Impact of Alberta Emission Reduction Policies on the Feasibility of CCUS at Natural Gas Power Plants

Afsahi LaFrenz, B.[1], Ghavidel, A.[2], Grimeau, K.N.[3], Huang, B.[1], Mustafa, F.[1]

[1] School of Public Policy, University of Calgary, behnaz.afsahi@ucalgary.ca; ben.huang1@ucalgary.ca; farhana.mustafa@ucalgary.ca
[2] Dept. of Mechanical Engineering, University of Waterloo, aghavidel@uwaterloo.ca
[3] Dept. of Geoscience, University of Calgary, kevin.grimeau@ucalgary.ca

Abstract

Carbon capture utilization and storage (CCUS) extracts carbon dioxide (CO_2) from an emission source for utilization and permanent storage, thus reducing the amount of anthropogenic CO_2 entering the atmosphere. With Canada a signatory to the Paris Agreement, CCUS is an important technology to achieve emission reduction goals. Alberta's Technology Innovation and Emissions Reduction (TIER) and an increasingly stringent federal carbon pricing framework, Greenhouse Gas Pollution Pricing Act (GGPPA), will motivate lower emissions in the years ahead. Alberta's coal power phase out will require capacity replacement through natural gas combined cycle (NGCC) power generation, such as the 900-megawatt (MW) Cascade Project. NGCC with CCUS can decrease greenhouse gas emissions while lessening the impact of emission reduction policies.

However, there are barriers for CCUS implementation such as the high cost associated with the technology and uncertainty around government policy involving emissions reduction. If capture technology is placed on Cascade, will the current policy framework support the implementation? In this study, the levelized cost of electricity (LCOE) of a 900 MW NGCC power plant with and without carbon capture is presented. The LCOE modelling illustrates that at low (\$40/tonne$_{CO2}$) carbon pricing, CCUS implementation adds \$0.025-0.03/kWh and therefore hurts the competitiveness of Cascade in Alberta's deregulated electricity market. Further modeling was conducted to illustrate the benefits of Cascade participating in TIER and how future reductions in TIER benchmarks would negatively impact NGCC facilities without CCUS. With the current TIER benchmark (0.37 tCO_2/MWh), the LCOE model shows the carbon price needs to be \$75/tonne$_{CO2}$ before it is beneficial to implement CCUS at Cascade, whereas it shows \$90/tonne$_{CO2}$ to make CCS beneficial. This study also describes utilization and storage options, Indigenous investment in Cascade, and a review of life cycle analysis for emissions generated over the facility's lifespan.

1.0 Introduction

Over the last decades, humans have encountered the grave consequences and controversial challenges of extreme fossil-fuel consumption; greenhouse gas (GHG) emissions, environmental impacts, and global climate change (Shortall et al., 2015). Natural gas will play an important role as economies transition towards renewable energy and away from traditional sources of electricity such as coal. With dark winters and an extremely variable climate, Alberta requires a reliable source for baseload power generation during periods of non-existent renewable energy generation. However, the combustion of natural gas emits GHG, including carbon dioxide (CO_2). Although the emissions from natural gas combustion are approximately half that of coal combustion, the large volume of natural gas required for power generation facilities will contribute anthropogenic CO_2. This results in a dilemma between producing lower emission electricity (vs. coal) and continuing to release greenhouse gas emissions which are contributing to climate change.

Alberta continues to have the highest GHG emissions in Canada. In 2018, Alberta accounted for 37% of national GHG emissions (Environment and Climate Change Canada, 2020). As a province rich in natural resources such as natural gas, Alberta is expected to continue using its resources well into the future with the demand for natural gas projected to increase 28% by 2029 which is mainly a result of coal-to-gas transitions (AER, 2020). One new natural gas combined cycle (NGCC) power plant is currently under construction in the province. The Cascade Project is a 900-megawatt (MW) natural gas combined cycle (NGCC) power plant near Edson, Alberta. Cascade is situated on Treaty 6 lands and the facility was invested in by the Indigenous Communities Syndicate LP (ICS). ICS is represented by six First Nations - Alexis Nakota Sioux Nation, Enoch Cree Nation, Kehewin Cree Nation, O'Chiese First Nation, Paul First Nation and Whitefish Lake First Nation. These First Nations received a loan from the Alberta Indigenous Opportunities Corporation (AIOC) for investment into Cascade. Although the construction of Cascade can be regarded as a positive move to create jobs and replace higher emission coal fired power generation in the province, the facility will still contribute GHG emissions from the combustion of natural gas.

Carbon capture, utilization, and storage (CCUS) technology has the ability to play an important role in decarbonizing natural gas electricity generation. However, carbon capture technology is high cost (\$76-114 USD/tonne$_{CO_2}$ for capture; Irlam, 2017) and industrial emitters will face additional expenses to deploy, operate, and maintain the technology over the life of the facility (James et al., 2019). Government funded initiatives such as the *Carbon Capture and Storage Funding Act (2009)* provided financial assistance to companies for carbon capture technology in Alberta. Two of these carbon capture projects are currently in operation today and include Quest which is sequestering CO_2 into a deep saline aquifer and the Alberta Carbon Trunk Line (ACTL) which is transporting CO_2 for enhanced oil recovery (EOR). Due to high costs for CCUS infrastructure, implementing CCUS at Cascade would impact levelized cost of electricity (LCOE) and the revenue of investors, including ICS. This study evaluates the cost of the technology and current government policy that will impact the economic feasibility of implementing carbon capture technology to Cascade. Specifically, how changes to Alberta's Technology Innovation and Emissions Reduction (TIER) benchmark for electricity generation and carbon price may motivate NGCC facilities to incorporate CCUS technology to remain competitive in Alberta's deregulated electricity market.

