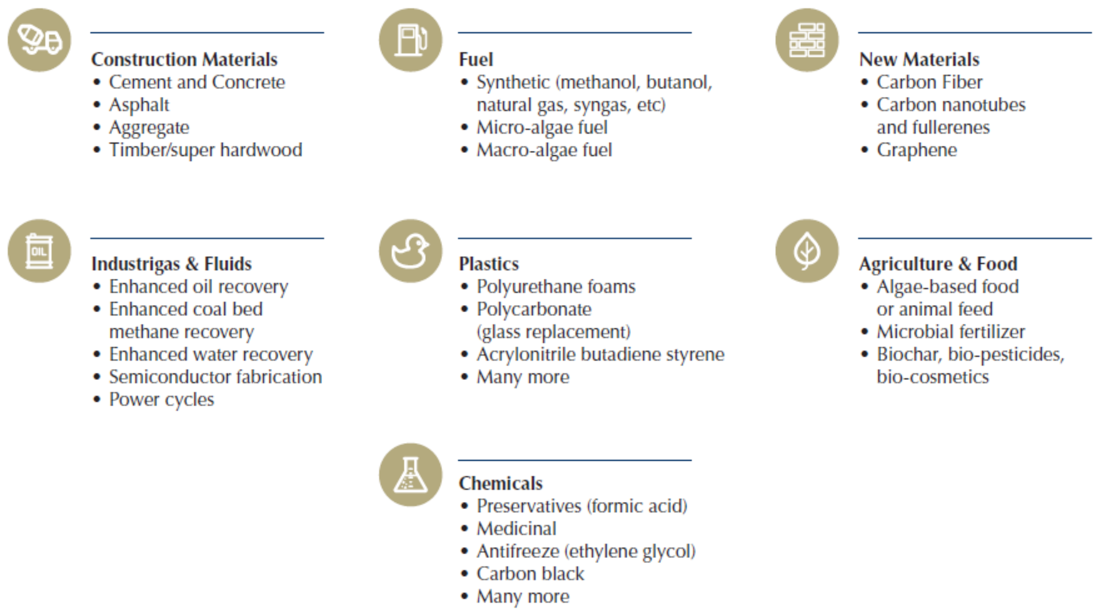

Figure 9 : General categories of utilisation technologies

Source: A Roadmap for the Global Implementation of Carbon Utilization Technologies https://assets.ctfassets.net/xg0gv1arhdr3/5VPLtRFY3YAIasum6oYkaU/48b0f\48e32d6f468d71cd80dbd451a3a/CBPI_Roadmap_Executive_Summary_Nov_2016_web.pdf

Market size and GHG reduction potential of the various sectors

It is imperative to understand that each of the sectors has a different market size and GHG reduction potential. The figure below helps to comprehend this. For instance, the current market value of low-carbon concrete is greater than all other sectors, as is its level of greenhouse gas reduction. And while concrete promises to remain the largest CCU sector in terms of market value, the potential greenhouse gas reduction contributed by other sectors, including low-carbon fuels, algae-based fuels and products, and aggregates, may surpass that of concrete by 2030. This infers that, given favorable policies, all CCU sectors have significant potential for market growth and emission reduction. (Bobeck, Peace, & Ahmad, 2019)

