Optimization model for the Integration of Nuclear Energy in Oil Sand Operations

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Abstract

Currently, conventional power generation technologies are being utilized to power the oil sands industry. The increasingly stringent regulations on emissions from these technologies require the use of carbon capture technologies, which have very high capital and operating costs. Nuclear energy has a much smaller carbon footprint than any other conventional power generation technology and is also the cheapest possible option forward. This has paved the way for possible nuclear energy integration in oil sands operations. This study considers eight power generation technologies; two currently operational generation III nuclear reactors, two currently under construction generation III+ nuclear reactors, and the conventional pulverized coal (PC) and natural gas combined cycle (NGCC) technologies with and without carbon capture. Eight different case studies are considered to discuss and analyze different possibilities for integrating nuclear energy. The optimal solution integrates 25% of nuclear power to the current power generatiing system for meeting Alberta's electricity demand. The overall total cost of the optimal solution is approximately $USD 85 billion over a lifespan of 60 years. Scenarios involving secondary revenue streams such as steam and hydrogen production, and selling excess electricity to the power grid have also been considered to determine their effect on the optimal results.

1.0 Introduction

Canada is one of the largest energy consumers in the world. It is among the eight most industrialized countries in the world in terms of per capita energy consumption. The largest contributor to the high per capita energy consumption of Canada is the province of Alberta. Alberta's per capita consumption is two-and-a-half times higher than the national average (Menard 2005). A significant part of the increase in energy consumption is a result of increased oil sands production in northern Alberta. Bitumen extraction and upgrading from oil sands is a very energy intensive process, requiring large amounts of hydrogen, steam, electricity and heat ("Alberta Facts and Statistics" 2013). The world's second largest oil deposit and the increasing demand for oil are responsible for the significant increase in energy demand in northern Alberta. World demand for oil is expected to increase by 54 per cent in the first 25 years of the 21st century. To meet this demand, the world's oil-producing countries will have to pump out an additional 44 million barrels of oil every day by 2025 ("CBC News: Supply and demand" 2005). Oil production from the oil sands has been continuously rising and is expected to reach at least 5 million barrels per day by 2020 ("Alberta Facts and Statistics" 2013).

Currently most of Alberta's electricity needs are met by plants using conventional technologies, i.e. plants that burn coal or natural gas ("Alberta Facts and Statistics" 2013). Recently, power and oil companies have been forced to follow new regulations and policies implemented by the provincial government. Over the last few years, more stringent environmental policies such as Kyoto Protocol have been developed to address concerns regarding greenhouse gas emissions. Since Canada has ratified the Kyoto Protocol, it must take all necessary steps to reduce and curb its greenhouse gas emissions so as to meet its Kyoto targets. Canada's Kyoto objectives, while satisfying the power and electricity demands, can only be achieved by substituting current power production technologies with technologies that emit fewer or no greenhouses gases such as nuclear power and carbon capture technologies. Nuclear power plants have the smallest 'footprint' in terms of the amount of energy generated per hectare of land.

Moreover, these nuclear power plants are more efficient, easier to operate and control and have lower operating costs (Andre 2009).

Canada is the only country in the world to possess high-grade ore bodies with more than 2% uranium by mass. Hence, it has great cost advantage in using nuclear power due to abundant high-grade uranium deposits in the country (Johnson 2010). Large high-grade ore deposits and the highly efficient nuclear power generation process put Canada at the forefront of nuclear power generation and development. In the highly volatile deregulated electricity market, operators employing nuclear power for their operations can offset periods of low demand in the electricity market with profits from a secondary product such as hydrogen production (Ordorica-Garcia 2008). Nuclear power is cost competitive with other forms of electricity generation, except in the rare case where there is direct access to low-cost fossil fuels. Fuel costs for nuclear power plants are a minor proportion of total generating costs, though capital costs are higher than those for coal-fired and gas-fired plants.

