Fuel Cell Repowering of Coal Plant

3 December 2017

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1) Introduction:

In 2014, Jacobs Engineering completed a report for the Canadian Clean Power Coalition (CCPC) evaluating the use of molten carbonate fuel cells to reduce the GHG emission intensity of the Lingan coal plant in Nova Scotia to .42 t CO_2/MWh. Jacobs worked closely with Fuel Cell Energy Inc. (FCE) and the Electric Power Research Institute to derive the cost and performance data for the fuel cells used in the study. Much of the data for the Lingan plant was taken from an earlier study completed by the Electric Power Research Institute. That study evaluated the cost and impact of adding post-combustion capture technology to the Lingan plant.

Natural gas and water is supplied to the anode of the fuel cell which reforms it to CO_2 and H_2. The CO_2 is diverted to the cathode and mixed with flue gas and air. CO_2 reacts with oxygen at the cathode to form CO_3. CO_3 passes through the electrolyte reacts with H_2 to form CO_2 and water at the anode where the CO_2 is removed, dried and any remaining combustibles are removed.

This study helps answer the question of whether the cost of power from a coal plant retrofitted with molten carbonate fuel cells would be lower than the cost of power from a new natural gas combined cycle (NGCC). The key alternative to retrofitting an existing coal plant with post combustion capture (PCC) is to use the capital instead to build a new NGCC. This report describes the economic analysis completed on the fuel cell study results. It also compares the economics of this repowering to other forms of power production. The economic analysis shows how sensitive the results are to changes in various key assumptions. In addition, cost estimates and economic results were completed for Alberta conditions and are reported at the end of this document.

2) Lingan Cases:

Nova Scotia Power's Lingan Generation Station is a four-unit, pulverized coal-fired, steam-electric generating power plant with a nominal gross power rating of 660 MW. The plant burns imported Columbian steam coal.

Six generation cases were created for comparison purposes:

- NGCC: A new plant without CCS as key power supply alternative
- Lingan: Base coal plant assumed to be new build
- Lingan & FCE: New base coal plant plus fuel cells
- Lingan w PCC: New base coal plant plus post-combustion capture (Amine)

- R Lingan & FCE: A retrofit of the Lingan plant with fuel cells
- R Lingan w PCC: A retrofit of Lingan plant with post-combustion capture (Amine)

Only the incremental costs for the fuel cell repowering case were studied in detail and the costs for all the other cases were based on rough estimates.

The final two cases in Table 1 were used to determine the cost of power for the existing Lingan plant retrofitted with molten carbonate fuel cells licensed by Fuel Cell Energy Inc. (FCE) and post-combustion capture technology. All the costs for fuel and O&M for the underlying coal plant plus cost recovery for the capital, O&M and fuel associated with the molten carbonate fuel cell were used to determine the required selling price of power from the retrofitted plant. The original capital cost for the Lingan plant was not included in this analysis for the two retrofit cases. It was assumed that most of the original capex has been recovered. The fuel cells provide additional power for sale. The contribution of this extra power was included in the estimation of the required selling price.

Table 1: Base Information

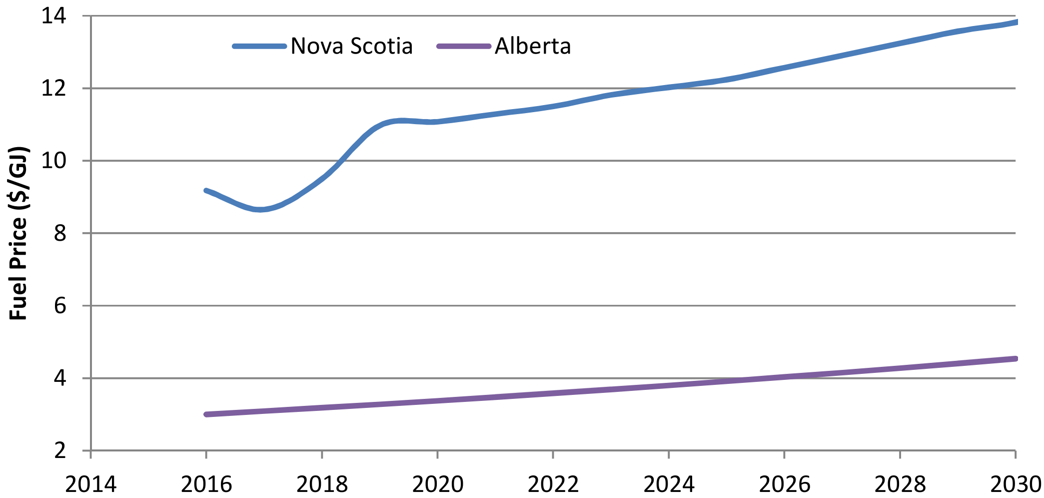
	NGCC	Lingan	Lingan & FCE	Lingan w PCC	R Lingan & FCE	R Lingan w PCC
Net Power Production (MW)	535	621	444	439	444	439
Derate (MW)			-134	183	-134	183
% Derate			-43%	29%	-43%	29%
Coal Heat Rate (GJ/MWh)		10.83	7.57	15.34	7.57	15.34
NG Heat Rate (GJ/MWh)	7.11		2.78		2.78	
CF First Year	90%	90%	90%	90%	90%	90%
Design Life	30	35	35	35	35	35
Coal Cost ($/GJ)		4.00	4.00	4.00	4.00	4.00

The net power for the Lingan and Lingan w PCC includes output from all four units. The net power for the FCE cases was based on only two of the Lingan units or an initial 310 MW. A positive derate indicates that employing post-combustion capture reduces the output of the plant. A negative derate for the FCE cases indicates that the fuel cell provides an additional 134 MW of power. The natural gas heat rate is related to the fuel required by the fuel cell divided by the net capacity of the retrofitted plant. A coal cost of roughly $4.00/GJ corresponds to recent forecasts for coal published by Nova Scotia Power.