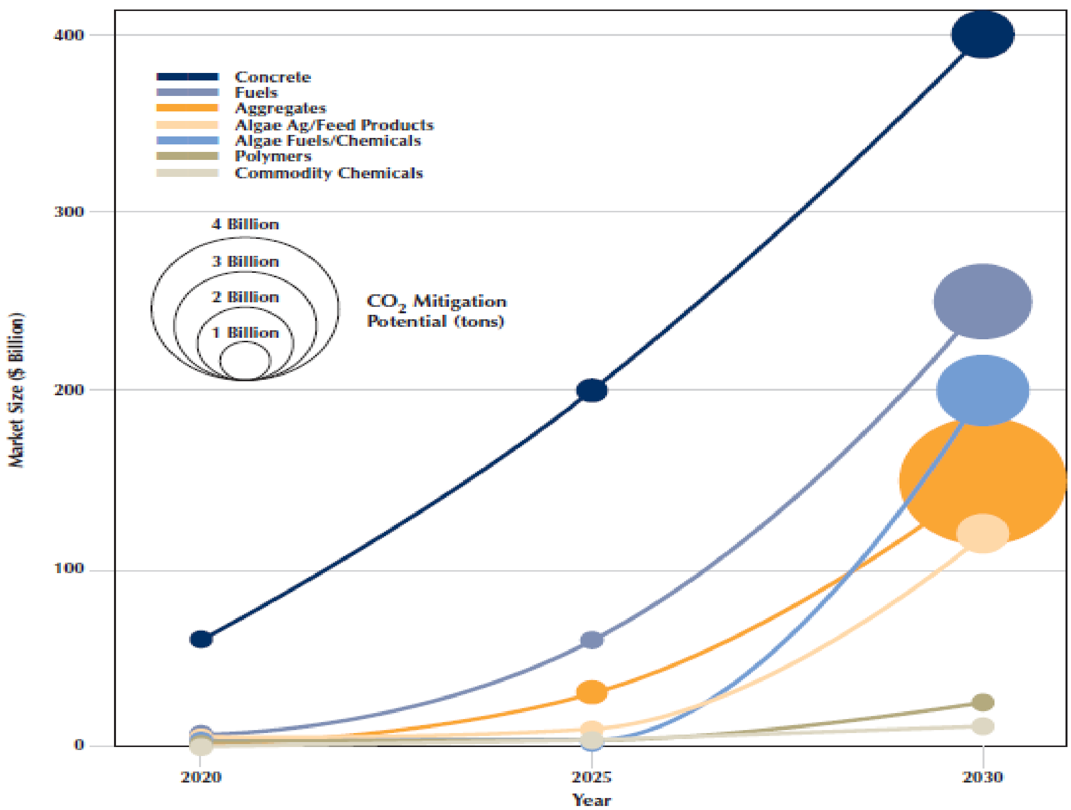

Figure 10 : Market size and GHG mitigation potential of selected CCU sectors

Source: C2ES/Cogent Solutions analysis of market trends and potential greenhouse gas reduction capacity based on market projections from the Global CO2 Initiative's Roadmap.

Prospective Utilisation Sectors

5.1 Construction Material

Construction materials represent a large, near-term opportunity for carbon utilization, principally through cement and aggregate (the gravel, sand, or crushed stone used with cement to form concrete). The current global market for concrete is around 30 billion tons which is estimated to grow to about 40 billion tons by 2030. Similarly, the global aggregates market is 25 billion to 35 billion tons, which is estimated to grow to about 50 billion tons by 2030. If carbon is used as an input and replacement for calcium carbonate, the Global CO2 Initiative estimates the associated emissions reduction potential in the construction materials sector could be in the range of 1 billion to 10 billion tons by 2030. Technologies to develop new structural materials from captured carbon, such as carbon fibers, are also in development. (Bobeck, Peace, & Ahmad, 2019)

Utilisation techniques

One of the most significant challenges of utilizing CO2 is that it is a very low-energy molecule. For most applications, a form of energy (either thermal, chemical, or electrical) has to be added to convert CO2 into a different molecule to form fuels and chemicals. In contrast, carbonates are even lower energy than CO2, which minimizes the energy needed to form them. When CO2 is incorporated into the production of cement and aggregate (and thus concrete), forming carbonates, it is not necessary to add energy to overcome thermodynamic constraints. This is important because the energy required to make large volumes of material could be extremely expensive, rendering the materials non-cost competitive and potentially less beneficial to greenhouse gas reduction efforts. (Bobeck, Peace, & Ahmad, 2019)

