HOW CAN CCUS PLAY ITS NEEDED ROLE IN CLIMATE POLICY

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Abstract: Numerous scenarios show Carbon Capture, Utilization, and Storage (CCUS) playing a significant role in meeting global climate targets for the coming decades. However, many barriers to making these scenarios a reality exist. Except for a very small amount of carbon that is currently captured and used for enhanced oil recovery (EOR) and other small uses, little CO2 is currently sequestered. As the climate benefits accrue to the many, while the sequestration costs accrue to the few, the market has and will fail to provide the desired sequestration. As with other externalities, policy will be needed to accomplish a significant amount of CCUS. The contribution in our survey project will be to summarize barriers to CCUS implementation, consider the policies that have been implemented and that are needed to incentivize CCUS, look at the status of existing and planned CCUS projects, collect existing cost estimates for CCUS, and survey the existing economic models in support of CCUS policy analysis. From the survey, we will provide the best available information to stakeholders in CCUS as well as making recommendations for best practice and future avenues of research. This paper will report the progress made to date on our larger project.

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I. Introduction

With rising ferocity and frequency of extreme weather and ecological events (e.g., droughts, hurricanes, floods, rising sea, dying coral reefs), climate change no longer seems a figment of climate scientist's imaginations and models. Rather, it is here; it is now. Thus, many are considering how to limit global temperature increase to less than 1.5℃ as set in the Paris Agreement in 2015 (Delbeke et al., 2019). Most long-term scenarios see a role for CCUS (NPC, 2019). For example, IEA argues that to meet the Paris Agreement, 1/5 of industrial CO2 emissions will have to be sequestered by 2060, amounting to an estimated 28 gigatonnes (Gt) (note tonnes in this paper will refer to metric tonnes) (IEA, 2019). Although effort has been expended on its technical feasibility and cost, very little carbon and other greenhouse gases have been deliberately sequestered. Around 32 Gt of CO2 were emitted from fossil fuel combustion in 2020, whereas only an estimated 40 megatonnes (Mt) were captured and sequestered in 2019 (GCCSI, 2020). The CO2 captured for most of the existing projects were for use in enhanced oil recovery (EOR). Thus, use is an exceptionally small part of CO2 emitted and is likely to remain so near term. Nevertheless, we will refer to these processes as CCUS throughout the paper unless surveyed studies have focused exclusively on carbon capture and sequestration (CCS) for geological sequestration.

There have been a few cases of commercial CCUS projects that have operated for decades, but these opportunities seem quite limited. There are some other market forces such as investor pressure to sequester CO2. For example, ExxonMobil has committed to building a huge CO2 hub in the Houston Ship Channel (Joe Blommaert, 2021). However, since CO2 emissions have negative externalities, markets alone have and will likely fail and less than an optimal amount of CO2 will be sequestered.

Numerous barriers exist to prevent large scale CCUS. In this paper, we will consider cost, risk and other limiting barriers. As these barriers are likely to persist, many governments have passed or are considering passing policies to encourage CCUS and cleaner energy technologies. They include policies more generally targeting carbon price such as carbon emission taxes (e.g., Norway’s carbon tax at Sleipner and Snøhvit fields) and cap and trade of emission permits (e.g., E.U. carbon trading) or policies that more specifically target CCUS (e.g., U.S. 45Q tax credits) (GCCSI, 2019). In our project, we will collect information on such policies that have been proposed or passed, consider the pros and cons of the policies, and indicate the needed institutional framework for the policies to succeed.

Currently there are 28 active CCUS projects (Global CCS Institute, 2020). We will summarize these existing commercial and pilot projects as well as those that plan to soon be sequestering carbon. They will be categorized by region, country, capture type, and storage noted. The projects will be analyzed to see what lessons can be learned, what recommendations can be made, and what future directions seem most promising.

Cost will be an important input into policy decision making and supporting economic modeling efforts of CCUS. For any market-based policies, the price of sequestration will have to cover its economic costs. We will survey the most recent literature on costs by sequestration stage (capture, transport, storage). The uncertainty around these cost estimates will be quantified if possible.

Such cost estimates are needed for the limited number of economic models relating to CCUS. In these models, the following three stages may be included: capture, transport, and storage (geological storage as well as utilization). Economic models may focus on an integrated process of CCUS. While others have modeled one or more of the three stages. Most are single objective optimization models with the goal of minimizing cost, maximizing profits, maximizing oil or gas production, or minimizing environmental impact. Their methodologies include linear programming (LP), nonlinear programming (NLP), mixed integer programming (MIP), and network optimization models. A few optimize over multi-objectives (e.g., minimize total cost (including capture, transport, and sequestration, etc.) and environmental impact). Such models can be static or dynamic and with or without uncertainty. Some of the studies include generic models that are not geographically specific, others use a specific geographical region to apply their model. The geographical boundaries or level of aggregation across these latter studies range from as small as an oil field used to sequester up to countries within a region such as Europe.

Within our CCUS survey project, our main focus will be on economic issues. This paper reports our progress to date relating to the literature on policies, projects, costs, and economic modeling of CCUS. The structure of the paper is as follows. Part II will provide an overview of the existing barriers to commercial and prototype projects. Part III will consider policies and the legal framework needed to address CO2 externalities. Part IV will summarize existing projects, while Part V will consider what we know about CCUS cost. These costs will be essential to economic modelling of CCUS. Such models are reviewed in part VI. Expected results and suggestions for further work will be given in part VII.