A WACC of 9% was used in this analysis. A carbon tax was not assumed for Nova Scotia. However, a carbon tax was assumed for the Alberta Cases. A carbon tax of $30/t in 2020, $40/t in 2021 and $50/t in 2022 was assumed. A carbon tax is paid if the difference between the emission intensity of project is greater than a performance standard of .42 t/MWh multiplied the energy produced. If this value is negative then a credit is generated.

Figure 1 shows the natural gas price forecasts used in the model. The prices for Nova Scotia were based on recent forecasts released by Nova Scotia Power. The Alberta forecast is based on roughly $3.00/GJ escalated by 3% per year.

Figure 1: Natural Gas Price Forecasts



Base Plant in Table 2 below refers to the rough cost to build a new coal plant without CCS. Life extension costs are estimates for how much it may cost to extend the life of the existing coal plant for several decades. This cost will vary from plant to plant. Flue Gas Desulfurization (FGD) will be required to remove sulfur in the flue gas before it enters the fuel cell. The flue gas processed by the fuel cells will emit very little sulfur and NOx into the atmosphere. These economic results show the costs for a FGD processing all the flue gas from the two Lingan units providing flue gas to the fuel cells. Most of the sulfur must be removed from the flue gas entering the fuel cell. The fuel cell is expected to convert roughly 70% of the NOx in the flue gas to nitrogen. The term FCE refers to the estimated cost of the fuel cells and related balance of plant to process the CO_2. The term CCS refers to the estimated cost of the post-combustion capture technology as estimated by EPRI. Factors to account for contingency, boiler modifications, foreign exchange and OSBL costs were added as appropriate. In most cases escalation has been added to bring all costs up to a 2014 basis. The commercial operation date for all cases was assumed to be January 2016.

Incremental capital cost is the difference between the capital costs for Lingan & FCE or Lingan w PCC less the capital cost for the Lingan case which is divided by two. The Lingan costs are divided by two because they represent the costs for all four units whereas only two units are retrofitted.

Table 2: Capital Costs

$ million	NGCC	Lingan	Lingan & FCE	Lingan w PCC	R Lingan & FCE	R Lingan w PCC
Base Plant	957	2,209	1,105	2,209		
Life Extension			0	0	75	150
FGD			220	440	220	440
Fuel Cells			793		793	

CCS				999		999
Escalation	181	419	209	692	0	301
Total	1,138	2,628	2,327	4,340	1,088	1,891
Capex ($/kW)	2,130	4,230	5,405	10,301	2,448	4,310
Incremental Capital Cost			1,013	1,712	1,088	1,891

Table 3 shows the GHG emissions associated with the plants. 49% of the CO_2 generated by the coal plant and the natural gas consumed in the fuel cell is captured. Only half of the CO_2 generated by the two units at the coal plant is processed in the fuel cell. The other half continues on up the stack. The fuel cell captures roughly 83% of the CO_2 presented to it. All the cases with CO_2 mitigation have emission intensities of .42 t/MWh.

Table 3: CO_2 Capture

	NGCC	Lingan	Lingan & FCE	Lingan w PCC	R Lingan & FCE	R Lingan w PCC
GHG Intensity (t/MWh)	0.35	0.97	0.42	0.42	0.42	0.42
GHG Produced (t/yr)		4,746,825	2,856,186	4,746,825	2,856,186	4,746,825
CO_2 Captured (t/yr)		0	1,392,065	3,417,714	1,392,065	3,417,714
GHG Emissions (t/yr)		4,746,825	1,464,121	1,329,111	1,464,121	1,329,111
% Captured		0%	49%	72%	49%	72%

Table 4 shows the economic results for the cases. The first-year COE is the required selling price of power in the first year. The first-year required selling price, when escalated by inflation in future years, will recover all the costs of the project including the operating cost of the coal plant and yield a project NPV of zero.

The required selling price of power for the NGCC case is estimated to be $114/MWh. The required selling price for the plant retrofitted with molten carbonate fuel cells is estimated to be $125/MWh. With additional optimization the cost of power from the plant retrofitted with fuel cells may get closer to that expected for an NGCC. The NGCC in this case is assumed to operate 90% of the time. In reality, they may not operate at this high a capacity factor and may dispatch down or off at night when power prices are insufficient to cover the high fuel cost. The required selling price for the NGCC will rise as the capacity factor decreases. This uncertainty regarding capacity factor makes it difficult to compare the baseloaded coal plant required selling price to an NGCC that may run at a lower capacity factor.

The avoided cost is based on the difference between the first-year cost of power, for the reference plant and the retrofitted plant, divided by the difference in GHG emission intensity, for the reference plant and the retrofitted plant. The reference plant in this case was the new build coal plant without CCS and it was compared to a new build plant with fuel cells or CCS. The avoided cost of CO_2 for the FCE case is significantly lower than for the post-combustion capture case. One of the key reasons for this is that the fuel cells produce power while the post-combustion capture technology consumes power. In fact the efficiency of the coal plant retrofitted with fuel cells is expected to increase by 1.7%. In addition waste heat from the fuel cells is used in the coal plant for boiler feed water heating purposes.

The capture cost is based on the change in the first-year cost of power, for the reference plant and the retrofitted plant, multiplied by the energy produced by the retrofitted plant in a year divided by the mass of CO_2 captured. The cost of capture is expected to be below $100/t for the fuel cell case. The cost of capture for the post-combustion capture case is rather high compared to other studies. Part of the reason it is so high is that the cost of the FGD and the life extension costs have been included. Many other studies do not include these costs in the cost of capture. In addition, the high cost of coal and natural gas contribute to the high capture costs. The cost of capture for the post-combustion capture case without life extension and FGD costs is estimated to be $102/t. The cost of capture for the fuel cell retrofit case without life extension and FGD costs is estimated to be $58/t.