This paper investigates the feasibility of integrating nuclear energy power generating facilities with existing technologies in Alberta's oil sands operations. The objective of this work is to evaluate and compare various technologies suitable for energy production. The goal is to develop a mathematical model geared towards cost minimization while satisfying a set of constraints, such as satisfying electricity demands of the oil sands operations and meeting environmental constraints. The optimization problem will also be used to consider several different case studies such as scenarios where nuclear power could be used to consider alternatives such as production of H_2, generation of steam, selling excess electricity to the power grid alongside other viable options.

2.0 Power generation alternatives

Nuclear and conventional power generating technologies were considered as alternatives in this study. Figure 1 summarizes the total costs required for implementing these technologies and their capacities (David and Herzog 2000; "AECL: Technical summary" 2007; Komanoff 2009; Black 2012). The nuclear power generation technologies considered include:

- CANDU-6: Canadian Deuterium Uranium nuclear reactors are the current mainstay for Canadian nuclear power generation, being the only active nuclear power reactors in Canada.
- ACR-1000: Advanced CANDU nuclear reactor is a generation III+ reactor based upon the older CANDU-6 reactors. Currently there are no completed and operational ACR-1000 units in the world. However, there are numerous units that are under construction worldwide.
- ACR-700: It is an evolution of the older CANDU-6 reactors with an output comparable to it while also utilizing the same improvements that were included in the ACR-1000. To date no ACR-700 units have been constructed.
- AP-1000: The AP-1000 is a refinement of generation III pressurized light water reactors. There are currently four AP-1000 reactors under construction in China as well as two planned for the Vogtle Nuclear Facility in Burke County, Georgia ("Atlanta Business Chronicle" 2008). Twelve other AP-1000 units are awaiting Combined Construction and Operating Licences (COL) in the US in addition to the two units at Vogtle before construction can commence ("United States Nuclear Regulatory Commission" 2010).

The conventional power generation technologies considered include:

- Pulverized Coal (PC1): Coal dust is used exclusively instead of bulk coal so as to improve the degree of combustion of the coal particles due to an increased surface area of the coal, which increases the amount of energy released per tonne of coal (Ahmed 2009).
- Natural Gas Combined Cycle (NGCC1): Natural Gas Combined Cycle (NGCC) power generation plants use a combined cycle gas turbine to generate electricity through the combustion of natural gas (Klara and Wimer 2007).
- Carbon Capture Technologies (PC2, NGCC2) : They can reduce carbon emissions by up to 80-90% in a modern conventional power plant using direct gas scrubbing (Metz et al. 2005). Carbon-capture technologies can approximately double the cost of construction and operation of a conventional power plant. In this study we would consider carbon capture with only pulverized coal power plants (PC2) and natural gas combined cycle power plants (NGCC2).

