Life Cycle Evaluation of GHG Emissions and Land Change Related to Selected Power Generation Options in Manitoba

February 25, 2003

Project: 256-001

Prepared by:
Matt McCulloch, P.Eng.
Jaisel Vadgama

Pembina Institute
for Appropriate Development

About the Pembina Institute

The Pembina Institute is an independent, citizen-based organization involved in environmental education, research, public policy development, and corporate environmental management services. Its mandate is to research, develop, and promote policies and programs that lead to environmental protection, resource conservation, and environmentally sound and sustainable resource management. Incorporated in 1985, the Institute's main office is in Drayton Valley, Alberta, with additional offices in Calgary and Ottawa, and research associates in Edmonton, Toronto, Saskatoon, Vancouver, and other locations across Canada. The Institute's mission is to implement holistic and practical solutions for a sustainable world.

For more information on the Pembina Institute's work, please visit our Web site at www.pembina.org, or contact:

The Pembina Institute
Box 7558
Drayton Valley, AB T7A 1S7
tel: 780-542-6272 fax: 780-542-6464
e-mail: info@pembina.org

Calgary Office:

The Pembina Institute
Suite 517, 604 – 1st Street SW
Calgary, AB T2P 1M7
tel: 403-269-3344 fax: 403-269-3377

Disclaimer

The Pembina Institute was engaged by Manitoba Hydro to complete a streamlined life cycle analysis of the selected energy supply options discussed in this paper. The analysis is limited to an assessment of greenhouse gases and land change only and should not be considered a comprehensive environmental or social analysis of the options evaluated.

Seven options were considered: a hydroelectric generating facility (the Wuskwatim Generating Station and Transmission Project), proposed by Manitoba Hydro, as well as six hypothetical generation projects involving different fuels. Factual information on the Wuskwatim project was provided by Manitoba Hydro, as were all major assumptions associated with the hypothetical options evaluated.

Although conducting a life cycle analysis improves understanding of the environmental considerations associated with different energy supply options, it cannot in any manner be construed as an endorsement by the Pembina Institute of any one of these options.

Table of Contents

Figures

Tables

1.0 Introduction

The Pembina Institute was engaged by Manitoba Hydro to provide an assessment of the greenhouse gas (GHG) emissions and land changes associated with the proposed Wuskwatim Hydro project and six other options for electricity generation. Factual information and data have been used for the Wuskwatim analysis, while the remaining analyses are based on hypothetical parameters that are considered to be realistic. Each option is considered to be a prominent alternative to the Wuskwatim Hydro project for near-term power generation.

All seven options evaluated in this study are described in outline in Table 1.1. A detailed exposition of the operating parameters and assumptions used in analyzing the impacts of each system is provided in the appendices to this document.

The methodology used in the analysis is based on the principles of life cycle value assessment (LCVA) – a tool that integrates environmental and social considerations into decision-making processes. LCVA offers two key advantages: (i) a system for including upstream and downstream impacts in project thinking, and (ii) a system for identifying and responding to key environmental and social factors at the project design phase. The general LCVA methodology is presented in section 1.1 for reference.

This evaluation for Manitoba Hydro only draws on a subset of the full LCVA toolkit. Upstream and downstream impacts are incorporated in the evaluation, however the study is limited to a quantitative assessment of greenhouse gas emissions and land change. Emissions and land impacts are reported without being placed in the context of either existing emission profiles or ecological sensitivities for given geographical regions. No design improvement opportunities are addressed. A more detailed explanation of the methodology and limitations is provided in section 1.2.

Finally, it should be highlighted that this analysis does not evaluate demand-side management (DSM) strategies as an alternative to new power generation infrastructure. DSM activities must play an integral role in any comprehensive plan for energy provision and should be considered alongside the options studied in this report.

1.1 Principles of Life Cycle Value Assessment Methodology

A complete life cycle value assessment (LCVA) involves six distinct steps: goal definition, scoping, inventory assessment, impact analysis, design improvement, and reporting. These steps are laid out in general terms below. Section 1.2 describes the steps which have been included in this life cycle evaluation of electricity supply options.

An LCVA is normally used to inform a particular decision, such as the development of a new project. The **goal definition** lays out the options being considered as well as the key questions that will be answered about each option.

Scoping consists of sub-dividing each option, or system, into individual activities that occur during planning, production, use and retirement phases of the life cycle. Each activity is called a unit process, and a preliminary assessment is made as to which unit processes may have significant environmental or social impacts.

The **inventory assessment** involves collecting data to quantify selected inputs and outputs of the unit processes in every system. These data are entered into a model which aggregates the information to provide net input and output information for each system.

The **impact analysis stage** involves assessing these input and output results in terms of their environmental, social and financial impacts. This step considers the relative change in total environmental loadings and the sensitivity of exposed areas, along with capital and operational costs.

Design improvement is a series of steps taken in tandem with the four main analysis stages. When undertaken systematically, a design improvement analysis ensures that a comprehensive and serious effort is made to find opportunities for reducing the financial, environmental and social impacts of process activities and material supply choices across the full life cycle.

Reporting involves presenting a synthesis and summary of the findings, along with conclusions and recommendations about the project decision being studied. The results are usually compiled in a report or presentation to decision-makers that are responsible for project approval.

1.2 Methodology Used in this Life Cycle Evaluation of Electricity Supply Options

This life cycle evaluation uses elements of the LCVA methodology, but provides an analysis of more limited scope. In particular, this evaluation does not include a thorough impact analysis or present any design improvement recommendations.

Instead, the goal definition restricts this study's focus to a quantitative assessment of greenhouse gas (GHG) emissions and land changed associated with the various electricity supply options. A complete scoping analysis has been conducted for each option, along with a full inventory assessment. However, only the direct GHG and land change results of this assessment are presented in the report. There is no comprehensive analysis of the environmental and social **impacts** of either factor.

A unique exception is the evaluation of the GHG emission impacts of land change. Terrestrial ecosystems are an important repository for organic carbon, and land changes may result in the net release of carbon to the atmosphere or the net sequestration of carbon from the atmosphere. In order to provide a more complete quantitative analysis of GHG emissions, it was deemed necessary to consider this particular environmental impact of land change.

Initial estimates suggested that in the Wuskwatim Hydro system, land-related GHG emissions would be roughly equal to emissions from other sources such as construction activities. Although there is significant uncertainty associated with quantifying carbon flows resulting from land change, these emissions were considered to be an indispensable component of the overall results. By contrast, GHG emissions due to land change were estimated to be less than 0.05 times the emissions from other sources in the remaining six systems. As a result, no land-related GHG emissions were included in the analysis due to the combination of high uncertainties and a limited expected effect on the final results. A full explanation of the assumptions regarding land-related GHG impacts is presented in Appendix 7.

In summary, this evaluation takes advantage of the life cycle perspective in calculating complete 'cradle to grave' estimates of GHG emissions and land change for each electricity supply option studied. It does not, however, consider the social and environmental impacts of these two quantities, except where the GHG emissions implications of land change are significant.

Table 1.1: Description of Electricity Supply Options Compared in the Study

Name of Electricity Supply Option	Capacity (MW)	Technology	Generating Facility Location	Fuel	Fuel Source	Requirement for New Transmission Infrastructure?	Operating Factor[1]	Project Life (years)	Lifetime Generation (GWh)	Trans-mission Losses	Lifetime Delivered Power (GWh)
Wuskwatim Hydro	200	Hydroelectric generating station	Taskinigup Falls	n/a	n/a	Yes[2]	0.87	100	152,400	10%	137,200
Pulverized Coal	400	Pulverized coal boiler + steam turbine	Brandon	Sub-bituminous coal	Powder River Basin, Montana	No	0.85	30	89,400	5%	84,900
IGCC	570	Coal-fed Integrated Gasification Combined Cycle system	Brandon	Sub-bituminous coal	Powder River Basin, Montana	No	0.85	30	127,300	5%	120,900
Biomass[3]	25	Flax straw boiler + steam turbine	Southwest Manitoba	Flax straw	Farms in Southwest. Manitoba	No[4]	0.95	30	6,200	5%	5,900
Natural Gas (NG) Simple Cycle	250	Two 125 MW gas turbines	Brandon	Natural gas	Alberta	No	0.95	30	62,400	5%	59,300
Natural Gas (NG) Combined Cycle	250	One 250 MW gas + steam combined cycle system	Brandon	Natural gas	Alberta	No	0.93	30	61,100	5%	58,000
Wind	50	Thirty 1.65 MW turbines	Southwest Manitoba	n/a	n/a	No[4]	0.35	30	4,600	5%	4,400

[1] 'Operating Factor' refers to the fraction of time during which a facility is available to generate electricity at 100% of total capacity (i.e. not restricted by maintenance or fuel supply limitations). In fact, many facilities may not be operated during the entire time that they are available. This would lead to a lower annual and lifetime electricity output than is shown in the table, and would tend to increase the life cycle emissions and land change calculated for 'one-time' activities (e.g. facility construction) where impacts are averaged over the project life cycle.
[2] The Wuskwatim Hydro proposal includes 300 km of new high-voltage transmission lines, connecting the generating station to the grid at Birchtree. The requirement for significant new transmission infrastructure is a result of the large capacity and remote location of the Wuskwatim facility.
[3] The *economic* viability of the biomass system is beyond the scope of this analysis. It is estimated that sufficient flax straw is produced in the province of Manitoba to fuel a 25 MW generating plant; however, it is not known whether (a) the opportunity costs of using flax straw for fuel production and (b) the actual costs of collecting and transporting the straw would fall within reasonable bounds.
[4] No specific site has been designated for the biomass and wind generating facilities. However, for this study, Manitoba Hydro has limited the set of possible locations to within 10 km of existing transmission lines. Thus, any additional transmission infrastructure required for these alternatives may be considered negligible.

2.0 Comparing Electrical Generation Systems

This analysis estimates the extent of GHG emissions and land change *that would be caused by producing 1 GWh of delivered electricity*[1] under each of the seven generation scenarios. Impacts are reported per GWh to facilitate comparison between systems which have different total instantaneous outputs of electricity (capacities), different average annual energy production and different project lifespans.

Although this type of analysis provides important insights, there are many limitations. In particular, it is important to note that a GWh of electricity is not equivalent in each system, since it cannot be generated under the same time and load specifications in each case. It is also critical to note that each electricity supply option *will not* generate an equivalent amount of electricity and that the options are not being considered as direct substitutes for one another.

Some of the operating factors that distinguish the various options are:

Capacity: The peak capacity of each option is different. For example, the wind option has a 50 MW peak output, while the pulverized coal option has a 400 MW peak output.

Dispatchability: With certain options, such as pulverized coal, a lengthy start-up period is required before the plant operates at full capacity. Thus, the system cannot be brought on-line and off-line "on demand," and is instead likely to be kept running continuously. In the wind option, generation levels depend on airflow speeds, which change throughout the day and cannot be controlled. By contrast, the hydropower and natural gas combustion technologies offer quick start-up times and are more flexible for supplying varying demands.

Fuel availability and stability: The certainty and reliability of fuel supply is different for each option. For instance, the power that can be generated by the Wuskwatim Hydro facility may vary from year to year, depending on annual rainfall. While combustion fuels are almost always available, their prices can vary significantly. Natural gas prices, for example, change continually, and have been relatively volatile in recent years. The price of coal, by contrast, has tended to be stable for many years.

Lifespan: The Wuskwatim Hydro project has an estimated lifespan of 100 years, while the other options have estimated lifespans of approximately 30 years.

[1] Delivered electricity refers to the amount of electricity that is supplied to consumers at their point of connection to the grid. This number is lower than the amount of electricity produced at generating plants due to losses during transmission. Assumptions regarding transmission losses are given in Table 1.1.

3.0 Life Cycle Greenhouse Gas Emissions

Emissions resulting from human activities, particularly the burning of fossil fuels, are increasing the atmospheric concentrations of several greenhouse gases (GHGs), notably carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). This process is enhancing the greenhouse effect, contributing to an overall warming of the Earth's surface.[1] In this analysis, the quantity of CO_2, CH_4, and N_2O emissions expected for each electricity supply option was estimated, and is reported in terms of CO_2 equivalents, or CO_2e.[2]

Sulphur hexafluoride (SF_6) is another, especially potent, greenhouse gas associated with electricity generation. In particular, SF_6 is used as an insulator in transformer equipment, and is currently deployed at several Manitoba Hydro facilities. However, expected emissions of SF_6 arising from the electricity options under study are low relative to emissions of CO_2, CH_4, and N_2O[3], and are not expected to vary significantly between the options. Thus, SF_6 emissions were not included as a quantitative component in the analysis.

3.1 Results

Table 3.1 presents the total greenhouse gas emissions associated with each electricity supply option considered, as well as the distribution of emissions across the various life cycle stages. Figure 3.1 presents these results graphically.