The cost of both coal and natural gas are relatively high in Nova Scotia; therefore, the avoided cost and capture costs are high for the post-combustion capture case. The fuel cells will produce about 26 m^3/hr of clean water. No economic value has been attributed to this. Fuel cells are also expected to convert roughly 70% of the NOx to N_2. No economic value has been attributed to this either. Perhaps this is fair when comparing to a NGCC which may have low NOx emission already.

Table 4: Cost of Capturing CO_2

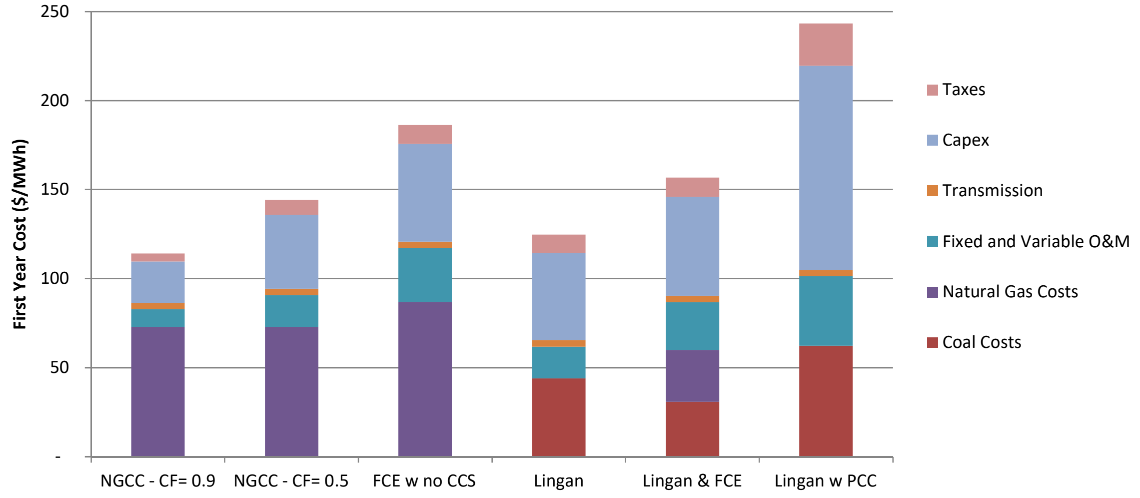
	NGCC	Lingan	Lingan & FCE	Lingan w PCC	R Lingan & FCE	R Lingan w PCC
First Year COE ($/MWh)	114	125	157	243	125	165
Avoided Cost ($/t)			58	217	58	217
Capture Cost ($/t)			81	120	81	120

3) <u>Detailed Results for Nova Scotia</u>

Figure 2 shows estimates of the required selling price of power in the first year. The first case is a NGCC with a capacity factor of 90% followed by a NGCC with a capacity factor of 50%. The FCE w no CCS case is an estimate of the cost of the standalone fuel cell plant without carbon capture. It may be possible to complete carbon capture on this case. Additional power will be required, primarily to compress the CO_2 generated by the fuel cell. This may increase the required selling price of power but the plant might emit very little CO_2.

The column labelled Lingan is an estimate of the cost of building a new Lingan plant without CCS. The Lingan & FCE case shows the cost of building a new Lingan plant with fuel cells incorporated. The cost of a new coal plant with molten carbonate fuel cells has a first year required selling price of power greater than that for a new NGCC. This is not surprising and this comparison is not the focus of the study. It should be noted that the first year cost of power for a new plant with fuel cells has a much lower cost than for a plant with PCC.

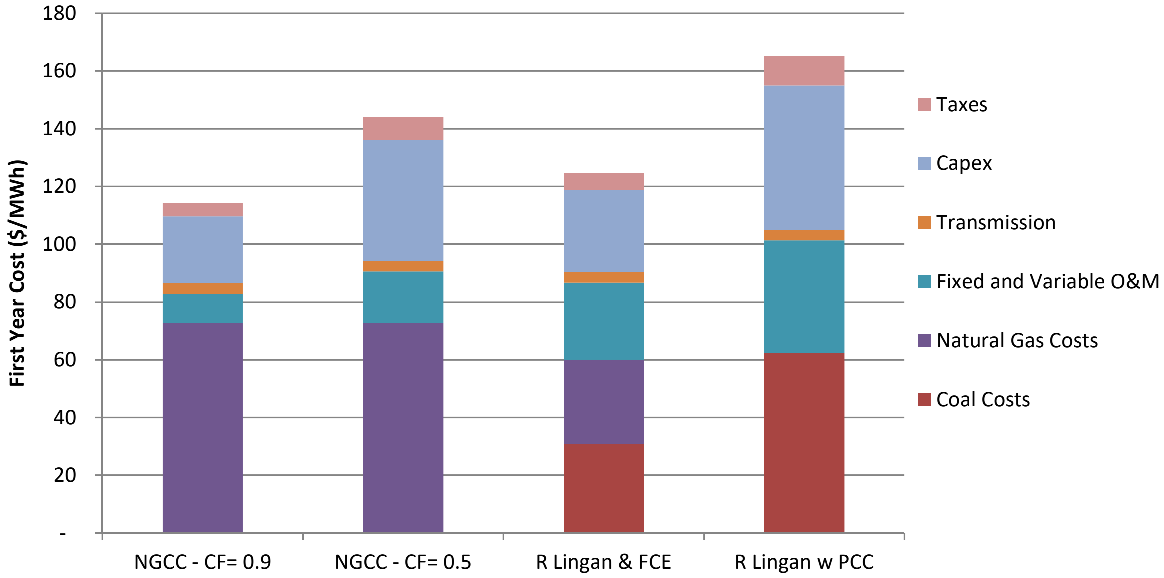
Figure 2: First Year Cost of Power - New Build Lingan



The first two bars in Figure 3 show the required selling price of power in the first year for a NGCC with 90% and 50% capacity factor. The right most column shows the required selling price of power for the Lingan plant retrofitted with post-combustion capture technology. It has a cost of power significantly greater than that for a NGCC. The column labelled R Lingan & FCE is Lingan retrofitted with molten carbonate fuel cells. It has an estimated required selling price of power in the first year just greater than a baseloaded NGCC. Further optimization and cost reductions for this case may make this technology even more competitive.