II. Barriers to CCUS

When considering technical fixes, we need to know if the fix is technologically feasible. So can we burn fossil fuels, capture the CO2 before or after combustion, stick it in the ground and keep it there in perpetuity? We think the answer is, "Yes we can". Indeed, IEAGHG (2014) indicates that CO2 has been separated from other gases since the 1920s. CCUS has been employed commercially in conjunction with enhanced oil recovery (EOR) in Texas since 1972. This Texas project required separation of CO2 from natural gas streams, transportation of the gas by pipeline and injecting it underground (GCCSI, 2020). CO2 has been extracted from fossil fuel processing as well. The Great Plains Synfuels Plant in North Dakota has been extracting CO2 from its lignite gasification process and selling it commercially to two oil fields in Canada for EOR since 2000 (Dakota Gasification Company, 2020). Two more recent projects that have been retrofitted to captured CO2 from flue gas are Boundary Dam Power Plant in Saskatchewan Canada and Petro Nova Unit 8 near Houston. Both commenced operation around 2017 with the CO2 sold for EOR. However, Petro Nova stopped CCUS in 2020 citing low oil prices as the reason. It could commence operations again if the oil market gets strong enough (IEA, 2017; NRG Energy, 2018; Schlissel, 2020).

When the CO2 is used for EOR, about 90% of the CO2 get recycled and remains in the ground. However, when we burn the oil products, CO2 is put back in the atmosphere. Overton (2016) estimates that less than 25% of the original CO2 emitted from processing the coal is ultimately sequestered in the process. Thus, CCS to EOR may help. In some cases, it is commercially successful, but it will not solve the problem.

Thus, we know how to capture the CO2, we can transport it, and we can sequester it, but do we have enough underground space to store it? In 2020, BP Statistics (2021) estimates global emissions of CO2 from burning fossil fuels are more than 32 Gt, while IPCC (2018) suggest we will need to sequester 5.6 Gt CO2 per year by 2050 with a total of 220 Gt stored between 1920-2070. The most likely possibilities for sequestering include the ocean or geological formations - deep saline formations, depleted oil and gas reservoirs, and coal seams. The ocean is currently thought to sequester about a third of our carbon emissions (WRI, 2020). However, unknown environmental effects, efficiency, and chemical processes make additional sequestration in the ocean a less likely near-term prospect. Geological storage is better understood with successful examples already in place and is likely abundant (Heyes & Urban, 2019). Malischek and McCulloch (2021) cite global geological storage capacity of 8,000 – 55,000 Gt suggesting potential storage capacity for some time to come.

So what then are the major barriers to CCS. Davies, Uchitel, and Ruple (2013) surveyed 229 CCS experts and found the primary barriers are recovering costs, lack of financial incentives, long term accident and environmental risks, and a need for an effective policy environment.

Irlam (2017) demonstrates the increase in levelized cost of output for a number of countries and carbon intensive industries including coal electricity generation and a few other carbon intensive industries – iron and steel, cement, and fertilizer. For these applications, except for fertilizer, first of a kind (FOAK) CCS would increase levelized costs of output in the U.S. from 30%-70%. The levelized cost of CO2 sequestered would likely range from $66-$124/tonne. The effects on fertilizer would be significantly lower raising levelized output costs by only 3-4% with CO2 sequestration costs of $25 per tonne. He suggests an nth of a kind (NOAK) project might lower these costs by 20-30%. A related issue is the risk from high upfront capital costs with an uncertain future. EIA (2021) suggests that for a new supercritical coal electricity generation plant overnight capital costs are $3,672/kilowatt (kW) but adding CCS that sequesters 90% of the CO2 raises cost to $5861/kW. Even if one company wants to sequester, they will not be able to remain cost competitive unless all companies sequester. Without effective policy, universal compliance is quite unlikely.

High cost alone is not sufficient to keep ventures off the table provided the rewards can compensate for the high costs and risks. The very small amount of current sequestration again suggests that the current commercial price of CO2 is not sufficient. However, GCCSI (2021) suggested a CO2 tax of US $40-80/tCO2 by 2020, US $50-100/tCO2 by 2030 would put us on track to meet the 1.5 degree climate goal.

Storage is not without risks. Herzog and Golomb (2004) suggest that for such storage to be competitive not only costs and the economic environment need to be favorable, but CO2 will need to be stored for a very long time, accident and environmental risks will need to managed, and the whole process will need to obey local and international laws.

Some worry that leakage could be a problem. Although CO2 is not generally toxic to humans, if it leaks into low lying pockets leaving the oxygen content too low humans or animals might be asphyxiated. Further, if CO2 leaks it rather defeats the purpose. Given that oil and gas have been stored for millions of years underground, it seems likely that long-term leakage can be prevented with proper reservoir choice and management (Herzog & Golomb, 2004). Too much CO2 forced into geological unstable areas could cause earthquakes with surface damage and some potential for leakage (Zoback & Gorelick, 2012). Again, however, proper reservoir choice and management is protection against damaging earthquakes (Juanes et al., 2012). Nevertheless, the private sector is unlikely to want to deal with unlimited and potentially perpetual storage liability under laws and regulations that have not even been passed yet.