Life cycle greenhouse gas emissions were found to be highest for the two coal-fired options: 1,108 and 963 t CO_2e/GWh for the pulverized coal and IGCC cases, respectively. Emissions are lower for natural gas–fired generation, at 837 and 509 t CO_2e/GWh for the simple cycle and combined cycle cases, respectively. The lower emissions for the combined cycle option reflect the greater efficiency of this technology, and, in particular, the large difference between simple cycle and combined cycle efficiencies assumed in this study (see Table A1.1 for a list of assumed efficiencies). In all four cases, the operation stage of the life cycle accounts for the majority of emissions. Fuel combustion (electricity generation) is the largest contributor to emissions in this stage, although fuel extraction and fuel transportation are also significant. By contrast, emissions during the construction stage of the life cycle are insignificant, accounting for less than 0.05% of total emissions when normalized over the project lifespan in each case.

Emissions from the biomass option are an order of magnitude lower than in the fossil fuel options: 68 t CO_2e/GWh over the project life cycle. Again, the operation stage accounts for the majority of emissions, and fuel combustion (electricity generation) is the largest contributor to emissions in this stage. CO_2 generated during the combustion of biomass is *not* counted in the combustion emission totals, since the CO_2 released is assumed to be equivalent to the amount of CO_2 sequestered by photosynthesis when the biomass was grown. Instead, the fuel combustion emissions of 48 t CO_2e/GWh are comprised entirely of CH_4 and N_2O.

Life cycle emissions in the Wuskwatim Hydro and wind options are a further order of magnitude lower than the biomass option, and are the lowest among the alternatives considered in this study. Emissions are

---

[1] *Summary for Policy Makers: A Report of Working Group 1of the International Panel on Climate Change.* Geneva: IPCC, 2001.

[2] CH_4 and N_2O have 100-year global warming factors of 21 and 310 times that of CO_2, respectively. The combined effect of these emissions is presented as an equivalent of CO_2, or CO_2e.

[3] "VCR 2002 Update, Electricity and Natural Gas Operations." Manitoba Hydro. Electricity generation for 2001 was 32,000 GWh. Total SF_6 emissions were 5 kilotonnes for the same year. This equates to 0.156 t CO_2e/GWh and is considered to be relatively insignificant. SF_6 has a global warming capacity of 23,900 that of CO_2.

3.8 and 7.9 t CO_2e/GWh for the Wuskwatim Hydro and wind cases, respectively. In contrast to all of the other systems, the majority of emissions for hydroelectricity and wind are associated with the construction stage of the life cycle.

Results for the Wuskwatim Hydro option are subdivided further in Table 3.2 and Figure 3.2. Emissions are broken down into the four parts of the construction stage: building material manufacturing, building material transportation, on-site construction activities (equipment operation) and forest clearing. The analysis also separates emissions associated with building the dam and generating facility from emissions associated with building transmission lines. Significant new transmission infrastructure is an integral requirement for the Wuskwatim project because of the relatively large capacity (200 MW) of the facility and the remote location of the generating station. Under the assumptions used in this study, none of the other electricity supply options meets these dual criteria of large capacity and remote location, and thus no other project is said to require significant new transmission infrastructure.

The greatest quantity of GHG emissions in the Wuskwatim case is associated with forest clearing: 1.60 t CO_2e / GWh. The extent of GHG production due to forest clearing is difficult to predict, and depends on a multitude of factors such as the method of clearing and the fate of cleared vegetation (e.g. incineration, decay, or re-use in lumber products). Appendix 7 lists the factors assumed in this study, and provides a qualitative sensitivity analysis of the assumptions used.

The remaining emissions sources during the construction phase are building material manufacturing – 1.19 t CO_2e / GWh, on-site construction activities (fuel combustion for equipment operation) – 0.33 t CO_2e / GWh, and building material transportation – 0.08 t CO_2e / GWh.

During facility operation, two sources of GHG emissions are significant in the Wuskwatim Hydro option: manufacturing and transport of replacement parts – 0.20 t CO_2e / GWh, and CO_2 and CH_4 emissions from the dam reservoir – 0.20 t CO_2e / GWh. Reservoir emissions are highly uncertain, and depend heavily on the particular morphology and geography of the flooded area. Assumptions used in calculating the reported emissions figures are presented in Appendix 7.

Table 3.1 Life Cycle GHG Emissions per Unit of Delivered Power for Each Electricity Supply Option

Electricity Supply Option	Life Cycle GHG Emissions per Unit of Delivered Power (t CO_2e/GWh)					Total Life Cycle GHG Emissions (kt CO_2e)				
	Construction[1]	Operation			Total	Construction[1]	Operation			Total
		Fuel Extraction	Fuel Transportation	Electricity Generation			Fuel Extraction	Fuel Transportation	Electricity Generation	
Wuskwatim Hydro	3.35	0	0	0.4	**3.8**	460	0	0	56	520
Pulverized Coal	0.32	31	85	992	**1,108**	27	2,600	7,220	84,200	94,100
IGCC	0.32	27	75	860	**963**	39	3,270	9,100	104,000	116,000
Biomass	0.29	11.5	8.2	48	**68**	1.7	68	48	280	400
NG Simple Cycle	0.18	124	68	644	**837**	11	7,370	4,050	38,200	49,600
NG Combined Cycle	0.18	76	42	392	**509**	11	4,390	2,410	22,740	29,600
Wind	7.7	0	0	0.1	**7.9**	34	0	0	0.5	34

Table 3.2 Breakdown of Life Cycle GHG Emissions for the Wuskwatim Hydro Option

Facility Component	Life Cycle GHG Emissions per Unit of Delivered Power (t CO_2e/GWh)					
	Construction				Operation	Total
	Building Material Manufacturing	Building Material Transportation	On-site Construction Activities (Equipment Operation)	Forest Clearing	Electricity Generation	
Generating Station	1.19	0.07	0.30	0.18	0.41[2]	2.15
Access Road	0	0	0[2]	0.41	0	0.41
Transmission Lines	0.14	0.01	0.03	1.01	0	1.19
Total	1.32	0.08	0.33	1.60	0.41	**3.8**

[1] Construction emissions cover: (i) construction material manufacturing, (ii) construction material transportation, and (iii) on-site construction activities (equipment operation). In the case of the Wuskwatim Hydro option, construction emissions also include (iv) carbon loss from tree clearing (to build the generating facility as well as transmission lines). Tree clearing is insignificant in all other systems.

[2] Electricity generation emissions in the Wuskwatim Hydro case are due to equipment replacement (0.20 t / GWh) and to reservoir carbon dioxide and methane emissions (0.20 t / GWh)

[3] Equipment operation emissions associated with building the access road are included in the Generating Station figure, 0.30 t / GWh.

Figure 3.1 Life Cycle GHG Emissions per Unit of Delivered Power for Each Electricity Supply Option

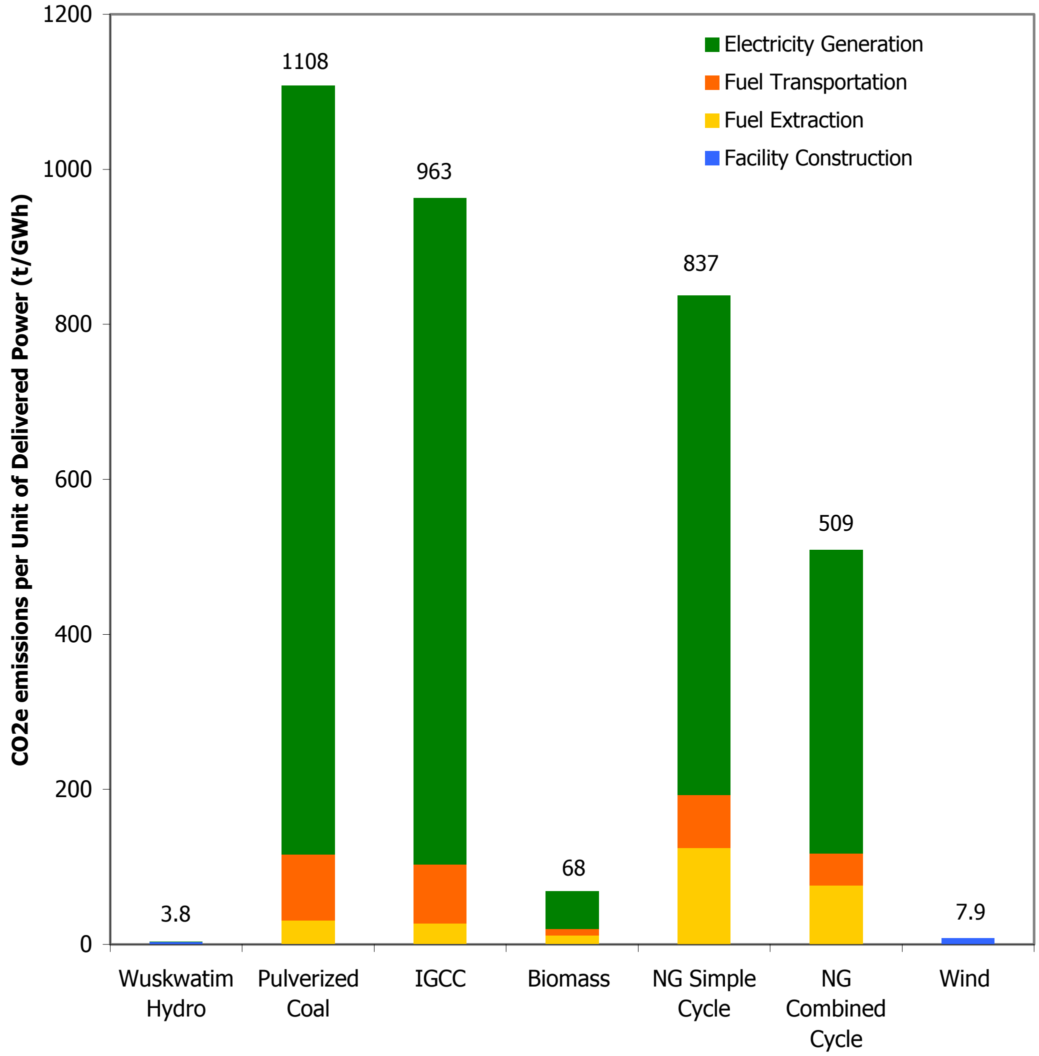
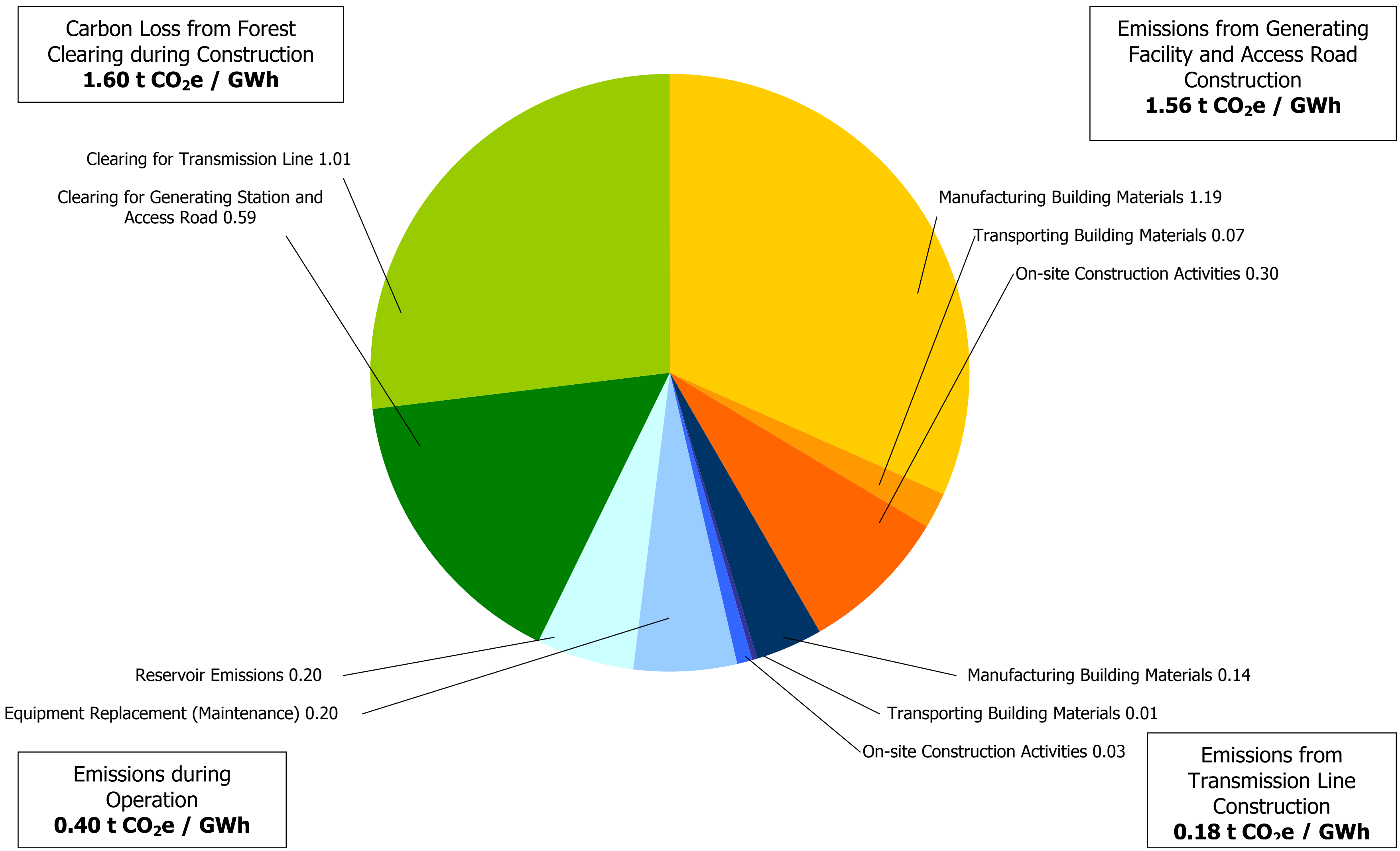


Figure 3.2 Breakdown of Life Cycle GHG Emissions per Unit of Delivered Power for the Wuskwatim Hydro Option (t CO_2e / GWh)



4.0 Life Cycle Land Change

Land impacts may include effects on existing land uses, on the suitability of land for future use, on the environmental quality of land, and on wildlife habitat, etc. However, the varied nature of land and the nebulous concept of "impacts" makes the quantification of land impacts inherently difficult. This analysis focuses on one aspect of land impact – namely, land change – to give a preliminary indication of how each of the seven electricity options would affect land. For each system, the analysis estimates land change as the total area of land whose surface characteristics would be altered at any point during the project life cycle. Land change is reported both in hectares (ha) and in the normalized units of m^2/GWh of delivered electricity.