The bottom red and purple bars show the fuel costs for these cases. Fuel cost is roughly the marginal cost of a technology and many utilities dispatch the lowest marginal cost plants first. The sum of these two bars for the R Lingan & FCE case, is about $60/MWh. This is lower than the roughly $70/MWh marginal cost for the NGCC case running baseloaded. It is still higher than the roughly $45/MWh marginal cost for Lingan shown in Figure 2. This means the R Lingan & FCE case will likely run with a relatively high capacity factor and that the 90% capacity factor assumed is likely reasonable.

Figure 3: First Year Cost of Power – Retrofit Cases Lingan

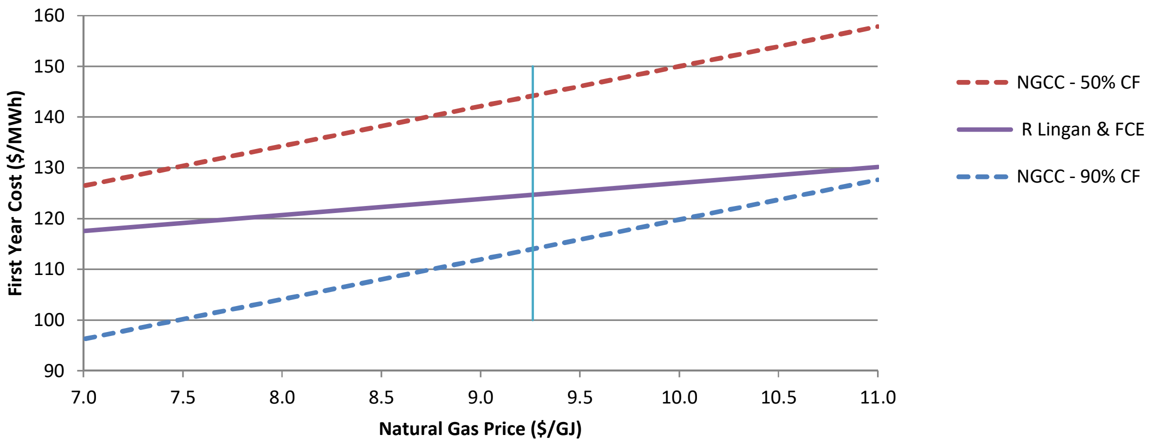


4) <u>Sensitivities for Lingan</u>

The dashed blue line in Figure 4 below shows how the cost of power for the NGCC with a capacity factor of 90% changes as the natural gas price changes. The dashed red line is for the NGCC case with a capacity factor of 50%. The purple line is for Lingan retrofitted with fuel cells. Given that much of the power generated by this case is produced with coal, the purple line has a shallower slope than the NGCC cases.

The vertical blue line shows the gas price used for Nova Scotia in 2016. As gas prices rise the R Lingan & FCE case becomes more competitive with an NGCC running baseloaded.

Figure 4: Natural Gas Price Sensitivities – Lingan



The dashed lines in Figure 5 below show the first-year cost of power for the NGCC cases. The green line shows how the first-year cost of power changes as the capital cost changes for Lingan retrofitted with fuel cells. Likewise, the purple line shows the result for Lingan retrofitted with post-combustion capture technology. Only the capital cost for the fuel cell and post-combustion capture technology have been adjusted in Figure 5.

Figure 5: Capital Cost Sensitivity – Lingan

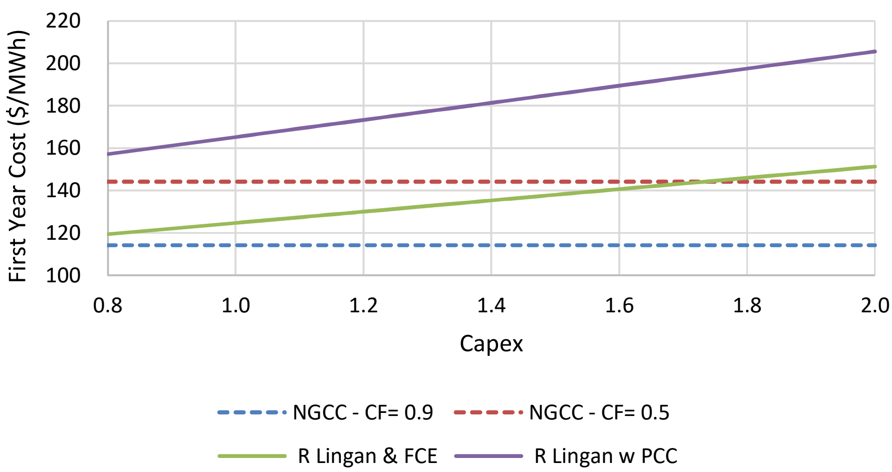


Figure 6 shows the impact of increasing the cost of the fuel cell plant by $200 million.