Another way that CO2 can be used in construction materials is referred to as direct utilization or adding CO2 to concrete during curing. This reduces the amount of cement required to produce equivalent-strength concrete, reducing emissions from cement production in addition to the CO2 incorporated into the concrete. The company Carbon Cure has applied this approach to over 100 conventional, Portland Cement-based ready-mix concrete plants in the United State and Canada. CO2 is injected into the concrete mix, and as the concrete cures, the CO2 is permanently mineralized. Solidia Technologies uses a cement that contains more silica-rich materials than conventional Portland Cement. This unconventional cement binds with more CO2 during curing and can be used to make low-carbon, high-strength, precast materials. The technology has been demonstrated at pilot scale and is anticipated to be ready for commercialization soon. (Bobeck, Peace, & Ahmad, 2019)

Drawback

However, the use of carbonate as aggregate has a significant cost barrier. Current gravel aggregate costs are typically near $50/ton depending on location, while technology developers say low-carbon aggregate might sell for $70 to $100/ton. Thus, it is unlikely that CO2-based aggregate could be widely competitive purely on price, and instead would require some form of policy support. (Bobeck, Peace, & Ahmad, 2019)

5.2 Fuels /Chemical / Plastics

Fuels, chemicals and plastics represent a significant opportunity for utilization technologies. Their potential markets are diverse and varied, but they are considered together here because their carbon utilization production processes tend to have some commonalities. (Bobeck, Peace, & Ahmad, 2019)

Fuels

The Global CO2 Initiative Roadmap estimates the total market size potential for the three product categories to range from $1 billion to more than $250 billion per year. That corresponds to an emissions reduction potential of 100,000 to 2.1 billion metric tons per year. Again, while these estimates may represent high-end market potentials, a key takeaway is that fuels may have a much larger market and a much larger emission reduction potential than chemicals and polymers. Industrial emissions containing CO and CO2 already are being biologically converted to low-carbon fuels at commercial scale today, creating fuels with over 70-percent greenhouse gas reductions compared to their fossil counterparts. (Bobeck, Peace, & Ahmad, 2019)

Chemicals

The conversion of CO2 to fuels and chemicals entails adding hydrogen (either in molecular form or from other reaction partners) to the carbon in CO2 to produce hydrocarbons. The two primary pathways for doing this are direct hydrogenation of CO2, and indirect production (Figure 6), which involves conversion of CO2 to carbon monoxide (CO) followed by synthesis of specific products. The most widely produced chemicals are

Methanol and Ethanol. In general, the two leading methods of hydrogen production are SMR and electrolysis of water.Current examples of carbon capture technology paired with steam methane reforming include the Shell Quest project near Edmonton, Canada, an Air Products facility in Port Arthur, Texas, and the Tomakomai project in Hokkaido, Japan. (Bobeck, Peace, & Ahmad, 2019)

Plastics

Plastics are included in this section on fuels and chemicals because the building blocks of most polymers include the commodity chemicals discussed above. Processes that generate commodity chemicals from CO2 will inherently produce polymers with lower life-cycle carbon emissions than those generated from petrochemicals. Polymers can also play a significant role in carbon utilization through direct inclusion of CO2 into the polymer matrix of various materials. For example, Covestro has developed a process that imbeds CO2 within the polymer chain of polyols used in the manufacture of foams for products such as mattresses. Production using this approach started in 2016 near Cologne, Germany. The facility now produces approximately 5,000 tons/year of foams that incorporate CO2. Research is being conducted to develop approaches that incorporate more CO2 into their polymer blends. (Bobeck, Peace, & Ahmad, 2019)

Drawback

The major drawback here is that the use of CO2 for fuels, chemicals, or polymers does require significant energy inputs to convert CO2 into products. Hydrogen production using SMR is currently much less expensive than water electrolysis. However, electrolytic production of hydrogen is an area of active research, and there is significant potential for reduced costs in the future. If demand for hydrogen to support CCU increases in the short term, it is likely that SMR coupled with carbon capture would be the lowest-cost option for meeting that short-term demand. (Bobeck, Peace, & Ahmad, 2019)