2.0 Price Competition in Alberta's Deregulated Electricity Market

Alberta's electricity market is deregulated. Established by the *Electric Utilities Act (2003),* the Act sets up a power pool that promotes fair and open competition among electricity producers. In this framework, the market forces will decide on pricing and investment in the market. Customers in the market can make purchases according to their personal preference on the competitive choices.

In a deregulated electricity market, electricity from a given power generation facility is selected and dispatched based on hourly pricing. This favours low-cost generation such as renewables, and the result is a market where lower cost electricity is dispatched preferentially over more expensive electricity. This market style leads to competitiveness between electricity producers and favours the low-cost producers such as renewable energy sources over more traditional power generation such as fossil fuel-based combustion. Once in operation, Cascade will participate in Alberta's deregulated market and the theoretical implementation of CCUS infrastructure will impact Cascade's competitiveness. Any increase to Cascade's LCOE could reduce their dispatch frequency, making such a facility less competitive and ultimately reluctant to deploy carbon capture.

2.1 Natural Gas Electricity Generation in Alberta

Fossil based power generation, such as natural gas combined cycle (NGCC) facilities are expected to play a crucial role in Alberta's near and long-term electricity outlook (AESO, 2019). This projection is influenced by the Alberta government's phase out of coal fired power generation by 2030, which is now projected to take place by the year 2023. AESO (2019) states that natural gas will be the primary fuel source to replace coal fired electricity generation. Coal phase out regulations such as the *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations (2018)* and *Regulations Limiting Carbon Dioxide Emissions from Natural Gas-fired Generation of Electricity (2018)* have provided regulatory foundation to reduce emissions in coal-fired electricity generation. The drive to reduce emissions from coal-fired electricity favours lower emission sources including NGCC facilities like Cascade.

3.0 Review of Current Policy Framework for Carbon Capture

There is no direct policy support for carbon capture, utilization and storage (CCUS) in Canada. Carbon pricing and credit system is the major tool in Canada supporting carbon capture implementation. By signing the Paris Agreement in 2016, Canada is set to reduce emissions by 30% below 2005 levels by 2030 and ultimately achieve net-zero emissions by 2050. Hence, both the federal and Alberta government have established their carbon pricing schemes to align and achieve the goals set out by the Paris Agreement. With supreme court upholding the federal government's climate plans, Alberta is obligated to establish a carbon tax credit equal to its federal version.

Alberta's TIER system and carbon pricing (GGPPA) are the primary policies relating to natural gas electricity generation and the associated emissions with such facilities. While TIER can provide carbon credit for emitters with better emission performance, the cost can be considerable for emitters that surpass the benchmark. Uncertainty around government policy, such as TIER, will delay the deployment of CCUS infrastructure in the years ahead. Clarity and consistency on such regulations will be required to incentivize implementation of CCUS for industrial emitters.

3.1 Carbon Price System in Alberta and the Effect on NGCC Facilities

The current Alberta carbon price system is the Technology Innovation and Emission Reduction Regulation (TIER). TIER is designed considering output-based allocation to help maintain competitiveness of emission-intensive industries while rewarding carbon emission reduction. This carbon pricing design sets the emission intensity standards. For NGCC facilities, their emission measures are based on the industry benchmark known as "good-as-best-gas". This benchmark is set at 0.37 t/MWh (Government of Alberta, 2020). NGCC facilities can obtain credits by having their emissions below this benchmark. If their yearly emissions remain below the set standard, they will gain credits for the difference between their emissions and the benchmark. These credits can be used by the emitter or sold to another emitter. Alternatively, they will pay a carbon tax for emissions exceeding this benchmark. Figure 1 demonstrates the importance of TIER for natural gas electricity facilities in Alberta. Without TIER, a NGCC facility will be required to pay the increasingly stringent carbon price which will substantially increase the LCOE for a NGCC facility.