Figure 6: Capex Cost Increase – Lingan

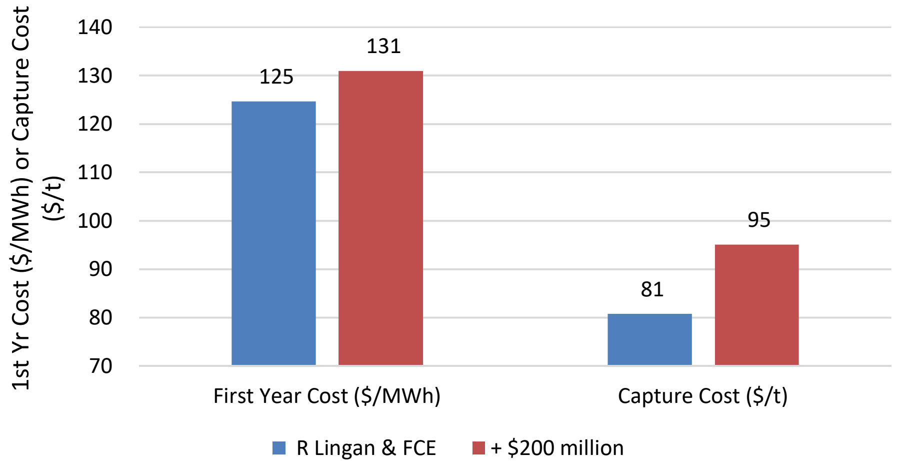
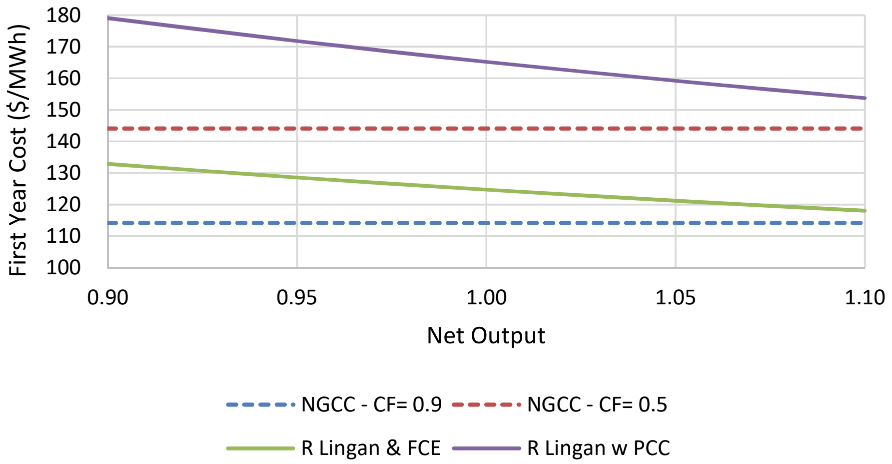


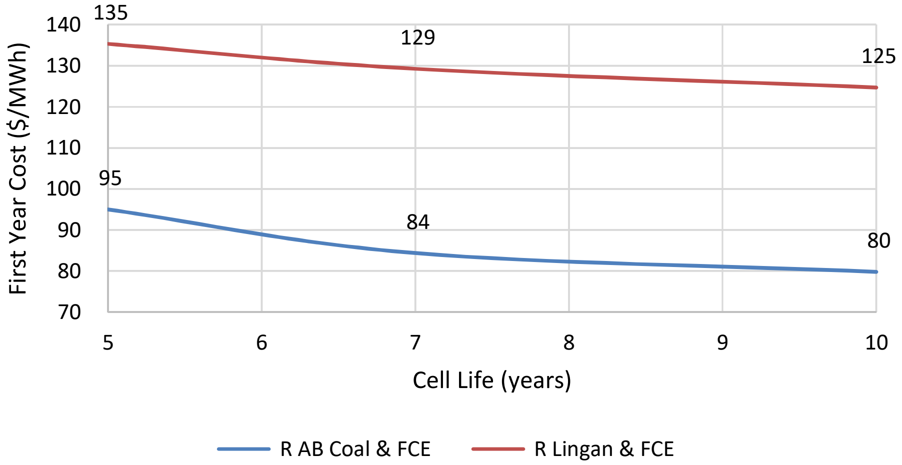
Figure 7 shows the impact of changing the output for the fuel cell and post-combustion capture cases. This sensitivity is for the whole plant not just the fuel cell portion; therefore, a 10% change in output amounts to about 44 MW or 26% of the gross fuel cell output.

Figure 7: Power Output Sensitivity – Lingan



The fuel cell stacks in the plant will need to be replaced periodically. The base assumption is that these stacks will need to be replaced every 10 years or twice during a 30 plant life. Figure 8 shows the impact on the first-year selling price of power if these stacks are replaced more often.

Figure 8: Impact of Fuel Cell Life



5) <u>Alberta Cases</u>:

The Alberta plant is a generic 311 MW plant created for modelling purposes. It has the same base GHG emission intensity as the Lingan plant. The capital and fuel costs have been modified to be consistent with expectations in Alberta.

Six Alberta cases were created for comparison purposes:

- NGCC: A new plant without CCS as key power supply alternative
- AB Coal: Base coal plant assumed to be new build
- AB Coal & FCE: New base coal plant plus fuel cells
- AB Coal w PCC: New base coal plant plus post-combustion capture (Amine)
- R AB Coal & FCE: A retrofit of a new coal plant with fuel cells
- R Lingan w PCC: A retrofit of a new coal plant with post-combustion capture (Amine)

The costs for these cases were largely based on the costs for the Lingan cases.

All coal cases in the table above are based on the base 311 MW plant capacity. A positive derate indicates that employing post-combustion capture reduces the output of the plant. A negative derate for the FCE case indicates that the fuel cell provides additional power. The natural gas heat rate is related to the fuel required by the fuel cell divided by the net capacity of the retrofitted plant. A coal cost of $1.30/GJ is a rough estimate for the cost of coal at Alberta plants in 2016.

Table 5: Base Information for Alberta

	NGCC	AB Coal	AB Coal & FCE	AB Coal w CCS	R AB Coal & FCE	R AB Coal w CCS
Net Power Production (MW)	535	311	444	266	444	266
Derate (MW)			-134	45	-134	45

% Derate			-43%	14%	-43%	14%
Coal Heat Rate (GJ/MWh)		9.60	6.71	12.00	6.71	12.00
NG Heat Rate (GJ/MWh)	7.11		2.79		2.79	
CF First Year	90%	90%	90%	90%	90%	90%
Design Life	30	35	35	35	35	35
Coal Cost ($/GJ)		1.30	1.30	1.30	1.30	1.30

The description of the capital costs for Table 6 is found above Table 2.