Pathways and their prospects

The below table shows a comparison of the potential scale and cost of different CO2 utilisation pathways. Overall, CO2 utilisation has the potential to operate at large scale and at low cost, meaning it holds the prospect of being a booming business in the future. (Adlen & Hepburn, 2019)

The values mentioned here have been estimated for the year 2050 and scale evaluations for 2050 come from a process of structured estimates, expert consultation and large scoping reviews. The cost estimates shown are breakeven costs, meaning they take into account revenue, and are presented as the interquartile ranges from techno economic studies collected from scoping reviews. This means that the costs are backward looking and likely to underestimate the ability of the pathways to achieve economies of scale. Negative costs mean that the process is profitable under present day assumptions. (Adlen & Hepburn, 2019)

S. No	Utilization Pathway	Utilisation Scale (Giga tonnes of CO_2 a year in 2050)	Cost (US dollars per tonne of CO_2)
1	Chemical	0.3 to 0.6	-80 to 300
2	Fuels	1 to 4.2	670
3	Micro algae	0.2 to 0.9	230 to 920
4	Concrete building materials	0.1 to 1.4	-30 to 70
5	Enhanced oil recovery	0.1 to 1.8	-60 to -40

Table 4 : Comparison of carbon utilization pathways Source: (Adlen & Hepburn, 2019)

It is evident from the above table that there is uncertainty in the costs of the utilization pathways. The positive cost means that there would be a net cost associated with it & business wouldn't be profitable on its own. Wherever, the cost is positive, the government has to bring the relevant subsidies or incentives in place in order to promote the carbon capture and utilization in those sectors.

5.3 Precipitated Calcium Carbonate

The transformation of CO_2 into a precipitated mineral carbonate is a promising solution for the permanent storage option of CO_2. Carbon capture and storage technologies aim for capturing carbon dioxide from point sources like power plants, industries and then transport this captured CO_2 to storage sites or for utilizing in various industries. Calcium carbonate is used in the paper industry, plastics, paints, adhesive, rubber etc. Thus, developing CO_2 into a commodity can offset the cost of CCS technology.

Feasibility for UBC

Generally, the paper industry, cement industries are already emitting GHG emissions into the atmosphere. So, it makes more sense to install the carbon capture technology at those point sources and utilize the captured carbon to develop into a meaningful product because it will save the emissions associated with transportation of carbon dioxide. However, the possible tie up with any nearby industry which is already manufacturing the PCC, surely offers advantages.

6.0 Financial Assessment of Carbon Capture Technologies

To understand the economics of setting up a carbon- capture plant, a company named C-capture, who designs chemical processes for the capture of carbon dioxide was contacted. As requested by the organization, the financial estimates provided are meant to be kept confidential. Thus, such details cannot be a part of public knowledge and thus have been excluded from this report. However, some technical details along with reasonable assumptions made for arriving at the cost estimate are discussed below: -

- CO_2 capture fraction - 90%
- Estimated footprint of the CCS unit – approx. 423 m_2.
- Electrical efficiency, losses, CO_2 drying technology, footprint reference from 5000 T/d carbon capture plant
- Cooling water inlet 15 ºC and outlet 25 ºC
- Steam, flue gas temp at 170 ºC
- SOx and NOx < 50 ppm and price of steam and electricity as per UK standards

For calculation of higher degree of accuracy, a desk-based engineering exercise will be needed and a reasonable estimate regarding the same was provided by the company. The deliverables of this professional engineering study would be:

- Preliminary process description
- Preliminary process flow diagram (PFD)
- Preliminary heat and mass balance
- Preliminary sized equipment list