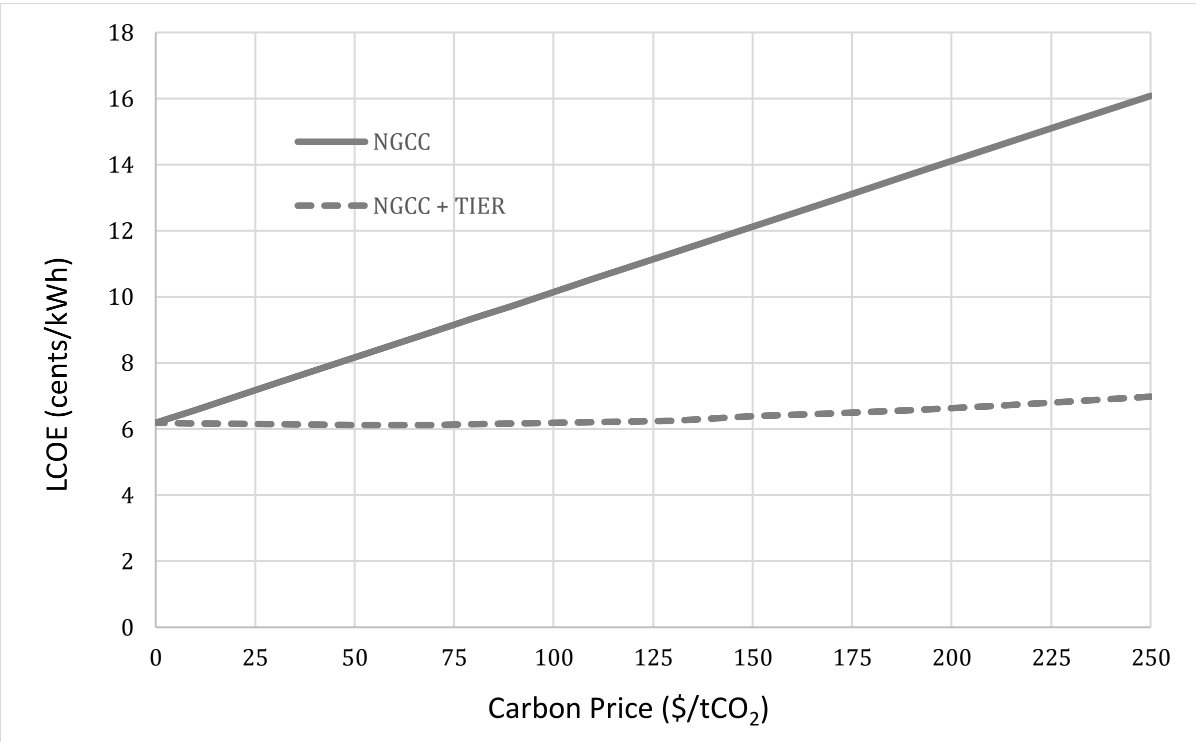

Figure 1: Impact of TIER credits (fixed at 0.37 tCO2/MWh) on LCOE for NGCC power plants in Alberta. A NGCC facility without credits earned under TIER will have to pay the full carbon price.

With the federal government set to increase the carbon price to \$170/tonne$_{CO2}$ by 2030, the current TIER framework may be determined inadequate and require more stringent benchmarks. Inevitably, this would impact the levelized cost of electricity for NGCC facilities like Cascade. NGCC facilities without carbon capture will need to incorporate the technology to avoid paying for their emissions, specifically, if TIER becomes more stringent. However, for most firms operating by themselves, carbon capture technology represents a financial hurdle. With the current carbon price and credit trading system in Alberta, TIER can offset some financial costs as to reward high performance in carbon reduction. This means the action of carbon capture can result in carbon price credit through TIER, which can relieve some of the cost for carbon capture. This is illustrated in Section *5.2* and *5.3*, (Figures 3 and 4) that demonstrates the importance of utilization or storage of CO_2 alongside TIER credits.

3.2 Political Uncertainty

Political uncertainty is one of the most important variables for CCUS implementation in this analysis. Modifications to TIER, such as the restructuring of the system and redesign of the benchmarks is a major uncertainty. Specifically, increases to the federal carbon price may result in the TIER system in its current state being deemed inadequate. Also, the federal and provincial re-election might play a role in altering Alberta's current carbon tax system. For example, the Conservative Party of Canada or Alberta's National Democratic Party would likely have different party platforms and political priorities compared to the current governing parties in Alberta and Canada. With the current federal government, a more stringent carbon pricing policy is anticipated in the years ahead. As Canada is approaching its international environmental commitment and the Supreme Court has upheld legitimacy of the Liberal Party's carbon pricing plan against the province of Alberta, it is probable that NGCC facilities without CCUS will financially suffer from the effects of an increasing carbon price and adjustments to the TIER system. This highlights the importance for stable benchmarks within TIER for natural gas electricity generation so that facilities such as Cascade can plan ahead accordingly. Rapid changes to the benchmark structure could significantly and negatively impact these facilities and their investors. Therefore, clarity and consultation with the electricity facilities is needed before future adjustments take place.

4.0 CCUS Costs and the Impact on LCOE

4. 1 Cost Summary of CCUS Components

It is assumed that CO_2 would be captured and compressed near Cascade, then transported and stored in a nearby geological formation. The costs reported in Table 1 are based on literature for CCUS components of NGCC power plants: post-combustion capture, transportation, and storage (Rubin et al., 2015; Schmelz et al., 2020; Rubin & Zhai, 2012; IEAGHG, 2012; USDOE, 2011; USDOE, 2013). The cost of transportation is for a pipeline with a capacity of 10 Mt/year and a length of 250 km. Generally, depleted oil and gas reservoirs costs less than saline aquifers. Both storage options in this study are considered for Cascade and discussed in more detail in Section *5.2* and *5.3.* Table 1 illustrates that capture infrastructure is the most expensive component of CCUS and is regarded as one of the most important factors limiting CCUS growth (Irlam, 2017).

Table 1. Cost of CCUS components.

	Average Cost (US $/t$CO_2$)	Minimum cost (US $/t$CO_2$)	Maximum cost (US $/t$CO_2$)
Post-combustion capture	76	49	114
Transportation	3	2	4
Storage (saline aquafers)	6	3	15
Storage (oil and gas reservoirs)	5	1	13

4.2 Impact of Carbon Pricing, Cost Variation and TIER on LCOE

Figure 2 shows the effect that carbon pricing (without TIER credits) will have on LCOE at NGCC plants with/without carbon capture. It is assumed that the emissions are reduced from 353 Kg of CO_2/MWh to 42 pre and post carbon capture addition. The breakeven carbon price (at which the LCOE of both plants are the same) is around $105/t$CO_2$. For a carbon price above this value, the natural gas plant with 90% CO_2 captured has a lower LCOE than the uncontrolled plant, thus making carbon capture economically attractive. However, the NGCC plant without carbon capture is more economical at carbon price lower than breakeven carbon price due to the high costs of carbon capture infrastructure.

