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A Life Cycle Assessment of Greenhouse Gases and Select Criteria Air Contaminants

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KEEYASK GENERATION PROJECT

STAGE IV STUDIES - PHYSICAL ENVIRONMENT

A LIFE CYCLE ASSESSMENT OF GREENHOUSE GASES AND SELECT CRITERIA AIR CONTAMINANTS

REV 0

DELIVERABLE GN 9.5.5

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PREPARED FOR:
HYDRO POWER PLANNING DEPARTMENT
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THE PEMBINA INSTITUTE

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Pembina would also like to acknowledge the assistance of Gerdau AmeriSteel. AmeriSteel provided Pembina with detailed information on steel recycling. Their assistance allowed Pembina to include a more appropriate steel recycling factor in the assessment.

This report could also not have been completed without the assistance of Manitoba Hydro's consultants. The consultants patience with our hundreds of questions and their detailed responses saved us time and effort.

Keeyask Generating Station

A Life Cycle Assessment of Greenhouse Gases and Select Criteria Air Contaminants

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Pembina prepared a detailed LCA for the Keeyask facility and then compared it with the published life cycle values for the comparison technologies. The results of the LCA of Keeyask show that the majority of the NO_x and SO_2 emissions result from material manufacturing during the construction phase of the project. GHG emissions result equally from land use change emissions and the combined emissions from material manufacture, construction and transportation. GHG, NO_x and SO_2 emissions are much lower during the operating and decommissioning phases of the project.

In comparison with the alternative technologies, Keeyask's life cycle GHG, NO_x and SO_2 emissions are much lower. Figure 1 contains the results of the GHG analysis. The NO_x and SO_2 results are similar.

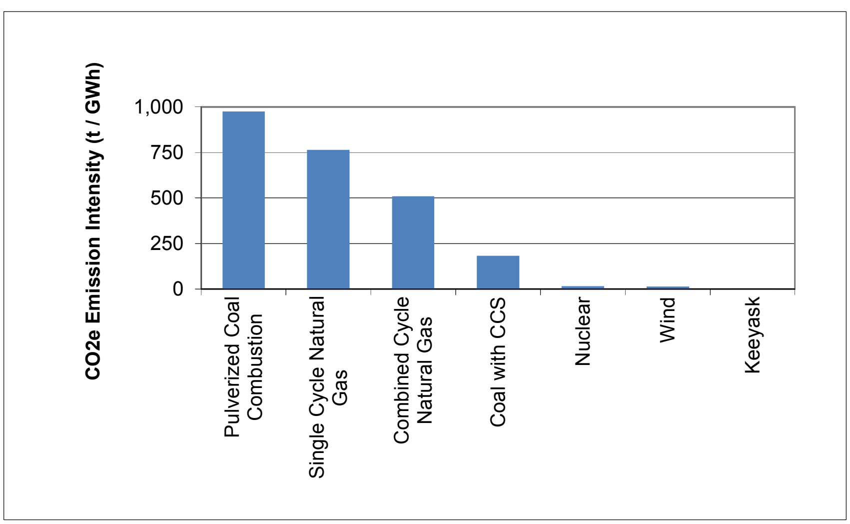

Figure 1: Life cycle CO_2e emissions for the Keeyask facility and the comparison technologies

Generally, Keeyask's emission intensities are significantly lower than any of the fossil fuel technologies, coal and natural gas, and lower but closer to nuclear and wind electricity generating technologies.

1. Introduction

1.1 Background

Manitoba Hydro has contracted the Pembina Institute to prepare a detailed quantitative life cycle analysis (LCA) for the Keeyask generating stations and then compare this generating station with six other electricity generating technologies — pulverized coal combustion, coal with carbon capture and storage (CCS), natural gas combined cycle, natural gas single cycle, wind and nuclear — on a life cycle basis based on GHG, nitrogen oxides (NO_x) and sulphur dioxide (SO_2) emissions, the two select Criteria Air Contaminants (CACs).

This report presents the results for the Keeyask generating station (the generating station). The proposed location for the generating station is on the Nelson River 725 km (1,000 km by road) north of the City of Winnipeg. The proposed 695 MW generating station would be the sixth generating station on the Nelson River if it is constructed.

The principles of the LCA process, methodology and project objectives are described below. These sections are followed by a description of the Keeyask project, a detailed description of the comparison technologies, the methodology used to quantify life cycle emissions for the project, and the results of the analysis and conclusions.

1.2 LCA Process and Methodology

The analysis presented in this report follows the ISO 14040 life cycle standard[1]. The following is a generic description of the LCA methodology. A more detailed description of the methodology used in this assessment is available in Section 4 – Methodology. In general LCA analyses include these five distinct steps:

1. **Goal Definition –** The goal definition phase includes understanding the background of the project, listing the primary questions that need to be answered and determining the objectives. Goal definition requirements are included in Section 1 – Introduction and Section 2 – Keeyask Generating Station Description.

2. **Scoping –** The scoping phase includes determining the common basis of comparison or functional unit, the key activities to be included in the project, for example producing cement for construction of the generating station, and determine what evaluation criteria should be used. The scoping phase is discussed in detail in Section 4 - Methodology with more detail provided in the appendices as required.

3. **Inventory Assessment –** The inventory assessment includes gathering and analyzing data to fulfill the requirements of the goal definition and scoping stages. Manitoba Hydro

[1] ISO, "Environmental Management - Life Cycle Assessment - Principles and Framework," in *ISO 14040:2006(E)*, ed. ISO (2006).

provided the majority of the data used in the assessment. Manitoba Hydro also contracted Environnement Illimité Inc.to calculate expected reservoir GHG emissions for the generating station. Pembina supplemented Manitoba Hydro and Environnement Illimité's data with information from a similar life cycle study Pembina prepared for the Wuskwatim Hydro project[2] and public data when necessary. Pembina also developed a custom LCA model to calculate results and analyze the data provided by Manitoba Hydro. A more detailed description of the model is available in Appendix 8 – Details on the model. All the data provided by Manitoba Hydro and public sources used in the assessment are available in the appendices.

4. **Impact Assessment –** The impact assessment stage includes assessing the results of the inventory assessment in a broader context. For example, if the project is assessing NO_x and SO_2 emissions the impact assessment would typically provide answers to questions such as: 1. Do the quantities determined in the LCA lead to an increased risk of acidification in the project area? 2. How do the emission rates compare with local, regional, national or international regulations? 3. How do these emissions compare with alternative technologies or processes? In this report the impact assessment portion includes only attempts to answer question 3 with life cycle data for the comparison technologies based on a literature survey. Questions 1 and 2 are not answered in this report, but are addressed in the environmental impact statement being prepared for Keeyask.

5. **Report Writing –** The final stage includes the communication of the above steps in a concise and transparent report. All results, methodologies, assumptions and sources are included in the final report.

This analysis also follows the ISO LCA principles:

1. Life cycle perspective
2. Environmental focus
3. Relative approach and functional unit
4. Iterative approach
5. Transparency
6. Comprehensiveness
7. Priority of scientific approach

1.3 Project Objectives

The primary objectives of this LCA are to:

- Quantify life cycle GHG, NO_x and SO_2 emissions that result from the construction, land use change, operation and decommissioning of Manitoba Hydro's proposed generating station.

[2] Matt McCulloch, Jaisel Vadgama. "Life Cycle Evaluation of Ghg Emissions and Land Change Related to Selected Power Generation Options in Manitoba." 50. Calgary: The Pembina Institute, 2003

- Compare the life cycle GHG, NO_x and SO_2 emissions of the generating station to the six comparison generating technologies.

2. Keeyask Generating Station Description

The proposed generating station will be constructed on the Nelson river approximately 725 km north of Winnipeg (Figure 2).

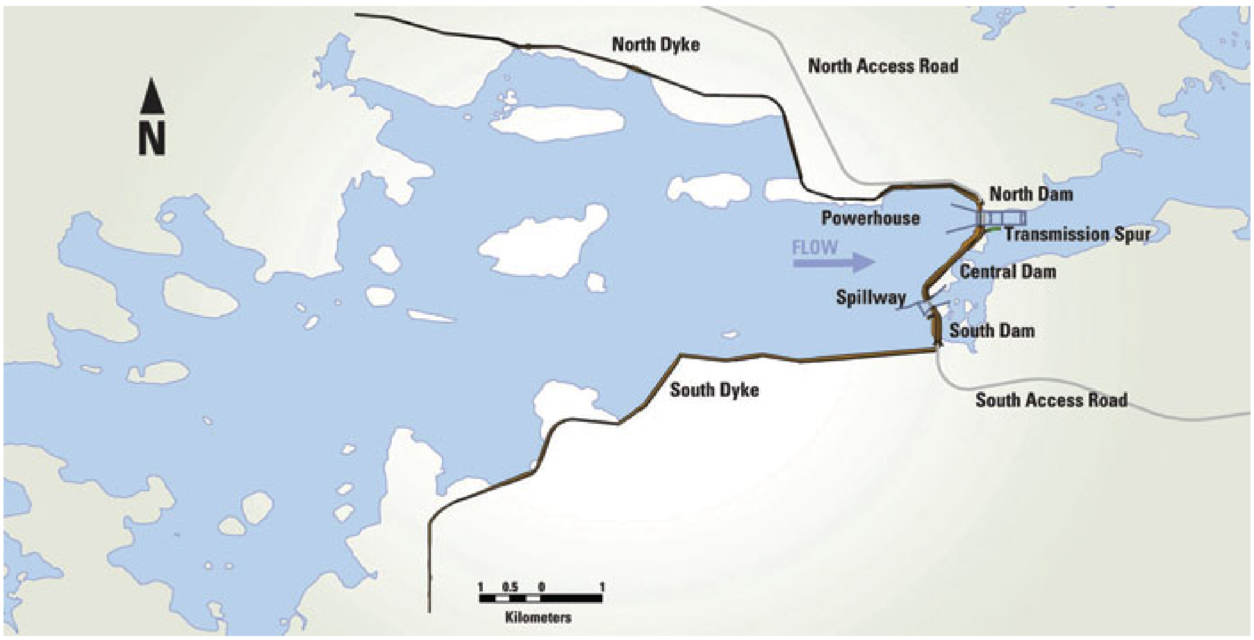

Figure 2: Keeyask Generating Station[3]

[3] Manitoba Hydro, "Keeyask Generating Station," http://www.hydro.mb.ca/projects/keeyask/gif/2.jpg.

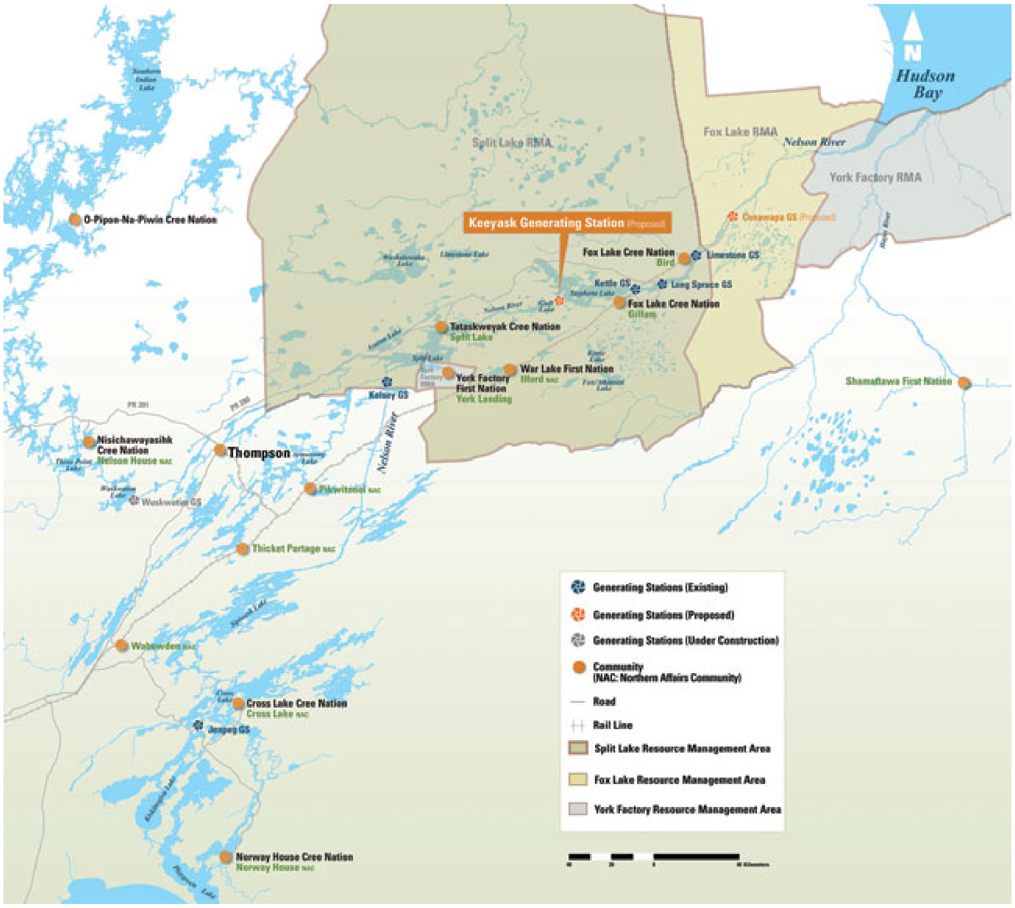

Figure 3: location of the Keeyask generating station[4]

The generating station will be a modified run of river plant that will provide peak and base load electricity depending on the needs of the electrical grid. The generating station will require the construction of a north and south dyke, north and south access roads, transmission lines, powerhouse, spillway, substations and dam systems. Earthen dykes will be used to limit the extent of flooding. The north and south access roads will occupy 373 ha of relatively undisturbed areas. These access roads will be used during the construction phase of the project and will be maintained during the operation phase as well. Transmission lines will connect the generating station to the current transmission network and will disturb 600 ha of primarily previously undisturbed land. The powerhouse will be built of concrete and house seven generators and turbines for a total capacity of 695 MW. The new spillway will be of concrete and will help to control water levels during the construction of the facility and during floods that may occur over the life of the generating station. The dykes will be primarily earthfill dams that transition into concrete structures near the powerhouse and spillway.

The construction of the components discussed above will collectively require 360,000 m^3 of concrete (124,100 tonnes of cement), 64,200 tonnes of steel and 47,800 m^3 of diesel. Concrete will be used as the primary construction material for the powerhouse and spillways. Steel will be used to reinforce the concrete and as a primary component in the mechanical and electrical

[4] Manitoba Hydro, "Keeyask Location Map," http://www.hydro.mb.ca/projects/keeyask/index.shtml.

systems such as turbines and generators. Diesel will be used primarily during the construction phase in construction equipment such as backhoes, trucks, excavators and bulldozers.

The generating station will ultimately create a 100.4 km^2 reservoir which will flood an area of 52.4 km^2.[5]

Although engineering studies are ongoing construction is planned to begin in 2011 with completion in 2019.

[5] Manitoba Hydro. 2008. “Keeyask Project Description.”

3. Description of Comparison Technologies

The six comparison technologies researched for this assessment are pulverized coal combustion, coal with carbon capture and storage, natural gas combined cycle, natural gas single cycle, wind and nuclear. Each of these technologies is described below.

3.1 Pulverized coal combustion (PCC)[6]

In older power plants coal is combusted to produce subcritical steam, but greater efficiencies can be obtained by using higher steam pressures and temperatures in the supercritical range.[7] Both subcritical and supercritical processes begin with grinding the coal into a fine powder. The powdered coal is blown with air into the boiler through a series of burner nozzles where combustion takes place at temperatures from 1,300–1,700°C, depending largely on the coal type. Subcritical pulverized coal combustion (PCC) plants use steam in the range of 16 megapascals (MPa) pressure at 550°C, while supercritical PCC plants use steam with pressures as high as 30 MPa at 600°C. Higher steam temperature and pressures allow for higher achievable energy efficiencies of 38–45%, compared with 33% for subcritical plants. However, supercritical plants have higher capital costs and some added risk due to the higher pressure and temperature. They have only recently come into commercial service in Canada.[8]

The typical size of a coal plant is in the range of 100-1,000 MW. This type of plant generates a reliable supply of electricity, typically used to provide base load power to the grid, with an average capacity factor from 70 to 90%[9]. Coal power plants have limited flexibility to meet peak demand. The majority of electricity produced in Alberta, Saskatchewan and Nova Scotia is from coal plants. Just under a quarter of electricity in Ontario and New Brunswick is from coal, while

[6] Description of technologies adapted from Winfield, Horne, McClenaghan and Peters, “Power for the Future,”Appendix 4, 171–184.

[7] Many fluids have a supercritical temperature and pressure. In power plants operating in the supercritical range leads to increased efficiency because the temperature is higher than in sub-critical plants.

[8] The first such facility in Canada, EPCOR’s Genesee Facility, came into service in 2006.

[9] Renewable Energy Research Laboratory, "Wind Power: Capacity Factor, Intermittency, and what happens when the wind doesn't blow?" University of Massachusetts at Amherst. http://www.ceere.org/rerl/about_wind/RERL_Fact_Sheet_2a_Capacity_Factor.pdf

a very small fraction of coal power exists in Manitoba and Quebec.[10] Coal provided approximately 17% of the electricity generated in Canada[11] and 49% of the electricity produced in the United States[12] in 2006. There are 18 proposed supercritical plants proposed in the United States.[13]

3.2 Coal with Carbon Capture and Storage (CCS)

Carbon capture may become feasible for large point sources of CO_2, such as coal-fired power plants. Carbon capture technology can either be included as part of new facility construction or can be added to current facilities. For current facilities, CO_2 is separated from the rest of the gases by using a commercial capture technology such as chemical or physical absorption. The captured CO_2 can then be compressed and transported in pipelines at high pressure to a storage location within or outside a plant's boundaries. Finally, the CO_2 is pumped underground for storage.

Storage options in Canada include deep saline aquifers, as well as depleted gas, oil and bitumen reservoirs. Another storage option is to inject CO_2 into existing oil and gas reservoirs that are nearing depletion in order to increase oil and gas recovery. This process is commonly known as enhanced oil recovery (EOR).

Capturing and compressing CO_2 requires a large amount of energy and would increase fuel requirements of a coal-fired plant with CCS by 25%-40%, according to the IPCC.[14] There are currently four industrial scale CCS projects in operation worldwide. Two CCS projects are run offshore in the North Sea and Barents Sea by StatoilHydro. Another project in Algeria injects 1.2 million tonnes CO_2 per year from a natural gas reservoir.[15] The final project is the Weyburn CO_2 project where CO_2 from a coal gasification plant in North Dakota is sent by pipeline to southern Saskatchewan and used for EOR.[16]

As mentioned above in Section 3.1, generating electricity in coal plants is reliable and is commonly used to provide baseload power to the grid with limited flexibility to meet peak demand.

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[10] National Energy Board: The Canadian Industry, http://www.neb.gc.ca/clf-nsi/rnrgynfmtn/prcng/lctrct/cndnndstry-eng.html

[11] Environment Canada (2008) National Inventory Report 1990-2006, Annex 9, page 492.

[12] EIA. Department of Energy (2008) Summary Statistics for the US, Table ES1. http://www.eia.doe.gov/cneaf/electricity/epa/epates.html

[13] NETL. "Tracking New Coal-Fired Power Plants." 18: NETL, 2009.

[14] IPCC special report on Carbon Dioxide Capture and Storage. Prepared by working group III of the Intergovernmental Panel on Climate Change. Metz, B., O.Davidson, H. C. de Coninck, M. Loos, and L.A. Meyer (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp

[15] Paul W. Parfomak and Peter Folger, "CRS Report for Congress: Carbon Dioxide (CO2) Pipelines for Carbon Sequestration: Emerging Policy Issues," Updated January 17, 2008

[16] Allan Casey, Carbon Cemetery, Canadian Geographic Magazine, Jan/Feb 2008, p. 61

3.3 Natural Gas Combined Cycle (NGCC)[17]

A natural gas combined cycle (NGCC) plant, so named because it includes both a gas turbine and steam turbine cycle, combusts natural gas in a gas turbine to produce electricity. The turbine produces a significant amount of hot exhaust gas which in a combined cycle power plant is used to generate steam. The steam is then used to produce additional electricity in a steam turbine. The output from both the gas turbine and the steam turbine electrical generators produce electricity more efficiently.

A NGCC plant can have efficiencies up to 60%[18] and can be built in modules to accommodate a range of power demands. This type of electricity plant supplies both base load and peak demands. The average capacity factor for a natural gas power plant is 60%[19].

3.4 Single Cycle Natural Gas

The single cycle process is identical to combined cycle, but excess heat is wasted and not captured for further electricity generation. Single cycle gas turbine plants, without a steam cycle, are sometimes installed as emergency or peaking capacity to help balance electricity production and loads on the electrical grid. The efficiency of a single cycle natural gas plant is 35-40%. Natural gas is a relatively expensive fuel; however, high running cost is offset by the low capital cost and relatively low running hours per year. These plants can be built modularly to satisfy a range of electricity demand. Natural gas power plants, including single and combined cycles generated 5% of electricity in Canada[20] and 22% of electricity in the United States[21] in 2006.

3.5 Wind (>100MW)

Wind farms consist of multiple wind turbines that convert wind energy into electricity from blades turning a generator. Turbines are built to adapt to changing wind conditions. The blades can rotate to face the wind to optimize electricity generation from wind coming from nearly any direction.

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[17] Description of technologies adapted from Winfield, Horne, McClenaghan and Peters, “Power for the Future,”Appendix 4, 171–184.

[18] The General Electric H System combined cycle gas turbine, for example, reaches 60% fuel efficiency. http://www.gepower.com/prod_serv/products/gas_turbines_cc/en/h_system/index.htm

[19] Renewable Energy Research Laboratory, "Wind Power: Capacity Factor, Intermittency, and what happens when the wind doesn't blow?" University of Massachusetts at Amherst. http://www.ceere.org/rerl/about_wind/RERL_Fact_Sheet_2a_Capacity_Factor.pdf

[20] Environment Canada (2008) National Inventory Report 1990-2006, Annex 9, page 492.