4.1 Results

Table 4.1 presents the land change associated with each electricity supply option considered in this study. The results are subdivided into construction-related and operation-related land change. Figure 4.1 presents these results graphically, indicating the type of land (e.g. forest, farmland) changed.

Construction-related activities include: (i) off-site manufacturing of building materials, (ii) building material transportation, and (iii) on-site construction activities including forest clearing. Off-site building material production is expected to have negligible land change effects. No new production infrastructure (e.g., new manufacturing facilities) is expected for any of the projects assessed, and a proportional allocation of land change caused by *existing* production infrastructure is generally insignificant.[1] Transportation of building materials is expected to cause negligible land change for the same reasons: no new transportation infrastructure is expected, and a proportional allocation of land change caused by *existing* infrastructure is insignificant. Thus, on-site facility construction accounts for the majority of construction-related land change.

Operation-related activities include: (i) fuel extraction, (ii) fuel transportation, and (iii) on-site electricity generation. Fuel transportation is expected to cause minimal land change for the same reasons as building material transportation, outlined above. On-site power generation makes use of facilities built during construction and affects no more land than has already been changed. Thus, fuel extraction accounts for the majority of land change in the operation stage of the project life cycles.

Life cycle land change is found to be greatest for the two natural gas–fired options, at 1,070 m^2/GWh and 650 m^2/GWh for the simple cycle and combined cycle options, respectively. The impact occurs almost entirely (more than 99.9%) in the fuel extraction step, during natural gas exploration and well development. Land change is lower for the Wuskwatim Hydro option, at 200 m^2/GWh. In this case, however, all of the land change occurs during the on-site construction step of the life cycle. Of the total, 130 m^2/GWh (65%) of land change is caused by construction of transmission lines and transmission right-of-ways, 65 m^2/GWh (33%) is caused by construction of the generating station and an access road, and 3 m^2/GWh (2%) is caused by flooding.

Land change caused by the two coal-fired options is an order of magnitude lower than the natural gas and Wuskwatim Hydro options. The altered area is 31 m^2/GWh and 28 m^2/GWh for the pulverized coal and IGCC options, respectively. Most of the land change (about 99%) occurs during the fuel extraction step – surface mining in the Powder River Basin of Montana.

[1] Existing facilities supply numerous customers, or even entire markets, and since the required project materials are very small relative to a given facility's total output, each project is only responsible for a small fraction of that facility's impacts.

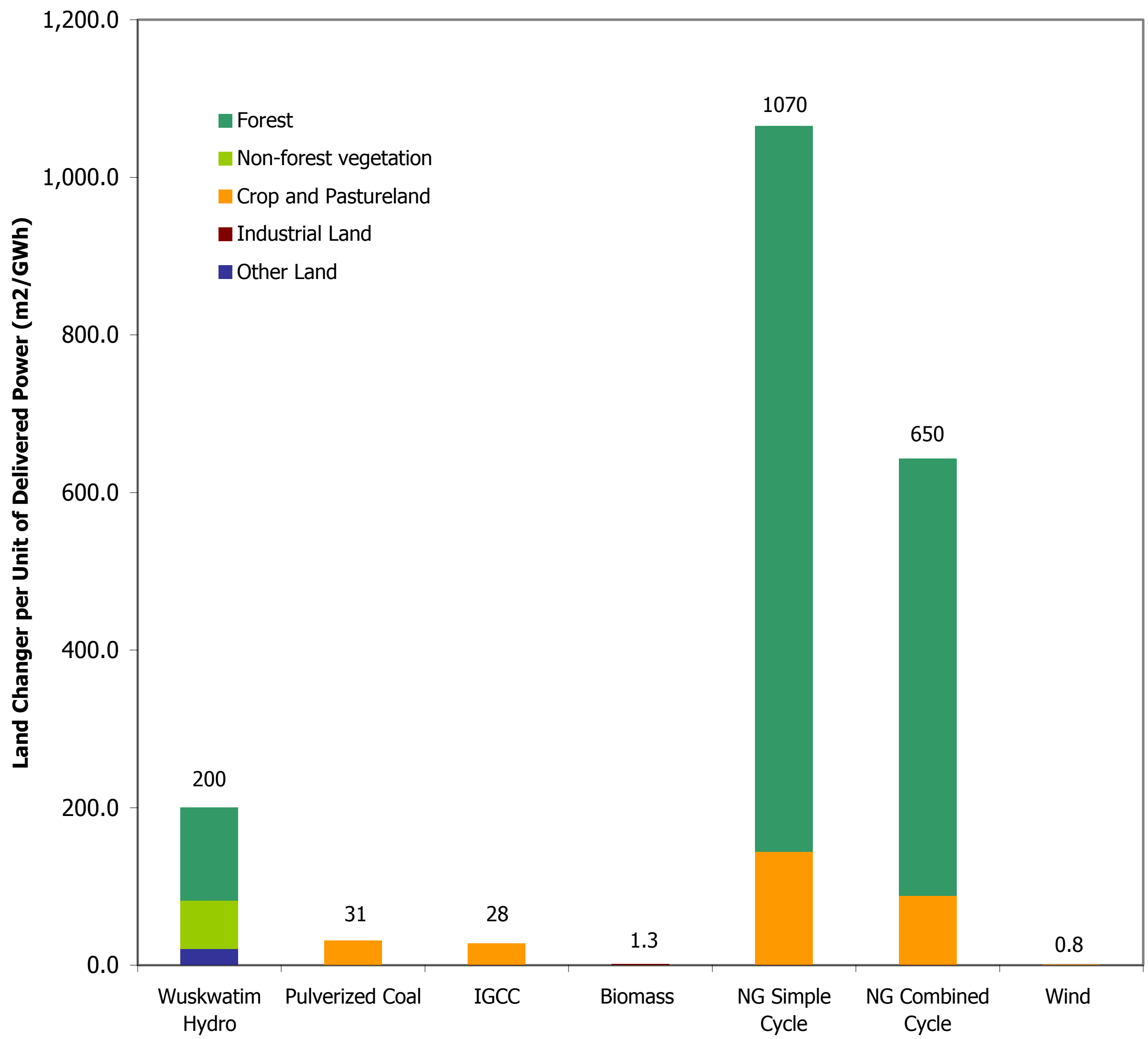
Life cycle land change is lowest for the biomass and wind options, a further order of magnitude lower than the two coal alternatives. The altered area is 1.3 m^2/GWh and 0.8 m^2/GWh for the biomass and wind options, respectively. In both cases, land change is entirely due to construction of the generating facility. However, although there is no land *change* caused by fuel extraction in the biomass system, a large area of farmland would be required to supply adequate quantities of fuel for the boiler. This area is two orders of magnitude larger than even the natural gas simple cycle land change result, at 235,000 m^2/GWh.

Table 4.1 Life Cycle Land Change for Each Electricity Supply Option

Electricity Supply Option	CONSTRUCTION-RELATED					OPERATION-RELATED					TOTAL	
	Activity	Area of Land Change (ha)	Area of Land Change per Unit of Power Delivered (m^2/GWh)	Original Land Type	Changed Land Type	Activity	Area of Land Change (ha)	Area of Land Change per Unit of Power Delivered (m^2/GWh)	Original Land Type	Changed Land Type	Area of Land Change (ha)	Area of Land Change per Unit of Power Delivered (m^2/GWh)
Wuskwatim Hydro	Build Generating Facility	84	6.1	Forest	Cleared withGeneration Infrastructure			n/a			2,720	**200**
		330	24	Forest	Temporarily Disturbed and/or Cleared During Construction							
	Build Access Road	324	24	Forest	Cleared with Access Road							
		158	11.5	Non-forest Vegetation	Cleared with Access Road							
	Flood Forebay Area	34	2.5	Forest	Cleared, then flooded							
		5	0.4	Peat Bogs	Flooded							
	Build Transmission Lines	850	62	Forest	Cleared withTransmission Infrastructure							
		680	50	Non-forest Vegetation	Cleared with Transmission Infrastructure							
		260	20	Other	Cleared with Transmission Infrastructure							
Pulverized Coal	Build Generating Facility	4	0.5	Vacant Industrial Land	Generation Infrastructure	Mine Coal	263	31	Crop and Pasture Land	Coal Pits, Mine Infrastructure	270	**31**
IGCC	Build Generating Facility	4	0.3	Vacant Industrial Land	Generation Infrastructure	Mine Coal	332	27	Crop and Pasture Land	Coal Pits, Mine Infrastructure	340	**28**
Biomass	Build Generating Facility	0.8	1.3	Crop and Pasture Land	Generation Infrastructure	Grow and Harvest Flax Straw	0[1]	0[1]	Crop Land	Crop Land	0.8	**1.3**
NG Simple Cycle	Build Generating Facility	2	0.3	Vacant Industrial Land	Generation Infrastructure	Extract NG	5,470	840	Forest	Cleared Right-of-ways, NG Extraction Infrastructure	6,320	**1,070**
							850	230	Crop and Pasture Land	NG Extraction Infrastructure		
NG Combined Cycle	Build Generating Facility	2	0.3	Vacant Industrial Land	Generation Infrastructure	Extract NG	3,250	530	Forest	Cleared Right-of-ways, NG Extraction Infrastructure	3,760	**650**
							510	120	Crop and Pasture Land	NG Extraction Infrastructure		
Wind	Build Generating Facility	0.3	0.8	Crop and Pasture Land	Generation Infrastructure			n/a			0.3	**0.8**

[1] Flax straw fuel would be supplied by existing flax farming operations in the biomass system. Hence, the area of *changed* land associated with this fuel extraction step is zero: the farmland would continue to be used as farmland. However, a very large area of existing farmland would be required to supply adequate fuel: 139,000 ha in total, or roughly 235,000 m^2/GWh of electricity.

Figure 4.1 Life Cycle Land Change per Unit of Delivered Power for Each Electricity Supply Option



4.2 Qualitative Analysis of Land Change Patterns

In trying to reach a more complete understanding of the overall land impacts of each project, many additional factors need to be studied alongside the area of land altered. For instance, what were the land characteristics before any changes took place? How would the altered land be spatially distributed – would the impact be concentrated in a small area, or spread out in patches over a larger area? What would the effect on surrounding land be? On wildlife? On nearby communities? Would the alteration be permanent? If not, would the land be restored to its original state? How long would restoration take?

In short, several qualitative aspects of a given land change need to be considered, including the exact nature of the affected land and its ecosystem, the time scale of change, and indirect or cumulative effects of the impact. Although addressing these issues comprehensively is beyond the scope of this report, two qualitative analyses have been included to begin a discussion on these topics. Table 4.1 above provides some background on the characteristics of affected land, both before and after alteration. Figures 4.2 and 4.3 on the following pages illustrate patterns of land impact for each system – i.e., how changed areas would be situated within surrounding land. From the illustrations, it is clear that altered land is more concentrated in some systems and more fragmented in others. In particular, land change due to fuel extraction in the natural gas systems is spread out over large areas of forest and farmland in Alberta. These areas, estimated at 25,000 m^2/GWh and 15,000 m^2/GWh for the natural gas simple cycle and combined cycle options, respectively, are far greater than direct land change areas calculated for any of the other systems studied.

Figure 4.2 Construction-Related Land Change – Illustration of Impact Patterns

The schematic illustrations on this page depict how changed land is situated within surrounding land types. Changed land is represented in all cases as white, with a uniform scale across illustrations. Therefore, the size of white spaces in each illustration can be compared across systems to determine the relative magnitudes of land change in each case.

In this figure, each mm^2 of white space represents 1.3 m^2/GWh of changed land. (Note: this is a different scale from Figure 4.3.) The amount of surrounding land, however, is only **approximately** scaled on this figure (on a per GWh basis) to give a sense of the area over which land changes may be spread. The areas of surrounding land have **not** been analytically quantified.