Table 6: Capital Costs for Alberta

$ million	NGCC	AB Coal	AB Coal & FCE	AB Coal w CCS	R AB Coal & FCE	R AB Coal w CCS
Base Plant	957	1,105	1,105	1,105		
Life Extension					75	75
FGD			220	220	220	220
Fuel Cells			793		793	
CCS				550		550
Escalation	181	209	209	356	0	160
Total	1,138	1,314	2,327	2,230	1,088	1,005
Capex ($/kW)	2,130	4,230	5,237	8,384	2,448	3,779
Incremental Capital Cost			1,013	916	1,088	1,005

The description of CO_2 captured below are found above for Table 3.

Table 7: CO_2 Capture in Alberta

	NGCC	AB Coal	AB Coal & FCE	AB Coal w CCS	R AB Coal & FCE	R AB Coal w CCS
GHG Intensity (t/MWh)	0.35	0.97	0.42	0.42	0.42	0.42
GHG Produced (t/yr)			2,861,235	2,373,413	2,861,235	2,373,413
Mass of CO_2 Captured (t/yr)		-	1,392,065	1,495,250	1,392,065	1,495,250
GHG Emissions (t/yr)		2,373,413	1,464,121	878,163	1,464,121	878,163
% Captured			49%	63%	49%	63%

The required selling price of power for the NGCC case is estimated to be $65/MWh in Alberta. The required selling price for the plant retrofitted with molten carbonate fuel cells is expected to be $80/MWh.

The NGCC in this case is assumed to operate 90% of the time. In reality, they may not operate at this high a capacity factor and may dispatch down or off at night when power prices are insufficient to cover the high fuel cost. The required selling price of power for the NGCC will rise as the capacity factor increases. This may make it difficult to compare the baseloaded coal plant required selling price to an NGCC that may run at a lower capacity factor.

The avoided cost is very low for the fuel cell case when compared to the post-combustion capture case. One of the key reasons for this is that the fuel cells produce power while the post-combustion capture technology consumes power. The cost of capture for the post-combustion capture case is rather high compared to other studies. Part of the reason it is so high is that the cost of the FGD and the life extension costs have been included. The cost of capture for the post-combustion capture case without life extension and FGD costs is estimated to be $88/t. The cost of capture for the fuel cell case without life extension and FGD costs is estimated to be $32/t.

The cost of capture for the fuel cell case is quite low compared to other technologies in other studies. Part of the reason for this is that the power produced by the fuel cells offsets the cost of capturing and compressing the CO_2.

Table 8: Cost of Capture CO_2 in Alberta

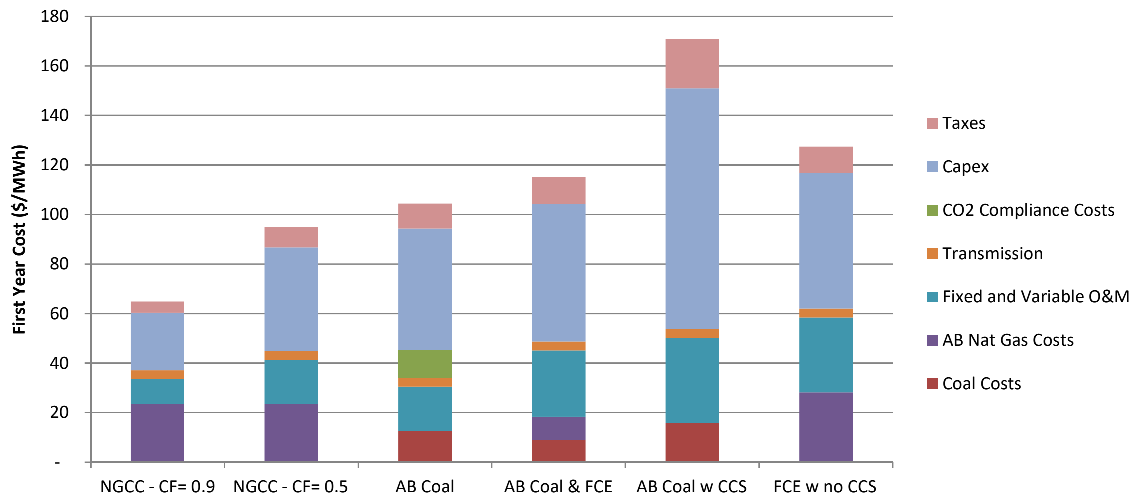
	NGCC	AB Coal	AB Coal & FCE	AB Coal w CCS	R AB Coal & FCE	R AB Coal w CCS
First Year COE ($/MWh)	65	104	115	171	80	107
Avoided Cost ($/t)			39	141	39	141
Capture Cost ($/t)			55	109	55	109

6) Detailed Results for Alberta

Figure 9 shows estimates of the required selling price of power in the first year. The first case is a NGCC with a capacity factor of 90% followed by a NGCC with a capacity factor of 50%. The AB Coal case shows the estimated cost of building a new coal plant in Alberta without CCS. The AB Coal & FCE case shows the estimated cost of building a new coal plant in Alberta with fuel cells incorporated. The cost of a new coal plant with molten carbonate fuel cells has a first-year required selling price of power greater than that for a new NGCC. This is not surprising and this comparison is not the focus of the study.