[21] EIA. Department of Energy (2008) Summary Statistics for the US, Table ES1. http://www.eia.doe.gov/cneaf/electricity/epa/epates.html

Wind farms contain individual turbines as large as 3 MW. Since wind speeds are not constant the productivity of a turbine is calculated using its capacity factor. Typical wind farms exhibit capacity factors of 20-40%. Since wind power is intermittent, one critique is that it cannot supply reliable base load electricity to the grid. Wind power generated 0.8% of electricity in Canada[22] and 0.6% of electricity in the United States[23] in 2006.

3.6 Nuclear

There are several reactor technologies used in the world, but all of them operate on the same principle. Fission heat is used to generate steam which is subsequently used to generate electricity in a steam turbine. Canadian nuclear power plants use Canadian Deuterium-Uranium (CANDU) reactor technology to generate electricity. In simple terms, this technology uses fission to heat heavy water which is then used to create steam that turns a turbine attached to an electrical generator. The Enhanced CANDU 6 design delivers a gross output of 740 MW per unit. Nuclear power generation is a consistent source of electricity for base load power, but there is almost no flexibility to meet peak demand.

Nuclear power plants have a capacity factor from 60-100%, with the US average of 92% in 2002[24]. Nuclear power generated 17% of electricity in Canada[25] and 19% of electricity in the United States[26] in 2006. A typical nuclear power plant consists of several generating units with an average total size of 1000 MW[27]. CANDU installations range from 200 – 4,120 MW. There are currently five commercial nuclear power generating stations in Canada, all using CANDU reactors: three in Ontario (Pickering – eight reactors, Darlington – four reactors, and Bruce – eight reactors); one in Quebec (Gentilly-2 – one reactor) and one in New Brunswick (Point Lepreau – one reactor).[28]

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[22] Environment Canada (2008) National Inventory Report 1990-2006, Annex 9, page 492.

[23] EIA. Department of Energy (2008) Summary Statistics for the US, Table ES1. http://www.eia.doe.gov/cneaf/electricity/epa/epates.html

[24] Renewable Energy Research Laboratory, "Wind Power: Capacity Factor, Intermittency, and what happens when the wind doesn't blow?" University of Massachusetts at Amherst. http://www.ceere.org/rerl/about_wind/RERL_Fact_Sheet_2a_Capacity_Factor.pdf

[25] Environment Canada (2008) National Inventory Report 1990-2006, Annex 9, page 492.

[26] EIA. Department of Energy (2008) Summary Statistics for the US, Table ES1. http://www.eia.doe.gov/cneaf/electricity/epa/epates.html

[27] Nuclear Energy Institute http://www.nei.org/keyissues/reliableandaffordableenergy/factsheets/nuclearpowerplantcontributions

[28] The Pembina Institute (2006) Nuclear Power in Canada: An Examination of Risks, Impacts and Sustainability. p 61.

4. Methodology

4.1 Basis of Comparison and Comparison Criteria

The Keeyask generating station, as discussed in Section 2 – Keeyask Generating Station Description is compared to common electricity generating technologies based on the life cycle GHG, NO_x and SO_2 emissions produced in delivering one gigawatt hour (GWh) to the electrical distribution network. We chose one GWh of electricity because it provides a common basis of comparison. Most individual electrical facilities will produce tens of thousands of GWh of electricity over their lives. By using one GWh of electricity *delivered* as apposed to one GWh of electricity *produced*, this assessment takes into consideration any losses associated with the transfer of electricity. For example, most thermal electrical plants, such as gas turbines, can be located closer to the actual users of the electricity. Hydro facilities are located at the site of the renewable resource which may be a considerable distance from the consumer. Transmitting electricity from these facilities may result in higher losses than an equivalent thermal facility. The Keeyask facility is expected to last 100 years.

With the functional unit determined, the next question is what comparison criteria to use to evaluate the relative performance of each technology. Manitoba Hydro required that the assessment include at a minimum GHG emissions supplemented by select CACs. Pembina and Manitoba Hydro selected two of the six CACs[29] founded on environmental significance, data availability, relative difference between the technologies and importance to Manitoba Hydro. Based on applying these four criteria, the final metrics include GHG emissions (carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)), nitrogen oxides (NO_x) and sulphur dioxide (SO_2). Table 1 lists the criteria included, the justification for inclusion and environmental significance. Justifications for the exclusion of other CACs are available in Appendix 2 – Scoping - Criteria Selection.

Table 1: List of evaluation criteria, justification and environmental significance

Criterion [Metric/Indicator]	Why	Relevance and Importance of Criteria
Greenhouse gases (GHGs) [tonne CO_2eq]	Environmentally significant (global impact) Very accurate and recent data available Clear differences between technologies	Emissions resulting from human activities are substantially increasing the atmospheric concentrations of several important GHGes, especially carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These are increasing the greenhouse effect, resulting in an overall average warming of the earth's surface.

[29] The six criteria contaminants are nitrogen oxides, sulphur dioxide, carbon monoxide, volatile organic compounds, particulate matter and ammonia.

		Current climate science calls for an aggregate reduction in industrialized countries' emissions to 25-40% below the 1990 level by 2020 and 85-90% below 1990 levels by 2050.[30]
Nitrogen Oxides (NO_x) [kg NO_x]	Environmentally significant (local and regional impact) NO_x emissions are frequently included in publicly available data sources. Clear differences between technologies	Contributes to acid deposition which leads to impacts on soils, lakes, forests, crops and buildings. When present with VOCs, NO_x is also a contributing factor to ground level ozone, which can cause adverse effects on humans, including lowered lung function and the development of chronic respiratory diseases. Ground-level ozone also has significant impact on reducing the productivity of agricultural crops and forests. NO_x has approximately 70% the acidifying potential of SO_2. Acid deposition exceedance models indicate that between 0.04% - 7% of Manitoba's soils are currently receiving acid deposition loads that exceed their buffering capacity.[31]
Sulphur Dioxide (SO_2) [kg SO_2]	Environmentally significant (local and regional impact) SO_2 emissions are frequently included in publicly available data sources. Clear differences between technologies	SO_2 is also a significant contributing factor to acid deposition impacts (see NO_x).

4.2 Boundary Selection

With the selection of the functional unit and comparison criteria, the next question is defining the boundary for the assessment. That is, what activities, such as producing steel or producing concrete, should be included in the assessment? Every activity that uses energy will likely result in GHG, NO_x and SO_2 emissions. Figure 4 displays a simplified life cycle activity map of the activities included in this assessment. A more detailed map available in Appendix 2 – Scoping contains a list of all activities included or excluded.

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[30] *The Case for Deep Reductions: Canada's Role in Preventing Dangerous Climate Change*, An investigation by the David Suzuki Foundation and the Pembina Institute, 2005.

[31] Julian Aherne. "Critical Load and Exceedance Estimates for Upland Forest Soils in Manitoba and Saskatchewan." 16: Trent University, 2008.

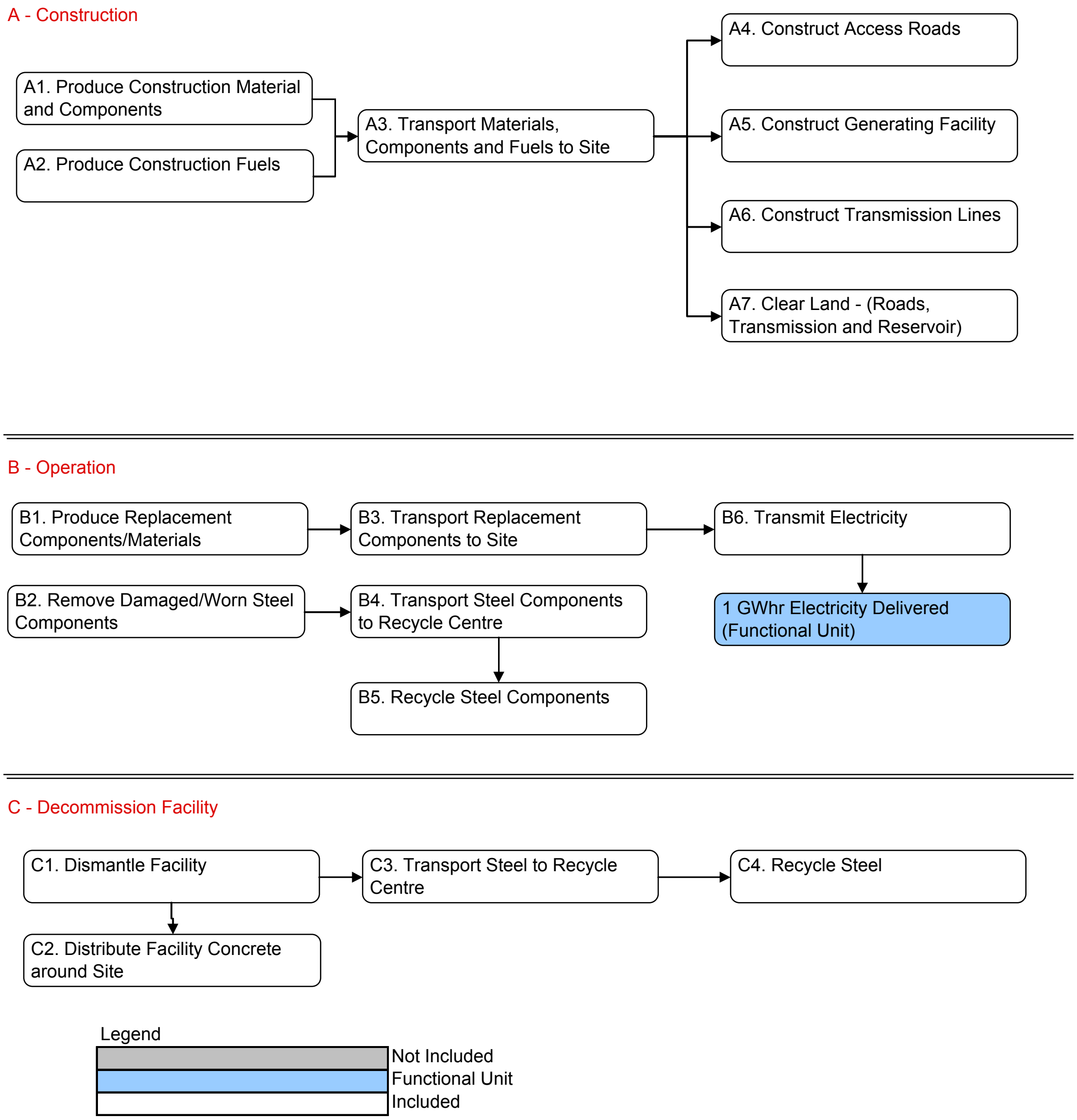

Figure 4: Simplified life cycle activity map

The life of the generating station can be divided into three distinct phases in time: construction, operation and maintenance, and decommissioning including the transmission network.

In addition to which phases to include, we also had to decide what activities to include within each phase. Accounting for and quantifying the life cycle emissions associated with every material required for the construction and operation of the generating station is not practical from a time and cost perspective and would also have a relatively small impact on the overall results. For example, assuming the project requires 100 kg of copper and 20,000 tonnes of steel, is it worth including copper in the assessment? The amount of analysis required to include the copper is the same as including the steel; however, the copper is only 0.0005% of the mass of the steel and will likely have a similarly proportional impact on the results of the analysis.

Pembina used the following principles to determine which activities to include and which to exclude.

1. **Relative mass, energy or volume** – If the activity requires an insignificant amount (mass, volume or energy) of material or fuel relative to the whole then the input is excluded. In this case we qualified significant as >1% of total material mass, volume or energy input to the life cycle. For example, the three main inputs to the system are concrete, steel and diesel fuel. Concrete and steel amount to approximately 1,000,000 tonnes. Any material input less than 1% of this mass was excluded, unless principles 2 or 3 are true.

2. **Environmental impact –** If the material or fuel production is particularly GHG, NO_x or SO_2 intensive then the material or fuel may be included even if it did not satisfy the first principle. Some activities, such as the production of aluminum, are extremely energy intensive, so while the mass used in the production of the generating station may be small the environmental impact may be comparatively large.

3. **Data availability –** Regardless of the two points above, if the data is readily available then the value is included.

A detailed list of the activities included and excluded is available in Appendix 2 – Scoping.

4.3 Key Assumptions and Notable Facility Details

The LCA is based on several important assumptions and notable facility details that influence the results of the analysis. The most significant assumptions and notable details are listed below. A more detailed list of assumptions and justifications is available in Appendix 2 – Scoping.

- **Delivered Electricity:** Electricity generated at the facilities will be transmitted via transmission lines that have losses. Incorporating transmission losses into the LCA will reduce the amount of consumable energy at major load centers and correspondingly increases the GHG, NO_x and SO_2 emission intensity of the project facility. Manitoba Hydro's modeling results show that the Keeyask generating station will add 4,000 GWh annually to the Manitoba grid for use at major load centers.[32]

- **Cement Production and Transportation:** Manitoba Hydro has not contracted cement suppliers at this design stage. This assessment assumes that all cement is produced in Edmonton and then transported to the construction sites by truck.[33] Manitoba Hydro has in the past sourced cement from Edmonton for the construction of hydro facilities.

- **Steel Production and Transportation:** Steel components used in the generating station, including rebar, structural steel and mechanical steel (such as steel in turbines), are sourced from many different locations around the world. For example, the generators and

[32] 4,000 GWhr is not the energy output of the facility but Manitoba Hydro's best estimate of Keeyask's expected impact on the grid in terms of available electricity at load centers (station output less transmission losses).

[33] Manitoba Hydro, personal communication, March 2009

turbines could come from South America, southeast Asia or eastern Europe.[34] To be conservative this assessment assumes all steel used in the generating station is sourced from China and is transported to site by cargo ship, train and truck unless a more specific location is known. For example, Manitoba Hydro expects rebar for the Keeyask project to come from St. Paul, Minnesota. In average global steel production up to 67% of iron in steel comes from recycled sources.[35] The analysis contained in this report assumes 100% virgin material. This assumption ensures the analysis is conservative.

- **Replacement Components:** All the mechanical steel, such as steel in the turbines and generators, is replaced once during the life of the project. However, concrete, rebar and structural steel will not be replaced over the life of the project.
- **Recycling:** This analysis assumes all mechanical steel is replaced, and all steel removed at the end of the project life are recycled. Emissions from steel recycling are included in the assessment. Recycling steel is significantly less energy intensive than producing virgin steel but is still a significant source of emissions over the life cycle of the generating station. Manitoba Hydro is not credited for displacing virgin steel.
- **Land Use Change:** This assessment assumes that land disturbances of more than 100 years (like the reservoir and transmission line corridors) are permanent and may contribute to life cycle GHG emissions. The area of disturbances that are temporary in nature (<100 years), such as clearing for the borrow sources area, are not included in net GHG production calculations. Using the above assumptions, the Keeyask project permanently disturbs 5,920 ha of forested or semi-forested land. The reservoir accounts for the majority of this land disturbance (80%). Road, transmission line and dyke construction will disturb the remaining 20%. Environnement Illimité calculated the GHG emissions for the reservoir and Pembina calculated the GHG emissions associated with land use change for the roads, transmission line and dykes. Both assessments follow the Intergovernmental Panel on Climate Change's (IPCC) guidance document for land use change calculations.[36] The IPCC document provides direction on calculation methodology and also provides generic carbon contents for different forest types. See Appendix 3 – Inventory Assessment - Additional Detail on Land Use Change for more information.
- **Operation Phase:** Emissions during the operational phase are primarily associated with equipment replacement. Pembina's previous LCA report of the Wuskwatim Hydro dam concluded that other operational tasks such as transporting crews to the generating station for site maintenance accounted for <0.01% of onsite emissions.[37]

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[34] Manitoba Hydro, personal communication, March 2009

[35] B.K. Reck Jeremiah Johnson, T. Wang, T.E. Graedel, "The Energy Benefit of Stainless Steel Recycling," *Energy Policy* 36 (2007).

[36] Intergovernmental Panel on Climate Change, "Good Practice Guidance for Land Use, Land-Use Change and Forestry," (International Panel on Climate Change, 2003).

[37] Matt McCulloch, Jaisel Vadgama. "Life Cycle Evaluation of GHG Emissions and Land Change Related to Selected Power Generation Options in Manitoba." 50. Calgary: The Pembina Institute, 2003

4.4 Comparison Technologies

Pembina determined the life cycle emission intensities for the comparison technologies using a different approach than the one used for the generating station. The comparison technology intensities are based on the results of a literature survey of published life cycle values. Pembina first determined the boundaries for each of the technologies using life cycle activity maps. The life cycle activity maps are available in Section Appendix 2 – Scoping. Only published life cycle values that included the majority of the activities in the maps were included in our assessment. Once the literature review was complete, the list of values (a minimum of six for each technology) were analyzed and the median, average, maximum and minimum values determined. All the sources and life cycle values drawn from the sources are available in

Appendix 5 – Details on Literature Survey of Comparison Technologies, and a summary of the results is available in section Comparison with Competing Power Generation Technologies.

4.5 Limitations of Study

Although Pembina has made every effort to develop reasonable assumptions and quantify the life cycle emissions based on accurate and current data, there are several limitations to this assessment. These limitations are discussed below.

- **Steel Production:** Offsite steel production is the most energy-intensive and therefore emission-intensive activity associated with the construction of the hydro generating station. However, the steel components used are produced in many different countries including South East Asia, Eastern Europe, South America and North America. At the time of this study, Manitoba Hydro had not yet contracted specific companies to provide steel equipment that will be needed in the construction of the generating station. However, although Pembina assumes steel is produced in China there are no readily accessible steel emission factors for China. Pembina has therefore opted to use a generic North American steel emissions factor based on typical steel production and forging including mining, transportation, processing and steel production. Although this emission factor is likely representative of emissions from steel facilities it may be different than the actual emissions from the facilities used to produce the final components.

- **Replacement Components:** Manitoba Hydro's consultants provided Pembina with best estimates of likely material replacement requirements over the life of the project. However, estimating replacement components is difficult. The actual components replaced over the life of the project will depend on many different factors. Pembina performed a sensitivity analyses to address the potential impact on life cycle results from the variability in the quantity of materials replaced.

- **Transportation Distances:** Manitoba Hydro provided some direction as to the distances that materials will be transported to site. However, the final sources of many materials, such as steel discussed above, are unknown. In place of actual data this assessment uses plausible, conservative transport distances based on previous Manitoba Hydro experience. A list of all transport distances is available in Appendix 2 – Scoping.

- **Stage of Development:** All materials and fuel requirements are calculated from best estimates provided by Manitoba Hydro based on the most recent design documents. The actual construction of the generating station may require different quantities and types of materials.

- **Comparison Data:** The life cycle data for the comparison technologies is based on a literature survey. The data are therefore not specific to Manitoba, or in some cases North America. Although, the number of sources reviewed and the range of values found make it likely that any comparison technology constructed in Manitoba or its export client provinces or states will fit within the minimum or maximum values. However, the difference between the maximum and minimum values is in some cases quite significant. For example, published life cycle SO_2 emissions for a coal fired power plant ranged from 114 kg/GWhr to 12,271 kg/GWhr. The actual emission intensities will depend on a number of different factors such as the type of coal, pollution control technologies and equipment efficiencies.

5. Results and Discussion

5.1 Introduction

The results section is split into two sections. The first section presents and discusses the results of the generating station quantitative LCA. The second section compares the results of the quantitative life cycle assessment with the six comparison technologies.

The quantitative LCA results are disaggregated into construction emissions (material production, transportation and construction of the generating station, substations and transmission lines), land use change (emissions from the reservoir flooding and from land clearing for other permanent features), maintenance of the generating station (primarily the replacements of components over the projects life), operations (fuel use for electricity generation) and decommissioning of the generating station after 100 years of operation. More detailed results are presented in Appendix 3 – Inventory Assessment.

The comparison technology life cycle data are based on a literature survey of over 15 published life cycle journal articles. Some of the journal articles are themselves literature surveys. The results below are therefore based on the median of many life cycle assessments. Details of the sources and life cycle values used are available in Appendix 3 – Inventory Assessment.

5.2 Keeyask Life Cycle Results

Table 2 summarizes the greenhouse gas (GHG), nitrogen oxides (NO_x) and sulphur dioxide (SO_2) emissions per project phase. The construction phase includes all emissions on and off the project site that occur while the facility is being constructed. The operation phase includes all emissions from the first day of operation to when the facility is decommissioned. Decommissioning includes only emissions associated decommissioning the facility and recycling available materials. Land use change emissions are broken out separately and include emissions that occur during the construction phase, land clearing, and emissions during the operation phase, decomposition.

Table 2: Summary of emission sources for the Keeyask generating station

Air Emission	Units	Construction			Land Use Change	Operation	Decommissioning	**Total**
		Building Material Manufacture	Transportation	On-Site Construction Activities	Clearing for Roads, Transmission and Reservoir	Maintenance and Refurbishment	Decommissioning Activities	
Greenhouse Gas	tCO_2eq/GWh	0.68	0.12	0.34	1.24	0.03	0.05	**2.46 ($tCO2_{eq}$/GWh)**
Nitrogen Oxides	$kgNO_x$/GWh	1.51	1.31	7.04	0.00	0.09	0.57	**10.52 ($kgNO_x$/GWh)**
Sulphur Dioxide	$kgSO_2$/GWh	0.86	0.26	0.45	0.00	0.02	0.06	**1.66 ($kgSO_2$/GWh)**

GHG emissions are primarily associated with the construction and land use change, which produce 97% of life cycle GHG emissions. Of the construction phase 60% of the emissions result from building material manufacture. For example, steel production, including mining and processing, alone is responsible for 20% of life cycle GHG emissions. GHG emissions from the transportation of the materials and components to site are relatively high contributors to the construction phase emissions. The lengthy transportation distances (>10,000 km for most steel components) and the significant quantity of steel required (>60,000 tonnes) is responsible for the uncharacteristically high life cycle transport emissions. In comparison Pembina's previous LCA report assumed transport distances of only 2,700 km[38]. Emissions from onsite construction activities result from diesel combustion in construction equipment including trucks, backhoes, excavators and bulldozers. Land use change emissions account for 50% of all GHG emissions. The majority of land use change emissions are associated with the reservoir (95%). The remaining 5% result from land cleared for road ways, transmission lines and the dykes. GHG emissions during the operation phase of the project are primarily associated with offsite activities such as the production of replacement equipment, recycling of the damaged or worn steel components. This assessment assumes that over the life of the project 10% mechanical steel will be replaced.