Wuskwatim Hydro

Changed land totals 200 m^2/GWh, and is comprised of the following:

- (i) Land flooded to create a reservoir for the generating station (3 m^2/GWh)
- (ii) Land cleared for the generating station, or disturbed during construction (30 m^2/GWh)
- (iii) Land cleared for the access road (35 m^2/GWh)
- (iv) Land cleared for transmission line right-of-ways (130 m^2/GWh)

(i) The generating station would require some flooding of the banks of the Burntwood River, upstream of Taskinigup Falls. The changed land (white) is largely forest that would be cleared and then flooded, and is depicted as two narrow strips on either side of a river (blue), at the top of the illustration.

(ii) Land affected by the Wuskwatim generating station and borrow pits would be largely forest land. The land would be concentrated in two or three areas near Taskinigup Falls, and is depicted as a white block in the illustration. The borrow pits and construction areas (24 m^2/GWh) would be restored and reforested when construction is complete. The generating site (6 m^2/GWh) would remain cleared throughout the 100-year project life.

(iii), (iv) The access road and transmission lines would require long, narrow right-of-ways: roughly 100 m by 48 km for the road, and 60 m by 300 km for the transmission lines. The right-of-ways would pass through a mixture of forest land (dark green) and non-forest vegetation (light green), and would remain largely cleared throughout the 100-year project life. Some borrow material for the roadbed would be obtained from the right-of-way clearing. For simplicity, the two right-of-ways are combined on the diagram. Additionally, the two land types (forest and non-forest vegetation) are shown as distinct blocks, although, in reality, the land types would be interspersed.

Pulverized Coal

Changed land is simply the land used to build a generating facility. This is assumed to be a parcel of industrial land adjacent to the current Brandon generating complex, totaling 0.4 m^2/GWh. The site would be surrounded by other industrial park land.

IGCC

Changed land is simply the land used to build a generating facility. This is assumed to be a parcel of industrial land adjacent to the current Brandon generating complex, totaling 0.3 m^2/GWh. The site would be surrounded by other industrial park land.

Biomass

Changed land is simply the land used to build a generating facility. This is assumed to be a parcel of crop and pasture land in rural Southwest Manitoba, totaling 1.3 m^2/GWh. The site would be surrounded by other crop and pasture land

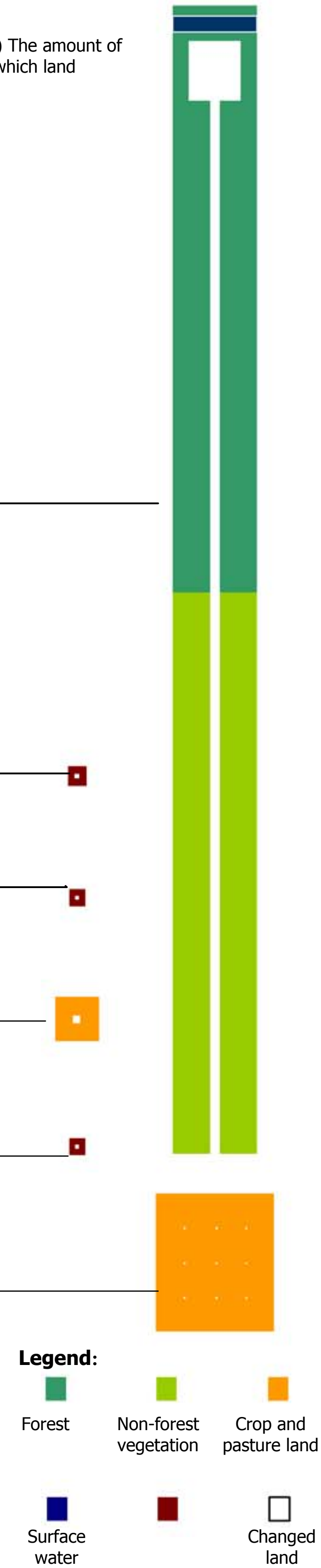
NG Simple Cycle & Combined Cycle

For both scenarios, changed land is simply the land used to build a generating facility. This is assumed to be a parcel of industrial land within the current Brandon generating complex, totaling 0.3 m^2/GWh. The site would be surrounded by other industrial park land.

Wind

Changed land (depicted as small white dots) totals 0.7 m^2/GWh and comprises the foundations for individual wind turbines. These would be spaced out across a much larger farm area, about 370 m^2/GWh for a typical rectangular grid arrangement of turbines, spaced 200 m apart.

Depending on the location of the wind farm, a new access road may also be needed. The road right-of-way would likely replace crop and pasture land. Assuming a 10 m width for the right-of-way, each km of road would cause a land type change equivalent to 2.3 m^2/GWh. This land change has not been included in the quantitative analysis, since the wind scenario does not specify a wind farm location or road length.



Scale: The white "changed land" square in the legend represents 10 m^2/Gwh.

Figure 4.3 Operation-Related Land Change – Illustration of Impact Patterns

The schematic illustrations on this page depict how changed land is situated within surrounding land types. Changed land is represented in all cases as white, with a uniform scale across illustrations. Therefore, the size of white spaces in each illustration can be compared across systems to determine the relative magnitudes of land change in each case. In this figure, each mm^2 of white space represents 7.5 m^2/GWh of changed land. (Note: This is a different scale from Figure 4.2.) The amount of surrounding land has been drawn to the same scale. An explanation of how surrounding land has been defined and quantified is given below for each system.

Legend:

Forest | Crop and pasture land | Changed land

Scale: The white "changed land" square in the legend represents 75 m^2/GWh.

Wuskwatim Hydro

There would be no land change associated with fuel extraction in the Wuskwatim Hydro proposal. Land change associated with constructing generating and transmission facilities is illustrated in Figure 4.2.

Pulverized Coal

Changed land (depicted as a white box) is comprised of coal pits and infrastructure concentrated in a few sections of a larger designated mine lease in the Powder River Basin of Montana. The mine lease that surrounds the changed land is grassland and pasture land (orange). For the mine considered in this study, Spring Creek Mine, the area of changed land would be 31 m^2/GWh. The area of the surrounding mine lease would be about 88 m^2/GWh.

IGCC

Like the pulverized coal system, changed land (depicted as a white box) in this case occurs within a larger mine lease. The mine lease that surrounds the changed land is grassland and pasture land (orange). For the mine considered in this study, the area of changed land would be 28 m^2/GWh. The area of the surrounding mine lease would be about 79 m^2/GWh.

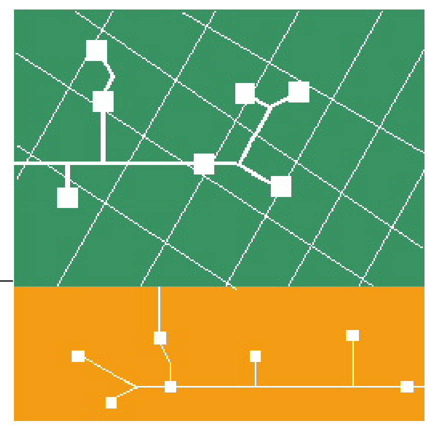
NG Simple Cycle

Changed land (white) totals 1,070 m^2/GWh and is associated with exploration for natural gas and well development in Alberta. Natural gas extraction occurs on both forest land (green) and crop and pasture land (orange) in the province.

In forest areas, trees are cleared for seismic surveys (thin diagonal lines), drilling pads (square blocks), and right-of-ways for access roads and gas collection pipes (thick lines). All cleared area is considered to be changed land. Forest begins to regrow on some of this land immediately (e.g., seismic lines), since clearing is only needed for a one-time exploration task. Other areas of land (e.g., around a well, collection pipe, or right-of-way) are kept cleared throughout the well's life (10 to 30 years), and trees are left to regrow only after this infrastructure is decommissioned.

In crop and pasture land areas, no clearing is necessary for exploration. Here, land change occurs only when farmland is cordoned off to make way for well-pads (square blocks) or roads and collection pipes (thick lines). This land change lasts at least as long as the infrastructure is in service.

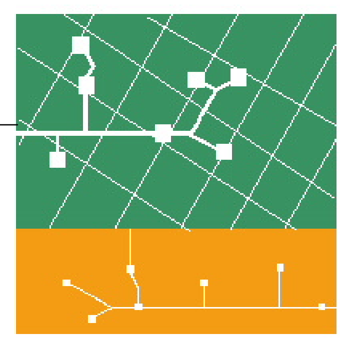
The pattern and density of clearing and infrastructure vary from region to region; a theoretical pattern is illustrated here as an example. On average, for natural gas originating in Alberta, about 80% of the gas would be produced from forest areas, and 20% from farm areas. Based on well productivity and typical infrastructure requirements in each region, this translates to about 840 m^2/GWh of changed land in forest areas, and 230 m^2/GWh of changed land in farm areas. Based on typical well densities for each region, the change due to forest wells would be spread out over about 16,300 m^2/GWh of forest, while the change due to farm area wells would be spread out over about 8,500 m^2/GWh of farmland.[1]



NG Combined Cycle

Impact patterns for the NG combined cycle scenario are equivalent to those in the NG simple cycle scenario, although total areas are smaller. Changed land (white) comprises about 530 m^2/GWh in forest areas and 120 m^2/GWh in farm areas. The change due to forest wells is spread over about 10,000 m^2/GWh of forest, while the change due to farm area wells is spread over about 5,200 m^2/GWh of farmland.[1]

[1] For a detailed calculation of land area changed during NG extraction, see Appendix, Section 7.



Biomass

Flax straw fuel would be supplied by existing flax farming operations in the biomass system. There would be no land **change** associated with this fuel extraction step – the farmland would continue to be used as farmland. However, a very large area would be involved: 139,000 ha in total, or roughly 235,000 m^2/GWh of electricity.

Wind

There would be no land change associated with fuel extraction in the wind system. Land change associated with constructing generating and transmission facilities is illustrated in Figure 4.2.

5.0 Conclusions

Seven prominent electricity supply options for the province of Manitoba have been compared on the basis of life cycle GHG emissions and land change per GWh of electricity delivered. These options include the proposed Wuskwatim Hydro generation and transmission project, as well as six hypothetical generation projects that use a variety of different fuels.

There are a number of key limitations to the analysis:
(i) a comparison of GHG emissions and land change per GWh delivered does not account for differences in generating system capacity and dispatchability, or in fuel availability and stability, which may influence the selection of generation technologies;
(ii) a quantitative assessment of GHG emissions and land change does not directly address the environmental and social implications of these factors, but rather provides a starting point for thinking about broader impacts;
(iii) a quantification GHG emissions which result from land change involves significant uncertainties, and has only been completed for the Wuskwatim Hydro option;
(iv) although demand-side management programs have not been included in the analysis, DSM options are often preferable to new generation capacity from a life cycle perspective.

Greenhouse gas emissions are found to be lowest for the Wuskwatim Hydro and wind options, at 3.8 t CO_2e/GWh and 7.9 t CO_2e/GWh, respectively. These emissions are more than two orders of magnitude lower than emissions expected from the fossil fuel–powered options, of which the pulverized coal option has the greatest emissions, at 1,108 t CO_2e/GWh.

The area of altered land is found to be lowest for the wind and biomass options, at 0.8 m^2/GWh and 1.3 m^2/GWh, respectively. (Note, however, that the biomass option requires the collection of agricultural residue from large areas of existing farmland to supply adequate fuel, amounting to about 235,000 m^2/GWh.) These land change results are more than two orders of magnitude lower than altered areas expected from the Wuskwatim Hydro option (200 m^2/GWh) or the natural gas simple cycle and combined cycle options (1,070 m^2/GWh and 650 m^2/GWh, respectively). For the two natural gas options, the altered land area is expected to be particularly fragmented and spread out over a large region, thus affecting an area even larger than reported in the land change totals.

Appendices

Appendix 1: Basic Operating Parameters for Each System

Table A1.1 Basic Operating Parameters for the Electricity Supply Proposals and Scenarios Under Analysis

Name of Electricity Supply Option	Capa-city (MW)	Technology	Operating Factor[a]	Project Life (years)	Lifetime Output (GWh)	Location	Fuel	Fuel Source	Heat Rate – HHV basis[b] (BTU/kWh)	Efficiency – HHV basis[b]	Requirement for New Transmission Infrastructure	Transmission Losses
Wuskwatim Hydro	200	Hydroelectric generating station	0.87	100	152,400	Taskinigup Falls	n/a	n/a	n/a	n/a	Yes	10 %
Pulverized Coal	400	Pulverized coal boiler + steam turbine	0.85	30	89,400	Brandon	Sub-bituminous Coal	Powder River Basin, Montana	9,294	36.7 %	No	5 %
IGCC	570	Coal-fed Integrated Gasification Combined Cycle system	0.85	30	127,300	Brandon	Sub-bituminous Coal	Powder River Basin, Montana	8,225	41.5 %	No	5 %
Biomass[c]	25[1]	Flax straw boiler + steam turbine	0.95	30	6,200	S.W. Manitoba	Flax Straw	Farms in S.W. Manitoba	13,600[2]	25.0 %[2]	No[d]	5 %
NG Simple Cycle	250	Two 125 MW gas turbines	0.95	30	62,400	Brandon	Natural Gas	Alberta	11,500	29.7 %	No	5 %
NG Combined Cycle	250	One 250 MW gas + steam combined cycle system	0.93	30	61,100	Brandon	Natural Gas	Alberta	7,000	48.8 %	No	5 %
Wind	50	Thirty 1.65 MW turbines	0.35	30	4,600	S.W. Manitoba	n/a	n/a	n/a	n/a	No[d]	5 %

Data Sources:

All parameter values provided by Manitoba Hydro, with the following exceptions:

[1] The capacity of a flax straw-fueled biomass facility is limited by the availability of flax straw in Manitoba. A capacity of 25 MW is close to the maximum capacity possible, given current straw supplies.