Even if reservoirs are deemed safe, there may be other objections to fossil fuels and CCUS. Fundamental issues with the use of fossil fuels include energy security as well as non-climate environmental externalities associated with production, transport, and burning of fossil fuels. Also, NIMBY (not in my back yard) issues may be present in transporting CO2 and siting CCS storage, especially onshore. For CCS to happen we need not only regulations and policies for industry acceptance all along the supply chain, we also need public acceptability. This, too, is likely to need government intervention to communicate and coordinate to obtain all stakeholder buy in.

III. Policies

The CCUS annual capture capacity in 2020 was 40 megatonnes per annum (Mtpa), which is less than 1% of the expected amount needed to achieve net-zero GHG emissions by 2050 (GCCSI, 2021). In less than 30 years, Nykvist (2013) suggests we will need a tenfold increase in pilot plants, number of constructed large-scale demonstration plants, and annual funding by 2020 for the needed current technology to successfully meet global targets. Such global scale-up requires investments, significant government support, and years of planning and building. At the current rate, the technology is unlikely to contribute its needed share to meet the 1.5 degree emission target (IEA, 2020) putting us at a pivotal moment to accelerate its innovation and global deployment.

The policy framework needed for CCUS to succeed has four main characteristics: the capability to scale up development, proper economic incentives, short and long-term investment planning, and sustained support for innovation of the technology(IEA, 2019). Complementary significant additional public support will be essential. A five year delay could result in 50% less CO2 emissions being captured worldwide in 2030 and 35% less in 2040 than in the IEA Sustainable Development Scenario (IEA, 2021). It would also hold up the rate of decline in costs over time resulting from the missed opportunity for learning-by-doing (IEA, 2020). The CO2 not captured by CCUS will still have to be offset by other emission technologies. However, as CCUS is a relatively mature technology, it should not be delayed waiting for a silver bullet to appear in the future (Löschel & Otto, 2009).

Strong political support is needed for large-scale deployment. Successful implementation requires pipeline planning, and a clear process to make commercial CCUS attractive to potential investors (Scott, 2013). For example, government support will be very important in responding to the uncertainty associated with the rate of innovation and technical progress (Yang et al., 2018),the risk associated with an uncertain future demand for capturing facilities, and the high upfront cost for the transport and storage (IEA, 2020).

Planning and building facilities need time and a massive increase in investment in the coming months for the projected expansion of capacity later in the decade to be achieved. Any policy framework should recognize the importance of demonstration projects to showcase the technology and encourage short and long term investment planning and commercialization. As CO2 is a negative market externality, the private sector will likely not invest in CCUS unless it is obliged to do so, or it can make a profit or earn credits from the captured emission under a carbon pricing agreement (IEA, 2020). It should also recognize that to spur widespread deployment of the technology, carbon pricing alone will not be sufficient, measures such as initial capital grants and operating subsidies are crucial in building a business case to incentivize early investment (GCCSI, 2020). Sustained support for innovation is required as well to achieve CCUS technology's high potential for cost reduction. For example, the capital expenditure could be 20-25% lower for the Quest CCS project started in 2012 that if it were started five years later (IEAGHG, 2017).

The available instruments that policy makers can use to establish such a framework include direct capital grants, tax credits, carbon pricing mechanisms, operational subsidies (e.g., cost-plus open book, feed-in tariffs), regulatory requirements, public procurement of low-carbon products from CCUS-equipped plants, risk mitigation measures (loan guarantees, pain-gain risk-sharing mechanisms, CO2 liability ownership), and funding for RD&D (Research, Design, and Development)(IEA, 2020). Some of the instruments are already used by governments across the world. Examples in Europe include: the EU Innovation Fund (EUR 10 billion), the UK CCUS Infrastructure Fund (GBP 800 million), Norway's carbon tax on offshore oil and gas, European ETS (a cap on emissions with trading of emissions certificates), Netherlands' SDE++ scheme, the UK power sector CfD arrangements (covering the cost differentials between production costs and a market price), the EU Renewable Energy Directive II, UK's regulated asset base model, and EU Horizon

2020(IEA, 2020). In America there are: the US 45Q and 48A tax credits, Canada's Federal Output-Based Pricing System, allowable CO2 intensity from coal and natural gas power generation limitations in Canada, Canada/US Carbon XPRIZE, and the US Department of Energy CCUS R&D programs (IEA, 2020). In UAE, Saudi Arabia, and China, CCUS projects are usually directly supported by state-owned enterprises (GCCSI, 2020). A complete suggested framework can be found in Figure 1.

A complete policy framework should be sustainable and economically viable throughout the lifetime of a CCUS project. This requires the above policy measures to be used according to the current stage of the CCUS infrastructure development, the specific sector, and region. For example, while tax credits are a well-established policy mechanism in the U.S. with great incentives for mature CCUS technologies, they are not as effective for countries that are at earlier stages of development. In heavy industry (e.g., cement, iron and steel, and fertilizer), where the products are competitively international traded commodities, applying CCUS technologies is especially challenging, requiring more policy interventions.