The majority of the GHG emissions associated with decommissioning result from recycling of steel components and onsite diesel combustion in demolition equipment.

As noted in the discussion after Table 2, Figure 5 shows that 46% of life cycle GHG emissions are associated with the construction phase (blue wedges) of the project (5% from transportation, 13% from onsite construction activities and 28% from building material manufacture). GHG emissions from land use change, including reservoir and clearing land for roads and transmission lines accounts for an additional 50% of emissions. Operation phase emissions, primarily steel recycling and replacement material manufacturing, accounts for 1% of life cycle GHG emissions. The remainder, 2%, is a result of decommissioning activities including steel recycling and diesel combustion in demolition equipment.

Figure 5 presents the results in Table 2 disaggregated by phase.

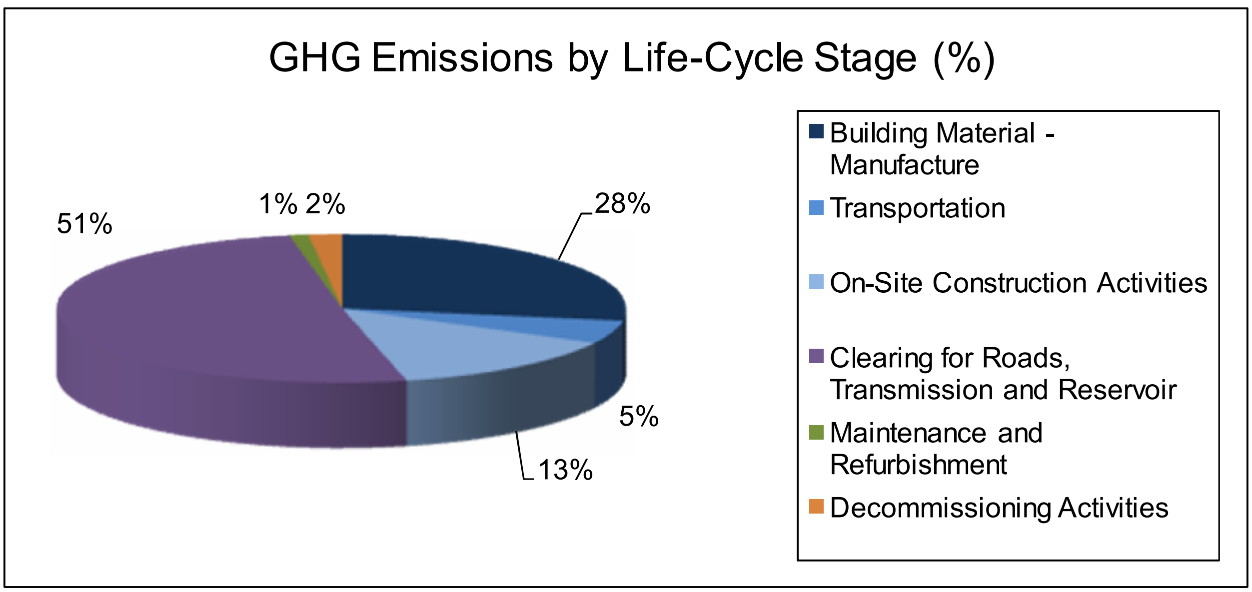

Figure 5: Breakdown of GHG emissions per primary activity

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[38] Matt McCulloch, Jaisel Vadgama. "Life Cycle Evaluation of GHG Emissions and Land Change Related to Selected Power Generation Options in Manitoba." 50. Calgary: The Pembina Institute, 2003.

In general, the NO_x and SO_2 emissions follow the GHG emission breakdown. However there are some important exceptions. In comparison with GHG emissions, NO_x emissions are relatively higher for transportation and construction activities. Onsite construction activities during the construction phase represent 67% of life cycle NO_x emissions but only 17% of life cycle GHG emissions. SO_2 emissions are associated with cement production to a greater degree than GHG and NO_x emissions are. Cement production accounts for 30% of SO_2 emissions whereas they account for only 8% of GHG and NO_x emissions.

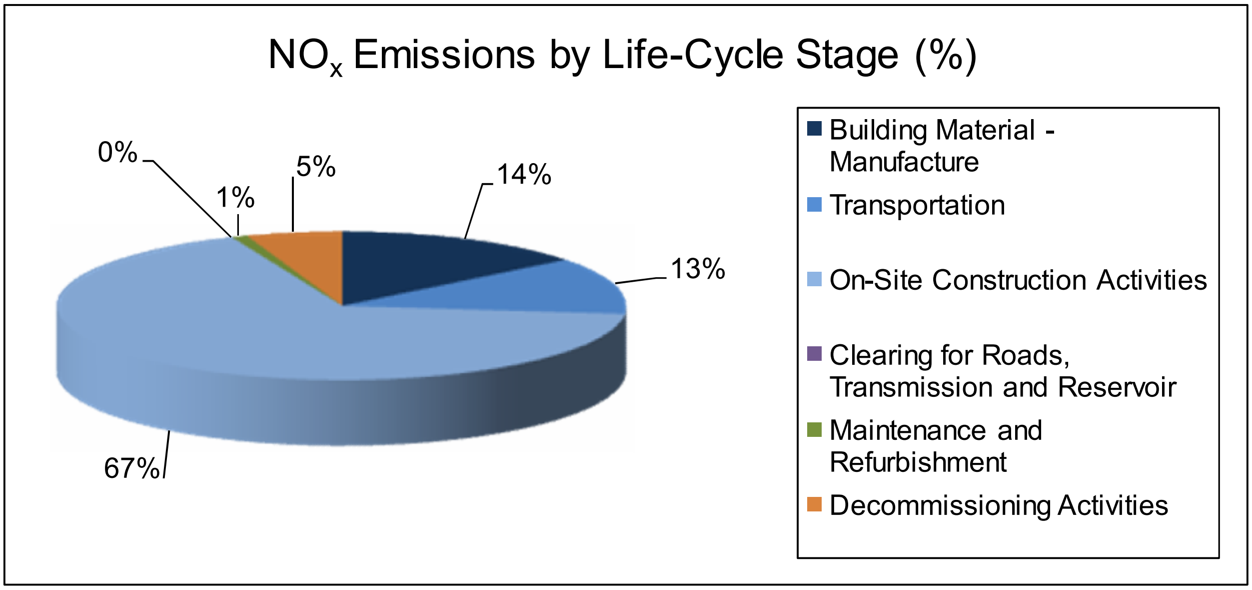


Figure 6: Breakdown of NO_x emissions per primary activity

In comparison to the distribution of GHG emissions over the life cycle of the project, life cycle NO_x emissions are more heavily associated with onsite construction activities (67%) and transportation of materials to site and building material manufacture (13% and 14% respectively) of life cycle NO_x emissions. These three activities account for 94% of NO_x emissions but only 46% of life cycle GHG emissions. Decommissioning and operational activities are comparatively similar sources of NO_x emissions.

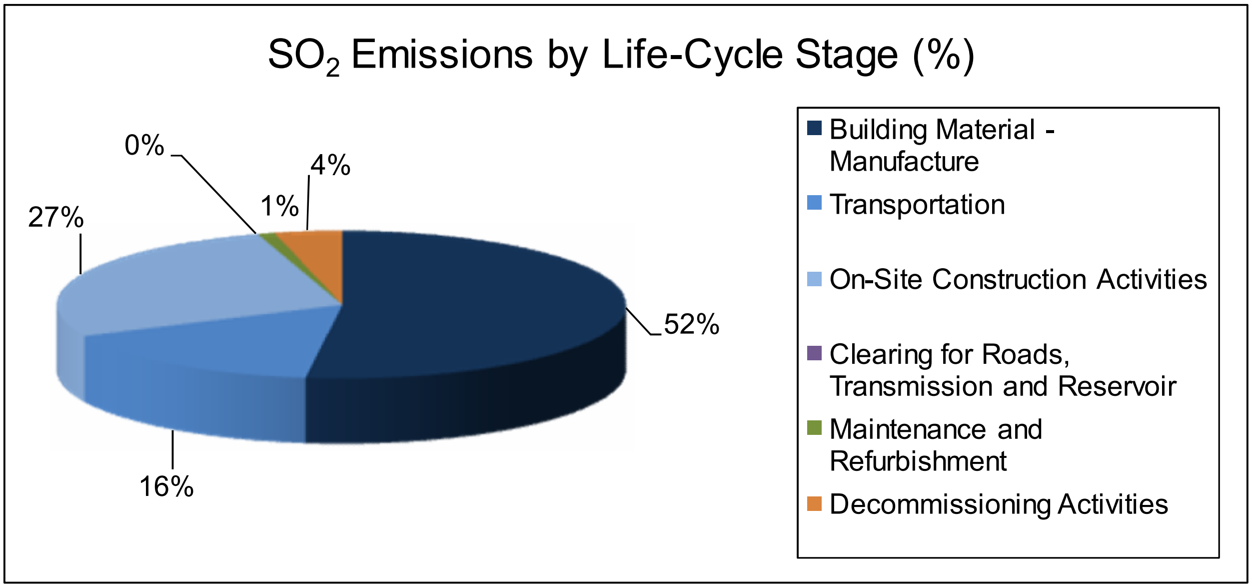


Figure 7: Breakdown of SO_2 emissions per primary activity

SO_2 emissions are primarily associated with building material manufacture during the construction phase of the generating station (52% of life-cycle emissions). Another 43% of emissions are associated with onsite construction and transportation. Operation and decommissioning activities are relatively similar to GHG and NO_x emissions in their contribution to life cycle emissions.

5.3 Comparison with Competing Power Generation Technologies

A comparison of the life cycle results for the alternative power generating technologies and the generating station are discussed below. The generating station is first compared with life cycle GHG and then NO_x and SO_2 emissions. Table 3 contains the median values for each of the comparison technologies and the life cycle results for the generating station.

Table 3: Life cycle CO_2e emissions comparison

Technology	Life Cycle GHG Emission Intensity ($t\ CO_2e/GWh$)
Pulverized Coal Combustion (PCC)	975
Natural Gas Single Cycle	766
Natural Gas Combined Cycle (NGCC)	509
Coal with Carbon Capture and Storage (CCS)	183
Nuclear	15
Wind	13
Keeyask	2.46

Figure 8 presents the above results graphically.

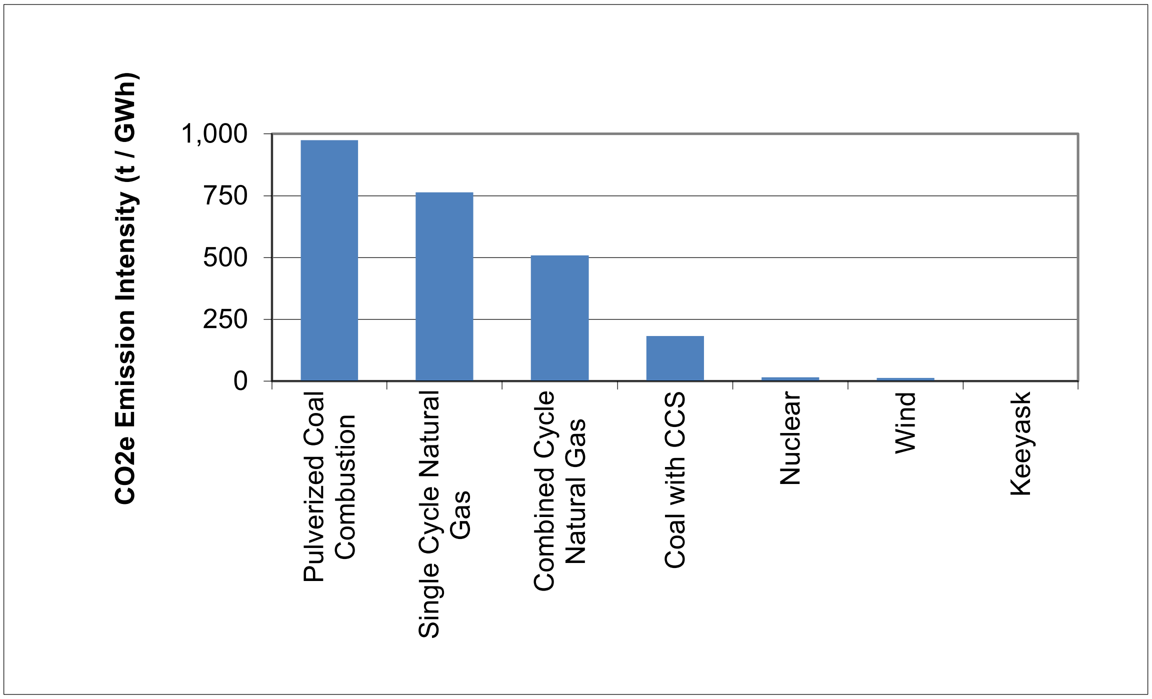


Figure 8: Life cycle GHG emissions comparison

As both Table 3 and Figure 8 demonstrate life cycle GHG emissions on a per GWh basis are significantly lower for the Keeyask case than for all of the fossil fuel alternatives, PCC, NGCC, natural gas single cycle and CCS. In addition the generating station is lower than the two non-fossil fuel options, nuclear and wind.

Table 4 and Figure 9 display the results for life cycle NO_x emission intensity of the generating station and the alternative technologies.

Table 4: Life cycle NO_x emissions comparison

Technology	Life Cycle NO_x Emission Intensity (kg / GWh)
Pulverized Coal Combustion (PCC)	1,206
Natural Gas Single Cycle	735
Natural Gas Combined Cycle (NGCC)	373
Coal with Carbon Capture and Storage (CCS)	147
Nuclear	17
Wind	15

Keeyask	10.5

Figure 9 presents the results above graphically.

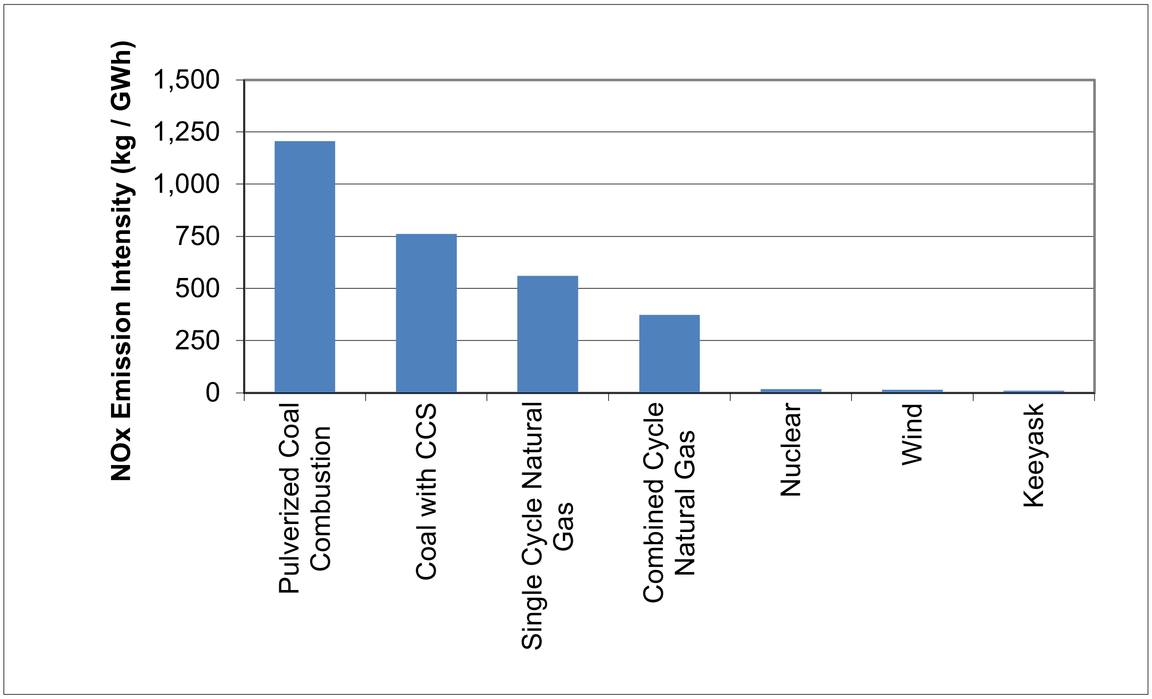


Figure 9: Life cycle NO_x emissions comparison

Generally the order from highest to lowest emission intensity is the same for GHG emissions and NO_x emissions. Single cycle natural gas facilities have higher life cycle NO_x intensities than NGCC facilities. Single cycle plants are less efficient than combined cycle plants so combust more natural gas, creating an equivalent increase in NO_x, per GWh of electricity produced. Nuclear, wind and the generating stations all have similar life cycle NO_x intensities.

It is also worth noting that most NO_x emissions for the fossil fuel technologies will occur at the facility, whereas NO_x emissions for the nuclear, wind and the generation station will be dispersed. Unlike GHG emissions, NO_x emissions are of regional concern.

Table 5 and Figure 10 display the results for the life cycle SO_2 emission intensities of the alternative technologies and the generating station.

Table 5: Life cycle SO_2 emissions comparison

Technology	Life Cycle SO_2 Emission Intensity (kg / GWh)
Pulverized Coal Combustion (PCC)	834
Natural Gas Single Cycle	149

Natural Gas Combined Cycle (NGCC)	128
Coal with Carbon Capture and Storage (CCS)	59
Nuclear	24
Wind	17
Keeyask	1.7

Figure 10 presents the results above graphically.

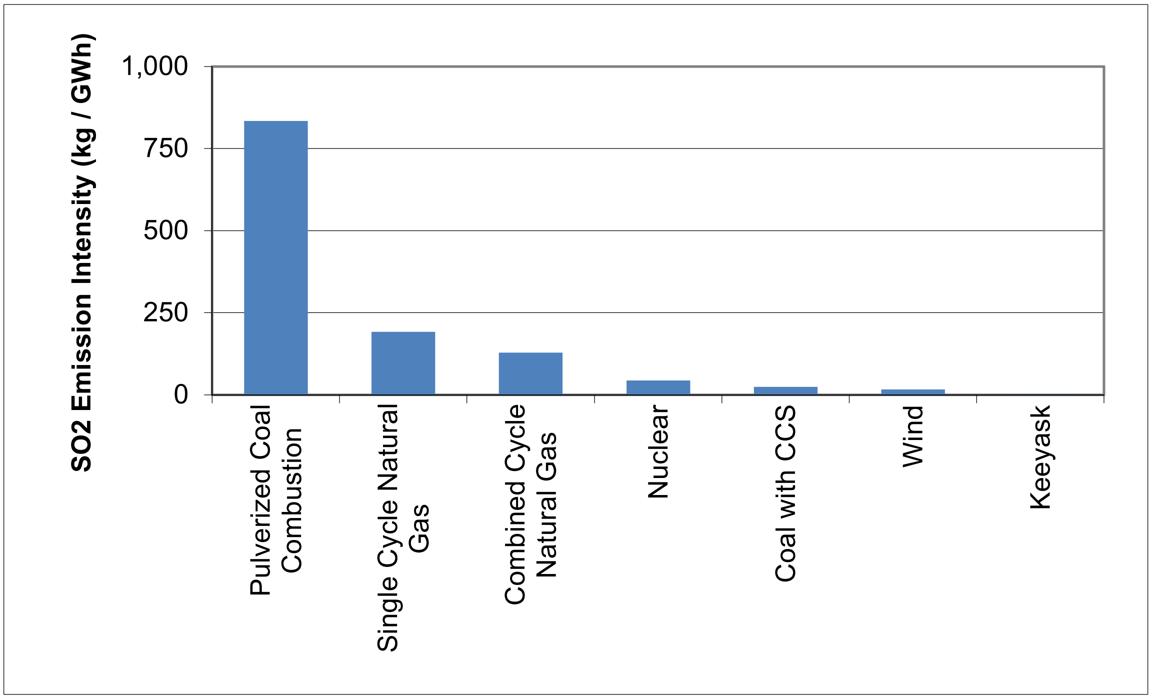


Figure 10: Life cycle SO_2 emissions comparison

As Figure 10 shows PCC facilities have much higher life cycle SO_2 intensities than all the alternative technologies. Single cycle SO_2 intensities are the next highest followed by NGCC and nuclear facilities. Coal with CCS is relatively low, which seems to contradict the NO_x results. To sequester CO_2 the CO_2 stream must be relatively pure. Contaminants such as sulphur must be removed, so any coal facility considering CO_2 capture would first have to install efficient sulphur removal equipment.

It is also worth noting that like NO_x emissions most SO_2 emissions for the fossil fuel technologies will occur at the facility, whereas SO_2 emissions for the nuclear, wind and the generation station will be dispersed.

In summary, fossil fueled power generating technologies will have higher GHG, NO_x and SO_2 emission intensities than nuclear, wind or the generating station. The generating station's life cycle emission intensity results are closest to, but still lower than, wind and nuclear and are significantly lower than any of the fossil fuel alternative

6. Sensitivity Analysis

Sensitivity analysis is used to determine the relative impact that changing important assumptions will have on the results of a study. This LCA analysis is based on a large list of assumptions. For example, the majority of the steel used in the facility is assumed to come from China. However, emission factors for Chinese steel forges are not readily available. Emissions from steel production are estimated from North American steel emission factors. The sensitivity analysis allows us to test the impact on the final results if actual emissions from the production of steel were higher. Pembina completed four sensitivities which are summarized below.