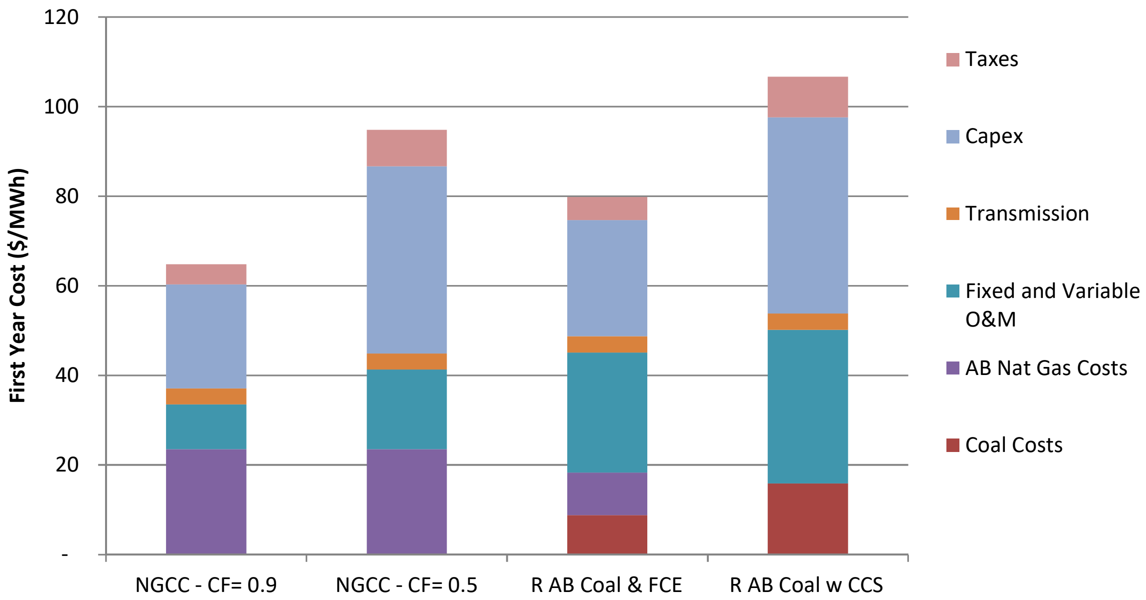
The FCE w no CCS case is an estimate of the cost of the fuel cell plant without carbon capture. It may be possible to complete carbon capture on this case. Additional power will be required primarily to compress the CO_2 generated by the fuel cell. This may increase the required selling price of power but the plant might emit very little CO_2.

Figure 9: First Year Cost of Power - New Build Alberta



The first two bars of Figure 10 show the required selling price of power in the first year for a NGCC with 90% and 50% capacity factor. The right most column shows the required selling price of power for a coal plant retrofitted with post-combustion capture technology. It has a cost of power significantly greater than that for a NGCC running baseloaded. The column labelled R AB Coal & FCE is an Alberta coal plant retrofitted with molten carbonate fuel cells. It has an estimated required selling price of power in the first year greater than a baseloaded NGCC; however, if the NGCC is expected to operate at a lower capacity factor than 90%, then the cost of energy from an NGCC may be comparable to a plant retrofitted with fuel cells.

Figure 10: First Year Cost of Power – Retrofit Cases Alberta

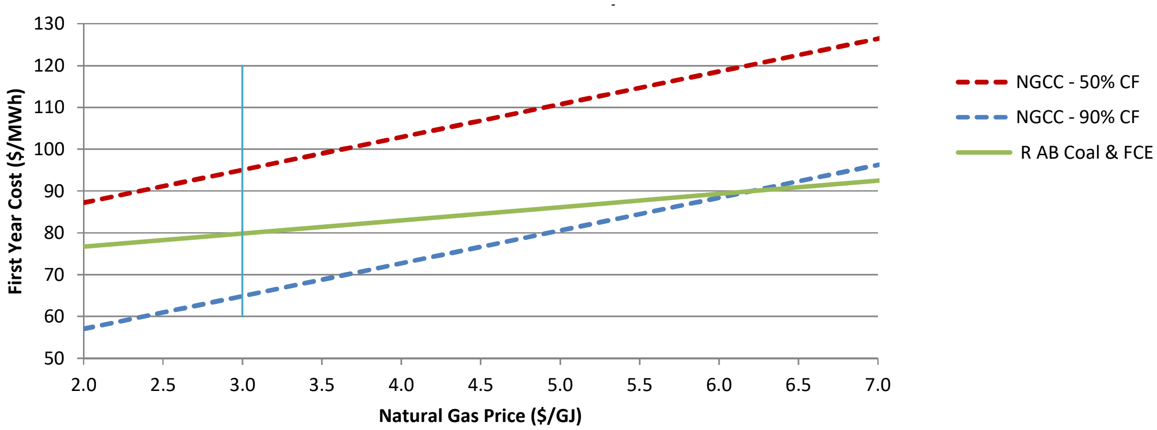


Further optimization and cost reductions for this case may make molten carbonate fuel cell technology even more competitive. The bottom red and purple bars in Figure 10 show the fuel costs for these cases. Fuel cost is roughly the marginal cost of a technology and many utilities dispatch the lowest marginal cost plants first. The sum of these two bars for the R AB Coal & FCE case, is about $20/MWh. This is lower than the roughly $25/MWh marginal cost for the NGCC case running baseloaded. It is still higher than the roughly $15/MWh marginal cost for a coal plant shown in Figure 9. This means R AB Coal & FCE case will likely run with a relatively high capacity factor and that the 90% capacity factor assumed is likely reasonable.

7) Sensitivities for Alberta

The dashed blue line in Figure 11 shows how the cost of power for the NGCC with a capacity factor of 90% changes as the natural gas price changes. The dashed red line is for the NGCC case with a capacity factor of 50%. The green line is for coal plant retrofitted with fuel cells. Given that much of the power generated by this case is produced with coal, the green line has a shallower slope than the NGCC cases. The vertical blue line shows the gas price used for Alberta in 2016. As gas prices rise the R AB Coal & FCE case becomes cheaper than a NGCC running baseloaded at about $6.30/GJ.

Figure 11: Natural Gas Price Sensitivities – Alberta



The dashed lines in Figure 12 show the first-year cost of power for the NGCC cases. The green line shows how the first-year cost of power changes as the capital cost changes for a coal plant retrofitted with fuel cells. Likewise the purple line shows the result for a coal plant retrofitted with post-combustion capture technology. Only the capital cost for the fuel cell and post-combustion capture costs have been adjusted above.