Figure 1:

A Suggested Policy Framework by Application Stage and Sector

<table>
<tr><th>CCUS pplication</th><th>Prototype</th><th>Demonstration</th><th>Early Adoption</th><th>Mature</th></tr>
<tr><td rowspan="8">Capture</td><td colspan="2"></td><td colspan="2">Chemicals (ammonia)</td></tr>
<tr><td></td><td colspan="2">Chemicals (methanol)</td><td></td></tr>
<tr><td colspan="2">Cement</td><td>Hydrogen (gas)</td><td>Natural gas processing</td></tr>
<tr><td colspan="2">Bioethanol</td><td colspan="2"></td></tr>
<tr><td colspan="3">Iron and steel</td><td></td></tr>
<tr><td>Direct air capture</td><td colspan="2">Power (coal)</td><td></td></tr>
<tr><td></td><td>Power (biomass)</td><td colspan="2"></td></tr>
<tr><td></td><td>Power (gas)</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Utilization</td><td>Synthetic fuels</td><td>Synthetic methane</td><td>Building materials</td><td>Chemicals (urea)</td></tr>
<tr><td></td><td>Methanol</td><td colspan="2"></td></tr>
<tr><td>Transport</td><td colspan="2">CO2 shipping</td><td>CO2 pipelines</td><td></td></tr>
<tr><td>Storage</td><td colspan="2">Depleted oil & gas reservoirs</td><td>Saline formations</td><td>Enhanced oil recovery (EOR)</td></tr>
<tr><td rowspan="8">Policy measure</td><td colspan="4">Innovation and R & D</td></tr>
<tr><td colspan="3">Capital grants</td><td></td></tr>
<tr><td></td><td colspan="3">Carbon pricing</td></tr>
<tr><td></td><td colspan="3">Operating subsidies</td></tr>
<tr><td></td><td colspan="3">Risk mitigation</td></tr>
<tr><td></td><td colspan="3">Market mechanisms</td></tr>
<tr><td colspan="2"></td><td colspan="2">Demand-side measures</td></tr>
<tr><td colspan="2"></td><td colspan="2">Regulatory standards and obligations</td></tr>
</table>

Source: IEA, 2020, Energy Technology Perspective

In contrast, for industrial processes such as natural gas processing, CCUS is a lower-cost, mature, and scalable option for capturing and reducing CO2, making it more economically viable and requiring relatively less interventions.

IV. Existing Projects

As a solution to CO_2 emission abatement, CCS/CCU/CCUS are being considered by many countries. To date, there are 135 large-scale commercial CCUS projects in the world. Among them, 27 projects are in operation (See Fig.2), with annual carbon capture and storage capacity of around 36.6 million tons, And 2 projects are reported to be suspended now, while the rest are under construction or different development stages (GCCSI 2020). In terms of the carbon sources of current operational projects, most of the demonstration and pilot CCUS projects capture carbon from fossil-fuel sources, mainly power/generating plants. Theoretically, CO_2 is formed during the combustion, and the choice of CO_2 removal technologies highly depends on the type of combustion process. And there are four CO_2 capture technologies, namely pre-combustion, oxy-fuel combustion, post-combustion, and chemical looping combustion, developed to capture CO_2 from fossil fuel source. CO_2 sources can be retrofitted with different capture technologies to capture CO_2 in different qualify for further purposes. Although existing research indicates promising prospects of fossil-fuel source CO_2 usage, only two available large-scale commercial CCS projects, including Boundary Dam CCS in Canada (Lanktree, 2014) and Petra Nova in U.S. (Hunter, 2014), have been equipped with corresponding capture technologies, and only Boundary Dam is currently operating. By contrast, majority of the projects isolate CO_2 from industrial sources such as fertilizer plant (Tapia et al., 2018).

After capture, compression, and transportation, then it comes to final treatments of CO_2, where utilization and storage serve as two options. In utilization options, CO_2 are mainly utilized for the production of chemical synthesis and energy products, alone with injection purposes such as enhanced oil recovery (EOR). For storeage purposes, by contrast, CO_2 can be stored within the oil and gas reservoir, deep saline aquifer, and unminable coal beds (Tapia et al., 2018). Three types of projects are developed accordingly: carbon capture and utilization (CCU), carbon capture and storage (CCS), and carbon capture, utilization, and storage (CCUS), where utilization and storage are coupled. Our highest level category for projects will be regional for the Americas, Europe, Middle East, and Asia-Pacific with information given by country, capture and storage technology.

Americas: In 2021, there were 13 large-scale commercial CCUS projects operating in the United States, accounting for over 25Mt CO_2 annually. Among them, Petra Nova (now inactive), the sole U. S. project that isolated CO_2 from power plants, was the largest post-combustion CO_2 capture project around the world. Subsidized with U.S. DOE grants and supported by an integrated power corporation named NRG in conjunction with Jippon NX, Petra Nova served as the first commercial CCUS project in the power generation sector in the U.S. Its lessons provide some insights for carbon emission mitigation within the fossil fuel industry (Mantripragada et al., 2019).