1. **Transportation Distances** – All steel used in the manufacturing of the generating station is assumed to come from China. However, it is possible that some steel will come from North American sources. This sensitivity assumes all steel is produced in North America, significantly reducing steel transportation emissions. This sensitivity reduces life cycle emission intensity.
2. **Steel Emission Factor** – The emission factor used in this assessment is for North American steel production. However, steel is assumed to come from China. The emission intensity of Chinese steel production is likely higher than North American steel production. This sensitivity determines the impact on the results of assuming steel production emissions are 30% higher. This sensitivity increases life cycle emission intensity.
3. **Concrete Emissions Factor** – Emissions from cement production are important contributors to total life cycle emissions. However, our analysis uses a generic concrete emissions factor for the average emissions intensity of producing cement in the United States. Individual cement production facilities may have higher or lower emissions. This sensitivity assumes emissions from cement production are 30% higher. This sensitivity increases life cycle emission intensity.
4. **Fuel Source**: The construction of the generating station will require significant amounts of diesel fuel. Diesel is refined from crude oil which can come from many sources. The base case uses the average volume of crude oils produced in Alberta to estimate the emissions associated with overall crude production for the diesel used in the project. However, crude oil derived from tar sands is replacing conventional crude oil sources. This sensitivity assumes all crude used to produce diesel comes from crude oil sources. This sensitivity increases life cycle emission intensity.

Detailed results for each of the sensitivities described above are available in Figure 8. In general, the sensitivities showed very little impact on the life cycle results. However, there were significant impacts on the construction phase, and specifically the building material manufacture sub-component. For example applying the three sensitivities that tend to increase life cycle intensities, sensitivities 2, 3 and 4, increased building material manufacture materials by ~30% for all indicators. Never-the-less even increases of this magnitude in the manufacture of building materials did not change over all life cycle results significantly in comparison with other generating technologies. Figure 11 displays the comparison graph with sensitivities 2, 3 and 4 included. The change in results is almost imperceptible in comparison with the results displayed in Figure 8.

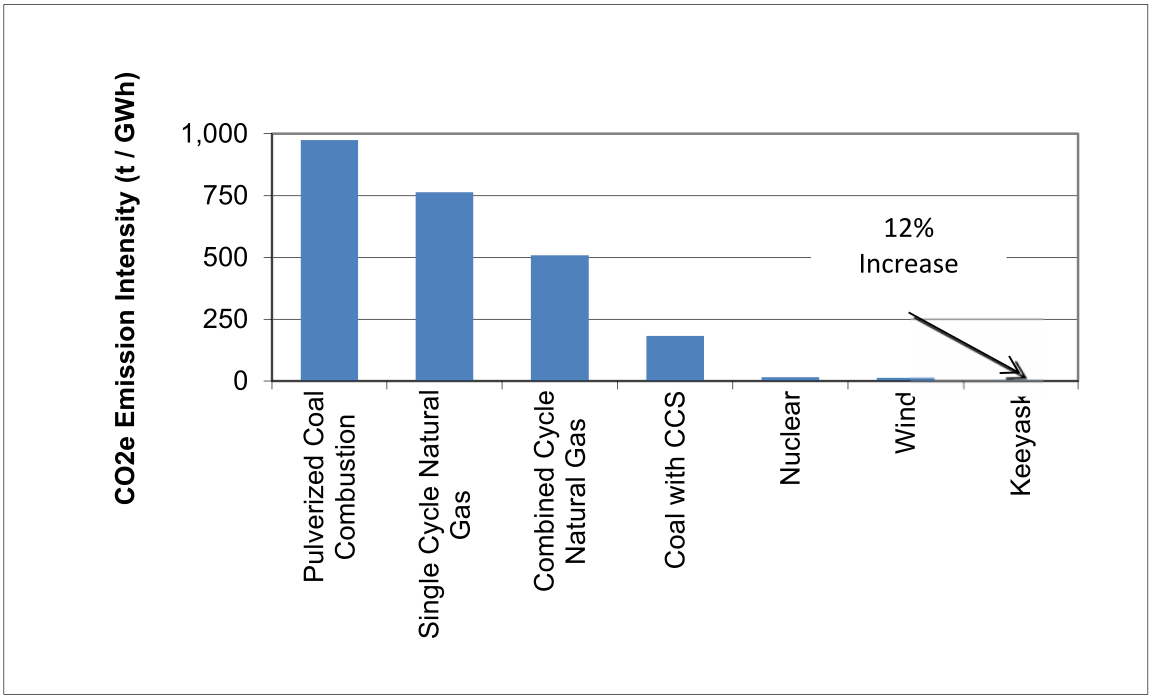


Figure 11: Comparison life cycle graph with sensitivities 2, 3 and 4

7. Conclusions

The primary conclusions of this LCA based on the parameters quantified are listed below:

- The life cycle activities contribute varying amounts of each criteria emission (GHG, NO_x and SO_2).
- The majority of life cycle GHG, NO_x and SO_2 emissions occur during the construction phase of the project.
- GHG emissions are primarily associated with the construction phase (46%) and more specifically the production of materials used in the construction of the generating station (60% of the 46%). Land use change emissions are also significant (50% of life cycle emissions). Operational and decommissioning phase emissions are less significant, contributing 1% and 2% of emissions respectively.
- NO_x emissions result primarily from transportation and construction activities within the construction phase. The life cycle NO_x emissions therefore occur in even greater quantities during the construction phase of the project (94% of life cycle emissions) in comparison with GHG emissions (46%).
- Land use change emissions are primarily associated with the reservoir and to a smaller extent land cleared for permanent disturbances (access roads, transmission lines and dykes).
- Life cycle GHG emission intensities from the generating station are far lower than fossil fuel technologies and are also lower than nuclear and wind generating technologies.
- The generating stations life cycle NO_x emission intensity is similar to wind and nuclear electricity generating technologies but far lower than the fossil fuel alternatives.
- The generation stations life cycle SO_2 emission intensity is lower than all other technologies but is closest to nuclear and wind.
- The majority of GHG, NO_x and SO_2 emissions associated with the generating station, wind and nuclear will not occur at the facility, whereas the majority of these emissions will occur at the plant site for the fossil fuel technologies.

8. Appendices

8.1 Appendix 1 – Goal Definition

8.1.1 What are the comparison options

Table 6 contains a list of the technologies that were considered in for the assessment and why they were included or excluded.

Table 6: List of possible comparison technologies and explanation of why they are included or excluded

Technology Type	Reason for inclusion/exclusion
Pulverized Coal Combustion	Manitoba Hydro exports a significant portion of its power to the Midwest United States. Power generation in this area includes coal, natural gas single and combined cycles, wind and nuclear. All of these electricity generating technologies are included in the assessment because they are likely alternatives to hydroelectric power generation.
Coal with Carbon Capture and Storage	Carbon capture and storage is not currently a common part of electricity generation. However, it is being considered for new coal power plants, or to retrofit current facilities. It is therefore included as a comparison technology.
Natural Gas Combined Cycle (NGCC)	Manitoba Hydro exports a significant portion of its power to the Midwest United States. Power generation in this area includes coal, natural gas single and combined cycles, wind and nuclear. All of these electricity generating technologies are included in the assessment because they are likely alternatives to hydroelectric power generation.

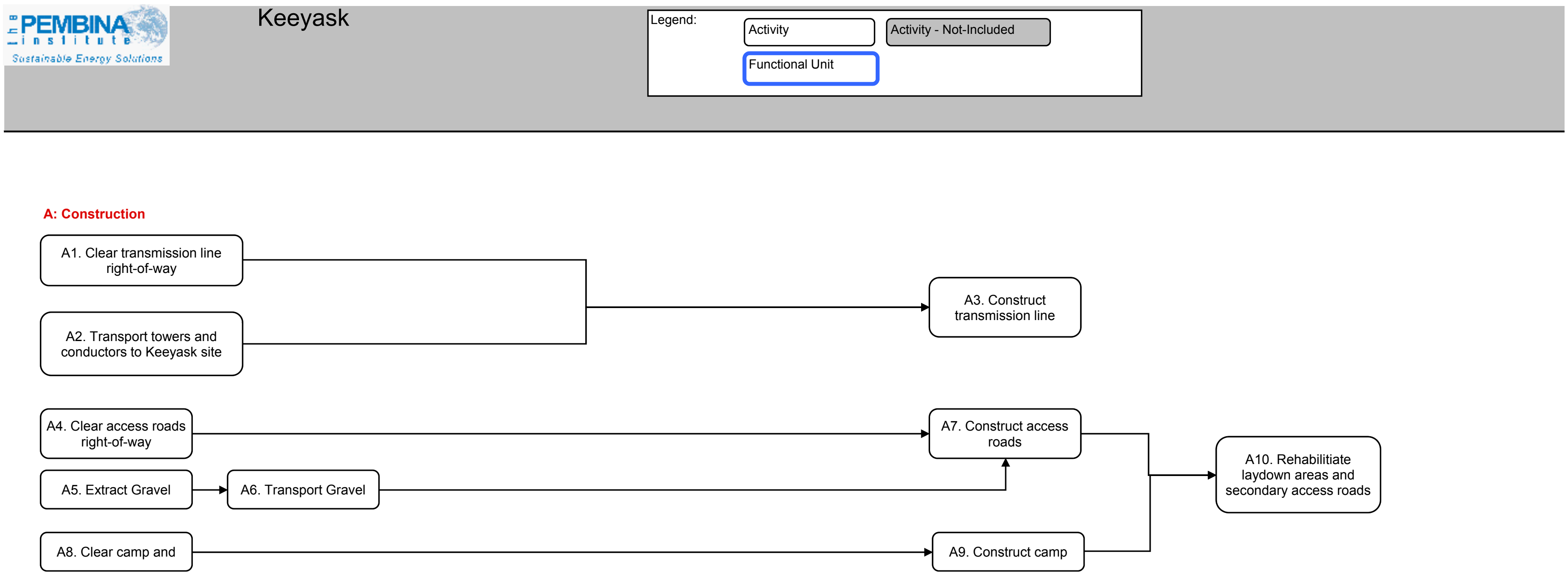
Natural Gas Single Cycle	Manitoba Hydro exports a significant portion of its power to the Midwest United States. Power generation in this area includes coal, natural gas single and combined cycles, wind and nuclear. All of these electricity generating technologies are included in the assessment because they are likely alternatives to hydroelectric power generation.
Wind	Manitoba Hydro exports a significant portion of its power to the Midwest United States. Power generation in this area includes coal, natural gas single and combined cycles, wind and nuclear. All of these electricity generating technologies are included in the assessment because they are likely alternatives to hydroelectric power generation.
Nuclear	Manitoba Hydro exports a significant portion of its power to the Midwest United States. Power generation in this area includes coal, natural gas single and combined cycles, wind and nuclear. All of these electricity generating technologies are included in the assessment because they are likely alternatives to hydroelectric power generation.
Solar	Solar, whether photovoltaic or thermal, is a promising technology for renewable electricity generation.
Demand Side Management	Manitoba Hydro recognizes that demand side management is amongst the best resource options for electricity . However, demand side management is the combination of numerous activities like installing more efficient furnaces and behaviour change. Finding data for all of these activities would not be practical given the scope of the project. Demand side management is therefore not included.

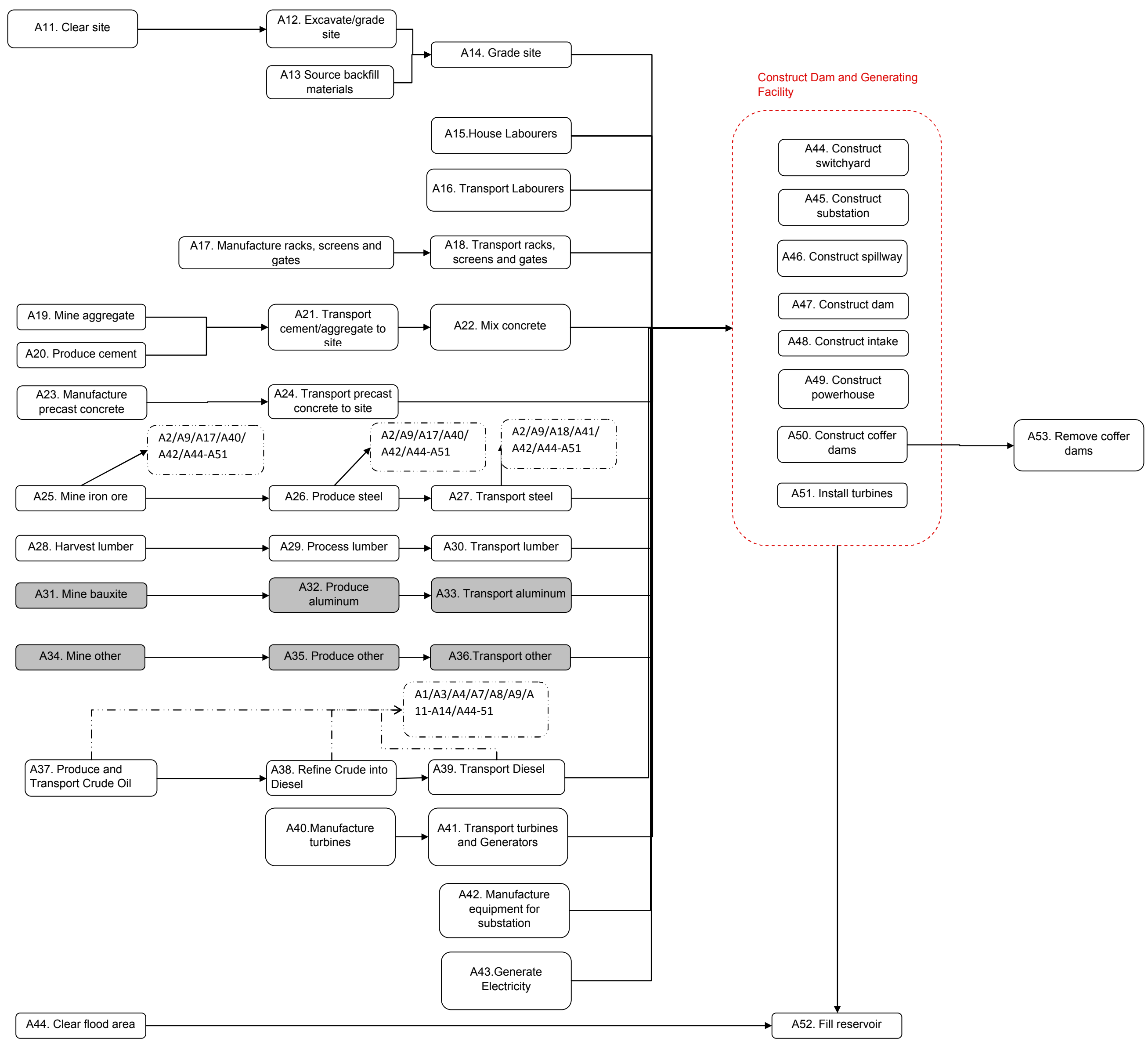
8.2 Appendix 2 – Scoping

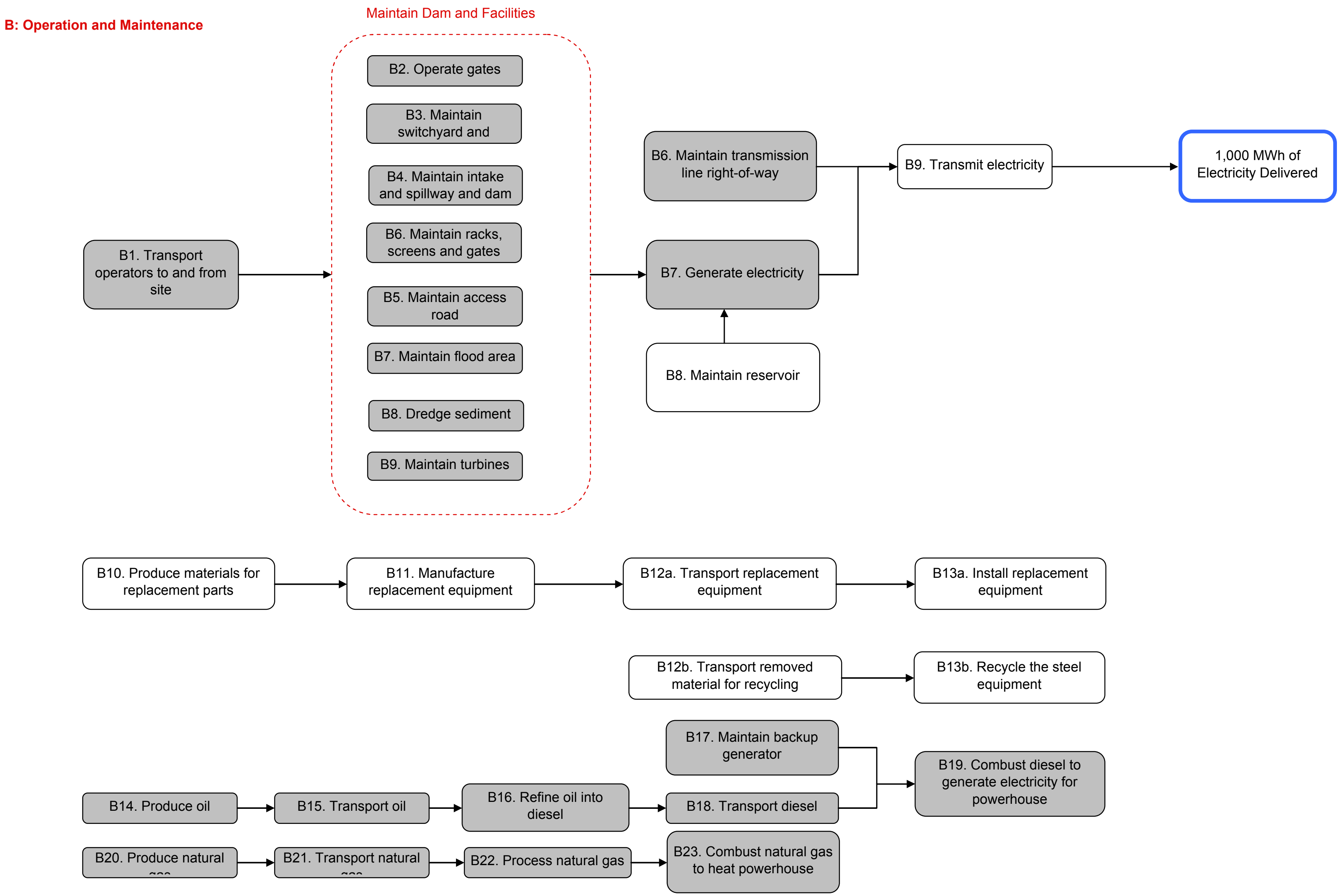
8.2.1 System Activity Maps

8.2.1.1 Keeyask Complete Activity Map

The activity map below lists all the activities that make up the construction, operation and decommissioning of the Keeyask generating station. This map includes the activities (in grey) that are not included in this assessment (see Section 4.2 – Boundary Selection). Activities in clear boxes are included in the assessment. The map is followed by descriptions of the activities and key assumptions related to each specific activity.