NGCC facilities with or without carbon capture under the current benchmark (0.37 tCO_2/MWh) will not pay a carbon price. This further demonstrates the benefit of TIER credits at their current value. Considering the effect of uncertainties in the natural gas price, capital cost of CCUS, financing rate, plant capacity factor and other factors. The two cost lines shown in Figures 2, 3 and 4 would shift and the resulting intersection or breakeven price would thus also vary. This means that a specific carbon price may or may not be adequate considering the uncertainties and variability that apply to new NGCC plants and that TIER credits are very important for NGCC facilities.

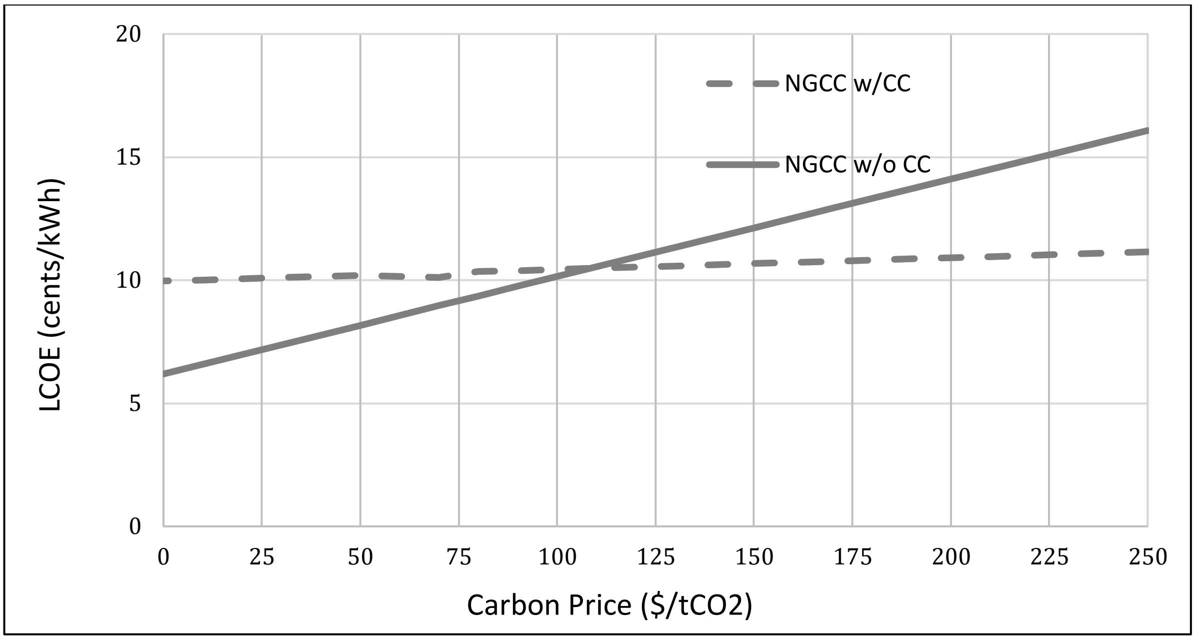

Figure 2: Graph illustrating the effect that the federal carbon price will have on LCOE at two NGCC facilities (with and without carbon capture, CC) without participation in the TIER system. Therefore, a facility faces the full cost of the carbon price for all emissions.

5.0 Transportation, Utilization, and Storage

If CCUS technology is placed on Cascade, transportation infrastructure will be required to move compressed CO_2 to utilization or storage locations. Such locations include depleted oil and gas reservoirs, or saline aquifers as discussed further in the following subsections. Although the following subsections acknowledge the importance of scientific study required for actual CCUS implementation, they are intended to provide an overview of options. Any future progression of CCUS development for Cascade would require much deeper evaluation.

5.1 Transportation

A reduction in pipeline length can improve the commercial feasibility of CCS and one potential option is to utilize existing pipeline infrastructure. However, this would require regulatory review and significant design constraints may be encountered. For example, oil and gas pipelines are designed to transport oil and gas, not CO_2. Oil and gas pipelines are designed with different operating pressures and design specifications which may not be suitable for the transportation of CO_2 and would require a full evaluation of pipeline integrity to be safely repurposed (Onyebuchi et al, 2018). It may be more economical and safer to construct a new pipeline that is designed specifically for CO_2 transportation. Due to Cascade's close proximity to depleted oil and gas fields and saline aquifer disposal, possible storage options exist within a 50 km radius of the facility which would reduce the length and cost of the pipeline required.

Another option would be to connect Cascade to existing CO_2 transportation infrastructure. However, Cascade is located over 200 km from the existing Alberta Carbon Trunk Line (ACTL). ACTL is 240 km in length and cost $245 million to construct which equates to $1.02 MM/km (ACTL Summary Report, 2014). Connecting to ACTL would require a pipeline similar in length to the ACTL itself, adding considerable cost to CCUS infrastructure on Cascade. Therefore, it is proposed that utilization and disposal sites neighbouring Cascade would be more preferential than connection to ACTL.

5.2 Revenue from CO_2 Sales for Enhanced Oil Recovery (EOR)

Subsurface geological storage currently presents the most viable solution to store large volume of CO_2 (Leung et al. 2014). Knowledge on different storage methods have been continuously improving in the last decades. Depleted oil and gas reservoirs present several advantages for CO_2 storage, such as sufficient available data, proven geological sealing (caprock), large volume storage due to being underpressurized, available surface and subsurface infrastructure (pumps, wells, pipelines, etc.), offering potential economic benefits through EOR. The ability to generate additional revenue through the sale of CO_2 to a neighbouring oil producer or the ability to generate additional revenue from the incremental production from oil reservoirs can help offset the cost of CCUS infrastructure (Kolster et al., 2017).