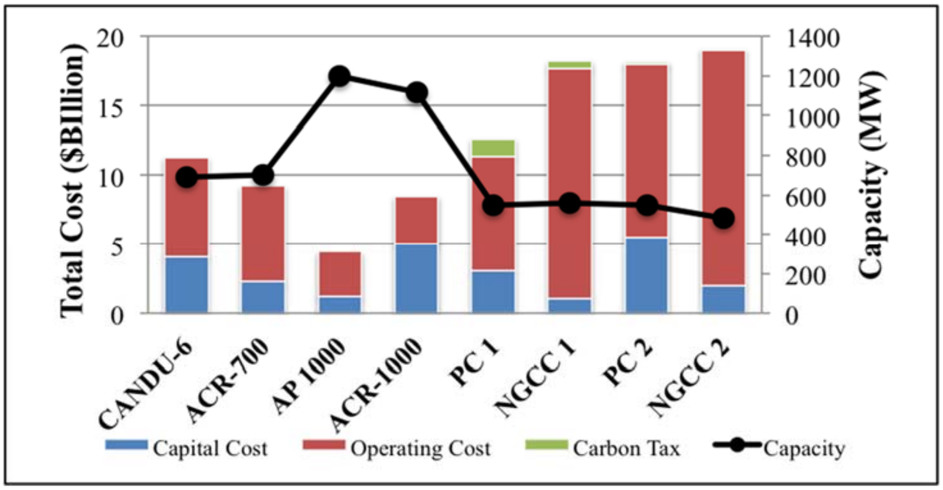

Figure 1: Total costs and capacities of power generating technologies

3.0 Mathematical model

A mathematical model is formulated as a supporting tool in the decision-making process of determining the optimal combination of nuclear power generating technologies to be integrated with the existing power plants. The dicrete binary decision variables are defined as the number of reactors for each power technology to be installed. For this optimization a cost minimization scheme is employed and Table 1 shows the total costs associated with each reactor technology that will be used to select an optimum combination of reactors that have the lowest combined cost. It is assumed that any technology selected by the optimization model will operate at its maximum capacity. Therefore, the total cost for each reactor technology can be lumped into a single term (i.e. a_j) that is comprised of capital cost, operating cost and any carbon emission related taxes. These cost estimates can then be used to develop the following objective function (eq. 1).

$$min \sum_i \sum_j a_{ij}\, x_{ij} \tag{1}$$

where a_{ij} is the total cost of the ith reactor of the jth technology, and x_{ij} is a binary decision variable. The objective function shows that the optimization model developed is an integer linear program (ILP). It can be solved using the optimization solver tool in Microsoft excel. The mathematical model is subjected to the constraint of electricity demand (eq. 2).

$$\sum_i E_i \geq Electricity\ demand \qquad \forall i \tag{2}$$

where E_j is the power output of the jth reactor (MW). The power technologies can be used to meet energy demand for oil sands as well as secondary requirements such as hydrogen and steam production, and providing provincial electricity. The energy requirement for oil sands is 1210 MW. For the purposes of this study, it is assumed that steam will be produced for nearby Steam Assisted Gravity Drainage (SAGD) facilities that in general, use saturated steam at 8118.9 kPa and 296^{o}C (Elliott and Kovscek, 1999). At least 41.47 MW of power is required for a steam production rate of 106,891,627.5 m^3/year [26]. Hydrogen can be produced via electrolysis or steam reforming, which have power requirements of 76MW and 28MW, respectively [24,25]. A power production output of 3000 MW is required to satisfy the demand for Alberta's provincial grid, which is expected to increase by 10,000 MW in the next 20 years [27]. The second constraint to the optimization problem that was considered was towards meeting the Kyoto greenhouse emission reduction targets (eq.3 and eq.4).

$$ER_p = \sum \frac{E_i\, EF_p}{HHV} \qquad \forall m \tag{3}$$

$$\sum_i \sum_j ER_p (1 - \eta_{ij}^{p}) \leq R_p \qquad \forall m \tag{4}$$

where, ER_p is the emission rate for pollutant p (ton/yr), HHV is the high heating value (MWh/lb), EF_p is the emission factor of pollutant p (ton/lb), η^{p} is the removal efficiency of each reactor for pollutant p, R_p is the reduction target set for each pollutant p.

Table 1: Total cost of each power technology

Reactor Type	Decision Variable	Total Cost ($Billion/yr)
Nuclear	CANDU-6	0.188
	ACR-1000	0.141
	ACR-700	0.153
	AP-1000	0.074
Non-Nuclear	PC1	0.210
	NGCC1	0.303
	PC2	0.302
	NGCC2	0.317

4.0 Results and Discussion

The following analysis includes a detailed discussion on the optimal solution for the proposed nuclear energy integration. In addition, it also discusses and compares numerous other relevant case studies to understand and appreciate the nature of the proposed integration. It must be noted that all costs and demands are calculated on an annual basis. Power generation distribution and total costs estimated for each case scenario are summarized in Figure 2 and Figure 3, respectively.