The results of the desk-based engineering study would be helpful in arriving at the capex requirement, the performance of the unit and annual operation & maintenance expenses. It would be interesting to see here that, though the capex and O&M expenses would be significant, the cost avoidance and potential revenue generation is also appreciable. The revenue generated and cost avoided (carbon offset) calculation and assumptions for those calculations are presented below: -

Cost Avoidance calculation		
Carbon offset price	25.00	$/ton
Amount of carbon to offset	24985.00	tons/year
Cost avoided	624625.00	$ yearly

***** Currently UBC pays a price $ 25/ton as carbon offset

* After installation of the new biomass extension, the GHG emissions of UBC are estimated to be around 24985 tons/year, which will incur a carbon offset cost to UBC.

Apart from the cost avoided of carbon offset, the net carbon emissions of UBC will become negative. This implies that UBC will then have certain carbon offsets which can be traded in the market and there is potential of revenue generation by selling those carbon offsets. The calculation pertaining to revenue generation by selling those carbon offsets is discussed below: -

Revenue Generated calculation		
Expected rate of Selling of Carbon offset	11.00	$/ton
Estimated Carbon emissions from Biomass plant	35000.00	tons
Carbon Captured from Biomass (90% fraction)	31500.00	tons
Offset available to sell	6515.00	tons
Revenue Generated	71665.00	$ yearly

***** Source of Price of selling of carbon offset

https://www2.gov.bc.ca/gov/content/environment/climate-change/industry/selling-offsets

* 90% carbon capture fraction estimated (typical value as per C-capture)

Thus, if we take both the revenue generated from the sale of carbon offset and the cost avoided in price paid for carbon offset, it comes to around 0.7 million CAD annually. It must be kept in mind that the costs considered above include only the costs incurred while capturing GHG emissions. However, if storage is to be included, there will be an additional component added to the costs above.

Now, to break even this potential revenue generation should be more than the yearly maintenance expenses and recover some portion of the capital investment.

Different technologies have different capex requirement, annual maintenance expenses but overall the cost of all technologies which can be scalable to 100 tons/day of CO_2 capturing is on the higher side. As the cost of carbon capture is expected to go down in future and prices of carbon offset have shown increasing trend so far, the installation of CCS may seem fruitful in the upcoming years.

However, it may be interesting to compare the levelized cost of carbon capture of different technologies ($/ton CO2e) to give a clear picture of where different carbon capturing technologies stand today.

The summary of the prices of some of the carbon capture technologies along with their sources are tabulated below: -

Carbon Capture Technology	**Levelized Cost of carbon Capture**	**Source of price of Carbon Capture**
Direct Air Capture	94-232 $ USD/t-CO2e ~ 125-307 CAD/t-CO2e	Carbon Engineering - A process for capturing CO2 from the atmosphere (Joule magazine)
Membrane technology	50 $ USD/t-CO2e ~ 67 CAD/t-CO2e	Article - High-throughput computational prediction of the cost of carbon capture using mixed matrix membranes Wilmer et al (2019)
Absorption Technology	~ 79.5 CAD/t-CO2e	Calculated based on discussions with a third party and assuming project life of 20 years

7.0 Conclusion

A number of carbon capture technologies have been explored in the past decade but only a few have become successful when it comes to the capturing of carbon at commercial scale. In the technologies studied, solvent based absorption technology looks more promising when compared to the rest and is largely adopted by various industries all over the world. In general, the capturing of carbon from point sources is relatively cheaper when compared to the cost of capturing carbon directly from the air but each technology has its own advantages.

According to the preliminary study and literature research done on various carbon capturing technologies, it can be concluded that the cost of carbon capturing is certainly high. An ideal scenario will be when the cost incurred in the installation of a carbon capture facility can be recovered using the revenue generated by selling carbon offsets or saving costs in terms of the price that UBC is paying for carbon offset. However, analysing the case of UBC BRDF facility in accordance with the current level of GHG emissions, prices of carbon offset etc. the financial costs cannot be recovered.