A11. Clear site
A12. Excavate/grade site
A13 Source backfill materials
A14. Grade site
A15.House Labourers
A16. Transport Labourers
A17. Manufacture racks, screens and gates
A18. Transport racks, screens and gates
A19. Mine aggregate
A20. Produce cement
A21. Transport cement/aggregate to site
A22. Mix concrete
A23. Manufacture precast concrete
A24. Transport precast concrete to site
A2/A9/A17/A40/ A42/A44-A51
A2/A9/A17/A40/ A42/A44-A51
A2/A9/A18/A41/ A42/A44-A51
A25. Mine iron ore
A26. Produce steel
A27. Transport steel
A28. Harvest lumber
A29. Process lumber
A30. Transport lumber
A31. Mine bauxite
A32. Produce aluminum
A33. Transport aluminum
A34. Mine other
A35. Produce other
A36.Transport other
A1/A3/A4/A7/A8/A9/A 11-A14/A44-51
A37. Produce and Transport Crude Oil
A38. Refine Crude into Diesel
A39. Transport Diesel
A40.Manufacture turbines
A41. Transport turbines and Generators
A42. Manufacture equipment for substation
A43.Generate Electricity
A44. Clear flood area
Construct Dam and Generating Facility
A44. Construct switchyard
A45. Construct substation
A46. Construct spillway
A47. Construct dam
A48. Construct intake
A49. Construct powerhouse
A50. Construct coffer dams
A51. Install turbines
A53. Remove coffer dams
A52. Fill reservoir


B: Operation and Maintenance
Maintain Dam and Facilities
B2. Operate gates
B3. Maintain switchyard and
B4. Maintain intake and spillway and dam
B6. Maintain racks, screens and gates
B5. Maintain access road
B7. Maintain flood area
B8. Dredge sediment
B9. Maintain turbines
B1. Transport operators to and from site
B6. Maintain transmission line right-of-way
B7. Generate electricity
B8. Maintain reservoir
B9. Transmit electricity
1,000 MWh of Electricity Delivered
B10. Produce materials for replacement parts
B11. Manufacture replacement equipment
B12a. Transport replacement equipment
B13a. Install replacement equipment
B12b. Transport removed material for recycling
B13b. Recycle the steel equipment
B17. Maintain backup generator
B19. Combust diesel to generate electricity for powerhouse
B14. Produce oil
B15. Transport oil
B16. Refine oil into diesel
B18. Transport diesel
B20. Produce natural
B21. Transport natural
B22. Process natural gas
B23. Combust natural gas to heat powerhouse

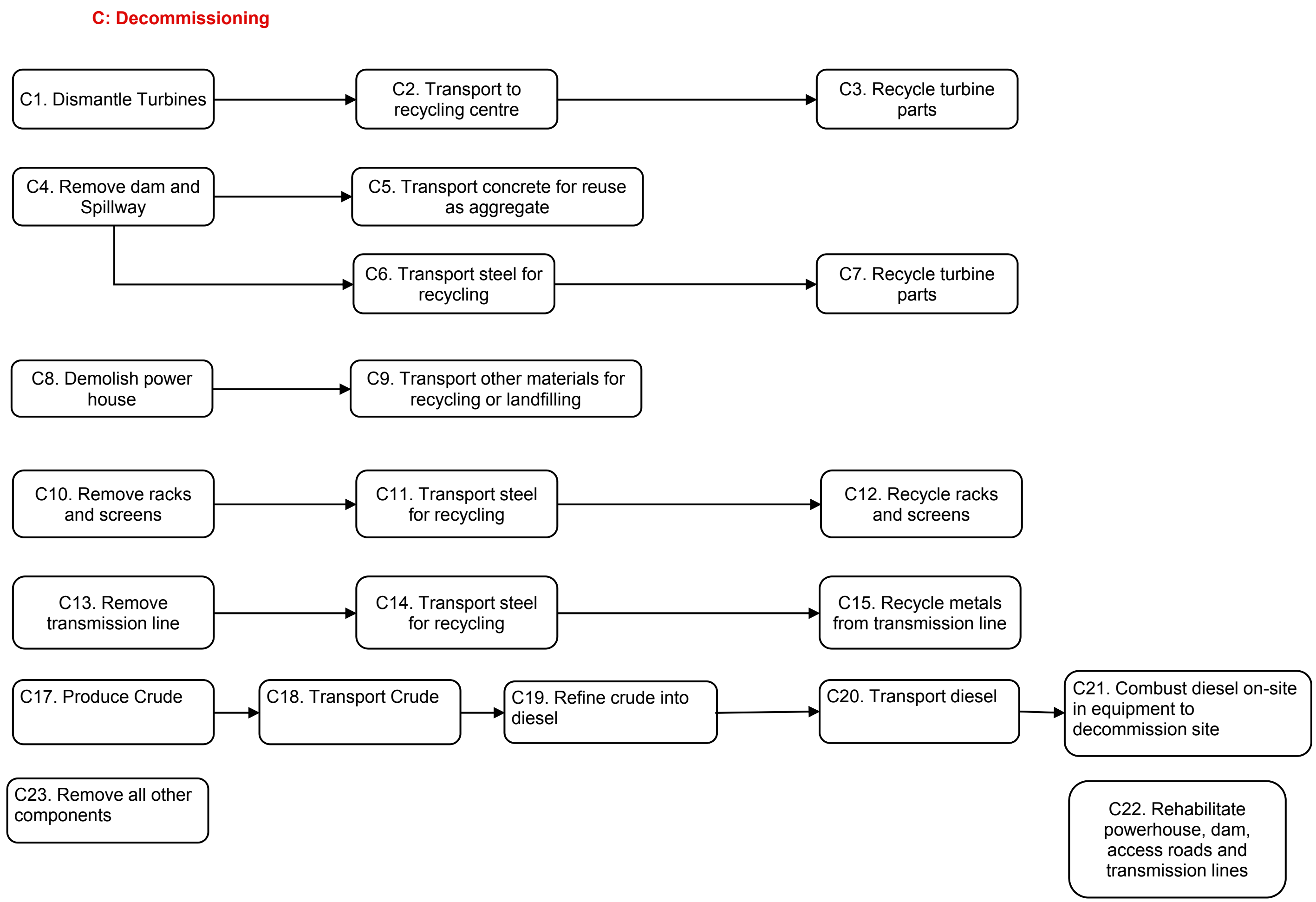


Figure 12: Life cycle activity maps for the Keeyask generating station

8.2.1.2 Comparison Technology Activity Maps

Figure 13 to Figure 18 display activity maps for each of the comparison technologies. Activities highlighted in grey were not included in the assessment.

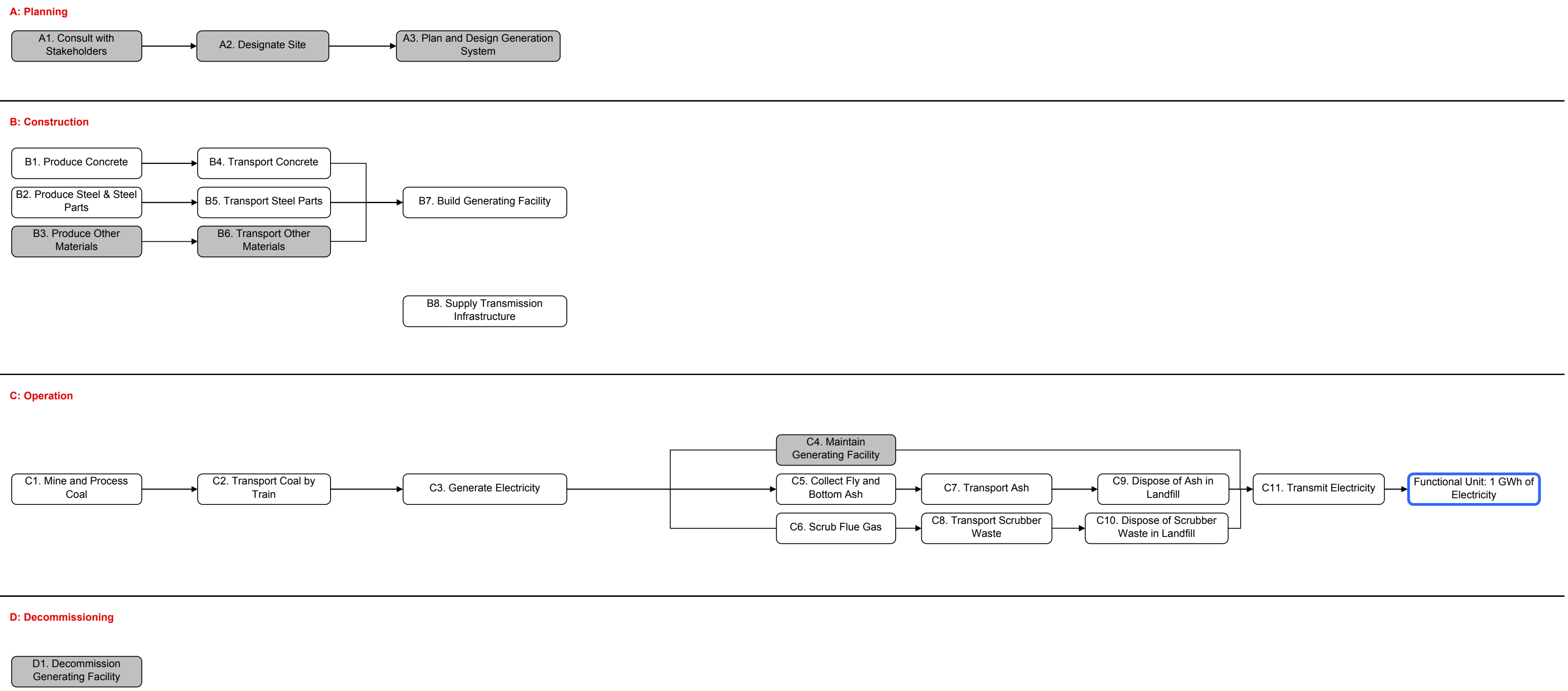


Figure 13: Pulverized coal combustion life cycle activity map

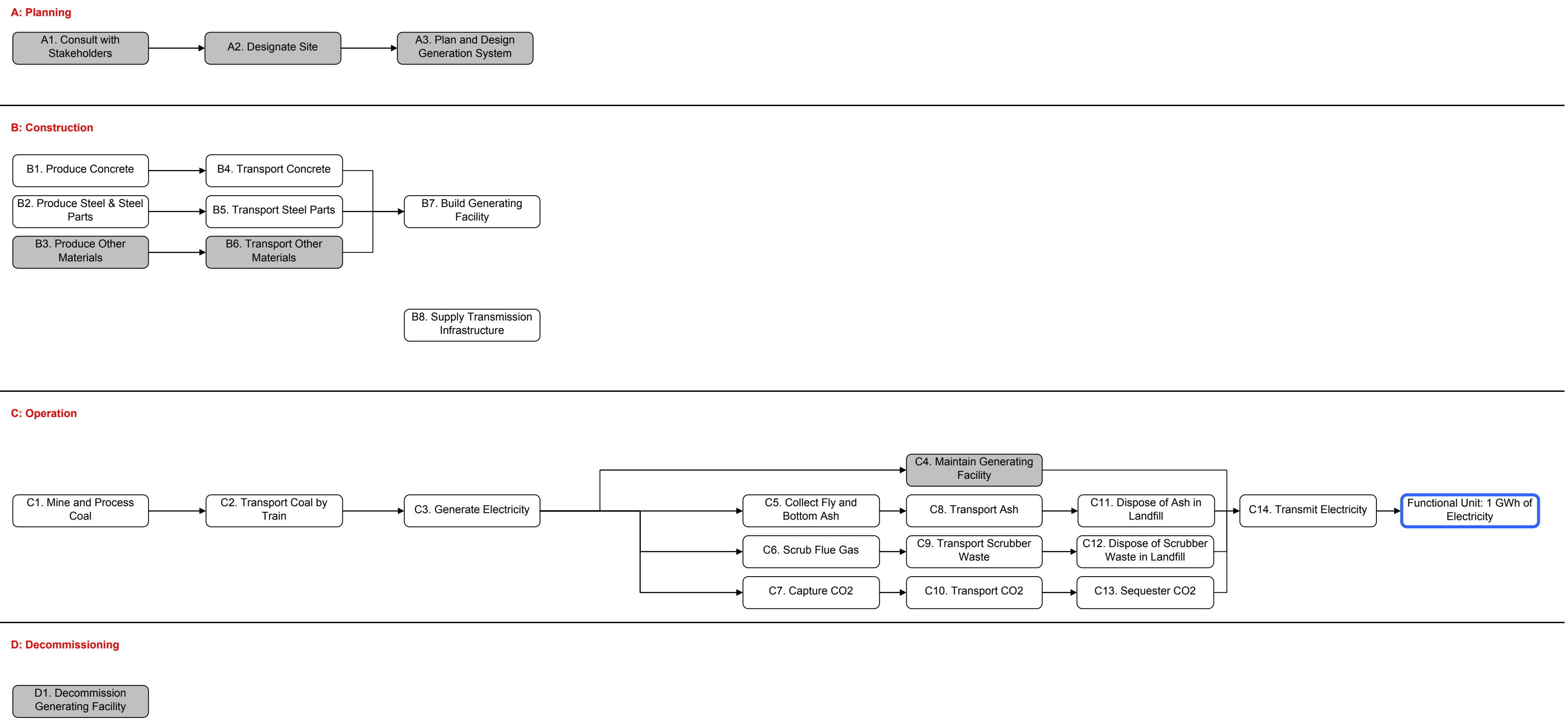


Figure 14: Coal with carbon capture and storage life cycle activity map

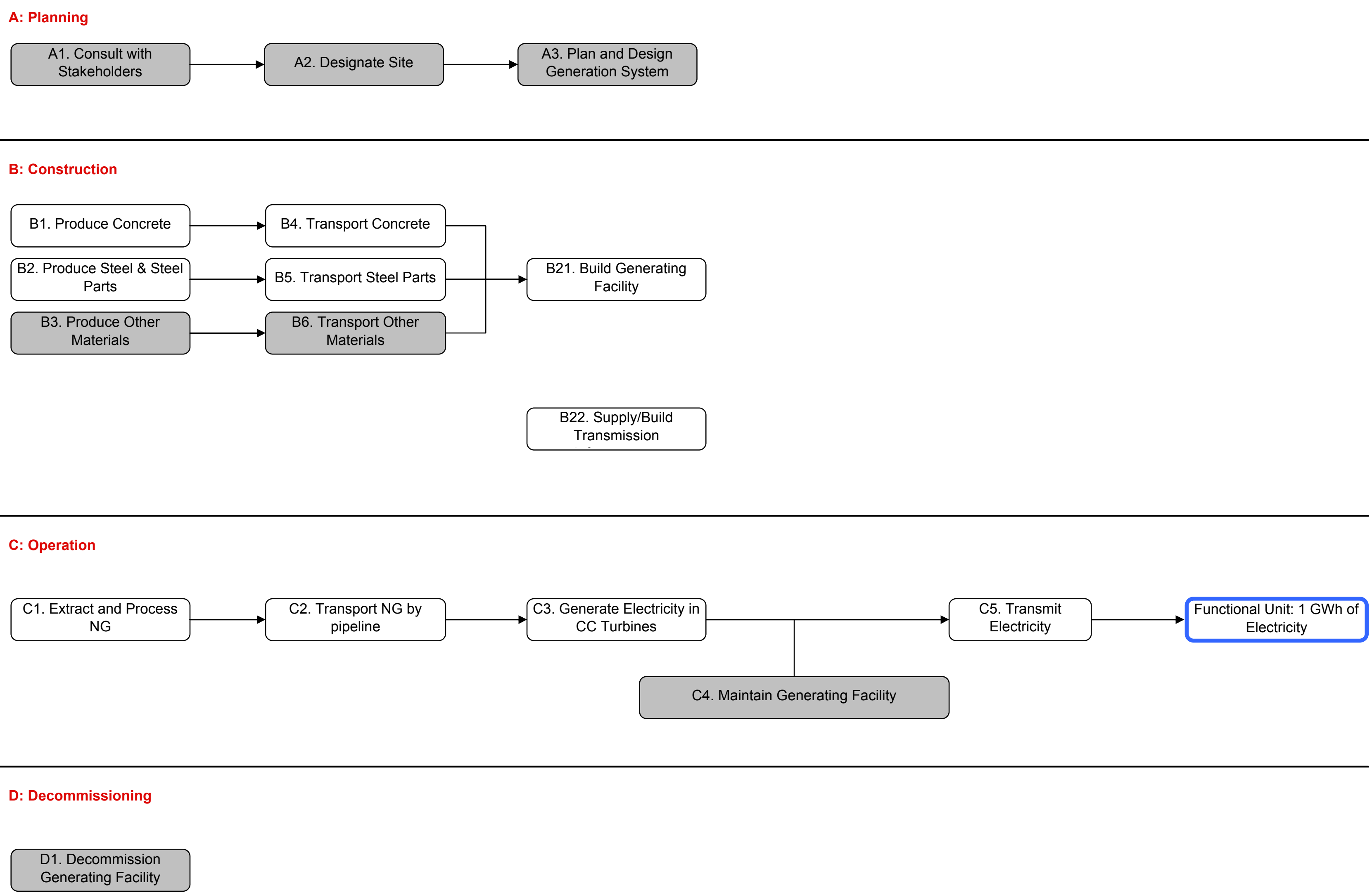


Figure 15: Life cycle activity maps for a NGCC generating station

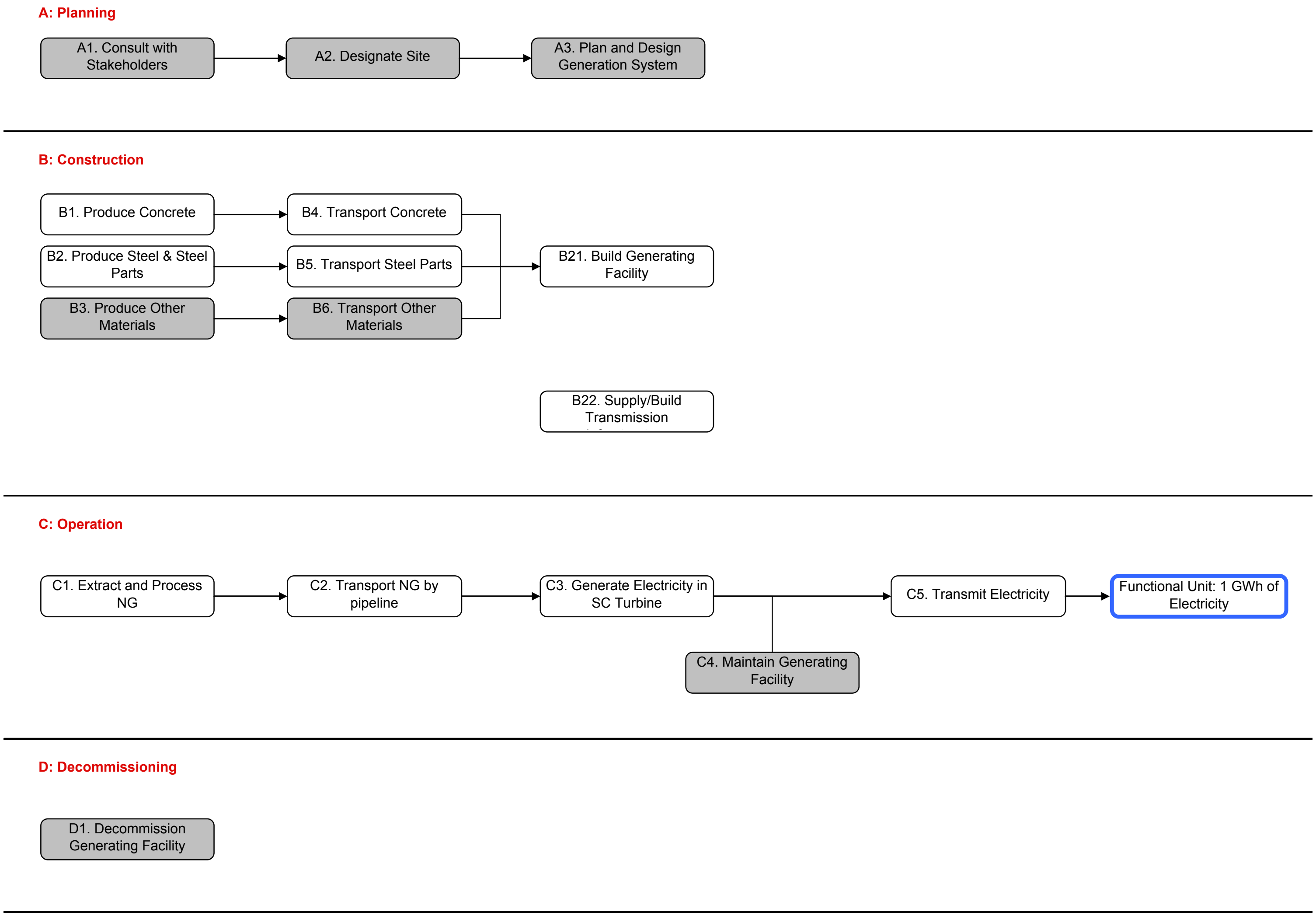


Figure 16: Life cycle activity maps for a single cycle natural gas generating station