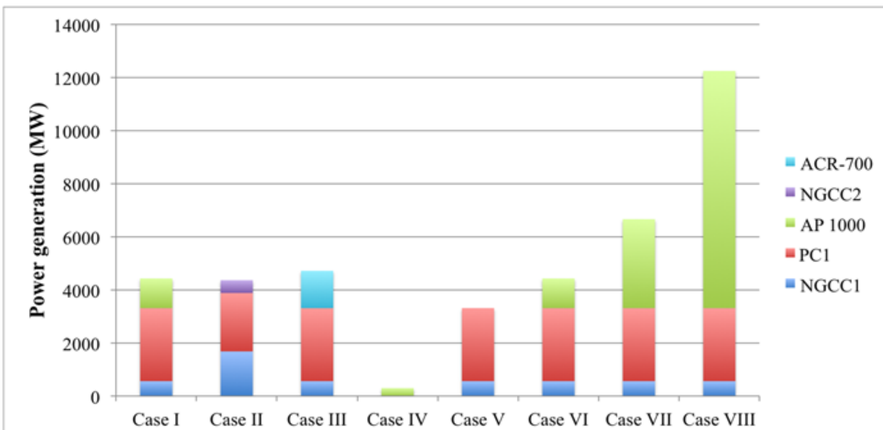

Figure 2: Power generation distribution for each scenario

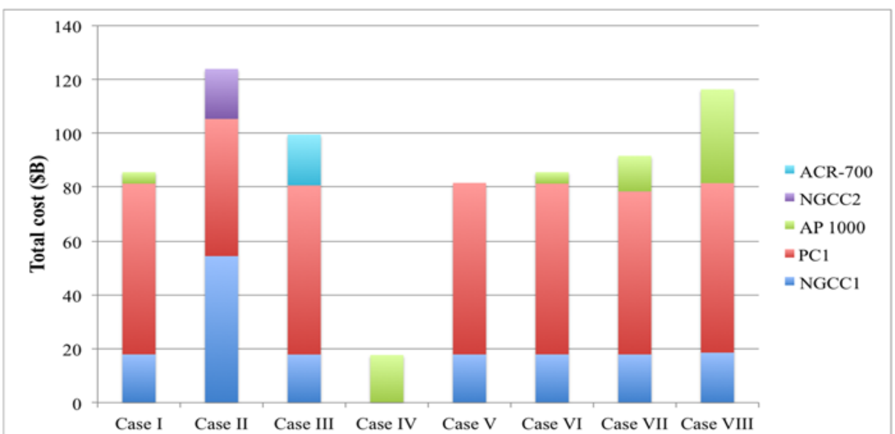

Figure 3: Estimated total cost for each scenario

4.1 Case I – Optimal Solution

This scenario considers the proposed optimal solution for integration of nuclear energy into Alberta's oil sands industry. All nuclear reactors as well as the conventional coal and natural gas technologies discussed in Table 1 are included as decision variables in the optimization model. In addition, hydrogen and steam production for SAGD facilities was also considered and included in the model. The excess energy in the model would be sold to the grid to generate revenue and will be used to meet the required hydrogen and steam demands for oil sands operations.

Approximately 25 % of the energy is be provided by the AP 1000. It has both the lowest initial capital investment and the lowest operating cost favouring its selection. AP 1000 contributes to significantly in the amount of energy produced (25%) for a very low cost contribution (5%). This implies that a unit of energy is produced for a much lower unit cost than in the case of conventional technologies. Their selection in combination with natural gas and coal technologies without carbon capture, which are considerably lower in cost relative to carbon capture technologies, is sufficient to meet the greenhouse gas emission target as set by the Kyoto Protocol (594 Mt/year).

The total cost of the optimal solution is $USD 85.5 billion over a facility life span of 60 years. Conventional technologies (PC1 and NGCC1) contribute about 95% of the total cost as the optimal solution involves multiple conventional units, i.e. reactors and these technologies tend to be slightly more expensive than nuclear technology. Overall, if nuclear energy was to be integrated into Alberta's oil sands today, only about 25% of conventional technologies would have to be replaced with nuclear power to meet the energy demand and greenhouse gas emission targets.

4.2 Case II – No Nuclear Energy

This scenario reflects the current situation in Alberta, where there is no nuclear energy integrated into Alberta's oil sands. The energy demand including hydrogen and steam for oil sands facilities is currently met only by conventional power technologies such as natural gas and coal.

Coal (PC1) without carbon capture is favoured over natural gas technologies by providing 50% of the total power required. This is primarily due to its lower cost. However, natural gas technology (NGCC1) is also selected and contributes about 39% of the power due to its lower greenhouse gas emissions to remain within the Kyoto limits. This also explains the selection of natural gas with carbon capture technology (NGCC2) to provide about 11% of the power. This is because the optimal solution is forced to meet the Kyoto targets and with no nuclear energy option present.