[2] Value chosen is typical for a biomass generating plant. Source: Wiltsee, G. *Lessons learned from existing Biomass Power Plants*. Golden, Colorado: National Renewable Energy Laboratory (NREL). 2000.

Additional Clarifications:

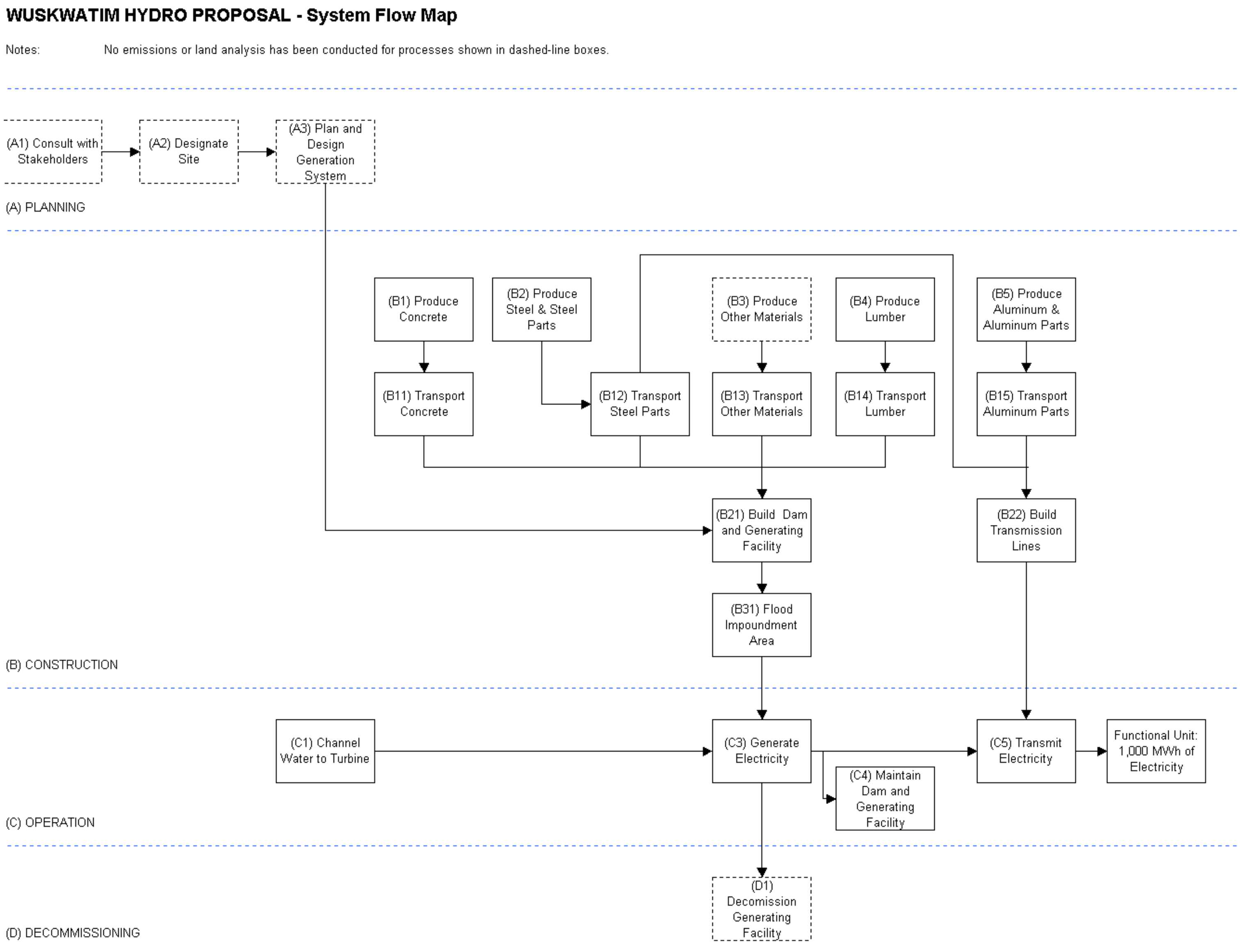
[a] "Operating factor" refers to the fraction of time during which the facility is able to generate electricity at 100% of total capacity. In the carbon-fueled options, an availability of less than 1 reflects operating limitations due to maintenance 'down-time'. In the Wind option, the relatively low availability factor reflects the fact that wind speeds are variable. In fact, many facilities may be operated for periods that shorter than the available limit. For instance, a Natural Gas Single Cycle plant may only be used to supply peak demand, and be run 30% rather than 95% of the time. If the availability factor is reduced, lifetime power production will also be reduced proportionally.

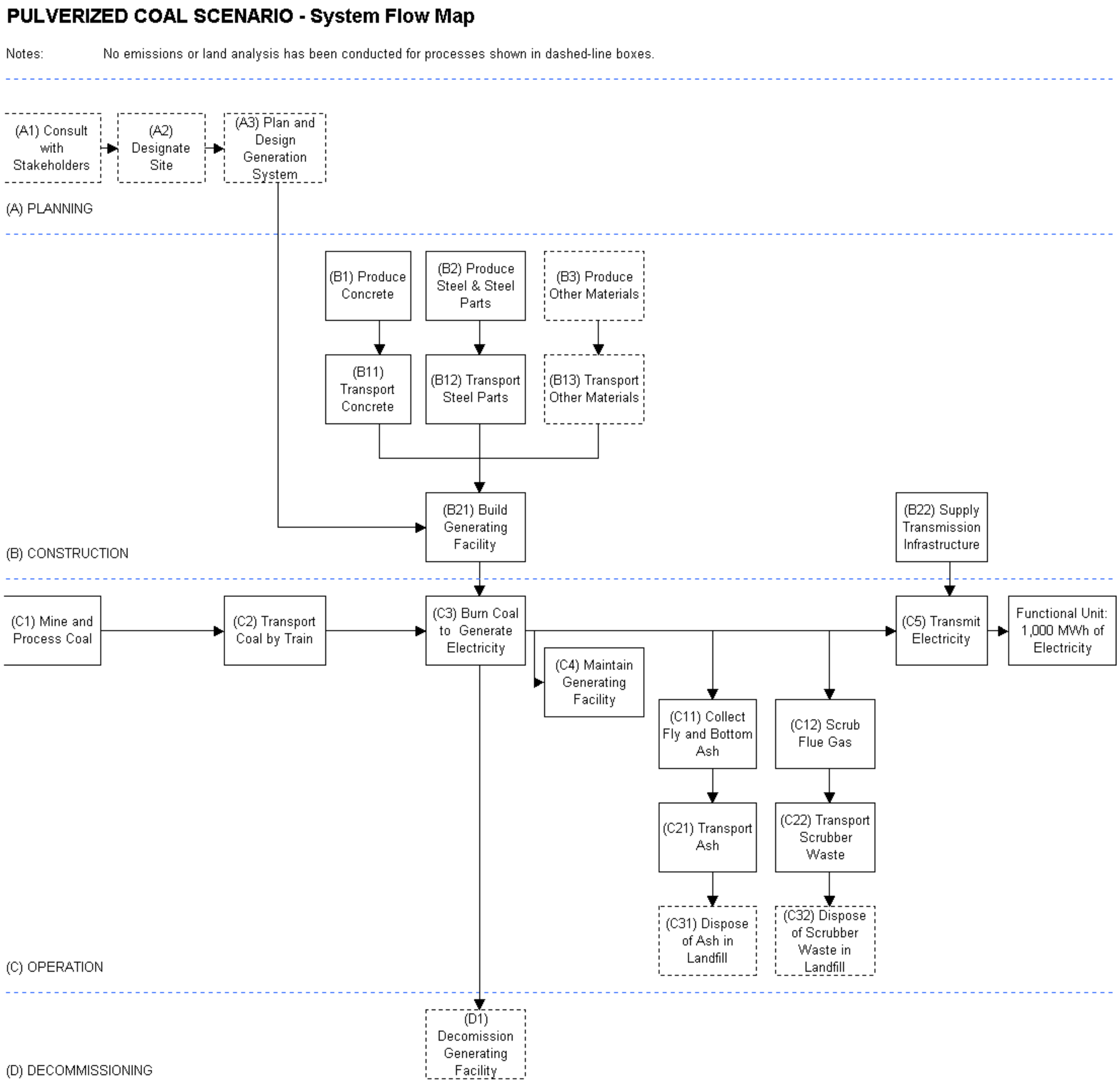
[b] Heat rates and efficiencies are expressed in terms of the Higher Heating Value (HHV) of carbon fuels throughout this report.

[c] The *economic* viability of the biomass system is beyond the scope of this analysis. It is estimated that sufficient flax straw is produced in the province of Manitoba to fuel a 25 MW generating plant, however it is not known whether (a) the opportunity costs of using the straw for fuel production, and (b) the actual costs of collecting and transporting the straw would fall within reasonable bounds.

[d] No specific site has been provided for the biomass and wind generating facilities. However, Manitoba Hydro has limited the set of possible sites to locations within 10 km of existing transmission lines. Thus, any additional transmission infrastructure required for these alternatives may be considered negligible.

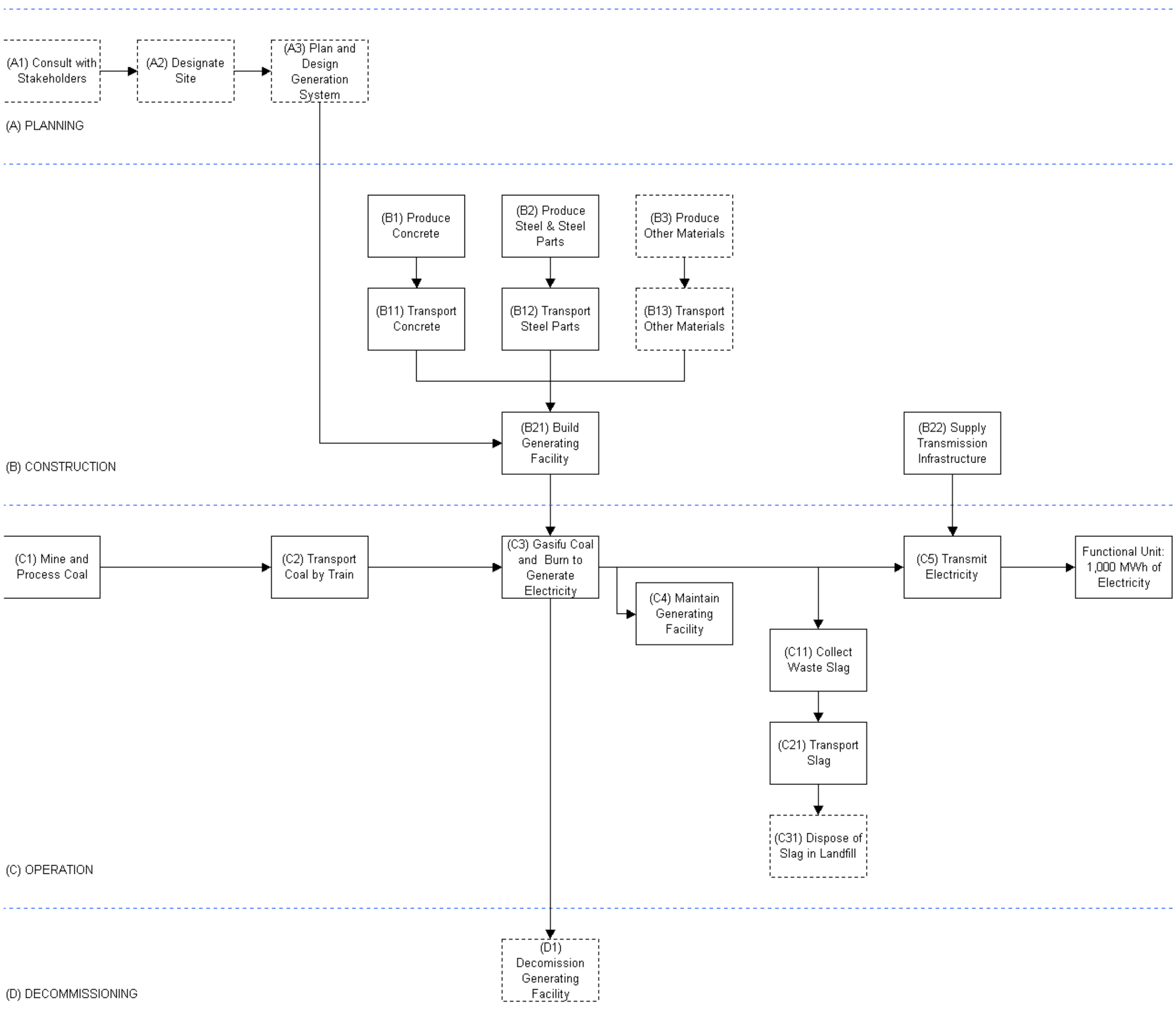
Appendix 2: System Flow Maps




PULVERIZED COAL SCENARIO - System Flow Map
Notes:
No emissions or land analysis has been conducted for processes shown in dashed-line boxes.
(A1) Consult with Stakeholders
(A2) Designate Site
(A3) Plan and Design Generation System
(A) PLANNING
(B1) Produce Concrete
(B2) Produce Steel & Steel Parts
(B3) Produce Other Materials
(B11) Transport Concrete
(B12) Transport Steel Parts
(B13) Transport Other Materials
(B21) Build Generating Facility
(B22) Supply Transmission Infrastructure
(B) CONSTRUCTION
(C1) Mine and Process Coal
(C2) Transport Coal by Train
(C3) Burn Coal to Generate Electricity
(C4) Maintain Generating Facility
(C5) Transmit Electricity
Functional Unit: 1,000 MWh of Electricity
(C11) Collect Fly and Bottom Ash
(C12) Scrub Flue Gas
(C21) Transport Ash
(C22) Transport Scrubber Waste
(C31) Dispose of Ash in Landfill
(C32) Dispose of Scrubber Waste in Landfill
(C) OPERATION
(D1) Decomission Generating Facility
(D) DECOMMISSIONING