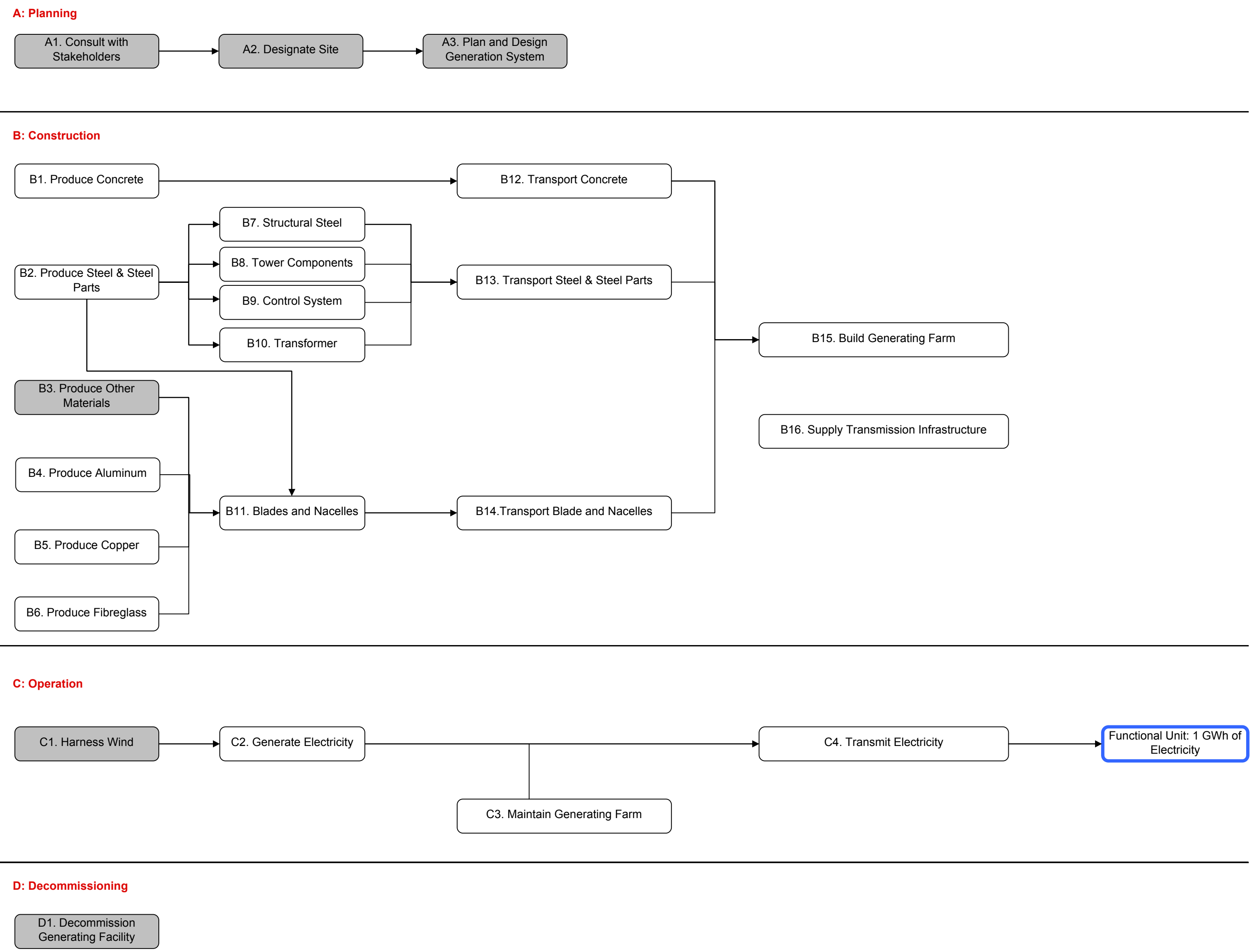


Figure 17: Life cycle activity map of a wind turbine

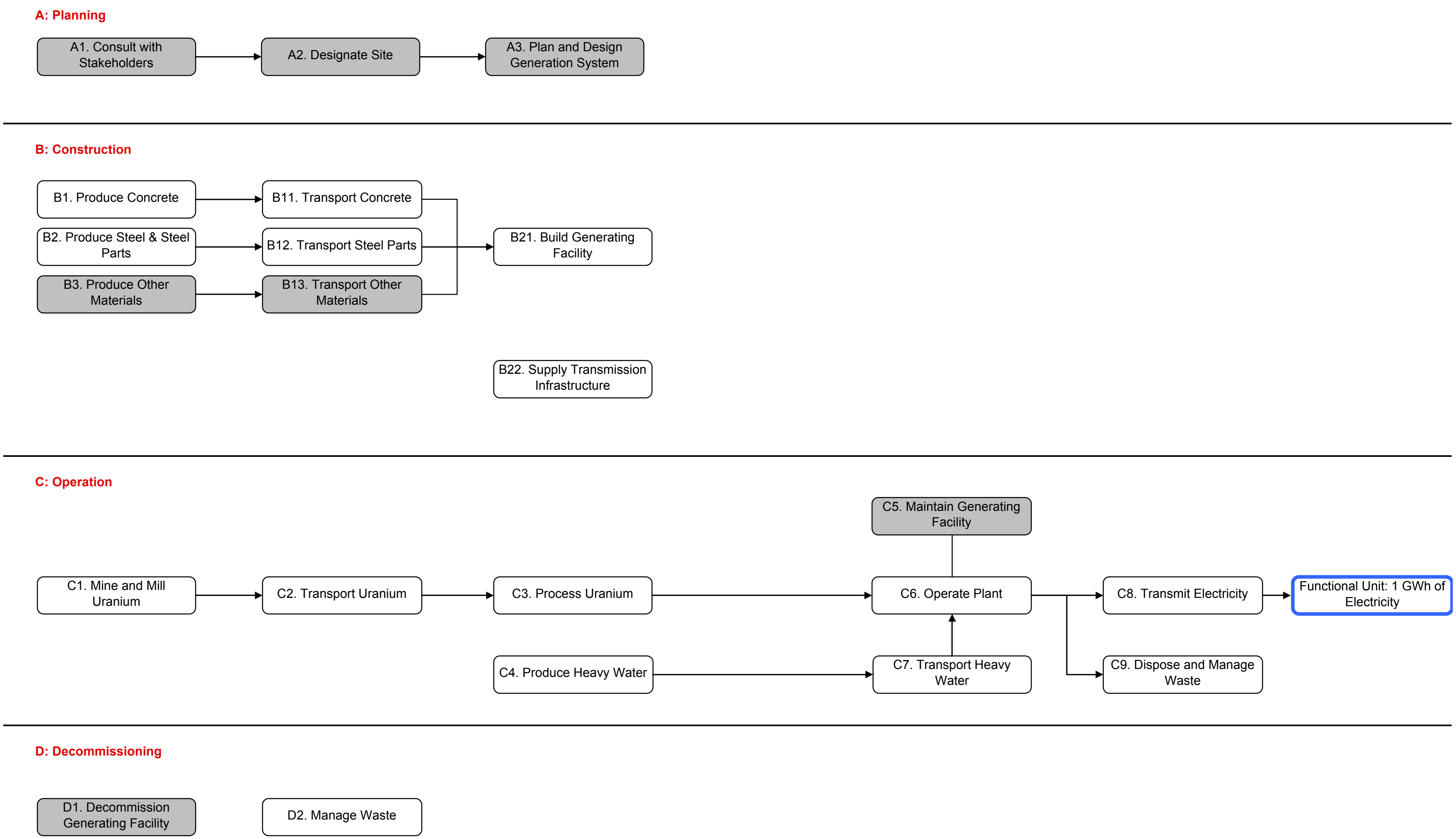


Figure 18: Life cycle activity map of a nuclear generating facility

Table 7 summarizes and describes the activities included in the assessment. Activities that are not included in the assessment (those highlighted in grey in the activity map) are not in the table.

Table 7: Description of activities included in assessment

Activity #	Title	Description
A1	Clear Transmission Line ROW	Includes emissions from the clearing of land for the transmission line right of way.
A2	Transport Towers and Conductors to Keeyask Site	Includes the emissions from the transportation of towers and conductors to site.
A3	Construct Transmission Line	Includes emissions from the combustion of diesel in construction equipment used to construct the transmission line.
A4/A5/A6/A7/A8/A9	Clear and Construct Access Roads and Camp/Work Areas	Includes emissions from construction equipment used to clear and construct the North and South access roads. Also includes emissions associated with clearing and constructing the work and camp areas. This activity includes all fuel use for activities A4/A5/A6/A7/A8/A9
A11/A12/A13/A14	Clear, Excavate and Grade Site	Includes emissions from equipment used to clear, excavate and grade the site. Includes activities A11/A12/A13/A14.
A11/A12/A13/A14	Source Backfill Materials	Includes emissions from equipment used to excavate backfill materials. Includes activities A11/A12/A13/A14.
A11/A12/A13/A14	Transport Backfill Materials	Includes emissions from equipment used to transport backfill materials. Includes activities A11/A12/A13/A14.
A16	Transport Labourers	Includes emissions associated with transporting labourers to site. Primarily plane and bus emissions.
A19	Mine Aggregate	Includes emissions associated with mining virgin aggregate.
A20	Produce Cement	Includes emissions associated with quarrying and crushing raw materials, grinding and blending, pyroprocessing and finish grinding. Transportation of all materials between these steps is included in this activity.
A21	Transport Aggregate (concrete)	Includes emissions from the transportation of aggregate to site.
A21	Transport Cement (Winnipeg to Keeyask)	Includes emissions from the transportation of cement from Winnipeg to site.
A21	Transport Cement (Source to Winnipeg)	Includes emissions from the transportation of cement from source (Edmonton) to Winnipeg.

Activity #	Title	Description
A23	Manufacture Precast Concrete	Includes quarry, raw material preparation, pyroprocessing, finish grinding and storage as well as raw material, solid fuel and gypsum and other cement material transportation.(i.e. portland cement manufacture, aggregate production, transport and concrete plant production).
A24	Transport Precast Concrete	Includes transportation of precast concrete to site.
A2/A9/A17/A40/A42/A44-A51	Mine Iron Ore and Produce Steel	Includes emissions associated with extraction of limestone, lime production, exploration, mining and processing of iron ore and coal, transportation to mill by ship, rail and truck (burnt lime, dolomite, iron ore and coal), primary processes (sinter plant, coke ovens, stoves, boilers, blast furnace and BOF), casting line and forging of steel into finished products. Steel is used in activities A2/A9/A17/A40/A42/A44-A51
A2/A9/A18/A41/A42/A44-A51	Transport Steel	Includes transportation of steel from steel source to site. Steel is used in activities A2/A9/A18/A41/A42/A44-A51
A28/A29	Harvest and Process Lumber	Includes emissions from harvesting and processing lumber.
A30	Transport Lumber (Winnipeg to Keeyask site)	Includes transportation of lumber from the saw mill to the Keeyask site.
A30	Transport Lumber (Source to Winnipeg)	Includes harvesting of logs, transport to saw mill and the saw mill.
A37/A38/A44-A51	Produce Diesel Fuel	Includes the transportation of diesel from the refinery to the Keeyask generating station. Includes activities A37/A38/A44-51.
A39	Transport Diesel to Keeyask	Includes emissions from the production of heavy, medium and light crude oil, transportation, processing and refining.
A43	Generate Electricity - Diesel	Includes emissions associate with electricity generation over the construction phase of the project from the diesel generator.
A43	Generate Electricity - Grid	Includes emissions associate with electricity generation for the Manitoba grid over the construction phase of the project.
A44-A51	On-site Diesel Combustion	Includes diesel combustion from all other construction activities not disaggregated above. Includes activities A44-A51.
B9	Transmit Electricity	Includes the electrical losses associated with transmitting electricity.
B10/B11/B12a/B13a	Replace Steel	Includes all activities associated with replacing parts during the operation phase of the generating station.
B10/B11/B12a/B13a	Replace Concrete	Includes activities associated with manufacturing replacement concrete.
B12b	Transport Steel for Recycling	Includes emissions associated with transporting steel for recycling.
B13b	Recycle Discarded Equipment (Steel)	Includes emissions associated with steel recycling.

Activity #	Title	Description
C2/C6/C9/C11/C14	Transport Steel for Recycling	Includes emissions associated with transporting steel for recycling.
C3/C7/C12/C15	Recycle Steel	Includes emissions associated with steel recycling.
C1/C4/C5/C8/C10/C21	Dismantle and Demolish Site	Includes combustion of diesel in equipment used for decommissioning.
C17/C18/C19	Produce Diesel	Includes emissions from all activities associated with producing diesel fuel.
C20	Transport Diesel to Site	Includes emissions associated with transporting diesel to site.

8.2.2 Key Assumptions

Table 8 describes the assumptions each activity and the rationale for the assumption or assumptions.

Table 8: Key assumptions per activity for the generating station and transmission line

Activity #	Title	Assumption/Comment	Rationale
A1	Clear Transmission Line ROW	1. Fuel use based on professional opinion. 2. All fuel used in construction equipment.	1. Best available information. 2. Manitoba Hydro currently assumes construction equipment uses majority of fuel. Highway vehicles will use only a small portion of the fuel.
A2	Transport Towers and Conductors to Keeyask Site	1. Towers and conductors are manufactured in Hamilton. 2. Towers are transported by rail from Hamilton to Winnipeg. The rail distance is equivalent to the road distance.	1. Manitoba Hydro has not yet determined a supplier for towers and conductors. However, they will most likely come from either Ontario or Quebec. 2. The exact rail distance from Hamilton to Winnipeg is not available; however, the rail line closely follows the highways.
A3	Construct Transmission Line	All fuel is combusted in construction equipment. Fuel combustion is not disaggregated for this activity but is include in overall fuel use for the site in activities A44-A51.	Manitoba Hydro currently assumes construction equipment uses majority of fuel. Highway vehicles will use only a small portion of the fuel.

Activity #	Title	Assumption/Comment	Rationale
A4/A5/A6/A7/A8/A9	Clear and Construct Access Roads and Camp/Work Areas	1. Fuel combustion air emissions are based on typical construction equipment (backhoes, excavators and dozers). 2. Pembina estimated fuel combustion air emissions associated with mining and transportation of aggregate to site.	1. Manitoba Hydro's current equipment list includes typical construction equipment. 2. Manitoba Hydro does not have estimates for fuel use for these activities.
A10	Rehabilitate Laydown and Access Roads	1. Only haul roads will be allowed to return to a pre-disturbance state.	1. The North and South access roads will remain as permanent features on the landscape.
A11/A12/A13/A14	Clear, Excavate and Grade Site	1. Backfill and rock excavation are from local sources. 2. Air emissions are associated with diesel combustion in construction equipment and transportation equipment.	1. As per Manitoba Hydro's current estimate. 2. There are no other GHG emissions or NO_x, SO_2 emissions associated with this activity.
A11/A12/A13/A14	Source and Transport Backfill Materials		
A15	House Labourers	1. The working camp is electrically heated.	1. Based on Manitoba Hydro's current plan.
A16	Transport Labourers	1. Labourers will be transported by plane from Winnipeg to Thompson and then by bus from Thompson to Gillam. 2. Emissions calculated based on using a Dash-8 aircraft and 40 passenger bus both averaging 50% occupancy rates over the construction period.	1. Estimated by Manitoba Hydro based on labour estimates. 2. The Dash-8 is used regularly by northern airline companies, such as Bearskin Airlines and Air Creebec. Also, it is unlikely that the planes and buses will be full at all times. A 50% occupancy rates is a conservative estimate.
A19	Mine Aggregate	1. Aggregate requirements for concrete productions are based on the ratio of cement to concrete for the Pointe du Bois project.	1. Manitoba Hydro does not have an estimate of aggregate requirements for concrete production. In addition, concrete used for the Pointe du Bois generating station will likely be similar for the Keeyask generating station.

Activity #	Title	Assumption/Comment	Rationale
A20	Produce Cement	1. The cement used by Manitoba Hydro is produced in a manner similar to average Portland cement manufacture in the United States.	1. Best available information.
A21	Transport Aggregate (concrete)	1. Cement and aggregate are transported by train and truck. 2. Cement originally sourced from Edmonton. 3. Aggregate for concrete will come from local sources (6km).	1. As per Manitoba Hydro's previous experience. 2. The Keeyask design team has not determined the final cement supplier; however, they did suggest that Edmonton is one of the more likely cement sources. 3. Manitoba Hydro is planning on sourcing aggregate from this location for other uses such as road construction.
A21	Transport Cement (Winnipeg to Keeyask)		
A21	Transport Cement (Source to Winnipeg)		
A23	Manufacture Pre-cast Concrete	1. Pre-cast concrete will be rated to 7500 psi.	1. 7500 psi concrete manufacturing has the highest emission intensity of any type of precast concrete. This assumption is therefore conservative.
A24	Transport Pre-cast Concrete	1. Pre-cast concrete will come from Winnipeg.	1. Manitoba Hydro's current estimate of production location.
A2/A9/A17/A40/A42/A44-A51	Mine Iron Ore and Produce Steel	1. Emission factors for manufacturing steel are calculated as steel billet production and steel forging. It is assumed that steel production emissions are similar for all types of steel (rebar, mechanical and superstructure). Includes extraction of limestone, lime production, exploration, mining and processing of iron ore and coal, transportation to mill by ship, rail and truck (burnt lime, dolomite, iron ore and coal), primary processes (sinter plant, coke ovens, stoves, boilers, blast furnace and BOF) and casting line.	1. Primary steel production and forming energy use are similar for all steel types.

Activity #	Title	Assumption/Comment	Rationale
A2/A9/A18/A41/A42/A44-A51	Transport Steel	1. Rebar steel comes from St. Paul, Minnesota and is transported by truck. 2. All other steel comes from China and is shipped by ship, rail and truck.	1. As Manitoba Hydro's current expectation. 2. Steel is a part of many components including rebar, structural steel and mechanical components. These components are sourced from many regions including North America, South East Asia, South America and Eastern Europe. To be conservative we assume all steel other than rebar steel comes from China.
A28/A29	Harvest and Process Lumber	1. Emissions include harvesting, transportation of logs and operation of the saw mill. 2. Lumber is used on-site for concrete forms.	1. Manitoba Hydro expects to purchase timber from Winnipeg. 2. The original source of timber is unknown but is likely to come from forests within British Columbia.
A30	Transport Lumber (Winnipeg to Keeyask site)	1. Lumber is transported from Winnipeg to site via truck.	1. No rail connection.
A30	Transport Lumber (Source to Winnipeg)	1. Lumber is transported from BC to Winnipeg via truck.	1. Lumber can be sourced from many locations. To be conservative we use British Columbia as the source.
A31 to A33	Aluminum production and transport	1. The production and transportation of aluminum does not contribute significantly to life cycle emissions.	1. Manitoba Hydro's consultants do not expect any significant quantities of aluminum to be required for construction of the facility.
A34 to 36	Other material production and transportation	1. There are no other significant materials used in the construction of the hydro dam.	1. While there are many other materials required, such as explosives and copper, the material quantities are much lower than the primary material inputs, concrete, steel and diesel. Based on the estimates provided by Manitoba Hydro's consultants of other material needs and following the decision making process outlined in Boundary Selection Pembina chose not to analyze environmental impacts from these sources.

Activity #	Title	Assumption/Comment	Rationale
A37/A38	Produce Diesel Fuel	1. Crude oil used to produce diesel is made up of approximately 40% heavy oil (including oil sands derived bitumen) and 60% light/medium crude oil. 2. Crude oil is refined into diesel in Edmonton and shipped to Winnipeg via train.	1. Total crude oil production in Canada is 2.8 million bpd of which 1.1 million bpd is derived from oil sands.[39] 2. The main refinery concentrations in Canada are in Edmonton, Alberta and Southern Ontario. As Edmonton is closer we assume crude oil will first be upgraded in Edmonton and then shipped to Winnipeg.
A39	Transport Diesel to Keeyask	Diesel is transported from Winnipeg to site via truck.	Manitoba Hydro expects diesel to be transported to site.
A42	Generate Electricity - Diesel Generated Power	Diesel generators will be used to provide electricity to site before grid electricity is hooked up.	Manitoba Hydro's current electricity supply plan.
A42	Generate Electricity - Grid	Manitoba grid electricity emission factors are used to estimate emissions associated with electricity use.	The Manitoba grid will be used to supply electricity for the construction site.
A44-A51	On-site Diesel Combustion	All diesel will be used on-site in equipment similar to operation of backhoes, excavators and dozers. Manitoba Hydro assumed 27% of diesel will be used for transportation and 63% for equipment for its Pointe du Bois facility. Transportation includes emissions from transporting materials from only local material sources.	The Keeyask design team has not yet estimated the portion of fuel that will combusted in transportation vehicles vs. construction vehicles. Pembina assumes the ratio will be similar to that for the Pointe du Bois project.
B1 – B9	Facility Maintenance	Emissions from facility maintenance are negligible over the life of the project.	Pembina’s previous work on the Wuskwatim dam found maintenance activities to contribute only 0.01% of life cycle emissions.

[39] CAPP. "Crude Oil Forecast, Markets & Pipeline Expansions." 48: Canadian Association of Petroleum Producers, 2008.

Activity #	Title	Assumption/Comment	Rationale
B8	Maintain Reservoir	Reservoir emissions occur as a result of land use change from clearing at the beginning of the project and from decay over the life of the project.	All estimates provided by Environmental Illimité.
B9	Transmit Electricity	Transmission losses are 10%.	Transmission losses vary from day to day. However, Manitoba Hydro uses 10% transmission losses in project planning as a conservative estimate of transmission losses. The 10% value is based on operating data of Manitoba Hydro's current electrical grid.
B10/B11/B12a/B13a	Replace Steel	All equipment and embedded steel is replaced at least once during the life of the project.	MBH noted that many of these components would be replaced or refurbished. To be conservative the estimates below likely over estimate.
B10/B11/B12a/B13a	Replace Concrete	Assume 0% concrete replaced.	Manitoba Hydro's consultants assume, based on experience, that only small amounts of concrete will need to be replaced over the life of the project. This assessment therefore assumes that no concrete is replaced over the life of the project.
B12b	Transport Steel for Recycling	Steel will be transported from site to Winnipeg for recycling.	Largest and closest urban centre with capacity to recycle large quantities of steel.
B13b	Recycle Discarded Equipment (Steel)	Steel from worn or broken pieces of equipment will be recycled.	Assumed based on responses from the Keeyask design team.
B14 – B23	Heat and power powerhouse	Not included	Heat and diesel power requirements will be small over the life of the project.
C2/C6/C9/C11/C14	Transport Steel for Recycling	Steel will be transported from site to Winnipeg for recycling.	Largest and closest urban centre with capacity to recycle large quantities of steel.
C3/C7/C12/C15	Recycle Steel	All steel in the facility will be recycled.	As per Manitoba Hydro's current plan for the Pointe du Bois facility.

Activity #	Title	Assumption/Comment	Rationale
C1/C4/C5/C8/C10/C21	Dismantle and Demolish Site	Decommissioning diesel combustion is scaled based on fuel use from the Pointe du Bois facility using a mass ratio of installed concrete and steel.	Most recent information.
C17/C18/C19	Produce Diesel	1. Crude oil used to produce diesel is made up of approximately 40% heavy oil (including oil sands derived bitumen) and 60% light/medium crude oil. 2. Crude oil is refined into diesel in Edmonton and shipped to Winnipeg via train.	1. Total crude oil production in Canada is 2.8 million bpd of which 1.1 million bpd is derived from oil sands.[40] 2. The main refinery concentrations in Canada are in Edmonton, Alberta and Southern Ontario. As Edmonton is closer we assume crude oil will first be upgraded in Edmonton and then shipped to Winnipeg.
C20	Transport Diesel to Site	Diesel is transported to site via truck.	Manitoba Hydro expects diesel to be transported to site.

8.2.3 Criteria Selection

Table 9 lists all of the potential criteria air contaminants and notes whether the criteria is used or not and why. The environmental significance is provided for all criteria.

Table 9: Considered criteria: justification for inclusion/exclusion and importance

Criterion (Metric/Indicator)	Measure	Why/Why Not	Relevance and Importance of Criteria
Greenhouse gases (GHGs)	t CO_2eq	Included because: • Environmentally significant (global impact)	Emissions resulting from human activities are substantially increasing the atmospheric concentrations of several important GHGes, especially carbon dioxide (CO_2), methane

[40] CAPP. "Crude Oil Forecast, Markets & Pipeline Expansions." 48: Canadian Association of Petroleum Producers, 2008.

		• GHG emissions for many life cycle activities are readily available. • Clear differences between technologies • General public is interested in GHG emissions	(CH_4), and nitrous oxide (N_2O). These are increasing the greenhouse effect, resulting in an overall average warming of the earth's surface. Current climate science calls for an aggregate reduction in industrialized countries' emissions to 25-40% below the 1990 level by 2020 and 85-90% below 1990 levels by 2050.[41]
Nitrogen Oxides (NO_x)	kg NO_xeq	Included because: • Environmentally significant (local and regional impact) • NOx emissions are frequently included in publicly available data sources. • Clear differences between technologies • General public is interested in NOx emissions	Contributes to acid deposition leading to impacts on soils, lakes, forests, crops and buildings. When present with VOCs, NO_x is also a contributing factor to ground level ozone, which can cause adverse effects on humans, including lowered lung function and the development of chronic respirator diseases. Ground-level ozone also has significant impact on reducing the productivity of agricultural crops and forests. NO_x has approximately 70% the acidifying potential of SO_2. See VOCs below for more information on ground-level ozone.
Sulphur Dioxide (SO_2)	kg SO_2	Will include because: • Environmentally significant (local and regional impact) • SO_2 emissions are frequently included in publicly available data sources. • Clear differences between technologies • General public is interested in SO_2	SO_2 is also a significant contributing factor to acid deposition impacts (see NO_x).