Natural gas (NGCC1) is slightly more expensive than coal technology as it contributes to a larger extent in the total cost for a lower energy output in the power distribution as opposed to PC1. The total cost for this optimal solution is about $USD123.9 billion which is 45% more expensive than the proposed optimum solution in Case I. This confirms that the conventional technologies alone are significantly more expensive to provide energy for the ever-growing oil sands industry. Hence, integration of nuclear energy in Alberta's oil sands is an economically favourable decision.

4.3 Case III – Operational Nuclear Plants

In this scenario, an optimal solution was provided by only considering current operational nuclear technologies in the model. Since AP 1000 and ACR 1000 nuclear technologies are not in operation yet, they were removed from the optimization problem.

Conventional technologies contribute majority of the power demand where coal (PC1) provides about 58% of the required power to growing oil sands industry. As mentioned earlier, coal plants are cheaper than natural gas plants and thus PC1 is preferred over NGCC1. Similarly, nuclear reactors such as ACR 700 is favoured over coal due to its much lower cost but since the optimal solution is forced to meet greenhouse gas emissions constraints, it has to choose coal and natural gas to a much larger extent than ACR-700 as there are negligible greenhouse gas emissions from nuclear reactors.

The total cost for this case is about $USD 99.5 billion which is about 16.4 % larger than the proposed optimal solution in Case I. The main reason for this is that the newer nuclear reactor technologies such as AP 1000 and ACR 1000 benefit from the concept of economies of scale due to larger reactor sizes. Continuous research and development in nuclear power industry has helped lower the cost and improved the safety by introducing better, efficient and improved designs. If this case is compared to the current situation in Alberta, i.e. Case II, this optimal solution with operational nuclear technology is still cheaper than the existing situation of using no nuclear power. If this case is implemented in Alberta, about 25% cost savings can be achieved compared to 45% with the proposed optimal solution.

4.4 Case IV – No greenhouse gas emissions

In this scenario, the Kyoto constraint that forced the optimization model to emit a minimum amount of greenhouse gas emissions is relaxed to allow the possibility of minimizing greenhouse gas emissions constraints. One must note that nuclear power generation does result in greenhouse gas emissions but for the purposes of this investigation it is deemed negligible when compared to the greenhouse gases emitted by the conventional power generation technologies. The optimal solution chooses only one nuclear reactor namely AP 1000 to meet the total energy demand. AP 1000 not only has the lowest cost compared to other nuclear and conventional technologies but also emits no greenhouse gases. The total cost for this optimal solution is about $USD 17.7 billion which is significantly less (by about 80%) than the proposed optimal solution in Case I. It is clear that using nuclear energy to power oil sands growth is the cheapest and the best option with no greenhouse gas emissions. The increased total cost in all the previous cases is due to the use of conventional technologies.

However, this case is not practical in the current time as it would require decommissioning of all conventional power plants currently in use and the construction of new nuclear facilities, which will be very capital intensive and uneconomical. On the other hand, if nuclear energy is chosen as the path forward for the development of the oil sands, then construction of only nuclear power plants would be ideal as they would significantly reduce the overall cost. Moreover, this situation may be feasible 20-30 years in the future if nuclear energy is the primary source of power in the world.

4.5 Case V – No Secondary Products

In this scenario, the energy demand was modified to eliminate the production of secondary products such as hydrogen, steam and excess electricity for the grid. This scenario implies that there is no revenue generation as no electricity is sold to the grid. Moreover, it must be noted that hydrogen and steam must be purchased for the oil sands operations and thus would increase the overall cost of operation. This would be an external cost incurred by the facility and would vary on a case-by-case basis.

The optimal solution only favours conventional technologies, in particular coal (PC1), over nuclear technologies. This is due to the fact that nuclear technologies become infeasible at lower energy demands due to their high-energy output per reactor. Hence it can be concluded that hydrogen and steam production contributed significantly enough towards the total energy demand, which in turn made nuclear energy a feasible option in the previous cases. Moreover, this scenario again confirms that coal (PC1) is a favoured option over natural gas technologies (NGCC1) due to its much lower cost.