Instead of capturing CO_2 from the power sector as for Petra Nova, most of the other U.S. CCUS projects tended to focus on other industry sources, including natural gas processing as well as the production of ethanol, synthetic natural gas, and fertilizer. Terrell Nature Gas Processing, for instance, was initialized in Texas and commenced in 1972, and serves as the oldest CCUS facility in the United States with the capture capacity of around 0.5 Mtpa. It isolates CO_2 during natural gas processing and then distributes the CO_2 to oil fields for oil recovery. Having been capturing up to 3 Mt CO_2 per year, Dakota Gasification Great Plains Synfuels Plant possesses higher CO_2 capture capacity from coal conversion than other facilities and participates in the world's largest carbon sequestration project. To date, it has isolated and transported more than 40 Mt CO_2 for EOR in Saskatchewan, Canada since 2000. The CO_2 will remain sequestered after oil production has ceased.

What is worthy of notice is that projects like Coffeyville Plant, Great Plains Synfuel Plant, and Enid Fertilizer share a similar feature in their business models, where the CO_2 capture, transport, utilization and storage are operated by a third-party CCS corporation (Yao et al., 2018).

Another 5 large-scale commercial CCUS projects in the Americas locate in Canada and Brazil. Prior to Petra Nova, Boundary Dam in Canada (Mantripragada et al., 2019) is the prototype which takes advantage of post-combustion technology to capture CO_2. That is distributed to oil fields for EOR and the rest is sequestered in geological storage. Other industry milestones in Canada include Alberta Carbon Trunk Line system and Quest CCS project (Bourne et al., 2014). Alberta Carbon Trunk Line, with a transportation capacity of 14.6 Mt CO_2 per year, has become the world's biggest transportation infrastructure. Moreover, two plants connected with the system, Sturgeon Refinery as well as Agrim fertilizer plant (GCCSI, 2020) can totally capture 2 Mtpa CO_2 and then transport it through the line to recover oil fields in Central Alberta. Besides, Quest is the world's first oil sands CCS project, which is capable of absorbing nearly one third of CO_2 emission from hydrogen manufacturing units and then storing it into a deep Basal Cambrian Sandstones (Moradi & Lawton, 2014).

As for South America, due to the upsurge in fossil fuel consumption as the result of expanded population and production activities, a project called Petrobras Santos Basin Pre-Salt Oil field has been implemented off the coast of Rio de Janeiro by Brazil's government. It is regarded as the prototype for CO_2-EOR technology in an offshore oil field recovery.

Europe: Stimulated by EU's 10 billion Euro investment in low-carbon technology in July 2020 and the ensuing 2030 Climate Target Plan, the European CCUS industry seems to be promising. Thirteen large-scale commercial projects are in either the operational or development stage: seven in the United Kingdom, four in Norway, one in Ireland, and one in Netherlands. However, only the Sleipner CO_2 Storage, Snøvit CCS project, MOL Szank field CO_2 EOR, and Gorgon Carbon Dioxide Injection are available now. The first two of them are in Norway, and they have isolated over 22 Mt CO_2 so far. The captured CO_2 from the gas stream is necessary to meet quality specifications for exported natural gas or liquid natural gas, while the sequestration created an exemption to paying the Norwegian CO_2 tax. Particularly, commencing in 1996, the Sleipner CCS project is the first offshore CCS facility for ecological storage around the world. Therefore, it offers us a valuable learning experience. As a CCS hub, Sleipner also deals with the captured CO_2 liquid from a neighboring gas field (Ringrose, 2018).

Middle East: CCUS projects in Middle East are mainly in three countries: Saudi Arabia (Uthmaniyah), Qatar (Qatar LNG CCS), and United Arabic Emirates (Abu Dhabi CCS). Approximately 0.8 Mpta of CO_2 is separated from natural gas and consumed by Uthmaniyah for oil production. Qatar LNG CCS captures 2.1 Mpta of CO_2 from natural gas processing. The Qatar government plans to expand the application of CCS and increase the capture capacity up to 5 Mtpa at 2025 (GCCSI 2020).

As a prototype funded by the Abu Dhabi National Oil Company, Abu Dhabi CCS is the first CCS project applied in the iron and steel industry around world. By means of a novel CO_2 compression facility, it absorbs CO_2 (around 0.8 Mtpa) during iron production, processing, and transport. The CO_2 is used for improving oil production and replacing current water alternating natural gas injection (WAG). This application is expected to save about 40% of the total natural gas that could be used for power generation or export (Ustadi et al., 2017). Furthermore, the company is developing another CCUS project whose expected capacity is up to 2.3 Mpta.

Asia-Pacific: Currently, Asia-Pacific possesses four operating CCUS projects: Gorgon Carbon Dioxide Injection (Australia), CNPC Jilin Oil Field CO_2-EOR (China), Sinopec Zhongyuan CCUS (China), and Karamay Dunhua Oil Technology CCUS EOR (China). Initiated in 2019, Gorgon Carbon Dioxide Injection has a capture capacity around 3.7 Mtpa, where reservoir CO2 is captured and transported over a short distance and then injected deep into the subsurface of Barrow island.

China, on the other hand, has its earliest full-chain CCUS demonstration project--Shenhua Ordos Coal to Liquid (CTL) project which commenced in 2010 and ended in 2015 (X. Li et al., 2016) (Q. Li et al., 2017). Until now, China has 3 large-scale commercial CCS projects operating and another 3 projects in development or construction stages. In terms of available projects, all of them handle and transport CO2 for oil field recovery. CNPC Jilin Oil Field CO2 EOR, located in northeast China, has reached a capacity of 0.6 Mtpa after 12-year pilot and demonstration phase, whereas that of Sinopec Zhongyuan CCUS and Karamay Dunhua Oil Field CO2-EOR are 0.12 and 0.1 Mtpa respectively.