Figure 12: Capital Cost Sensitivity – Alberta

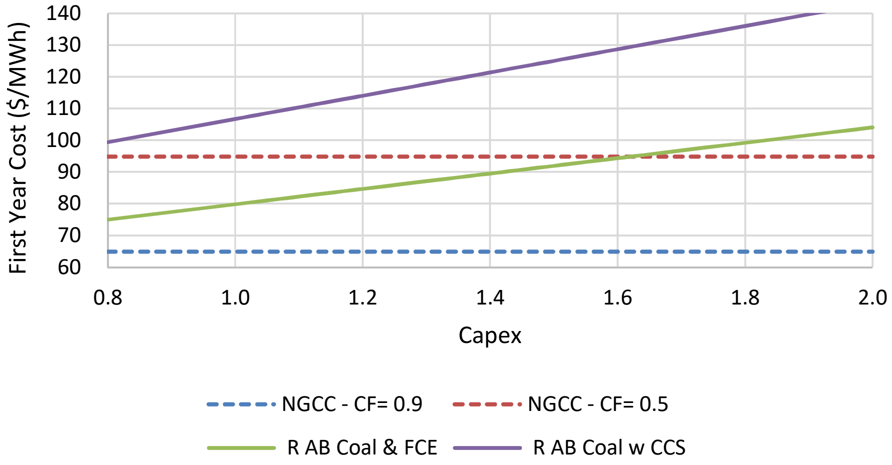


Figure 13 shows the impact of increasing the cost of the fuel cell plant by $200 million.

Figure 13: Capex Cost Increase – Alberta

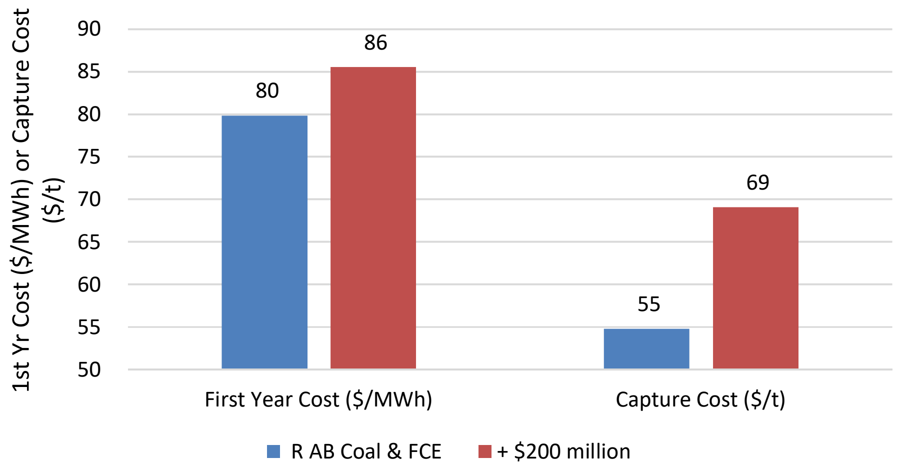
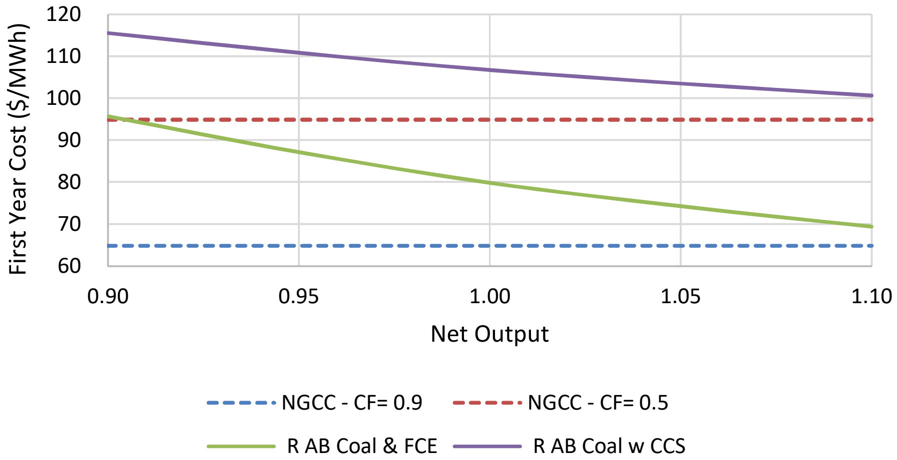


Figure 14 shows the impact of changing the output for the fuel cell and post-combustion capture cases. This sensitivity is for the whole plant not just the fuel cell portion; therefore, a 10% change in output amounts to about 44 MW or 26% of the gross fuel cell output.

Figure 14: Power Output Sensitivity – Alberta



8) <u>Conclusions</u>:

The cost of power from a coal plant in Nova Scotia and Alberta retrofitted with molten carbonate fuel cells appears to be a bit more expensive than building a new NGCC. The cost of capture with fuel cells is estimated for Alberta to be $55/t and $81/t for Nova Scotia. This is lower than any other post-combustion capture technology evaluated by the CCPC. This is remarkable given the capture costs include costs for life extension and for FGD. The capture costs reported in the literature often do not include these costs.

One of the virtues of this fuel cell technology is that no steam is required from the power plant to capture CO_2; therefore, expensive and extensive modifications to the plant steam cycle are not required as with other post-combustion capture options. In addition to capturing CO_2, the flue gas processed by the fuel cell process will be stripped of most of its sulfur and NOx components. This will substantially reduce the air emissions from the coal plant. The fuel cell is also a net producer of clean water at the rate of about 26 m^3/hr. No economic value has been attributed to this.

There may also be significant opportunities to optimize the performance of the fuel cells in carbon capture mode. These options should be investigated further via engineering estimates.

It is also hoped that Fuel Cell Energy will be able to demonstrate their fuel cells in carbon capture mode on coal flue gases in the future.