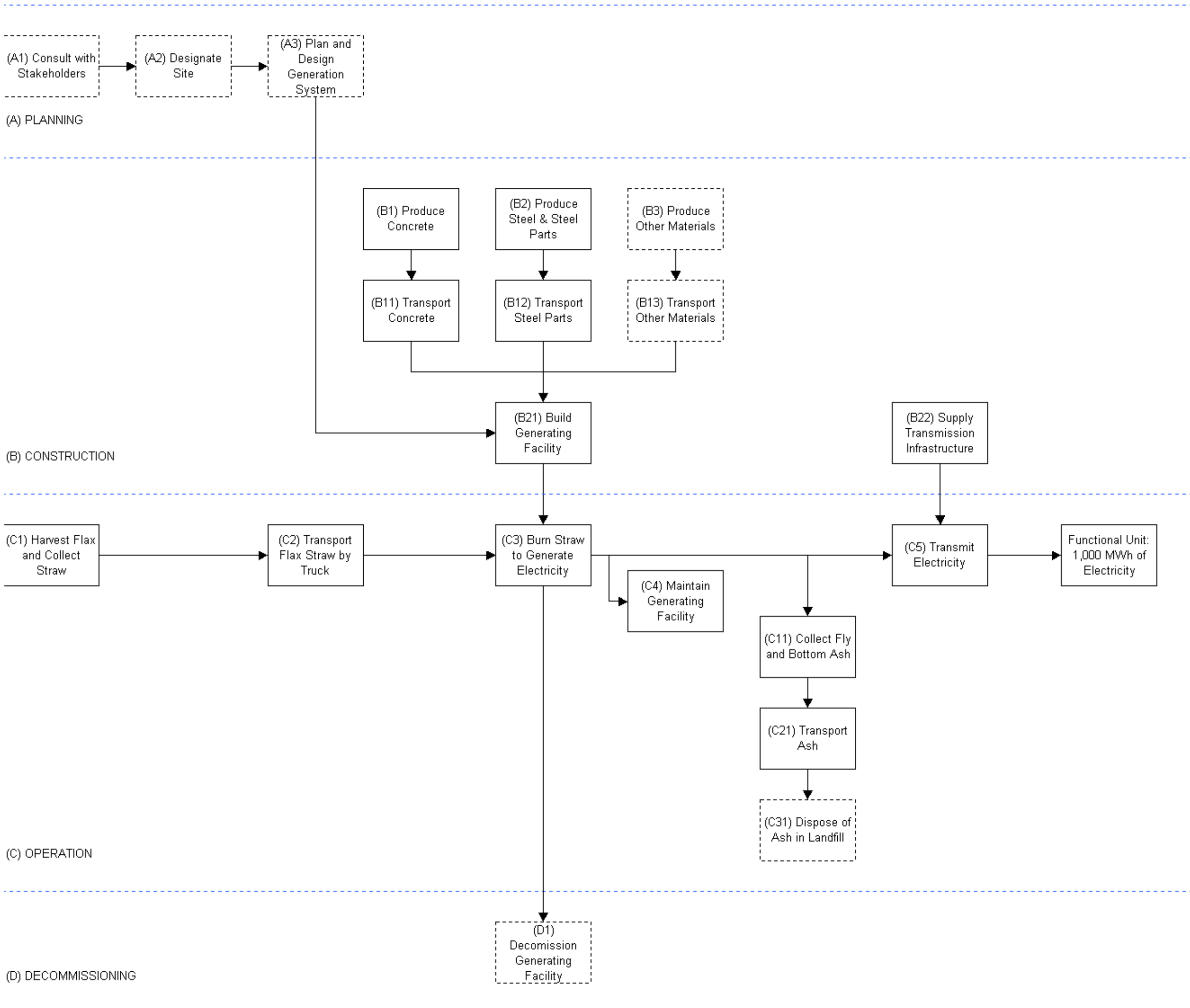
IGCC SCENARIO - System Flow Map

Notes: No emissions or land analysis has been conducted for processes shown in dashed-line boxes.



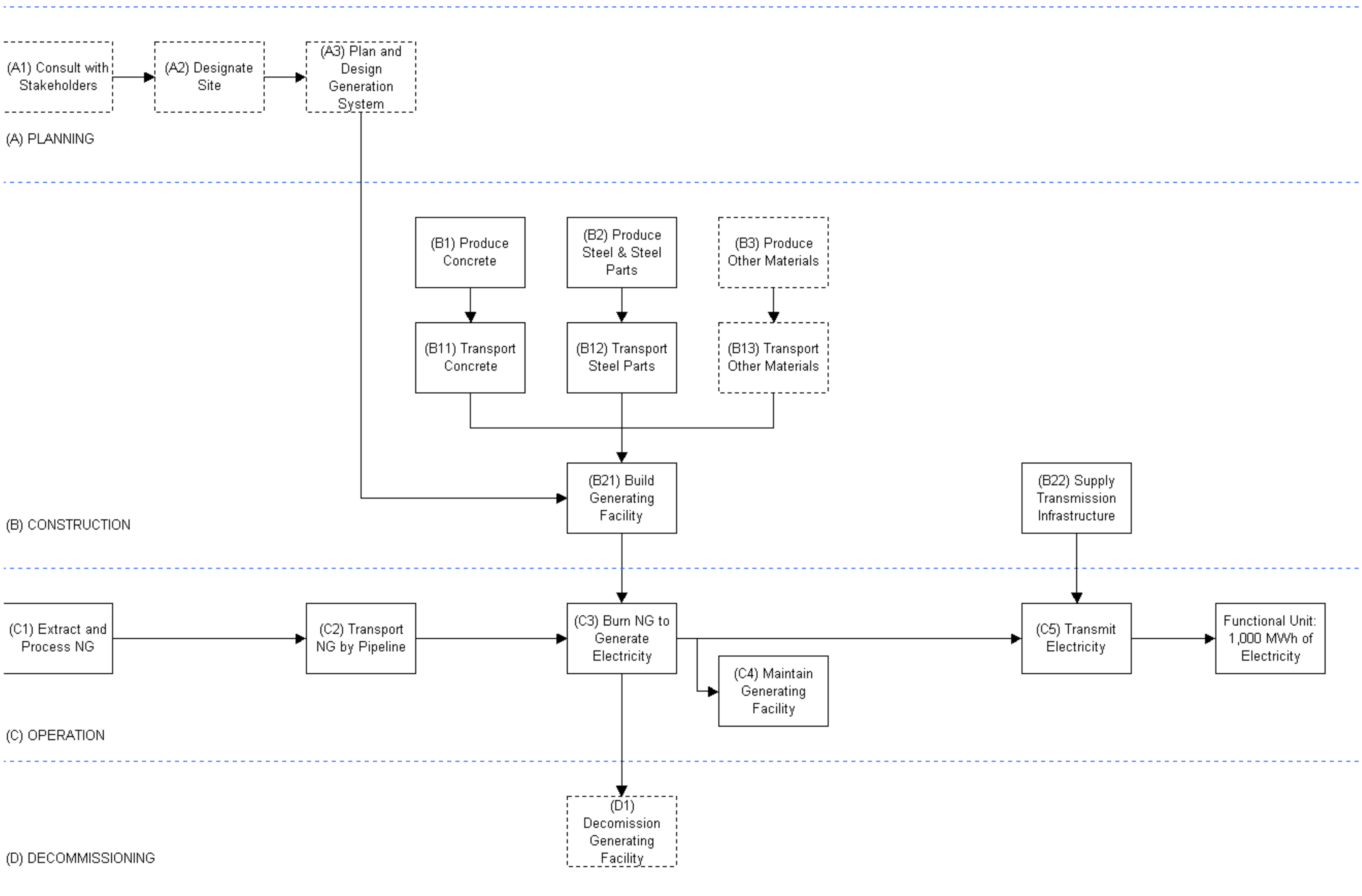
BIOMASS SCENARIO - System Flow Map

Notes: No emissions or land analysis has been conducted for processes shown in dashed-line boxes.



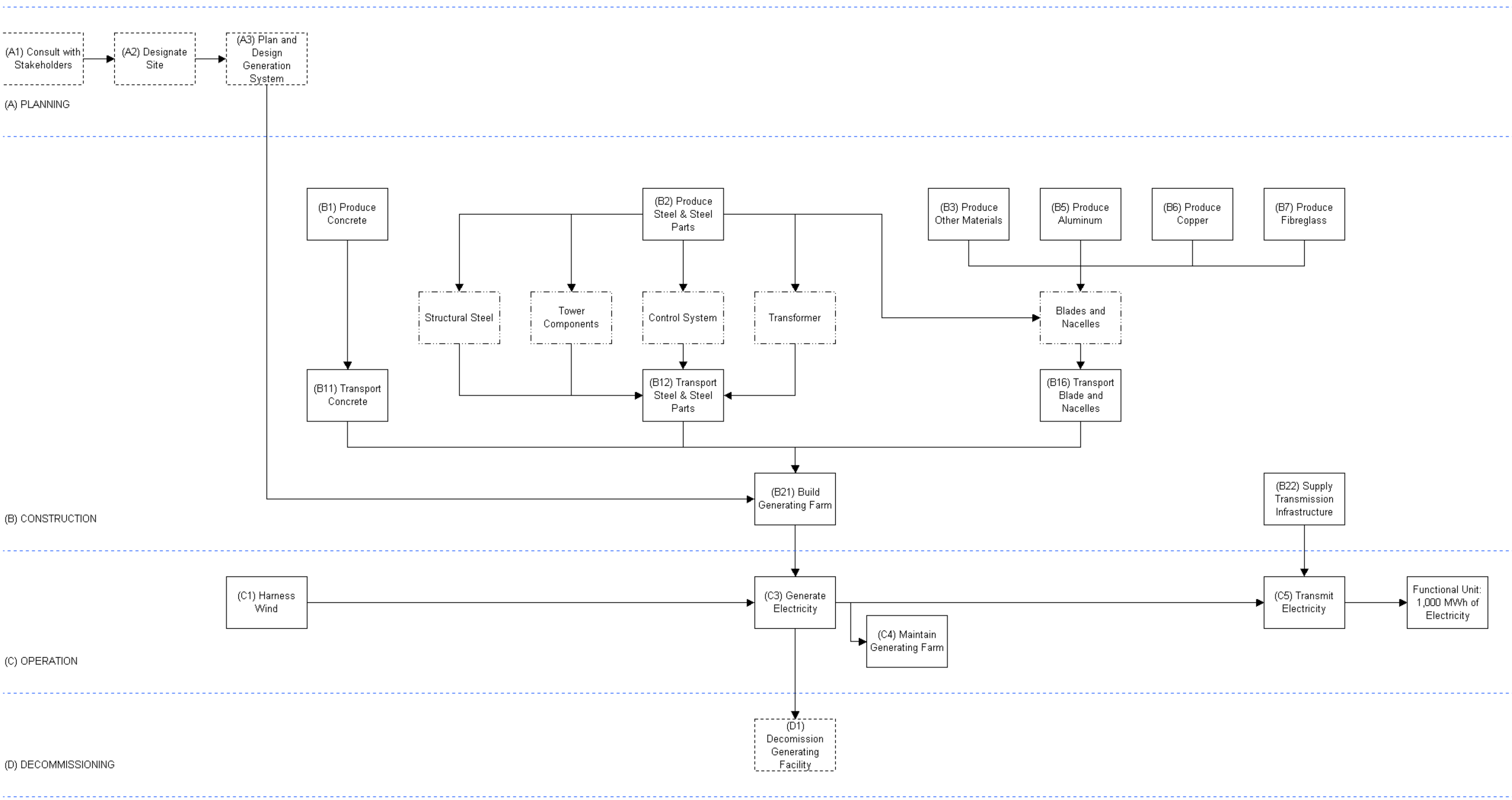
NG SIMPLE CYCLE and COMBINED CYCLE SCENARIOS - System Flow Map

Notes: No emissions or land analysis has been conducted for processes shown in dashed-line boxes.