Depleted oil and gas reservoirs are found within the immediate vicinity of Cascade and would only require a short pipeline (approximately 50 km) to access. One of the most productive geologic zones is the Cardium Formation. The Cardium Formation is a clastic (sandstone, conglomerate) deposit and contained 10.6 billion barrels of original oil in place (Hares, 2020). Therefore, it represents a potential EOR zone for captured emissions from Cascade. Our model predicts a break-even CO_2 price of around $75/tonne for CO_2-EOR to be viable for the Cardium, based on $50/bbl. WTI. If CO_2 is captured at Cascade, CO_2-EOR could be considered. Figure 3 illustrates the effect on LCOE from a NGCC facility with carbon capture, TIER, and revenue generated by EOR (CCUS) compared to a facility without CC and only the benefit of TIER.

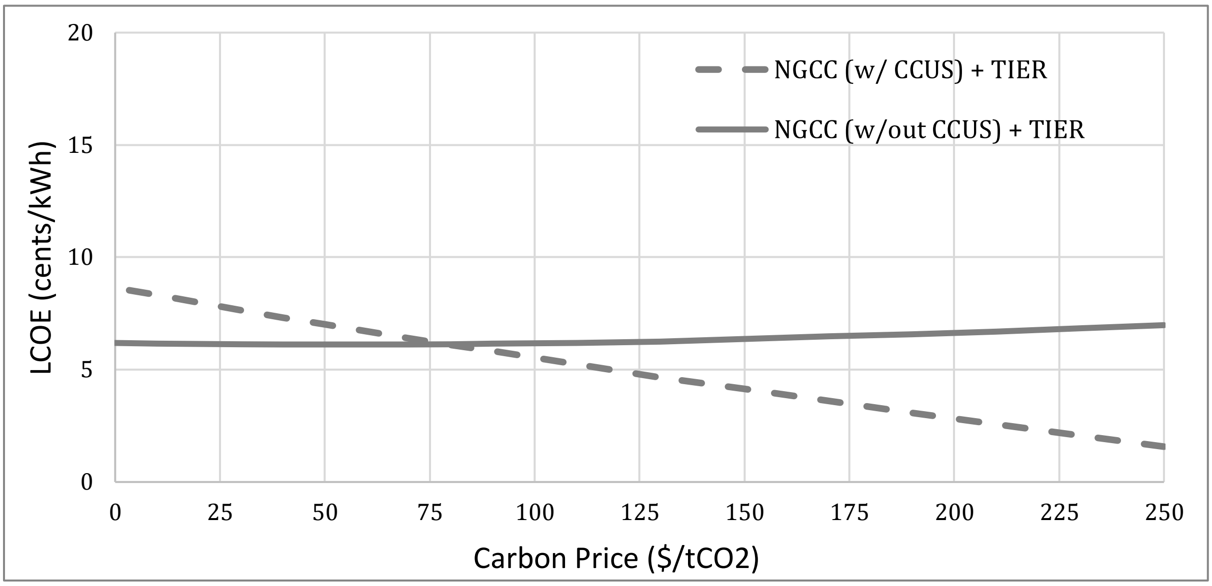

Figure 3: Graph illustrating the effect on LCOE from a NGCC facility with carbon capture, TIER, and revenue generated by EOR (CCUS) compared to a facility without CCUS and only the benefit of TIER.

5.3 Storage Through Saline Aquifer Disposal

Saline aquifers present one of the best options for CO_2 sequestration because they provide large storage volume and are filled with high-salinity water that is unfit for industrial, agricultural, or human use (Bachu, 2000). However, due to the capital cost for developing the associated infrastructures such as injection wells, pipelines and surface facilities, saline aquifers are not currently as desirable in an economic point of view as they do not generate incremental oil production revenue (Aminu et al. 2017).

Saline aquifer zones are found within the vicinity of Cascade. These include carbonate (limestone and dolostone) formations such as the Nisku and Leduc Formations. These formations were responsible for some of Alberta's most prolific oil and gas deposits, and they contain corridors of high porosity and permeability which are important components of saline aquifer disposal. Saline aquifer disposal can be regarded as a more environment-conscious storage option because the CO_2 is not utilized to extract additional hydrocarbons. Although saline aquifers are currently regarded as less favourable from a revenue perspective (compared to EOR), they represent immense storage volumes that could be used to sequester CO_2 from Cascade and eliminates the impact of carbon pricing. As with the previous EOR model (Figure 3), an additional model for saline aquifer disposal is provided below (Figure 4), showing $90/tonneCO2 carbon price to make saline aquifer disposal (CCS) beneficial.