Project	Research	Country	Industry	Utilization/Storage Options
Alberta Carbon Trunk Line (ACTL) with Sturgeon Refinery CO2 Stream	(GCCSI, 2020)	Canada	Hydrogen Production	EOR
Alberta Carbon Trunk Line (ACTL) with Agrim CO2 Stream	(GCCSI, 2020)	Canada	Fertiliser Production	EOR
Quest Carbon Capture and Storage	(Moradi & Lawton, 2014) (Bourne et al., 2014)	Canada	Hydrogen Production	EOR
Boundary Dam CCS facility	(Mantripragada et al., 2019)	Canada	Power Gneneration	various options considered
Illinois Industrial Carbon Capture and Storage	(GCCSI, 2020)	The United States	Ethanol Production	Dedicated Geological Storage
Coffeyville Gasification Plant	(Yao et al., 2018)	The United States	Fertiser Production	EOR
Air Products Steam Methane Reformer	(Preston, 2020)	The United States	Hydrogen Production	EOR
Lost Carbin Gas Plant	(GCCSI, 2020)	The United States	Natural Gas Processing	EOR
Century Plant	(GCCSI, 2020)	The United States	Natural Gas Processing	EOR & Dedicated Geological Storage
Great Plains Synfuels Plant and Weyburn-Midale	(Yao et al., 2018)	The United States	Sythetic Natural Gas	EOR
Shute Creek Gas Processing Plant	(Shute & Treating, 2018)	The United States	Natural Gas Processing	EOR
Enid Fertilizer	(Yao et al., 2018)	The United States	Fertiliser Production	EOR
Terrell Natural Gas Processing Plant	(GCCSI, 2020)	The United States	Natural Gas Processing	EOR
Arkalon CO2 Compression Facility	(GCCSI, 2020)	The United States	Ethanol Production	EOR
Bonanza Bioenergy CCUS EOR	(GCCSI, 2020)	The United States	Ethanol Production	EOR
Core Energy CO2-EOR	(GCCSI, 2020)	The United States	Natural Gas Processing	EOR
PCS Nitrogen	(GCCSI, 2020)	The United States	Fertiliser Production	EOR
Petrobras Santos Basin Pre-Salt Oil Field CCS	(Hatimondi et al., 2011)	Brazil	Natural Gas Processing	EOR
Snøhvit CO2 Storage	(Ringrose, 2018)	Norway	Natural Gas Processing	Dedicated Geological Storage
Sleipner CO2 Storage	(Ringrose, 2018)	Norway	Natural Gas Processing	Dedicated Geological Storage

MOL Szank field CO2 EOR		Hungary	Natural Gas Processing	EOR
Gorgon Carbon Dioxide Injection	(Trupp et al., 2013)	Australia	Natural Gas Processing	Dedicated Geological Storage
Uthmaniyah CO2 EOR Demonstration	(Yao et al., 2018)	Saudi Arabia	Natural Gas Processing	EOR
Qatar LNG CCS	(GCCSI, 2020)	Qatar	Natural Gas Processing	Dedicated Geological Storage
Abu Dhabi CCS	(Ustadi et al., 2017)	United Arab Emirates	Iron and Steel Production	EOR
Karamay Dunhua Oil Technology CCUS EOR	(Yang et al., 2018) (Xu et al., 2021)	China	Methanol Production	EOR
CNPC Jilin Oil Field CO2 EOR	(Xu et al., 2021) (Yang et al., 2018)	China	Natural Gas Processing	EOR
Sinopec Zhongyuan Carbon Capture Utilization and Storage	(Xu et al., 2021) (T. Zhang et al., 2017)	China	Chemical Production	EOR

Table 1. Large-scale Commercial CCUS Projects in Operation

Sources: GCCSI , 2020, Global Status of CCS 2020

V. CCS Costs

Each stage of CCUS technology is associated with different costs. For the capture stage, costs are divided by industrial sector and CO2 concentration. From the lowest to highest, the capture cost for high CO2 concentration sector ranges from 15 – 25 USD/tonne for natural gas processing and coal to chemicals, 25 – 35 USD/tonne for ammonia, bioethanol, and ethylene oxide; and 50 – 80 USD/tonne for hydrogen using steam methane reforming (SMR). For low CO2 concentration sectors, the capture cost ranges from 40 – 80 USD/tonne for power generation; 40 – 100 USD/tonne for iron and steel; 60 – 120 USD/tonne for cement; and 134 – 342 USD/tonne for direct air capture (GCCSI, 2017; IEAGHG, 2014; Keith et al., 2018; NETL, 2014; Rubin et al., 2015)The cost for pipeline transport varies greatly due to its high sensitivity to scale and location, ranging from 1.40 USD/tonne per 250 km (IPCC, 2014) for large-scale transportation (30 Mtpa) to 11.74 USD/tonne per 250 km (ZEP, 2020)for smaller capacity transportation (3 Mtpa).