WIND SCENARIO - System Flow Map

Notes: No emissions or land analysis has been conducted for processes shown in dashed-line boxes.



Appendix 3: Key Parameters and Assumptions Listed by System

Table A3.1 Key Parameters and Assumptions for the Wuskwatim Hydro Option

ID #	Process	GHG-related Parameter / Assumption → Rationale	Land Change-related Parameter / Assumption	→	Rationale
A1-A3	Planning	(No quantitative analysis conducted)	(No quantitative analysis conducted)		
B1-B5	Produce Building Materials	(See **Appendix 5** for building material quantities)	• Negligible land change	→	Would use only a small fraction of existing industrial infrastructure[a]
B11-B15	Transport Building Materials to Site	(See **Appendix 5** for transportation distances)	• Negligible land change	→	Would use only a small fraction of existing transportation infrastructure[a]
B21	Build Generating Facility	(See **Appendix 5** for fuel consumption quantities) (See **Appendix 7** for GHG emissions due to land impacts of facility construction)	Construction-related land change would occur in three areas: [i] Generating station land, [ii] Construction area and borrow pits, and [iii] Access road right-of-way:		
			• [i] Generating station would replace: 84 ha of forest Land would remain changed throughout 100-yr project life.	→	Current proposal for Wuskwatim generating station[1]
			• [ii] Construction camps and borrow pits would involve clearing and/or disturbing: 330 ha of forest Land is expected to be fully restored once construction is complete.	→	Current proposal for Wuskwatim generating station[1]
			• [iii] Access road right-of-way would replace: 324 ha of forest 158 ha non-forest vegetation[d] Land would remain changed throughout 100-yr project life.	→	Current proposal for Wuskwatim generating station[1]
B22	Build Transmission Lines	(See **Appendix 5** for fuel consumption quantities) (See **Appendix 7** for GHG emissions due to land impacts of transmission line construction)	• Transmission right-of-way would replace: 850 ha of forest 680 ha non-forest vegetation[d] 288 ha other land[e] Land would remain changed throughout 100-yr project life.	→	Current proposal for Wuskwatim generating station[1f]
B31	Flood Reservoir Area	(Reservoir emissions are accounted for in C3)	• TheWuskwatim reservoir would involve clearing, and then flooding: 34 ha of forest 5 ha peat bogs Land would remain changed throughout 100-yr project life.	→	Current proposal for Wuskwatim generating station[1]
C1	Channel Water to Turbine	(No direct impact on GHG emissions)	(Land change accounted for elsewhere)		Would occur on land already changed by flooding (B31), and generating facility construction (B21).
C3	Generate Electricity	(See **Appendix 7** for CO_2 and CH_4 emissions from the reservoir)	(Land change accounted for elsewhere)	→	Generation would occur on land already changed during facility construction (B21)

Table A3.1 Key Parameters and Assumptions for the Wuskwatim Hydro Option - Continued

ID #	Process	GHG-related Parameter / Assumption	→	Rationale	Land Change-related Parameter / Assumption	→	Rationale
C4	Maintain Facility	• Negligible emissions due to gasoline combustion in maintenance vehicles • Turbine and Generator would during project life	→ →	Based on data from Manitoba Hydro's Jenpeg generation station[g] Assumption	(Land change accounted for elsewhere)	→	Maintenance would occur on land already changed during generating facility construction (B21)
	Transmit Electricity	(No direct impact on GHG emissions)			(Land change account for elsewhere)	→	T ready c construction (B22)
D1	Decommission Generating Facility	(No quantitative analysis conducted)			(No quantitative analysis conducted)		

Data Sources:
[1] Data on land types and land areas has been obtained from preliminary work on the Wuskwatim project EIS. The information is provided by Manitoba Hydro.

Additional Clarification:
[a] If the Wuskwatim Hydro proposal uses some part of a facility, say x%, then it is responsible for x% of land change caused by that facility. In many cases, this land change is negligible since the percentage use (x) is negligible. For instance, plant construction may require just a few hundred trips on a highway is used for millions of trips over its lifetime.
[b] When forest is cleared, and felled trees are left to decay, carbon in the trees will be released to the atmosphere. If new trees are allowed to grow in the clearing, an equivalent amount of carbon will eventually be sequestered from the atmosphere. In the Wuskwatim proposal, there are two time-frames for clearing and re-growth:

Type (a) forest is cleared for construction, and reforested **during** the project life: borrow pits (696 ha)

Type (b) forest is cleared for construction, kept cleared throughout the 100 year project life, and reforested **after** project completion: Generating facility site (383 ha), access road right-of-way (311 ha), transmission line right-of-way (1340 ha).

For land type (a), since both clearing and re-growth occur during the project life, the net emission of CO_2 to the atmosphere is said to be 0.
For land type (b), since only clearing occurs during the project life, the net emission of CO_2 is said to be equal to emissions caused by clearing: 186 t / ha. [2]
(In fact, the transfer of carbon to the atmosphere in both cases is non-zero, but temporary. In (a), carbon from felled trees remains in the atmosphere for a relatively short period of time until new trees regrow (30-50 years), resulting in a relatively smaller impact on the environment. In (b), carbon remains in the atmosphere for a relatively longer period (> 100 years), with a greater impact on the environment).
[c] The analysis assumes that trees are a significant source of carbon, while other vegetation is not. Thus, any clearing of land with non-forest vegetation (i.e. grassland, fens, bogs) releases negligible quantities of CO_2 to the atmosphere. Similarly, any low vegetation (shrubs, grasses) which grows on cleared land involves only a negligible CO_2 uptake from the atmosphere and does not affect net CO_2 emissions significantly.
[d] Non-forest vegetation refers to fens, bogs, and grasslands.
[e] Other land refers to exposed rock, bare mineral soil and surface water
[f] The transmission line includes three segments. Two segments would be built only if the Wuskwatim generating station is completed. The third segment has been independently planned and is expected to be required whether or not the Wuskwatim project comes on-line The segment will, however, be built two years early if Wuskwatim is commissioned. This segment is not included in the land change totals since the one-time land change cannot be directly attributed to Wuskwatim. As a result, there are also no GHG implications of the land change caused by this segment's construction.
[g] Emissions from vehicle operation at the Jenpeg generating station (97 MW) are 0.003 t CO_2e / GWh. Assuming linear scaling of maintenance emissions with generating station capacity, estimated emissions for the Wuskwatim Hydro project (200 MW) are 0.006 t CO_2e / GWh. This is equivalent to ~ 0.1 % of total emissions for the Wuskwatim Hydro project (5.9 t CO_2e / GWh), and is considered negligible.

Table A3.2 Key Parameters and Assumptions for the Pulverized Coal Option

ID #	Process	GHG-related Parameter / Assumption	→	Rationale	Land Change-related Parameter / Assumption	→	Rationale
A1-A3	Planning				(No quantitative analysis conducted)		
B1-B3	Produce Building Materials	(See **Appendix 5** for building material quantities)			• Negligible land change	→	Would use only a small fraction of existing industrial infrastructure[a]
B11-B13	Transport Building Materials to Site	ansportation distances)			• Negligible land change	→	Would use only a small fraction of existing transportation infrastructure[a]
B21	Build Generating Facility	(See **Appendix 5** for fuel consumption quantities)			• Coal plant would occupy 10 acres of land in Brandon, adjacent to current MB Hydro generation site	→	As
B22	Build Transmission Lines		→	Only minimal new transmiss infrastructure would be required[6]	• Negligible land change		Only minimal new transmission infrastructure would be required[6]
C1		• Coal would be supplied by the Spring Creek mine in Montana (surface mine)	→	Current source of sub-bituminous coal for MB Hydro[b]	• 27.5 % of Spring Creek mine reserves would be required to supply fuel for the Pulverized Coal scenario	→	46,800,000 tons (US) of coal would be needed over the 30-yr project life[2]; 170,000,000 tons (US) of recoverable reserves exist at Spring Creek mine[3]
		• Emissions for coal mining at Spring Creek are equivalent to the U.S. average for surface mining		Best data available[1]	• Mines & mine infrastructure needed to provide coal for this scenario would larger, 750 ha mine lease	→	Area figures are 27.5 % of the totals for Spring Creek mine: 950 ha of impacted land within a
C2	Transport Coal	• Coal is transported 2030 km by train from Spring Creek to Brandon	→	Calculated from current routing of coal purchased by MB Hydro[5]		→	Would use only a small fraction of existing transportation infrastructure[a]
		• Coal haul losses during transport are 5%		Estimate used by NREL[1]			
C3	Burn Coal to Generate Electricity	(See **Appendix 6** for emissions factors)			(Land change accounted for elsewhere)	→	Generation would occur on land already
C4	Maintain Generating Facility	• Negligible emissions	→	Involves diesel/gas combustion to run coal combustion for power generation)	(Land change accounted for elsewhere)		Maintenance would occur on land already truction (B21)
C5	Transmit Electricity	(No direct impact on GHG emissions)			(Land change accounted for elsewhere)	→	Transmission would occur on land already changed during transmission line construction (B22)
C11	Collect Fly & Bottom Ash	• Negligible emissions	→	No fugitive emissions; involves diesel combustion to run equipment only (negligible compared to coal combustion for power generation)	(Land change accounted for elsewhere)	→	Ash disposal would occur on-site, on land already changed during facility construction (B21)

Table continued next page

Table A3.2 Key Parameters and Assumptions for the Pulverized Coal Option - Continued

ID #	Process	GHG-related Parameter / Assumption	→	Rationale	Land Change-related Parameter / Assumption	→	Rationale
C12	Scrub Flue Gases	• Emissions would be 4.4 t CO_2e / GWh, including: (i) fugitive emissions in the scrubber, (ii) emissions from upstream lime/limestone production.	→	Based on NREL data for Illinois No. 6 coal and typical scrubbing technology (best data available)[1c]	(Land change accounted for elsewhere)	→	Scrubbing would occur on land already changed during generating facility construction (B21)
	Transport Wastes to Landfill	• Ash disposed of on generating facility site • Scrubber waste transported 25 km to landfill	→ →	Current MB Hydro practice at Brandon Assumption	• Negligible land change	→	Would use only a small fraction of existing transportation infrastructure[a]
C31-C32	Dispose of Waste in Landfill	• Negligible emissions	→	No fugitive emissions; involves diesel combustion to run equipment combustion of coal for power generation)			Would use only a small fraction of existing waste disposal infrastructure[a]
	Decommission Generating Facility	(No quantitative analysis conducted)			(No quantitative analysis conducted)		

Data Sources:

[1] Spath, Pamela et al. *Life Cycle Analysis of Coal-fired Power Production*. Golden, Colorado: National Renewable Energy Laboratory (NREL). 1999.

[2] Result follows directly from basic operating parameters (Table A1.1) & assumed heat rates (Table A5.1) for the Pulverized Coal scenario: (1 t / 1000 kg) * (0.454 kg / 1 lb) * (1 lb coal mined / 0.95 lb coal delivered) * (1 lb coal / 9,350 BTU) * (9,294 BTU / kWh produced) * (1000 kWh / MWh) * (400 MW capacity x 0.85 operating factor x (24 hr / day) x (365 day / yr) x 30 yrs) = 42,500,000 t = 46,800,000 tons (US) during lifetime

[3] Information provided by the Kennecott Energy Company, in: *Guide to Coal Mines served by Burlington Northern and Santa Fe railway*. Fort Worth: Coal Business Unit, BNSF Railway.

[4] Information provided by Neil Harrington at the Industrial & Energy Materials Bureau, Department of Environmental Quality, State of Montana

[5] Routing: Spring Creek – Sheridan – Glendive – Fargo – Minot – Northgate – Brandon. Information provided by Gregory Richie at the Burlington Northern and Santa Fe Railway Coal Business Unit

[6] Basic operating parameter (Table A1.1) for the Pulverized Coal scenario

Additional Clarifications:

[a] If the Pulverized Coal scenario uses x% of a facility, then it is responsible for x% of land change caused by that facility. In many cases, this land change is negligible since the percentage use (x) is negligible. For instance, plant construction may require just a few hundred trips on a highway is used for millions of trips over its lifetime.

[b] It is possible that coal would be supplied by a few different mines over the life of the Pulverized Coal plant. It is likely, however, that all of these mines would be in the Powder River region of Montana and Wyoming. To make a simple estimate of land change due to mining in this region, the analysis assumes that coal is supplied by a single mine, Spring Creek, in Montana.

[c] Estimate assumes that fugitive and upstream limestone-related emissions per GWh are simply proportional to the sulfur content of coal. Thus, Illinois coal with 3.4% sulfur by weight causes 44 t / GWh of CO_2e emissions (NREL data)[1], and Spring Creek coal with 0.34% sulfur by weight[3] causes 4.4 t / GWh of CO_2e emissions.