In such scenarios, the utilization pathways for the carbon and associating with other entities makes a promising case for the future considerations. Utilization of carbon can be a potential source of further revenue generation from the captured carbon and it can offset the costs incurred in capturing the carbon.

Pathways to Future

It is evident from above that economics may be a bottleneck for the carbon capture facility. Moving forward, it may be interesting to analyse how NPVs vary depending on different time scales and with increasing prices of carbon offsets. Further, a third-party desk-based engineering study from a company like C-capture can provide a detailed technical and financial feasibility of the project and thus must be considered as a prospective next step.

To summarise, the next phase of the project should focus on the below:

1. Approach industry partners to conduct a detailed techno-economic analysis for the implementation of an absorption-based carbon capture plant at UBC BRDF
2. Study and arrive at the most suitable storage/utilisation option for the captured carbon. This will also require close interaction with industry partners. The use of carbon in PCC manufacturing seems promising and detailed study regarding the same can be taken up. Further market research on the uses of carbon in industries like paper mill, chemicals with industries specifically in B.C. can be done.
3. Study regarding costs associated with transportation of carbon should be taken up in B.C. specific scenario to have a clear understanding of the net cost of the technology.

8.0 Citation and Sources

1. Zakkour, P., Kemper, J., & Dixon, T. (2014). Incentivising and Accounting for Negative Emission Technologies. *Energy Procedia*, *63*, 6824-6833
2. 2018 B.C. Best Practices Methodological Guidance for Quantifying GHG emissions – Ministry of Environment and Climate Change Strategy, B.C
3. Chomitz, K.M., 2000: Evaluating carbon offsets for forestry and energy projects: how do they compare? World Bank Policy Research Working Paper 2357, New York
4. Herzog, H., K. Caldeira, and J. Reilly, 2003: An issue of permanence: assessing the effectiveness of temporary carbon storage, Climatic Change
5. Finland – National Inventory Report
6. Canada – National Inventory Report
7. https://www.iea.org/reports/direct-air-capture
8. Keith, D., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A Process for Capturing CO2 from the Atmosphere. *Joule*, *2*(10), 2179.
9. Singh, J., & Dhar, D. (2019). Overview of Carbon Capture Technology: Microalgal Biorefinery Concept and State-of-the-Art. *Frontiers In Marine Science*, *6*
10. https://www.hypergiant.com/
11. https://link.springer.com/article/10.1007/s11027-010-9255-9
12. https://www.vox.com/energy-and-environment/2019/10/2/20838646/climate-change-carbon-capture-enhanced-oil-recovery-eor
13. https://www.netl.doe.gov/sites/default/files/netl-file/CO2_EOR_Primer.pdf

14. Núñez-López, V., & Moskal, E. (2019). Potential of CO2-EOR for Near-Term Decarbonization. *Frontiers In Climate*, *1*

15. http://www.energybc.ca/oil.html

16. Calcium Carbonate Precipitation for CO2 Storage and Utilization: A Review of the Carbonate Crystallization and Polymorphism. Frontiers In Energy Research.

17. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_AnnexI_Glossary.pdf

18. Adlen, E., & Hepburn, C. (2019, November 11). *10 Carbon Capture methods compared: costs, scalability, permanence, cleanness.* Retrieved from energypost.eu- The best thinkers on energy: https://energypost.eu/10-carbon-capture-methods-compared-costs-scalability-permanence-cleanness/

19. Ben-Mansour, R., Habib, M., Bamidele, O., Basha, M., Qasem, N., Peedikakkal, A., . . . Ali, M. (2016). Carbon capture by physical adsorption: Materials, experimental investigations and numerical modeling and simulations – A review. *Applied Energy*, 225-255.