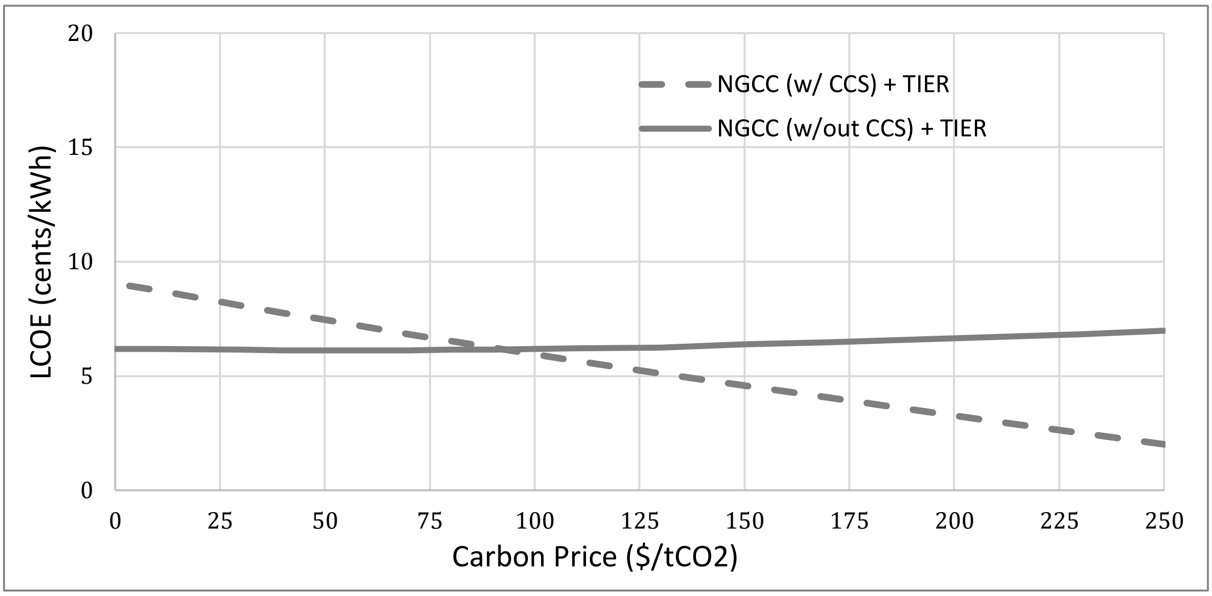

Figure 4: Graph illustrating base case (NGCC w/out CCS, operating with TIER credits) compared to a NGCC facility with CCS (depleted oil and gas reservoir or saline aquifer disposal).

6.0 Life Cycle Analysis of NGCC with and without CCUS

Previous life cycle analysis (LCA) of NGCC power plant with or without CCUS were evaluated to understand the impacts on the environment associated with the carbon capture process. The functional unit considered is 1 MWh (megawatt-hour) of produced electricity and the expected lifetime of the plant is 30 years. The unit processes considered for the LCA study are known as system boundaries. In this case, system boundaries include supply of natural gas, power plant operations, and carbon capture, compression, transportation, and storage. The main impact category associated with this process is global warming potential (GWP) expressed in GHG emissions in kg CO_2-equivalent. GWP is the amount of heat absorbed by any greenhouse gas compared to the same amount absorbed by CO_2. For CCUS, the majority of NGCC plants used post-combustion carbon capture technology via chemical absorption using MEA (Monoethanol Amine) (Cuéllar-Franca & Azapagic, 2015).

Emissions during construction of the power plant or CCUS facility were not considered as they contribute negligible (0.4 % of the total system) to GWP (Odeh & Cockerill, 2008; Spath & Mann, 2000). For example, construction of Cascade will result in an estimated 114 kt/y over three years compared to the yearly operating emissions 2,850 kt/y (Stantec EIA, 2019) (Table 2).

Table 2: Estimated GHG emissions of Cascade; modified from (Stantec EIA, 2019)

Pollutant	**Construction**				**Operation (kt/y)**
	Year 1 (kt/y)	**Year 2 (kt/y)**	**Year 3 (kt/y)**	**Total Over 3 Years (kt/y)**	
CO_2	44.13	59.062	10.735	113.927	2832*
CH_4	0.0018	0.0024	0.0004	0.0046	0.055**
N_2O	0.00004	0.0005	0.0001	0.00064	0.049
CO_{2e}	44.282	59.266	10.772	114.32	2848

Notes:
kt/y = kilotonnes per year
*Based on the assumption the 100% carbon in fuel is converted to CO2
**Based on Environment Canada emission factors (0.037 g/m3 for CH4 and 0.33 g/m3 for N2O for industrial sources

Emission intensities of NGCC plants with and without carbon capture from different studies are shown in Table 3.

Table 3: GHG emissions from NGCC plants with & without CCUS

Study	**Emission without CCUS (kg CO_2 eq./MWh)**	**Emission with CCUS (kg CO_2 eq./MWh)**	**GWP Reduction (%)**
Cuéllar-Franca & Azapagic (2015)	471	173	63
Singh et al. (2011)	425	125	64

LCA of CCS (I.e., saline aquifer disposal) versus CCUS (I.e., EOR or chemical production) is also studied by *Cuéllar-Franca & Azapagic* (2015). Their results demonstrated that average GWP from CCS is 276 kg CO_2 eq./t which is much lower than any process of carbon capture with utilization. For example, production of chemicals is the worst option to utilize captured CO_2 as it results in 216 times higher GWP (Cuéllar-Franca & Azapagic, 2015). EOR has 1.8 times higher GWP than carbon capture and storage in a saline aquifer (Cuéllar-Franca & Azapagic, 2015).

From this LCA review, storage of CO_2 without any form of utilization is the most environmentally suitable choice. As previously discussed, captured emissions from Cascade could be utilized for enhanced oil recovery or disposed of in deep saline aquifers. Based on the LCA review, saline aquifer storage would have the lowest environmental impact in terms of global warming potential (GWP). Life cycle studies of CCUS were done based on the lifetime of power plants which is 30 years on average. As a result, there was no evidence found on the impacts spanning seven generations. It is plausible that NGCC power plants will not be in operation for seven generations (140 years) from now with technological advancements and increased renewable energy capacity contributing to Alberta's electricity grid.

7.0 Indigenous Communities Syndicate Investment

Cascade is actively involved with Indigenous participation. This involvement incorporates the investment by the Indigenous Communities Syndicate (ICS) LP and includes six Indigenous communities in Treaty Six Territory. Investment into this project aligns with the values portrayed by the communities. For example, the investment will generate revenue and help bring financial independence to the communities. Additionally, Cascade will supply lower emission electricity than coal-fired leading to improved environmental performance of industry situated on Treaty Six Territory. However, the plant will still emit significant amount of GHGs. Emitted GHGs will affect local communities as well. The desire of Indigenous communities to protect the environment can be enhanced if CCUS technology is added to the power plant. Building the capture, transportation and storage infrastructure could open up additional job opportunities for neighbouring communities.