The cost of storage is relatively cheap but the cost of finding a suitable site could increase the cost by 60% – 80%, 150 million USD is considered to be the economic threshold for finding such a site (Heyes & Urban, 2019). In the United States, for example, the cost of onshore storage is in a wide spread of 25 – 60 USD/tonne. More than half of onshore storage capacity is estimated to be available at 5 – 9 USD/tonne (GCCSI, 2011), and in some cases can be negative if used in EOR projects (IEA, 2020).

The cost can be stabilized in the lower range and a further reduction in cost is possible with CCUS technology due to potential economies of scale and learning-by-doing. For example, the capture cost for the newer Petra Nova project is 35% lower than the Boundary Dam project, which was built a few years earlier (IEAGHG, 2018). A study from GCCSI (2019) also shows a potential 70% capital expenditure cost and operational cost reduction for the Boundary Dam project if it were built just five years later. Heyes and Urban (2019) suggest that by doubling the diameter of the pipeline, from 0.5 m to 1 m, the max CO2 flow will be quadrupled, which will also lead to a cost reduction in pipeline cost from 1.43 USD/tonne to 0.57

USD/tonne due to economies of scale. IEA (2020) estimates that between 2019 and 2070, the capture cost for CCUS technology can be reduced by 35% in both the power and industrial sectors.

VI. Review of economic modeling of CCUS

In terms of economic models, many studies have focused on the integral CCUS process and its subordinate phases. Among them, most are single objective optimization models with goal including cost minimization (Leonzio et al., 2020), profit maximization (Gorban et al., 2021), oil & gas extraction maximization, and environmental impact minimization by using linear programing (LP), nonlinear programming (NLP), mixed integer linear programming (MIP), etc. Tan et al., (2010) presented an integer programming optimization model to maximize the abatement of carbon emission caused by carbon capture facilities. Sarkar & Bhattacharyya (2012) linearized and improved discrete energy capacities within a CO2-enhanced oil recovery and CCUS system by inventing a two-stage transmitting network optimization model. d'Amore et al., (2021) determined optimal configuration and technology selection of a Europe-wide CCUS supply chain in order to minimize total cost.

Rather than a sole objective, some studies develop multi-objective optimization models so as to consider different issues simultaneously. Zhang et al. (2020), for instance, applied a novel multi-objective mixed integer linear programming (MILP) model to minimize both total cost, which includes carbon capture, transport, sequestration, along with environmental impact brought by a CCS supply chain in Northeast China. Another multi-objective optimization model concerning a joint maximization of both oil recovery and CO2 storage in Texas was proposed by Ampomah (2016). To make a balance between the environmental impact and latent uncertainty and risk in installation and operation of CCUS, Lee (2019) formulated a two-stage multi-objective optimization algorithm.

When it comes to geological and geographical scale, some studies use nonspecific generic models, whereas others apply their models on geologically or geographically specific regions. In fact, the geological boundaries or level of aggregation across these studies range from as small as an oil field (Balch et al., 2017) which is used to sequestrate CO2 to a continental scale CCUS system, particularly Europe (d'Amore, Romano, & Bezzo, 2021). For example, a life-cycle assessment was conducted by Thorne (2019) on a promising oil field in Norway to compare with the reference system and evaluated the potential of CO2-EOR system in Europe. By integrating Ohio-specific data, Fukai et al. (2017) incorporated a cost-benefit analysis to evaluate the economic feasibility of CO2-EOR in an oil field in Ohio.

CCUS systems at a national scale are contemplated as well, such as China (Cai et al., 2017) (Q. Li et al., 2017) South Korea (Kim et al., 2018), United Kingdom (Leonzio et al., 2020), Canada (Bachu, 2016), and the United States (Hasan et al., 2015), where large-scale commercial CCUS projects are either operational or under development. Wang et al. (2020) focused on existing coal-fired power plants in China which have access to CCS and evaluated development opportunity for domestic CCS projects. Three candidate CCUS supply chains with distinct storage sites in UK were considered and compared by (Leonzio et al., 2020) to determine the optimal combination with minimum cost.

Moreover, uncertainties, as key influential factors on the success of CCUS, should not be ignored as well and mainly exist in carbon capture, transport, and injection-storage phases (Middleton & Yaw, 2018). To measure and mitigate the impact brought by uncertainty on CCUS supply chain, various literature has incorporated parameter uncertainty into CCUS design and evaluation. With respect to carbon transport, (Mccoy & Rubin, 2008) established an engineering-economic model with a probabilistic analysis to quantify the sensitivity of carbon transport cost to uncertainty and variability of the model parameters. Melese (2017) employed Monte-Carlo simulation to model multiple uncertainties, including market, cost, technological, and regulatory uncertainties, in order to generate flexible transport infrastructure network.

Suzuki (2013), on the other hand, designed the CCUS system in Japan with consideration of landscape and geological uncertainty. Ampomah (2017) developed uncertainty quantification model to study the effects of geological uncertain variables on EOR and CO2 storage performance.