[41] *The Case for Deep Reductions: Canada's Role in Preventing Dangerous Climate Change*, An investigation by the David Suzuki Foundation and the Pembina Institute, 2005.

		emissions	
Particulate Matter (PM)	kg PM	Will not include[a]	Particulate matter is tiny pieces of solid and liquid matter small enough to be suspended in the air. The finest of these particulates are primarily soot and exhaust combustion products that may irritate the respiratory tract and contribute to smog formation. Secondary sources of PM result from SO_2, NO_x, and VOC emissions that act as precursors to PM formation in the atmosphere. Of particular concern are PM10 and PM2.5 particulates – fine particulates smaller than 10 and 2.5 microns in size that can penetrate deep into the lungs. These particulates can have a serious effect on respiratory function and have been linked to cancer, especially those particulates from diesel exhaust that contain carcinogenic fuel combustion products.[42]
Volatile Organic Compounds (NMVOCs)	kg VOC	Will not include[a]	When present with NO_x, VOCs are key precursors to the production of ground level ozone. The relationship between ground-level ozone and the NO_x and VOC precursors involves a very complex non-linear photo-oxidation process, and therefore representing the quantities and concentration of these precursors provides only a rough proxy for the actual environmental impacts of ground-level ozone. The scale of environmental impacts is regional, which can cause adverse effects on humans, including lowered lung function and the development of chronic respirator diseases. Ground-level ozone also has significant impact

[42] R.F. Webb Corporate Ltd., *The Environmental Effects of Transportation Fuels – Final Report*, Ottawa, ON: Natural Resources Canada, 1993.

			on reducing the productivity of agricultural crops and forests.
CO	kg CO	Will not include[a]	Carbon monoxide is a colorless, odorless gas. It is a by-product of incomplete combustion. The most common sources of carbon monoxide are cigarette smoke and the exhaust from internal combustion engines. It is a component of motor vehicle exhaust. In cities, 85 –95% of all CO emissions may come from motor vehicle exhaust. Carbon monoxide enters into the body through breathing. Once inside the body, carbon monoxide binds with the heme component of red blood cells to form a compound called carboxyhemoglobin (COHb). This process reduces the capacity of the red blood cells to carry oxygen to the tissues. This especially affects tissues with the greatest oxygen demand such as the heart, the brain and the exercising skeletal system.
NH_3	kg NH_3	Will not include[a]	Ammonia is a naturally occurring, colourless, acrid-smelling gas. It is widely used in a variety of manufacturing processes, but is mostly used as a fertilizer. Much of the ammonia in air results from the decomposition of organic matter and other biological activities. Air readily dilutes and degrades ammonia so it does not stay air borne for more than a week. Ammonia vapour is an irritant to the eyes and the respiratory tract. Damage to the bronchial epithelium and the alveolar membrane have been documented at high concentrations while severe acute over-exposure can lead to death within minutes.

[a] Manitoba Hydro did not require a life cycle analysis of particulate matter, volatile organic compounds, carbon monoxide or ammonia. While the local environmental implications can be significant these types of emissions are not typically reviewed on a lifecycle basis for electricity options and the data availability is uncertain. In addition emissions of this type will be primarily associated with manufacturing activities which will be dispersed over a large geographic area. Manitoba Hydro also noted that to the extent that there are any significant environmental issues associated with this facility that are related to these types of emissions, they will be full considered and dealt within the environmental impact assessment.

8.3 Appendix 3 – Inventory Assessment

8.3.1 Inputs

Table 10 contains a list of total material and energy inputs as well as transportation distances used in the assessment for each of the materials.

Table 10: List of material, energy and distance inputs used in the LCA

Phase	Quantity	Sources/Comment
Construction – Material	124,100 tonnes cement	Manitoba Hydro
Construction – Material	915,000 tonnes pre-cast concrete	Manitoba Hydro
Construction – Material	750,805 tonnes aggregate for concrete	Pembina – Estimated based on cement to aggregate ratio for Pointe du Bois.
Construction – Material	18,230,000 tonnes aggregate/backfill/earthfill	Manitoba Hydro
Construction – Material	64,200 tonnes steel	Manitoba Hydro
Construction – Material	3,600 tonnes wood	Manitoba Hydro
Construction – Fuel	47,800 m^3	Manitoba Hydro
Construction – Transport Cement	2,350 km	Road distance by road from Edmonton to Keeyask
Construction – Transport Aggregate	6 km	Manitoba Hydro – Assumes aggregate for concrete comes from same source as aggregate for other construction activities.

Construction – Transport Steel (Except Rebar)	9,797 km by ocean transport ship 2,202 km by rail 1,071 km by truck	Shipping distance from Shanghai to Vancouver Rail from Vancouver to Winnipeg Truck from Winnipeg to Keeyask
Construction – Transport Steel (rebar)	1,800 km	St. Paul Minnesota to Keeyask
Construction – Transport Towers and Conductors	2,114 km by rail 1,071 km by road	Rail distance from Hamilton, Ont. To Winnipeg. Road distance from Winnipeg to Keeyask
Construction – Transport Wood	2500 km truck 1,071 km truck	Road distance BC to Winnipeg Road distance Winnipeg to Keeyask
Construction Transport – Diesel	1,071 km truck	Diesel is transported by truck from Winnipeg to the Keeyask site.
Operation – Material	3,740 tonnes steel	Manitoba Hydro (10% of equipment/mechanical steel)
Operation – Material	0 tonnes cement	Manitoba Hydro (0% concrete replacement)
Operation – Material	0 tonnes aggregate	Manitoba Hydro (0% concrete replacement)
Operation – Transportation Steel	9,797 km by ocean transport ship 2,202 km by rail 1,071 km by truck	Shipping distance from Shanghai to Vancouver Rail from Vancouver to Winnipeg Truck from Winnipeg to Keeyask
Operation – Transportation Cement	1,279 km by rail 1,071 km by truck	Rail distance from Edmonton to Winnipeg. Road distance from Winnipeg to Keeyask
Operation – Transportation Aggregate	6 km	Manitoba Hydro – Assumes aggregate for concrete comes from same source as aggregate for other construction activities.
Decommissioning – Fuel	3,161 m^3	Scaled based on expected fuel requirements for the decommissioning of the current Pointe du Bois generation station.
Decommissioning –	1,071 km truck	Diesel is transported by truck from Winnipeg to the

Transport Diesel		Keeyask site.

8.3.2 Data Sets

Pembina uses life cycle data sets, such as the example concrete data set provided below in Table 11, to determine GHG, NO_x and SO_2 emissions for activities associated with the construction of the hydro facility. These data sets come from a variety of publicly available sources. Table 12 lists the sources for all of the data sets used in this life cycle assessment.[43]

Table 11: Example life cycle data set

Unit Process Name	Produce Portland Cement
Data Set Name	Life Cycle Inventory of Portland Cement Concrete
Description	Includes Quarry, Raw Material Preparation, Pyroprocessing, Finish Grinding and Storage as well as raw material, solid fuel and gypsum and other cementitius material transportation.(i.e.Portland cement manufacture, aggregate production, transport and concrete plant production)
Source of Data	Jan R. Prusinski, Medgar L. Marceau, Martha G. VanGeem (2003) *Life Cycle Inventory of Slag Cement Concrete,* Presented at the Eighth CANMET/ACI

[43] The data in the public sources listed must often be slightly modified (change of units) or aggregated with other data sets (mine iron ore combined with transport iron ore) to produce a final data set.

Assumptions/Considerations	Based on Ready Mixed Concrete (20MPa) with 100% Portland Cement,
Limitations of Use	Portland cement is a hydraulic cement composed primarily of hydraulic calcium silicates. Hydraulic cements harden by reacting chemically with water. During this reaction, cement combines with water to form a stonelike mass, called paste. When the paste (cement and water) is added to aggregates (sand and gravel, crushed stone, or other granular materials) it binds the aggregates together to form concrete, the most widely used construction material. Although the words “cement” and “concrete” are used interchangeably in everyday usage, cement is one of the constituents of concrete. Cement is a very fine powder and concrete is a stonelike material. Cement constitutes 8 to 15 percent of concrete’s total mass by weight. Using cement LCI data incorrectly as concrete LCI data is a serious error.
Uncertainty	

OUTPUTS	**Amount**	**Units**	**+\- %**	**Allocation**	**Primary Output**
Concrete	1	m3	0	1	Yes
ENVIRONMENTAL OUTPUTS				**Medium**	
CO2	228	kg		Air	
NOx	0.713	kg		Air	

SO_2	0.545	kg		Air

Table 12: Data Sources per Activity

Activity	Data Set Title	Source
A6/A7/A9/C1 /C4/C8/C10	Combust Diesel in Construction Equipment (backhoes, excavators, bulldozers)	Environmental Protection Agency. 1998. Exhaust Emission Factors for Nonroad Engine Modeling - Compression Ignition & Caterpillar Performance Handbook, Edition 28, 1997
A6/A7/A9/C1 /C4/C8/C10	Combust Diesel in Construction Equipment (Transportation trucks)	Transport Canada, 2007. Urban Transport Emissions Calculator Taken for heavy duty commercial vehicle operating on gasoline. Accessed online August 2007 at http://www.tc.gc.ca/programs/environment/UTEC/FuelEfficiency.aspx
A15/B14	Mine Aggregate	Statistics Canada. 2005. Non-metallic Mineral Mining and Quarrying NAICS 2123,http://www.statcan.gc.ca/pub/26-226-x/26-226-x2006000-eng.pdf.
A16/B14	Produce Cement	Jan R. Prusinski, Medgar L. Marceau, Martha G. VanGeem (2003) Life Cycle Inventory of Slag Cement Concrete, Presented at the Eighth CANMET/ACI
A17/A21/A24/ A33/A40/B16/ C2/C5/C6/C9/ C11/C20	Road Transport	National Renewable Energy Laboratory US Life-Cycle Inventory Database. Truck Transportation - Transport, combination truck, diesel powered, http://www.nrel.gov/lci/database/default.asp.
A19/B14	Mine Iron Ore	Jamie K. Meil, Vice-President of the ATHENA Sustainable Materials Institute. 2002. SS_Steel, billets, at plant.xls: National Renewable Energy Database,www.nrel.gov/lci.
A20a/A20b/B14	Forge Steel	Helene Berg and Sandra Haggstrom. "LCA Based Solution Selection." Chalmers University of Technology, 2002.
A22/A23	Produce Sawed Timber	LCA of Building Frame Structures, Environmental Impact over the Life Cycle of Wooden and Concrete Frames. T. Bjorklund, Anne-Marie Tillman. Chalmers University of Technology, 1997.
A31/A32/A6/A9	Produce crude and	This aggregated emission factor is made of several components. More detail is provided in

C17/C18/C19	refine into diesel	Table 13.
A42	Produce Electricity	GHGs: Environment Canada. 2006. National Inventory Report: GHG Sources and Sinks in Canada, 1990-2006, http://www.ec.gc.ca/pdb/ghg/inventory_report/2006_report/tdm-toc_eng.cfm. CACs: Environment Canada. 2006. National Pollutant Release Inventory, http://www.ec.gc.ca/pdb/cac/Emissions1990-2015/emissions_e.cfm.
B17c/C3/C7/C12	Recycle Steel	Life Cycle Inventories for Packaging, Vol 1, Swiss Agency for Environment, Forests, and Landscape, 1998.

Table 13 contains additional information on the sources used to develop the produce diesel emission factor.

Table 13: Additional detail on produce diesel emission factor

Name	Source
Produce Light Crude	Canadian Association of Petroleum Producers. "A National Inventory of Greenhouse Gas (GHG), Criteria Air Contaminant (CAC) and Hydrogen Sulphide (H_2S) Emissions by the Upstream Oil and Gas Industry, Volume 1, Overview of the GHG Emissions Inventory." 246: CAPP, 2005.
Produce Heavy Crude	Canadian Association of Petroleum Producers. "A National Inventory of Greenhouse Gas (Ghg), Criteria Air Contaminant (CAC) and Hydrogen Sulphide (H_2S) Emissions by the Upstream Oil and Gas Industry, Volume 1, Overview of the GHG Emissions Inventory." 246: CAPP, 2005.
Upgrade Heavy Crude	Shell Canada Limited, "Application for Approval: Scotford Upgrader Project" (1998)
Transport Crude	Gmaps Pedometer. 2009. Accessed online at http://www.gmap-pedometer.com/?r=2671734 . Represents virtual straight line distance between Fort McMurray and Edmonton.
Refine crude to diesel	Canadian Petroleum Products Institute. "Environmental and Safety Performance Report." 25: Canadian Petroleum Products Institute, 2004.

8.3.3 Additional Detail on Land Use Change

Land use change from land clearing for access roads, transmission lines and dykes are based on IPCC guidance documents[44]. Pembina used the following overarching assumptions to guide calculations. These assumptions are followed by details on the carbon contents used for each forest type cleared.

- All current land types are converted to grassland, with the exception of road ways. The majority, 2/3, of a road ROW is converted to grassland. The remainder, 1/3, is converted to road with no carbon content.
- CO_2 is released at the time of clearing because all biomass is combusted.
- There is no significant decay.
- There is no change in the intensity of land use. That is the carbon content of soils is unchanged after clearing.
- Roads constructed over peatland will not reduce the carbon content of peatland soils. The road will be designed to maintain current drainage patterns. The intent of this design is to ensure that peatlands on either side of the road will not become wetter or dryer because of road construction.
- Reservoir calculations are provided by Environnement Illimité. Pembina only calculated land use change emissions associated with the North and South access roads, transmission lines and the dyke.
- Any current burnt forest areas are assumed to have the same carbon content as its pre-burnt state. Pembina assumes disturbances of burnt forest will prevent the forest from re-growing.
- The carbon content of all forest types being cleared are based on generic carbon contents for the boreal region.

Table 14: Additional detail on Land use change calculations

Forest Type	Carbon Content (tonnes DM/ha)
Coniferous	46
Broadleaf	25
Mixed	40
Grassland	4.25
Peatland	146

[44] Intergovernmental Panel on Climate Change, "Good Practice Guidance for Land Use, Land-Use Change and Forestry."

8.4 Appendix 4 – Detailed Results

Table 15 provides a detailed breakdown of the GHG, NO_x and SO_2 emissions by activity number.

Table 15: Detailed emissions associated with the life cycle of the Keeyask Generating station

Summary Table of Life Cycle Emissions									Percent of Total (Check)		
Activity #	Activity	t CO2e	kg NOx	kg SO2	t CO2e / GWH	kg Nox / GWH	kg SO2 / GWH	% CO2 total\	% Nox Total	% SO2 Total
A1	Clear Transmission Line ROW	943	25,650	1,725	0.00	0.06	0.00	0.10%	0.61%	0.26%
A2	Transport Towers and Conductors to Keeyask Site	174	2,246	38	0.00	0.01	0.00	0.02%	0.05%	0.01%
A3	Construct Transmission Line	0	0	0	0.00	0.00	0.00	0.00%	0.00%	0.00%
A4/A7/A8/A9	Diesel Consumption for Access Roads and Camps	15,122	411,131	27,644	0.04	1.03	0.07	1.54%	9.80%	4.18%
A10	Rehabilitate Laydown and Access Roads	0	0	0	0.00	0.00	0.00	0.00%	0.00%	0.00%
A11/A12/A13/A14	Clear, Excavate and Grade Site	10,243	278,485	18,725	0.03	0.70	0.05	1.05%	6.64%	2.83%
A16	Transport Labourers	17,038	77,600	2,676	0.04	0.19	0.01	1.74%	1.85%	0.41%
A19	Mine Aggregate	0	0	0	0.00	0.00	0.00	0.00%	0.00%	0.00%
A20	Produce Cement	68,805	310,672	206,291	0.17	0.78	0.52	7.03%	7.41%	31.23%
A21	Transport Cement	13,632	149,884	81,476	0.03	0.38	0.20	1.39%	3.57%	12.33%
A23/A24	Manufacture Precast Concrete	0	0	0	0.00	0.00	0.00	0.00%	0.00%	0.00%
A9/A17/A40/A42/A44-A51	Mine Iron Ore and Produce Steel	153,948	222,028	69,698	0.39	0.56	0.17	15.72%	5.29%	10.55%
A9/A18/A41/A42/A44-A51	Transport Steel	14,725	262,432	20,221	0.04	0.66	0.05	1.50%	6.26%	3.06%
A28/A29	Harvest and Process Lumber	147	3,600	1,292	0.00	0.01	0.00	0.02%	0.09%	0.20%
A30	Transport Lumber (Winnipeg to Keeyask site)	308	2,052	68	0.00	0.01	0.00	0.03%	0.05%	0.01%
A30	Transport Lumber (Source to Winnipeg)	171	4,487	38	0.00	0.01	0.00	0.02%	0.11%	0.01%
A37/A38	Produce Diesel Fuel	31,561	46,829	63,021	0.08	0.12	0.16	3.22%	1.12%	9.54%
A39	Transport Diesel to Keeyask	3,434	22,876	756	0.01	0.06	0.00	0.35%	0.55%	0.11%
A42	Generate Electricity - Diesel Generated Power	16,373	17,247	3,594	0.04	0.04	0.01	1.67%	0.41%	0.54%
A42	Generate Electricity - Grid	3,900	13,802	9,492	0.01	0.03	0.02	0.40%	0.33%	1.44%
A44-A51	On-site Diesel Combustion	103,404	2,078,733	122,241	0.26	5.21	0.31	10.56%	49.56%	18.51%
B8	Maintain Reservoir	496,022	0	0	1.24	0.00	0.00	50.67%	0.00%	0.00%
B9	Transmit Electricity	0	0	0	0.00	0.00	0.00	0.00%	0.00%	0.00%
B10/B11/B12a/B13a	Replace Steel	10,025	34,959	5,841	0.03	0.09	0.01	1.02%	0.83%	0.88%
B10/B11/B12a/B13a	Replace Concrete	0	0	0	0.00	0.00	0.00	0.00%	0.00%	0.00%
B12b	Transport Steel for Recycling	320	2,132	70	0.00	0.01	0.00	0.03%	0.05%	0.01%
B13b	Recycle Discarded Equipment (Steel)	165	351	512	0.00	0.00	0.00	0.02%	0.01%	0.08%
C2/C6/C9/C11/C14	Transport Steel for Recycling	5,494	36,599	1,209	0.01	0.09	0.00	0.56%	0.87%	0.18%
C3/C7/C12/C15	Recycle Steel	2,838	6,026	8,786	0.01	0.02	0.02	0.29%	0.14%	1.33%
C1/C4/C5/C8/C10/C21	Dismantle and Demolish Site	8,052	180,276	11,197	0.02	0.45	0.03	0.82%	4.30%	1.69%
C17/C18/C19	Produce Diesel	1,961	2,910	3,916	0.00	0.01	0.01	0.20%	0.07%	0.59%
C20	Transport Diesel to Site	213	1,422	47	0.00	0.00	0.00	0.02%	0.03%	0.01%
Construction Emissions		**453,927**	**3,929,755**	**628,998**	**1.14**	**9.86**	**1.58**	**46%**	**94%**	**95%**
Operating Emissions		**506,532**	**37,442**	**6,423**	**1.27**	**0.09**	**0.02**	**52%**	**1%**	**1%**
Decommissioning Emissions		**18,559**	**227,232**	**25,155**	**0.05**	**0.57**	**0.06**	**2%**	**5%**	**4%**
Total Emissions		**979,019**	**4,194,428**	**660,576**	**2.46**	**10.52**	**1.66**	**100%**	**100%**	**100%**

8.5 Appendix 5 – Details on Literature Survey of Comparison Technologies

The following tables contain life cycle values used to develop the comparison charts in the report. The data tables contain the life cycle values for each of the sources. If there are two values for a specific source this is because the source provided maximum and minimum values. Each of the data tables is followed by complete references on the primary sources used to develop these values.