The total cost of this optimal solution is about $USD 81.5 billion, which is about 5%, lower than the proposed optimal solution in Case I. Since a larger percentage of coal technology (PC1) is required to meet the energy demand, the proportion of total cost contributed by coal is also high. However, natural gas (NGCC1) contributes to a slightly larger extent of about 22 % towards cost as compared to a 17% contribution in the power distribution. This is because it costs more to produce the same amount of energy using natural gas than coal technology.

4.6 Case VI – No Carbon Capture Technologies

In this case, all conventional technologies with carbon capture were removed from the optimization problem. This solution is exactly the same as the proposed optimal solution in Case I. It does not make any difference to the optimal solution whether or not carbon capture technologies are included in the model. This is also the case in most of the scenarios above where the optimization model does not favour any carbon capture technologies in the optimal solution. This is because carbon capture technologies are very expensive, primarily due to their high operating cost which makes them infeasible in the optimal solution. Even though carbon capture technologies have a lower carbon footprint and are environmentally friendly, they are not cost competitive with other technologies. The total cost of $USD 85.5 billion and cost distribution is exactly the same as in Case I.

4.7 Case VII – Hydrogen via Electrolysis
In all previous cases hydrogen was produced via steam reforming which is the most common method. In this case, the effect of hydrogen production via electrolysis on the optimal solution is analyzed.

As discussed earlier, hydrogen production via electrolysis is an energy intensive process making nuclear energy a more favourable option at high-energy demands. Coal technology (PC1) is the second largest contributor to the power demand due to its lower cost compared to natural gas. It should also be noted that AP 1000 is also one of the cheapest nuclear technology available allowing the nuclear option to be even more cost competitive over current conventional technologies. The total cost of this optimal solution is $USD 94.4 billion.

The optimization problem does not account for the greenhouse gas emissions that would be emitted with the production of hydrogen via steam reforming. From Equation 4, it can be estimated that 1 kg of hydrogen gas will produce at least 4.77 kg of greenhouse gases. Even though, electrolysis might appear to be an expensive option but the savings achieved by no greenhouse gas emissions might outweigh the cost of electrolysis. Hence, method of hydrogen production must be evaluated specific to the operating requirements at specific facilities.

4.8 Case VIII – Nuclear Power for Alberta
This case considers powering all of Alberta's energy growth requirements, i.e. 10000 MW of power, in the next twenty years. This growth includes the growth in the oil sands sector. It is evident that a greater percentage of AP 1000 nuclear reactors would be required to meet this high demand. This optimal solution reiterates the fact that nuclear energy is preferred at high-energy requirements. The selection of technologies is similar to the proposed optimal solution for oil sands in Case I except a larger percentage of nuclear energy is required to meet the demand.

The total cost of this optimal solution is $USD 116.3 billion which is expected to be high due to the higher energy demand from the province. Coal technology contributes the most (54 %) towards the total cost. The total cost of this solution is about 36 % higher than the cost of the proposed optimal solution in Case I. However, the cost is still 6% lower than the total cost of the optimal solution in Case II, which reflects the current situation in Alberta, but it, can provide a much larger energy output to cover Alberta's future energy growth of about 10000 MW. This optimal solution may be a feasible solution in the future if there is enough foresight where Alberta can gradually integrate nuclear energy to power Alberta's energy needs. To make this a reality, about 73% of current conventional plants would have to be de-commissioned to integrate the above optimal solution in Alberta.

5.0 Sensitivity Analysis
The following section presents a sensitivity analysis on some important parameters of the optimization problem. The sensitivity analysis mainly aims to focus on the factors that are relevant to carbon capture technologies. The analysis also considers the effect of overall power demand on the optimal solution. In all but one of the optimization case studies, carbon capture technologies were not selected as discussed earlier. On average, carbon capture technologies cost more than both nuclear and conventional technologies in terms of initial investment, and their operating costs are higher than those of nuclear technologies. It is believed that both these factors played a very important role in making carbon capture an unfavourable technology in the developed optimization model. The sensitivity analysis, which is presented in Table 2, would allow for better understanding of their effects on the overall favorability of carbon capture technologies. The new total cost is compared to a base case total cost of $ 85.5 B.