Although CCUS could be a positive addition to Cascade, there are negatives associated with the technology. Specifically, it would occupy additional traditional territory of First Nations. It could alter the way of traditional practices on those lands. For example, post-combustion carbon capture involves amine-based chemicals and results in toxic wastes which needs to be managed to prevent land or water pollution (Parfomak, 2008). Transportation of captured CO_2 would need pipelines and sequestration would need suitable geological storage sites. Pipeline right-of-way and subsurface storage locations would need to be determined with the consent and involvement of First Nations to reduce or eliminate the impact on traditional territory and lifestyles. Additional cost associated with CCUS infrastructure will reduce the revenue for Cascade and its investors. However, as carbon pricing increases, a facility without CCUS may not be able to compete in Alberta's deregulated market which will also negatively impact Cascade and its investors, including the ICS.

If the captured carbon is stored via saline aquifers, the profitability would be lower than the utilization of captured carbon through enhanced oil recovery (EOR) due to the additional revenue stream. Either stored or utilized, the carbon capture process would result in a lower

LCOE when carbon pricing is high and if TIER credits are eliminated. In this scenario, carbon capture would help Cascade's competitiveness in Alberta's deregulated electricity market. Such scenarios are important to understand to evaluate the impact and importance of policy, including TIER and an evolving carbon price. Specifically, how such changes would impact the revenue streams of Cascade and its investors.

8.0 Conclusions

This study evaluated the impact that government policy such as carbon pricing and TIER credits would have on the LCOE at Cascade. This study also provided a summary of the emission reduction potential in the event that Cascade utilises CCUS and how that may impact project investors and the ability for Cascade to operate within Alberta's deregulated electricity market. LCOE modeling in the scenario that does not include TIER (Figure 2) demonstrated that a NGCC facility's LCOE will increase when carbon pricing is less than $105/tonne and may influence its competitiveness in Alberta's deregulated electricity market in the near term. However, if carbon pricing increases above $105/tonne, then CCUS technology can result in a lower LCOE. With the current TIER benchmark (0.37 tCO_2/MWh), the LCOE model shows the carbon price needs to be \$75/$tonne_{CO2}$ before it is beneficial to implement CCUS at Cascade, whereas it shows \$90/$tonne_{CO2}$ to make CCS beneficial. Therefore, the implementation of carbon capture technology on Cascade may be a necessity in the coming years. Specifically, as renewable energy capacity increases or if the TIER benchmark is reduced or eliminated, Cascade will need CCUS remain competitive in the electricity market. The benefits of participating in the TIER system were also modeled which demonstrated the importance of the current benchmark with the addition of storage aquifer disposal or utilization of CO_2 for EOR. However, it is important to note that NGCC facilities without CCUS will face increased carbon pricing pressure if TIER benchmarks become more stringent. This is highly likely, especially after the Supreme Court upheld the federal government's carbon pricing framework over Alberta. Therefore, the TIER system will require lower benchmarks to be deemed adequate in the coming years.

It is important to understand the effects of additional infrastructure required for CCUS. Specifically, pipelines and suitable geologic storage locations. Cascade is situated in an area that is in close proximity to proven geologic formations that, in theory, have the potential to act as storage options. By utilizing geologic storage close to Cascade, the land impact of a

CO_2 pipeline could be minimized compared to connection with ACTL. However, further consultation and engagement with Treaty Six Nations would be required to advance such an addition to Cascade.

To date, the largest barrier for CCUS technology remains the cost. Although costs are high, CCUS presents an opportunity for innovation on behalf of government and industry. Projects including Quest and ACTL were able to progress with substantial government funding, but future projects can now benefit from the knowledge sharing agreements mandated as part of their funding agreements. Based on this study, adjustments to these government policies and technological advancements that lower the cost for CCUS technology have the potential to increase CCUS deployment on NGCC facilities. Clarity and certainty around future carbon pricing and TIER benchmarks is needed for CCUS technology deployment on NGCC facilities. This will lead to enhanced environmental performance in the natural gas electricity sector and help NGCC facilities remain competitive in Alberta's deregulated electricity market.

9.0 Acknowledgement

This study was made possible with funding from the Natural Science and Engineering Research Council of Canada (NSERC CREATE REDEVELOP, Grant #386133824) which we gratefully acknowledge. A special thank you to our mentors Dr. Jennifer Winter, Dr. Maurice Dusseault, Mike Johnson, Dr. Celia Kennedy, Dave Moffatt, and many others that provided valuable insight into the realm of CCUS and all the complexities associated with the technology.

10. References

ACTL Summary Report. (2014). Enhance Energy Inc. and North West Redwater Partnership Knowledge Sharing Report. ACTL, Government of Alberta, Natural Resources Canada. Retrieved from https://open.alberta.ca/dataset/267d0174-1091-4aab-9910-c6fe0b817d31/resource/c66114f3-18c7-45cf-afc7-f4ea4f051d55/download/ccsactlreport2014.pdf

AIOC. (2020). Alberta Indigenous Opportunities Corporation Announces First Participation in Cascade Power Project. Intrado-GlobeNewswire. Retrieved from http://www.globenewswire.com/news-release/2020/09/09/2091232/0/en/Alberta-Indigenous-Opportunities-Corporation-Announces-First-Participation-in-Cascade-Power-Project.html

AESO. (2019). Long-term outlook. Alberta Electric System Operator, AESO. Retrieved from https://www.aeso.ca/assets/Uploads/AESO-2019-LTO-updated-10-17-19.pdf

AER. (2020). Natural Gas Demand. Alberta Energy Regulator. Retrieved from https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st98/natural-gas/demand#:~:text=Forecast%20for%202020%20to%202029,by%202029%20relative%20to%202019

Aminu, M.D., Nabavi, S.A., Rochelle, C.A., and Manovic, V. 2017. A review of developments in carbon dioxide storage. Applied Energy, 208: 1389–1419. doi:10.1016/j.apenergy.2017.09.015.