20. Biniek, K., Henderson, K., Rogers, M., & Santoni, G. (2020, Junw 30). *Krysta Biniek, Kimberly Henderson, Matt Rogers, and Gregory Santoni.* Retrieved from McKinsey & Company: https://www.mckinsey.com/business-functions/sustainability/our-insights/driving-co2-emissions-to-zero-and-beyond-with-carbon-capture-use-and-storage

21. Finney, K. N., Akram, M., Diego, M. E., Yang, X., & Pourkashanian, M. (2019). Carbon capture technologies. *Science Direct*, 15-45.

22. llar-Franca, R. M., & Azapagic, A. (2015). Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of CO2 Utilization- Elseveir*, 82-102.

23. Santos, F. M., Goncalves, A. L., & Pires, J. C. (2019). Negative emission technologies. *Science Direct*, 1-13.

24. Webley, P. A. (2014). Adsorption technology for CO2 separation and capture: a perspective. *Springer*, 225-231.

25. Canada, G. o. (2016, January 6). Retrieved from The Paris agreement: https://www.canada.ca/en/environment-climate-change/services/climate-change/paris-agreement.ht

26. Leung, D. Y., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Elseveir - Renewable and Sustainable Energy Review*, 426-443.

27. https://www2.gov.bc.ca/assets/gov/environment/climate-change/offsets/pricing/carbon_offset_portfolio_pricing_2018_updated.pdf?forcedownload=true

28. Budhathoki, S., Ajayi, O., Steckel, J., & Wilmer, C. (2019). High-throughput computational prediction of the cost of carbon capture using mixed matrix membranes. *Energy & Environmental Science*, *12*(4), 1255-1264

29. *Dadhich, P., Dooley, J., Fujii, Y., Hohmeyer, O., & Riahi, K. (n.d.). Cost and economic potential. IPCC Special Report on Carbon dioxide Capture and Storage, 340-362. Retrieved from https://www.ipcc.ch.*

30. Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., & Masson-Delmotte, V. et al. (2008). Target Atmospheric CO: Where Should Humanity Aim?. *The Open Atmospheric Science Journal*, *2*(1), 217-231

Appendix 1 Emission Factors B.C.: Stationary Fuel Combustion (GJ)

(1) Fuel Type	(2) Energy Conversion Factor	Emission Factor (kg/ GJ)				
		(3) Bio CO_2	(4) CO_2	(5) CH_4	(6) N_2O	(7)[c] CO_2e
Natural Gas	0.03885 GJ/ m³	–	49.58	0.0010	0.0009	49.87
Propane	0.02531 GJ/ L	–	59.86	0.0009	0.0043	61.15
Light Fuel Oil	0.03880 GJ/ L	2.77	68.12	0.0007	0.0008	68.37
Heavy Fuel Oil	0.04250 GJ/L	–	74.26	0.0013	0.0015	74.74
Kerosene	0.03768 GJ/ L	–	67.94	0.0007	0.0008	68.20
Diesel Fuel	0.03830 GJ/ L	2.77	67.43	0.0035	0.0104	70.62
Marine Diesel	0.03830 GJ/L	2.77	67.43	0.0065	0.0019	68.16
Gasoline	0.03500 GJ/ L	3.22	62.86	0.0771	0.0014	65.22
Wood Fuel – Industrial (50% moisture)	0.00900 GJ/ kg	93.33	–	0.0100	0.0067	2.24
Wood Fuel – Residential (0% moisture)	0.01800 GJ/ kg	82.11	–	.6833	.0067	19.07
Ethanol (E100)	0.02342 GJ/L	64.43	–	a	a	a
Biodiesel (B100)	0.03567 GJ/L	69.36	–	b	b	b
Renewable Natural Gas	0.03885 GJ/ m³	49.58	–	0.0010	0.0009	0.29

[a] Gasoline CH4 and N2O emission factors (by mode and technology) are used for ethanol.
[b] Diesel CH4 and N2O emission factors (by mode and technology) are used for biodiesel.
[c] The CO_2e values in column (7) exclude Bio CO_2