Commonly, the high-content liquid CO2 stream is used for utilization or elimination after transportation. CO2-enhanced oil recovery (CO2-EOR), a dominant utilization option, has been frequently discussed, which technically refers to a process where water, CO2, or a mix of them are injected into oil wells so as to intensify the interior pressure and improve oil recovery. Given the fact that CO2 is not a free input, previous studies tended to figure out how to minimize the sequestration of CO2 during oil production process. Nevertheless, with the advent of anthropogenic CO2 usage subsidies, CO2 sequestration offers extra income to the oil field operators. Under this circumstance, researchers plan to discover a cost-effective way for CO2 storage in CO2-EOR project, then a dynamic co-operation between CCS and CO2-EOR has been proposed and studied consequently.

Among them, (Leach et al., 2009) initially built a dynamic cooperation model which integrated both oil extraction and CO2 sequestration, and then simulated the trajectory of optimal CO2 fraction within injection stream over the lifetime of a project. Likewise, (Wang et al., 2018) developed dynamic reservoir-simulation models of two different oil fields and examined the optimal CO2 injection path by maximizing projectors' NPV. Based on the research conducted by Leach et al. and Wang et al., (Abdulbaqi et al., 2018) proposed a similar two-stage dynamic optimization model to maximize operator's profits over both stages and tracked responsiveness of oil production and carbon movement towards prices and policies. Different from their counterparts' models, (Abdulbaqi et al., 2018) considered different CO2 sources and incorporated an extra sequestration stage after the cease of oil production so as to identify and quantify factors that might lead to transition from CO2-EOR to CCS. A consensus among those studies has been reached: increment in not just carbon tax but oil price can influence cumulative CO2 sequestration, and that sequestration is actually much more responsive to the oil price.

VII. Conclusion

Our overall objective for the project is to present the current state of CCUS to stakeholders (e.g., government policy makers, privately and government owned companies along the CCUS supply chain, interested non-government non-profit companies (NGOs), financial investors such as hedge funds, and society at large). We do not yet have many concrete recommendations for stakeholders. The object of this paper is to present the status of the Project.

Barriers exist that will prevent markets from providing the desirable amount of CCUS and policies will be needed. We are, however, convinced we need to have a mix of policies rather than one single policy applied to all occasions. The industry already has the technologies to perform all stages of CCUS. However, for them to actually implement CCUS at-scale, the framework needs to be sustainable, economically viable, and most of all publicly acceptable. To be sustainable, the framework has to include comprehensive and accessible financial support and regulatory guidance, each compatible with the others. To increase public acceptance and reassure reluctant investors about the technology, relevant uncertainties and concerns about safety and risks need to be addressed in the earliest stage of CCUS projects as well. A viable framework requires specific policies for CCUS in different stages, industries, and regions. Devising such policies requires a comprehensive understanding of CCUS performance in different situations. Further, the policies need to provide consistent support for innovation to ensure a continuous scaling of the CCUS technologies to reduce costs.

So far, we have been surveying the literature in four categories – policy, projects, costs, and economic models. Efficient CCUS policies need to specifically consider the different conditions across regions, industries, and the corresponding stages of CCUS. For example, while tax credits are a well-established policy mechanism in the U.S. and great incentives for mature CCUS technologies, they are not as effective for countries that are at earlier stages of development. In heavy industry (e.g., cement, iron and steel), where the products are competitively international traded commodities, applying CCUS technologies is especially challenging, requiring more policy interventions. In contrast, for industrial processes such as ethanol production, CCUS is a lower-cost, mature, and scalable option for capturing and reducing CO2, making it more economically viable and requiring relatively less interventions (IEA, 2020).

Existing projects show us that CCUS is technically feasible. The Terrell Natural Gas Processing Project, which began in 1972, is the oldest operating industrial CCUS project in the United States that has continuously captured and supplied CO2 for EOR (Mantripragada et al., 2019a). Alternatively, at least 6 coal-based CCUS demonstration projects have never seen the light of day from lack of funding or local opposition (Mulligan, n.d.). In terms of technology, a good post-combustion CO2 capture example is the Boundary Dam Projection in Canada, which successfully removes 90% of the CO2 emitted from burning coal to generate electricity.

The current costs for CCUS are still relatively high and undesirable especially for heavy industry and direct air capture. However, the technology has demonstrated an exceptional learning rate with costs having already fallen 35% in the power sector (IEA, 2020). With scaling and adequate storage space, we expect economies of scale and learning to yield even further reductions. Given market externalities, we know that this potential cannot be fully achieved and explored by private investors alone, but with the right institutional framework and incentives, we can succeed.

Since models are often designed for a specific situation or question, model recommendations will more likely offer suggestions on which models best inform stakeholders for given situations, along with any new modeling recommendations.

So within our four CCUS related topics, we will consider weaknesses and strengths for different situations. (e.g., what works in an oil producing country may be inappropriate for countries where coal dominates electricity generation, but little oil and gas are produced). Based on this analysis and where we have been, we will suggest current best practices in projects, policies, costs, and supporting modeling. Where quantitative measures are reported, we will summarize available information, provide some measure of uncertainty, note where needed information is missing, and recommend which information is most crucial for informed decision making. Where available, we will suggest promising near term incremental changes to improve CCUS as well as suggesting more innovative long-term alternatives.

From our literature review and analysis, we will also identify what seem to be the promising avenues for research on projects, policies, cost reducing technologies. Although the economic literature on CCUS is small. It is growing. From our survey of available published economic models and policy recommendations, we will also recognize what existing and new modeling efforts are needed to support such policy.

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