Cuéllar-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, 9, 82–102.* https://doi.org/10.1016/j.jcou.2014.12.001

Environment and Climate Change Canada. (2020). Canadian Environmental Sustainability Indicators: Greenhouse gas emissions. Retrieved from https://www.canada.ca/content/dam/eccc/documents/pdf/cesindicators/ghg-emissions/2020/greenhouse-gas-emissions-en.pdf

Government of Alberta (2009). Carbon Capture and Storage Funding Act. SA 2009, c C-2.5. Retrieved from https://www.qp.alberta.ca/1266.cfm?page=C02P5.cfm&leg_type=Acts&isbncln=9780779773602

Government of Alberta (2003). Electric Utilities Act, SA 2003, c E-5.1. Retrieved from https://open.alberta.ca/publications/e05p1

Government of Alberta. (2020). Technology Innovation and Emissions Reduction Regulation. Alta Reg 133/2019. Retrieved from https://www.qp.alberta.ca/documents/Regs/2019_133.pdf

Government of Canada. (2018). Greenhouse Gas Pollution Pricing Act, SC 2018, c 12, s 186. Retrieved from https://laws-lois.justice.gc.ca/eng/acts/G-11.55/

Government of Canada (2018). Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations. SOR/2012-167. Retrieved from https://laws-lois.justice.gc.ca/PDF/SOR-2012-167.pdf

Government of Canada (2018). Regulations Limiting Carbon Dioxide Emissions from Natural Gas-fired Generation of Electricity. SOR/2018-261. Retrieved from https://laws-lois.justice.gc.ca/PDF/SOR-2018-261.pdf

Hares, R. (2020). Feasibility of CCUS to CO2-EOR in Alberta (Unpublished master's project). University of Calgary.

IEAGHG. (2012). CO2 capture at gas fired power plants. Cheltenham, United Kingdom.

Irlam, L. (2017). Global costs of carbon capture and storage. Global CCS Institute. Melbourne, Australia.

James, R. E., Kearins, D., Turner, M., Woods, M., Kuehn, N., & Zoelle, A. (2019). *Cost and performance baseline for fossil energy plants volume 1: bituminous coal and natural gas to electricity* (No. NETL-PUB-22638). NETL.

Kolster, C., Masnadi, M. S., Krevor, S., Mac Dowell, N., & Brandt, A. R. (2017). CO_2 enhanced oil recovery: a catalyst for gigatonne-scale carbon capture and storage deployment?. *Energy & Environmental Science*, *10*(12), 2594-2608.

Leung, D. Y., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, *39*, 426-443.

Odeh, N. A., & Cockerill, T. T. (2008). Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. Energy Policy, 36(1), 367–380. https://doi.org/10.1016/j.enpol.2007.09.026

Onyebuchi, V. E., Kolios, A., Hanak, D. P., Biliyok, C., & Manovic, V. (2018). A systematic review of key challenges of CO2 transport via pipelines. *Renewable and Sustainable Energy Reviews*, *81*, 2563-2583.

Parfomak, P. W. (2008, July 29). Community Acceptance of Carbon Capture and Sequestration Infrastructure: Siting Challenges. Congressional Research Service.

Rubin E.S, Davison, J.E, Herzog, H.J. (2015). The cost of CO2 capture and storage. Int. J. Greenhouse Gas Control 40, 378–400. (doi:10.1016/j.ijggc.2015.05.018).

Rubin E.S, Zhai H. (2012). The cost of carbon capture and storage for natural gas combined cycle power plants. Environ. Sci. Technol. 46, 3076–3084. (doi:10.1021/es204514f).

Singh, B., Strømman, A. H., & Hertwich, E. (2011). Life cycle assessment of natural gas combined cycle power plant with post-combustion carbon capture, transport, and storage. International Journal of Greenhouse Gas Control, 5(3), 457–466. https://doi.org/10.1016/j.ijggc.2010.03.006

Spath, P. L., & Mann, M. K. (2000). Life Cycle Assessment of a Natural Gas Combined Cycle Power Generation System (NREL/TP-570-27715, 776930; p. NREL/TP-570-27715, 776930). https://doi.org/10.2172/776930

Stantec. (2019). Environmental Impact Assessment, EIA, Cascade. https://iaacaeic.gc.ca/050/documents/p80166/126765E.pdf

USDOE. (2013). Current and future technologies for natural gas combined cycle (NGCC) power plants. Department of Energy National Energy Technology Laboratory. Pittsburgh, PA: United States.

USDOE. (2011). Cost and performance baseline for fossil energy plants: vol. 3c: natural gas combined cycle at elevation. Department of Energy National Energy Technology Laboratory. Pittsburgh, PA: United States.

Schmelz, W., Hochman, G., & Miller, K. (2020). Total cost of carbon capture and storage implemented at a regional scale: northeastern and midwestern United States. *Interface Focus*, *10*(5), 20190065. https://doi.org/10.1098/rsfs.2019.0065