Table 16: Summary of sources reviewed and life cycle emissions for super critical pulverized coal

Source	CO_{2e} (t/GWh)	NO_x (kg/GWh)	SO_2 (kg/GWh)
Source 1	1163	N/A	N/A
Source 2	830	735	735
Source 2	1241	5537	1812
Source 4	1127	3507	7046
Source 5	788	N/A	N/A
Source 6	923	431	1313
Source 7	949	675	114
Source 7	1213	4608	12271
Source 8	975	N/A	823
Source 9	736	240	199
Source 10	916	N/A	662
Source 10	979	N/A	834
Source 11	1103	1677	3908
Average	**995**	**2176**	**2701**
Median	**975**	**1206**	**834**
Minimum	**736**	**240**	**114**
Maximum	**1241**	**5537**	**12271**
Standard Deviation	**163**	**2082**	**3776**

Table 17: Summary of sources for the above table

Source #	Reference	Included (yes/no)
1	Matt McCulloch, Jaisel Vadgama. "Life Cycle Evaluation of Ghg Emissions and Land Change Realated to Selected Power Generation Options in Manitoba." 50. Calgary: The Pembina Institute, 2003.	yes
2	IEA. "Hydropower and the Environment: Present Context and Guidelines for Future Action." 188: IEA, 2000.	yes
3	Rich Wong, Ed Whittingham. "A Comparison of Combustion Technologies for Electricity Generation." 37: The Pembina Institute, 2006.	no
4	Pamela L. Spath, M. K. M., Dawn R. Kerr. (1999). Life Cycle Assessment of Coal-fired Power Production. Springfield: NREL.	yes
5	Weisser, Daniel. "A Guide to Life-Cycle Greenhouse Gas (Ghg) Emissions from Electric Supply Technologies." Energy 32, (2006): 17.	yes
6	Naser A. Odeh, Timothy T. Cockerill. "Life Cycle GHG Assessment of Fossil Fuel Power Plants with Carbon Capture and Storage." Energy Policy 36, (2007): 13.	yes
7	Paulina Jaramillo, W. Michael Griffin, and H. Scott Matthews. "Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, Lng, and Sng for Electricity Generation." Environmental Science and Technology 41, no. 17 (2007): 6.	yes
8	Yucho Sadamichi, Seizo Kato. "Life Cycle Impact Assessment of Fuel Procuring and Electricity Generating Processes in Japan by Using an 'Lca-Nets' Scheme." International Journal of Emerging Electric Power Systems 7, no. 1 (2007).	yes
9	Joule Bergerson, Lester Lave. "The Long-Term Life Cycle Private and External Costs of High Coal Usage in the Us." Energy Policy 35, (2007): 9.	yes
10	Martin Pehnt, Johannes Henkel. "Life Cycle Assessment of Carbon Dioxide Capture and Storage from Lignite Power Plants." International Journal of Greenhouse Gas Control 3, (2009): 17.	yes
11	Jazayeri S, Kralovic P. Comparative Life Cycle Assessment (LCA) of Base Load Electricity Generation in Ontario. Calgary; 2008:226. Available at: http://www.cna.ca/english/pdf/studies/ceri/CERI-ComparativeLCA.pdf.	Yes

Table 18: Summary of data sources coal with carbon capture and storage

Source	CO_{2e} (t/GWh)	NO_x (kg/GWh)	SO_2 (kg/GWh)
Source 2	259	N/A	N/A
Source 3	268	620	9
Source 4	156	903	38

Source 4	201	1717	162
Source 5	131	312	50
Source 6	165	N/A	N/A
Average	**197**	**888**	**65**
Median	**183**	**761**	**44**
Minimum	**131**	**312**	**9**
Maximum	**268**	**1717**	**162**
Standard Deviation	**56**	**603**	**67**

Table 19: Summary of sources for the above table

Source #	Reference	Included (yes/no)
1	Rich Wong, Ed Whittingham. "A Comparison of Combustion Technologies for Electricity Generation." 37: The Pembina Institute, 2006.	No
2	Weisser, Daniel. "A Guide to Life-Cycle Greenhouse Gas (Ghg) Emissions from Electric Supply Technologies." Energy 32, (2006): 17.	Yes
3	Naser A. Odeh, Timothy T. Cockerill. "Life Cycle Ghg Assessment of Fossil Fuel Power Plants with Carbon Capture and Storage." Energy Policy 36, (2007): 13.	Yes
4	Paulina Jaramillo, W. Michael Griffin, and H. Scott Matthews. "Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, Lng, and Sng for Electricity Generation." Environmental Science and Technology 41, no. 17 (2007): 6.	Yes
5	Joule Bergerson, Lester Lave. "The Long-Term Life Cycle Private and External Costs of High Coal Usage in the Us." Energy Policy 35, (2007): 9.	Yes
6	Martin Pehnt, Johannes Henkel. "Life Cycle Assessment of Carbon Dioxide Capture and Storage from Lignite Power Plants." International Journal of Greenhouse Gas Control 3, (2009): 17.	Yes

Table 20: Summary of data sources for NGCC

Source	CO_{2e} (t/GWh)	NO_x (kg/GWh)	SO_2 (kg/GWh)
Source 1	509	N/A	N/A
Source 2	408	14	4

Source 2	537	1575	1575
Source 4	549	599	336
Source 5	420	N/A	N/A
Source 5	819	N/A	N/A
Source 6	512	147	0
Source 7	376	81	0
Source 7	818	4471	709
Source 8	393	131	99
Source 9	488	742	156
Average	**530**	**970**	**360**
Median	**509**	**373**	**128**
Minimum	**376**	**14**	**0**
Maximum	**819**	**4471**	**1575**
Standard Deviation	**155**	**1507**	**547**

Table 21: Summary of sources for the above table

Source #	Reference	Included (yes/no)
1	Matt McCulloch, Jaisel Vadgama. "Life Cycle Evaluation of Ghg Emissions and Land Change Realated to Selected Power Generation Options in Manitoba." 50. Calgary: The Pembina Institute, 2003.	yes
2	IEA. "Hydropower and the Environment: Present Context and Guidelines for Future Action." 188: IEA, 2000.	yes
3	Rich Wong, Ed Whittingham. "A Comparison of Combustion Technologies for Electricity Generation." 37: The Pembina Institute, 2006.	no
4	Pamela L. Spath, M. K. M. (2000). Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System: NREL.	yes
5	Weisser, Daniel. "A Guide to Life-Cycle Greenhouse Gas (Ghg) Emissions from Electric Supply Technologies." Energy 32, (2006): 17.	yes
6	Naser A. Odeh, Timothy T. Cockerill. "Life Cycle Ghg Assessment of Fossil Fuel Power Plants with Carbon Capture and Storage." Energy Policy 36, (2007): 13.	yes
7	Paulina Jaramillo, W. Michael Griffin, and H. Scott Matthews. "Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, Lng, and Sng for Electricity Generation." Environmental Science and Technology 41, no. 17 (2007): 6.	yes

8	Joule Bergerson, Lester Lave. "The Long-Term Life Cycle Private and External Costs of High Coal Usage in the Us." Energy Policy 35, (2007): 9.	yes
9	Jazayeri S, Kralovic P. Comparative Life Cycle Assessment (LCA) of Base Load Electricity Generation in Ontario. Calgary; 2008:226. Available at: http://www.cna.ca/english/pdf/studies/ceri/CERI-ComparativeLCA.pdf.	Yes

Table 22: Summary of data sources for single cycle natural gas

Source	CO_{2e} (t/GWh)	NO_x (kg/GWh)	SO_2 (kg/GWh)
Source 1	764	N/A	N/A
Source 2	613	20	6
Source 2	805	2363	2363
Source 4	824	898	504
Source 5	630	N/A	N/A
Source 5	1229	N/A	N/A
Source 6	769	221	0
Source 7	564	121	0
Source 7	1227	6706	1063
Source 8	589	197	149
Source 9	732	1113	234
Average	**795**	**1455**	**540**
Median	**764**	**559**	**192**
Minimum	**564**	**0**	**0**
Maximum	**1229**	**6706**	**2363**
Standard Deviation	**232**	**2261**	**820**

Table 23: Summary of sources for the above table

Source #	Reference	Included (yes/no)
1	Matt McCulloch, Jaisel Vadgama. "Life Cycle Evaluation of Ghg Emissions and Land Change Realated to Selected Power Generation Options in Manitoba." 50. Calgary: The Pembina Institute, 2003.	yes

2	IEA. "Hydropower and the Environment: Present Context and Guidelines for Future Action." 188: IEA, 2000.	yes
3	Rich Wong, Ed Whittingham. "A Comparison of Combustion Technologies for Electricity Generation." 37: The Pembina Institute, 2006.	no
4	Pamela L. Spath, M. K. M. (2000). Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System: NREL.	yes
5	Weisser, Daniel. "A Guide to Life-Cycle Greenhouse Gas (Ghg) Emissions from Electric Supply Technologies." Energy 32, (2006): 17.	yes
6	Naser A. Odeh, Timothy T. Cockerill. "Life Cycle Ghg Assessment of Fossil Fuel Power Plants with Carbon Capture and Storage." Energy Policy 36, (2007): 13.	yes
7	Paulina Jaramillo, W. Michael Griffin, and H. Scott Matthews. "Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, Lng, and Sng for Electricity Generation." Environmental Science and Technology 41, no. 17 (2007): 6.	yes
8	Joule Bergerson, Lester Lave. "The Long-Term Life Cycle Private and External Costs of High Coal Usage in the Us." Energy Policy 35, (2007): 9.	yes
9	Jazayeri S, Kralovic P. Comparative Life Cycle Assessment (LCA) of Base Load Electricity Generation in Ontario. Calgary; 2008:226. Available at: http://www.cna.ca/english/pdf/studies/ceri/CERI-ComparativeLCA.pdf.	Yes

Table 24: Summary of data for Nuclear generating station

Source	CO_{2e} (t/GWh)	NO_x (kg/GWh)	SO_2 (kg/GWh)
Source 1	2	3	2
Source 1	62	53	105
Source 2	15	32	95
Source 3	3	N/A	N/A
Source 3	25	N/A	N/A
Source 4	2	N/A	N/A
Source 4	88	N/A	N/A
Source 5	24	N/A	24
Source 6	2	3	9
Average	**25**	**22**	**47**
Median	**15**	**17**	**24**
Minimum	**2**	**3**	**2**

Maximum	**88**	**53**	**105**
Standard Deviation	**31**	**24**	**49**

Table 25: Summary of sources for the above table

Source #	Reference	Included (yes/no)
1	IEA. "Hydropower and the Environment: Present Context and Guidelines for Future Action." 188: IEA, 2000.	Yes
2	Henrikke Baumann, A.-M. T. (2004). The Hitch Hiker's Guide to LCA. Lund, Sweden: Studentlitteratur. Appendix 1, pg. 490	yes
3	Weisser, Daniel. "A Guide to Life-Cycle Greenhouse Gas (Ghg) Emissions from Electric Supply Technologies." Energy 32, (2006): 17.	Yes
4	Lenzen, Manfred. "Life Cycle Energy and Greenhouse Gas Emisisons of Nuclear Energy: A Review." Energy Conversion and Management 49, (2008): 22..	yes
5	Yucho Sadamichi, Seizo Kato. "Life Cycle Impact Assessment of Fuel Procuring and Electricity Generating Processes in Japan by Using an 'Lca-Nets' Scheme." International Journal of Emerging Electric Power Systems 7, no. 1 (2007).	Yes
6	Jazayeri S, Kralovic P. Comparative Life Cycle Assessment (LCA) of Base Load Electricity Generation in Ontario. Calgary; 2008:226. Available at: http://www.cna.ca/english/pdf/studies/ceri/CERI-ComparativeLCA.pdf.	Yes

Table 26: Summary of data for wind turbines

Source	CO_{2e} (t/GWh)	NO_x (kg/GWh)	SO_2 (kg/GWh)
Source 1	10	N/A	N/A
Source 2	8	15	17
Source 2	42	55	96
Source 3	9	N/A	N/A
Source 3	33	N/A	N/A
Source 4	1	13	3
Source 5	16	93	61
Source 6	17	N/A	N/A
Average	**17**	**35**	**35**

Median	**13**	**15**	**17**
Minimum	**1**	**0**	**0**
Maximum	**42**	**93**	**96**
Standard Deviation	**14**	**38**	**42**

Table 27: Summary of sources for the above table

Source #	Reference	Included (yes/no)
1	Matt McCulloch, Jaisel Vadgama. "Life Cycle Evaluation of Ghg Emissions and Land Change Related to Selected Power Generation Options in Manitoba." 50. Calgary: The Pembina Institute, 2003.	no
2	IEA. "Hydropower and the Environment: Present Context and Guidelines for Future Action." 188: IEA, 2000.	yes
3	Weisser, Daniel. "A Guide to Life-Cycle Greenhouse Gas (Ghg) Emissions from Electric Supply Technologies." Energy 32, (2006): 17.	yes
4	Jan Weinzettel, Marte Reenaas, Christian Solli, Edgar G. Hertwich. "Life Cycle Assessment of a Floating Offshore Wind Turbine." Renewable Energy 34, (2007): 6.	yes
5	Fulvio Ardente, Marco Beccali, Maurizio Cellura, Valerio Lo Brano. "Energy Performances and Life Cycle Assessment of and Italian Wind Farm." Renewable and Sustainable Energy Reviews 12, (2008): 17.	yes
6	Brice Tremeac, Francis Meunier. "Life Cycle Analysis of 4.5 Mw and 250 W Wind Turbines." Renewable and Sustainable Energy Reviews Articles in Press, (2009): 7.	yes

8.6 Appendix 6 – Critical Review

Introduction

- Why is the critical review being undertaken?
    - The critical review is being undertaken to add credibility to the study. The data will be provided to the public and used in the Manitoba regulatory process.
    - A critical review is also being performed for the study to better match ISO 14044 – Environmental Management Life Cycle Assessment – Requirements and Guidelines. Section 6.1 states "In order to decrease the likelihood of misunderstandings or negative effects on external interested parties, a panel of interested parties shall conduct critical reviews on LCA studies where the results are intended to be used to support a comparative assertion intended to be disclosed to the public"
- The reviewer will comment on the following:
    - The methods used to carry out the LCA are consistent with this [ISO 14044] International Standard
    - The methods used to carry out the LCA are scientifically and technically valid
    - The data used are appropriate and reasonable in relation to the goal of the study
    - The interpretations reflect the limitations identified and the goal of the study
    - The study report is transparent and consistent[45]

Comments from the Critical Reviewer

Pembina asked Maryse Lambert, Senior Advisor – Air Quality at Hydro-Québec, to review the report and life cycle model. Among her other responsibilities at Hydro-Québec Maryse reviews life cycle assessments for Hydro-Québec's electricity generating station and equipment. Currently Maryse is the primary reviewer for Hydro-Québec's LCA of the Eastmain hydroelectric facility and a LCA of Hydro-Québec's electricity production and distribution network. Maryse's assessment of the report is provided below.

"The numbers are often different in sections talking about the same data (for example 58 or 57% for the same statistic). It's the same thing for some assumptions. They could also be different in

[45] ISO, "Environmental Management - Life Cycle Assessment - Principles and Framework."

the same table (example lumber come from MB or BC). In its present form, the report creates a doubt on the validity of the study because there are some inconsistencies. Someone should revise all data and assumptions to ensure that the data and assumptions in the model, in tables and in the text correspond to the same thing."

Response: Pembina performed a thorough review of the report to ensure consistency throughout the report in response to this comment.

"The results of this study for the three indicators are lower than those for the Pointe du Bois project. How is it possible since this project consume more concrete, steel, fuel and is further away from Winnipeg than Pointe du Bois? You should ensure that this project and Pointe du Bois uses the same basic hypothesis regarding emission factors."

Response: Pembina updated both the Keeyask and Pointe du Bois reports with the same assumptions. At the time of the external review we had assumed 100% of mechanical steel would be replaced for Pointe du Bois but only 10% for Keeyask. These different assumptions resulted in a higher life cycle emission intensity for Pointe du Bois and a relatively lower emission intensity for Keeyask. Based on further discussion with Manitoba Hydro and their consultants we determined 10% to be the most likely amount of steel to be replaced over the life of the project. This change did have a significant impact on the results. In addition, the Keeyask facility will produce significantly more electricity over its life for the total amount of steel and concrete required in its construction. For example the Pointe du Bois facility will require 400 kg of steel for every GWh or electricity produce; Keeyask will require only 161 kg of steel for every GWh of electricity produced. For this reason, even though Keeyask will require more construction material and will have higher reservoir emissions the life cycle GHG intensity (tonnes CO_2/GWh) for Keeyaks will be similar to the life cycle GHG intensity of Pointe du Bois. However, absolute (tonnes CO_2) GHG emissions for Keeyask will be higher.

"Considering that the points mentioned above will be checked and corrected before the report is consider final, the report is complete and covers all major activities associated with the project. The indicators selected are the best for comparison with the chosen modes of electricity generation. The assumptions used are reasonable in relation to the goal of the study. All specific comments and recommendations of improvement are included in the report."

Pembina addressed all of the comments raised by Maryse Lambert.

8.7 Appendix 7 – Sensitivity Analysis

Table 28 to Table 32 include the percent changes associated with the four sensitivities and a combination of the sensitivities.

Table 28 presents the percent decrease in life cycle emissions if steel is transported from steel plant in North America instead of one in China.

Table 28: Reductions in transportation emissions per life cycle phase when shipping from China is removed

Air Emission	Units	Construction			Land Use Change*	Operation	Decommissioning	Total
		Building Material - Manufacture	Transportation	On-Site Construction Activities	Clearing for roads, transmission and reservoir	Offsite	Decommissioning Activities	
Greenhouse Gas		0%	13%	0%	0%	6%	0%	1%
Nitrogen Oxides		0%	33%	0%	0%	42%	0%	5%
Sulphur Dioxide		0%	17%	0%	0%	26%	0%	3%

Table 29 presents the percent increase in life cycle emissions if steel production is 30% more emission intensive than the base case.

Table 29: Increased emission intensities for steel production

Air Emission	Units	Construction			Land Use Change*	Operation	Decommissioning	Total
		Building Material - Manufacture	Transportation	On-Site Construction Activities	Clearing for roads, transmission and reservoir	Offsite	Decommissioning Activities	
Greenhouse Gas		17%	0%	0%	0%	26%	0%	5%
Nitrogen Oxides		11%	0%	0%	0%	10%	0%	2%
Sulphur Dioxide		6%	0%	0%	0%	19%	0%	3%

Table 30 presents the percent increase in life cycle emissions if all crude is sourced from heavy oil sources. The base case assumes 40% of the crude comes from heavy oil and 60% from light oil sources.

Table 30: Increased emission intensity from crude from heavy crude production

Air Emission	Units	Construction			Land Use Change*	Operation	Decommissioning	Total
		Building Material - Manufacture	Transportation	On-Site Construction Activities	Clearing for roads, transmission and reservoir	Offsite	Decommissioning Activities	
Greenhouse Gas		*10%*	*0%*	*0%*	*0%*	*0%*	*9%*	*3%*
Nitrogen Oxides		*3%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Sulphur Dioxide		*13%*	*0%*	*0%*	*0%*	*0%*	*11%*	*7%*

Table 31 presents the percent increase in life cycle emissions if cement manufacturing is 30% more intensive.

Table 31: Increased emission intensity for cement production

Air Emission	Units	Construction			Land Use Change*	Operation	Decommissioning	Total
		Building Material - Manufacture	Transportation	On-Site Construction Activities	Clearing for roads, transmission and reservoir	Offsite	Decommissioning Activities	
Greenhouse Gas		*11%*	*0%*	*0%*	*0%*	*0%*	*3%*	*3%*
Nitrogen Oxides		*16%*	*0%*	*0%*	*0%*	*0%*	*0%*	*2%*
Sulphur Dioxide		*22%*	*0%*	*0%*	*0%*	*0%*	*4%*	*12%*

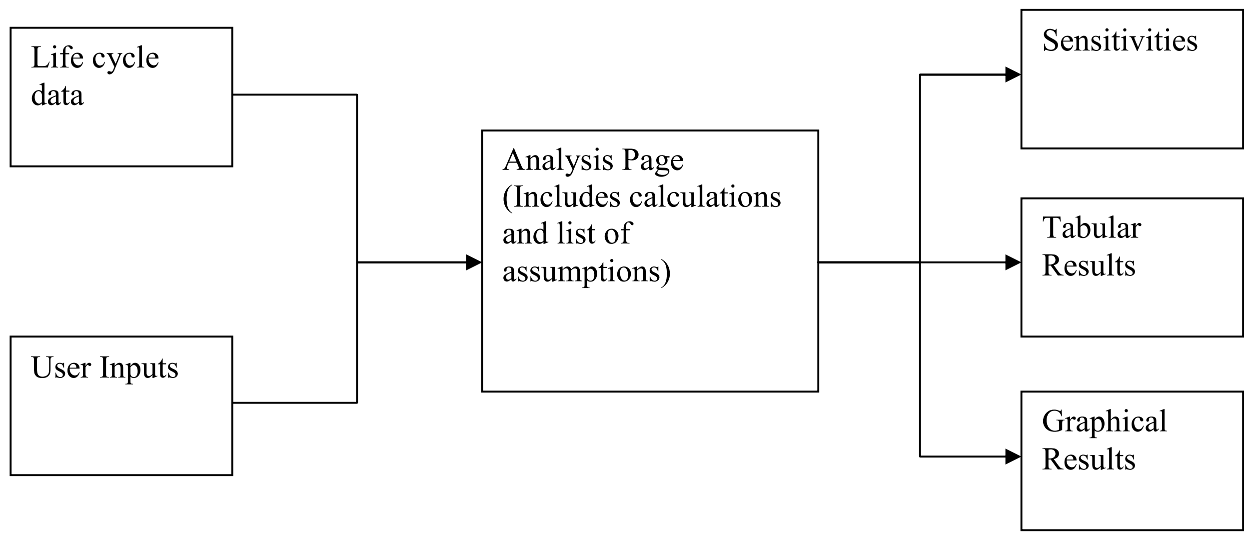
Table 32 presents the percent difference in the sensitivities presented in Table 29 to Table 31 are combined. The table presents the results if steel and concrete manufacture are 30% more emission intensive and all crude oil is heavy.

Table 32: Combined increase from increased intensities for steel, crude and cement production

Air Emission	Units	Construction			Land Use Change*	Operation	Decommissioning	Total
		Building Material - Manufacture	Transportation	On-Site Construction Activities	Clearing for roads, transmission and reservoir	Offsite	Decommissioning Activities	
Greenhouse Gas		*35%*	*0%*	*0%*	*0%*	*26%*	*9%*	*10%*
Nitrogen Oxides		*30%*	*0%*	*0%*	*0%*	*10%*	*0%*	*4%*
Sulphur Dioxide		*37%*	*0%*	*0%*	*0%*	*19%*	*11%*	*20%*

8.8 Appendix 8 – Details on the model

Pembina used a customized excel based life cycle model to contain all the data and calculate the life cycle results in the model. We've made every attempt to include all the important details and assumptions in the body of this report. However, those who would like to replicate the results would need access the model itself. Manitoba Hydro has the version of the model on which the results calculated in this report are based. A high level diagram of the model and a brief description is available below.



In general the model can be broken down into three components, input, calculations and output. The input data includes all the life cycle data sets for activities like concrete manufacture. In addition key factors, such as transport distances, can be varied in the user input section. The analysis page combines all the life cycle data and user inputs to calculate emissions for all of the parts of the construction, operation and decommissioning of the hydroelectric facility. The analysis page then outputs the calculations to the various results pages. The results pages organize the information into the graphs and tables that are included in the report. The sensitivities are also outputted to a separate page in the model.