Table 2: Sensitivity analysis for proposed optimization model

Parameter	Current Level	Sensitivity Limit	New Total Cost ($B)
Electricity Demand (MW)	4356.2	3300	81.15
Carbon Tax ($/tonne CO_2)	7.8	401	442.32
Operating Cost for PC2 ($/MWh)	43.4	12	85.53
Operating Cost for NGCC2 ($/MWh)	67	14	85.22

It was determined that if the overall electricity demand reduced to 3300 MW from the current 4356 MW, then the optimal solution to the problem will change. At this point, no nuclear energy would be used for power generation and all the power would be generated using a mix of both conventional power plants and carbon capture technologies. As mentioned earlier, this is only true because the Kyoto targets have been imposed on the optimization problem. A 25% decrease in the overall electricity demand only reduces the cost by approximately 5%, which is not significant and does not justify eliminating nuclear technologies.

The next three parameters discussed below focus on carbon capture technologies. The sensitivity analysis indicates that carbon tax would need to increase by over 5000% for the optimal solution to change. If the carbon tax increases from $7.8/tonne of CO_2 to about $400/tonne CO_2 then the optimization model would prefer selecting carbon capture technologies over conventional power generation technologies. In this case the overall cost of the solution will increase drastically due to the selection of carbon capture technologies, which are considerably more expensive than both nuclear and conventional technologies were the total cost becomes $450 billion over the lifespan of the facility (i.e. 60 years). Secondly, operating conventional power plants would become significantly more expensive as their large carbon emissions would be heavily taxed. However, this situation is highly unlikely to occur, therefore, it can be concluded that carbon tax does not affect the optimal solution.

The other two parameters investigated were the operating costs for the pulverized coal plant with carbon capture (PC2) and the operating costs for the natural gas combined cycle plant with carbon capture (NGCC2). The operating cost for PC2 needs to reduce from $43/MWh to about $12/MWh to affect the optimal solution. This would make the cost of operating PC2 comparable to operating any other nuclear technology. A decrease of the specified magnitude seems highly unlikely without a major technological innovation or discovery. A similar observation can be made for the cost of operating NGCC2. It can be concluded that these operating costs would not affect selection of carbon capture technologies in this optimization.

It is clearly evident that neither one of carbon tax and operating costs can affect the selection of carbon capture technologies, and only their capital cost remains as the only parameter that could affect their selection in the optimization model. Currently, these technologies are still in the research and development phase with very few operational facilities around the world. Thus, it is expected that the cost of this technology, both capital and operating, would significantly decrease in the future with advances in the technological research field pertinent to carbon capture technologies.

6.0 Conclusions

An optimization model was developed to investigate the possibilities of integrating different nuclear power generation technologies with conventional processes. The model was applied to various scenarios to determine the optimal fleet of stations on the basis of cost minimization while satisfying energy demand and emission constraints. The proposed optimal solution in Case I is a viable and promising option for Alberta government to move towards significantly reducing costs and trying to achieve greenhouse gas emission targets as set by Kyoto Protocol. According to Case I, only about 25 % of current conventional technologies would have to be replaced with the AP 1000 nuclear technology. The optimal solution suggests the integration of AP 1000, which is not operational yet but has a newer improved design for much safer and more efficient operation. Nevertheless, whether ACR-700 or AP 1000 is considered in the optimal solution, it is inevitable from all the cases that nuclear technology is the best option to effectively meet the ever growing electricity needs of Alberta while being environmental friendly. AP 1000 is the cheapest option over all nuclear and conventional technologies and if nuclear energy is not integrated into powering oil sands facilities, then the total cost incurred will be significantly high and will likely to further increase as was evident from Case II. Moreover, carbon capture technologies were not favoured in most of the optimization cases considered due to their significantly high capital and operating costs. Sensitivity analysis shows that the operating of carbon capture technologies and carbon tax do not have an effect on the results of the optimization model.

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Biography

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