Table A3.3 Key Parameters and Assumptions for the IGCC Option

ID #	Process	GHG-related Parameter / Assumption	→	Rationale	Land Change-related Parameter / Assumption	→	Rationale
A1-A3	P	(No quantitative analysis conducted)			(No quantitative analysis conducted)		
B1-B3	Produce Building Materials	(See **Appendix 5** for building material quantities)			•Negligible land change	→	Would use only a small fraction of existing industrial infrastructure[a]
B11-	Transport Building Materials to Site	**Appendix 5** for transportation distances)			•Negligible land change	→	on of existing transportation infrastructure[a]
B21	Build Generating Facility	(See **Appendix 5** for fuel consumption quantities)			•IGCC plant would occupy 10 acres of land in Brandon, adjacent to current MB Hydro generation site.	→	Assumption
B22	Bu ission Lines	•Negligible emissions	→	infrastructure would be required[6]	•Negligible land change	→	sion infrastructure would be required[6]
C1	Mine Coal	•Coal would be supplied by the Spring)	→	urce of sub-bituminous coal for MB Hydro[b]	•34.8% of Spring Creek mine reserves IGCC scenario	→	59,000,000 tons (US) of coal would be needed over the 30-yr project life[2]; 170,000,000 tons (US) of recoverable reserves exist at Spring Creek mine[3]
		•Emissions for coal mining at Spring Creek are equivalent to the U.S. average for surface mining	→	Best data available[1]	•Mines & mine infrastructure needed to provide coal for the IGCC scenario eplace 260 ha of grazing land within a larger, 750 ha mine lease	→	Area figures of 34.8 % of the totals for Spring Creek mine: 950 ha of impacted land within a larger, 2730 ha mine lease[4]
	Transport Coal	•Coal is transported 2030 km by train from Spring Creek to Brandon		Current routing of coal purchased by		→	Would use only a small fraction of existing transportation infrastructure[a]
		•Coal haul losses during transport are 5%		Estimate used by NREL[1]			
C3	Burn Coal to Generate Electricity	(See **Appendix 6** for emissions factors)			(Land change accounted for elsewhere)	→	Generation would occur on land already changed during facility construction (B21)
C4	Maintain Generating Facility	•Negligible emissions	→	Involves diesel/gas combustion to run vehicles only (negligible compared to coal combustion for power generation)	(Land change accounted for elsewhere)	→	Maintenance would occur on land already changed during facility construction (B21)
C5	Transmit Electricity	(No direct impact on GHG emissions)			(Land change accounted for elsewhere)	→	Transmission would occur on land already changed during transmission line construction (B22)
C11-C31	Collect & Dispose of Waste Slag	•Negligible emissions	→	No fugitive emissions; involves diesel combustion to run equipment only (negligible compared to coal combustion for power generation)	(Land change accounted for elsewhere)	→	On-site disposal or sale of slag to industrial customers[c]. No additional land would be changed.
D1	Decommission Generating Facility	(No quantitative analysis conducted)			(No quantitative analysis conducted)		

Data Sources:

[1] Spath, Pamela et al. *Life Cycle Analysis of Coal-fired Power Production*. Golden, Colorado: National Renewable Energy Laboratory (NREL). 1999.

[2] Result follows directly from basic operating parameters (Table A1.1) & assumed heat rates (Table A5.1) for the IGCC scenario: (1 t / 1000 kg) * (0.454 kg / 1 lb) * (1 lb coal mined / 0.95 lb coal delivered) * (1 lb coal / 9,350 BTU) * (8,225 BTU / kWh produced) * (1000 kWh / MWh) * (570 MW capacity x 0.85 operating factor x (24 hr / day) x (365 day / yr) x 30 yrs) = 53,500,000 t = 59,000,000 tons (US) during lifetime

[3] Information provided by the Kennecott Energy Company, in: *Guide to Coal Mines served by Burlington Northern and Santa Fe railway*. Fort Worth: Coal Business Unit, BNSF Railway.

[4] Information provided by Neil Harrington at the Industrial & Energy Materials Bureau, Department of Environmental Quality, State of Montana
[5] Routing: Spring Creek – Sheridan – Glendive – Fargo – Minot – Northgate – Brandon. Information provided by Gregory Richie at the Burlington Northern and Santa Fe Railway Coal Business Unit
[6] Basic operating parameter (Table A1.1) for the IGCC scenario.

Additional Clarifications:
[a] If the IGCC scenario uses x% of a facility, then it is responsible for x% of land change caused by the facility. In many cases, this land change is negligible since the percentage use (x) is negligible. For instance, plant construction may require just a few hundred trips on a highway is used for millions of trips over its lifetime.
[b] It is possible that coal would be supplied by a few different mines over the life of the IGCC plant. It is likely, however, that all of these mines would be in the Powder River region of Montana and Wyoming. To make a simple estimate of land change due to mining in this region, the analysis assumes that coal is supplied by a single mine, Spring Creek, in Montana.
[c] On-site slag disposal and sale of slag to industrial customers are both viable options for an IGCC plant. A preferred option has not been specified in the MB Hydro IGCC scenario.

Table A3.4 Key Parameters and Assumptions for the Biomass Option

ID #	Process	GHG-related Parameter / Assumption	→	Rationale	Land Change-related Parameter / Assumption	→	Rationale
A1-A3	Planning	(No quantitative analysis conducted)			(No quantitative analysis conducted)		
B1-B3	Produce Building Materials	(See **Appendix 5** for building material quantities)			• Negligible land change	→	Would use only a small fraction of existing industrial infrastructure[a]
B11-B13	Transport Building Materials to Site	(See **Appendix 5** for transportation distances)			• Negligible land change	→	Would use only a small fraction of existing transportation infrastructure[a]
B21	Build Generating Facility	(See **Appendix 5** for fuel consumption quantities)			• Generating plant would occupy 2 acres of farmland in S.W. Manitoba	→	Assumption (to be confirmed)
B22	Build Transmission Lines	• Negligible emissions	→	Only minimal new transmission infrastructure would be required[6]	• Negligible land change	→	Only minimal new transmission infrastructure would be required[6]
C1	Harvest Flax & Collect Straw	• Flax straw would be obtained from exisiting flax farming operations in S.W. Manitoba	→	176,000 t of flax straw required each year[1]; 221,000 t flax straw produced in Manitoba each year[2]; ∴ sufficient straw is available[b]	• No land change	→	Flax straw would be obtained from existing farm operations
		• 170.3 m^3 diesel is required to harvest a flax crop yielding 1 t of flax seed and 1 t of flax straw	→	0.514 t flax straw harvested per acre[3]; 1370 MJ fuel needed per ha of flax harvested[4]; assume exclusive use of diesel for harvesting			
		• 2.64% of flax harvesting emissions (from diesel combustion) allocated to flax straw	→	Based on market value of flax and flax straw[3c]			
C2	Transport Flax by Truck	• Flax is transported by truck an average of 100 km to generating facility.	→	Estimate[5]	• Negligible land change	→	Would use only a small fraction of existing transportation infrastructure[a]
C3	Burn Flax Straw to Generate Electricity	(See **Appendix 6** for emissions factors)			(Land change accounted for elsewhere)	→	Generation would occur on land already changed during facility construction (B21)
C4	Maintain Generating Facility	• Negligible emissions	→	Involves diesel/gas combustion to run vehicles only (negligible compared to straw combustion for power generation)	(Land change accounted for elsewhere)	→	Maintenance would occur on land already changed during facility construction (B21)
C5	Transmit Electricity	(No direct impact on GHG emissions)			(Land change accounted for elsewhere)	→	Transmission would occur on land already changed during transmission line construction (B22)
C11-C31	Collect & Dispose of Ash	• Negligible emissions	→	No fugitive emissions; involves diesel combustion to run equipment only (negligible compared to straw combustion for power generation)	(Land change accounted for elsewhere)	→	On-site disposal on land already changed during facility construction (B21)
D1	Decommission Generating Facility	(No quantitative analysis conducted)			(No quantitative analysis conducted)		

Data Sources:

[1] Result follows directly from basic operating parameters (Table A1.1) & assumed heat rates (Table A5.1): (1 t / 1000 kg) * (0.454 kg / 1 lb) * (1 lb straw / 7,300 BTU) * (13,600 BTU / kWh produced) * (1000 kWh / MWh) * (25 MW capacity x 0.95 operating factor x (24 hr / day) x (365 day / yr)) = 176,000 t straw / yr

[2] Based on [i] assumed 1:1 (mass) ratio of flax seed to flax straw production (standard assumption for grains), and [ii] annual Manitoba flax seed production (2000) statistics: Manitoba Agriculture[3]

[3] Manitoba Agriculture and Food: *Manitoba Grains & Oilseeds Industry Profiles 2000 – Flaxseed Sector* at: http://www.gov.mb.ca/agriculture/statistics/aac04s07.html

[4] Coxworth, E. et al. *Net Carbon Balance Effects of Low Disturbance Seeding Systems on Fuel, Fertilizer, Herbicide and Machinery usage in Western Canadian Agriculture: Final Report to a Major Western Utility*. 1994.

[5] Agricultural areas in Manitoba fall within an area of ~ 200 km radius, ∴ 100 km is an average distance travelled to a centrally-located biomass plant.

[6] Basic operating parameter for the biomass scenario (Table A1.1)

Additional Clarifications:

[a] If the Biomass scenario uses x% of a facility, then it is responsible for x% of land change caused by that facility. In many cases, this land change is negligible since the percentage use (x) is negligible. For instance, plant construction may require just a few hundred trips on a highway is used for millions of trips over its lifetime.

[b] Although an estimated 221,000 t of flax straw are produced in Manitoba each year, at least 135,000 t were sold for use in diverse industries (e.g. fine fibre for cigarette paper and currency)[3]. A proportion of the remainder was left on fields. As a result, it is not clear whether the alternative use of flax straw for power generation would be economically viable: other uses may reap more value from flax straw, and in addition, transportation costs to a biomass plant may be prohibitive. An economic analysis must therefore play a critical role in evaluating this biomass scenario.

[c] Emissions data are available for a combined harvest of flax and flax straw. The fuel-combustion emissions are allocated between the products based on market value: for a tonne of combined harvest (0.5 t straw, 0.5 t seed), the total market value is in the proportion 98.4 % seed to 2.6 % straw[3].

Table A3.5 Key Parameters and Assumptions for the Natural Gas Simple Cycle and Combined Cycle Options

ID #	Process	GHG-related Parameters / Assumptions →	Rationale	Land Change-related Parameter / Assumption →	Rationale
A1-A3	Planning	(No quantitative analysis conducted)		(No quantitative analysis conducted)	
B1-B3	Produce Building Materials	(See **Appendix 5** for building material quantities)		• Negligible land change →	Would use only a small fraction of existing industrial infrastructure[a]
B11-B13	Transport Building Materials to Site	(See **Appendix 5** for transportation distances)		• Negligible land change →	Would use only a small fraction of existing transportation infrastructure[a]
B21	Build Generating Facility	(See **Appendix 5** for fuel consumption quantities)		• NG Simple or Combined Cycle plant would occupy 5 acres of land within the current Brandon site →	Would use only a small fraction of existing transportation infrastructure[a]
B22	Build Transmission Lines	• Negligible emissions →	Only minimal new transmission infrastructure would be required[3]	• Negligible land change →	Only minimal new transmission infrastructure would be required[3]
C1	Extract and process NG	• All NG is produced in Alberta → • 126 m^3 of raw gas are extracted for every 100 m^3 of saleable NG →	Assumption[b] Estimate[1]	(See **Appendix C** for data on land change related to NG extraction)	
C2	Transport NG	• NG travels an average of 1700 km to Brandon via the TransCanada pipeline → • 1.4 % of raw gas extracted is lost as fugitive emissions during processing and transportation →	Estimate based on Hanmore Compressor station (NW Alberta) as an average point of origin NREL best estimate (Industry consensus range: 1-4%)[2]	• Negligible land change →	[i] Would use only a small fraction of existing pipeline infrastructure[c] [ii] The TransCanada pipeline is largely underground; only minimal surface land change has occurred as a result of the pipeline[c]
C3	Burn NG to Generate Electricity	(See **Appendix 6** for emissions factors)		(Land change accounted for elsewhere) →	Generation would occur on land already changed during facility construction (B21)
C4	Maintain Generating Facility	• Negligible →	Involves diesel/gas combustion to run vehicles only (negligible compared to NG combustion for power generation)	(Land change accounted for elsewhere) →	Maintenance would occur on land already changed during facility construction (B21)
C5	Transmit Electricity	(No direct impact on GHG emissions)		(Land change accounted for elsewhere) →	Transmission would occur on land already changed during transmission line construction (B22)
D1	Decommission Generating Facility	(No quantitative analysis conducted)		(No quantitative analysis conducted)	

Data Sources:
[1] Alberta average data compiled from a variety of sources
[2] Spath, Pamela et al. *Life Cycle Analysis of a Natural Gas Combined Cycle Power Generation System*. Golden, Colorado: National Renewable Energy Laboratory (NREL). 2000.
[3] Basic operating parameter for the NG scenarios
[4] TransCanada operations data at http://www.transcanada.com
[5] Information provided by Srikanth Venugopal at TransCanada

Additional Clarification:
[a] If the NG scenario uses x% of a facility, then it is responsible for x% of land change caused by the facility. In many cases, this land change is negligible since the percentage use (x) is negligible. For instance, plant construction may require just a few hundred trips on a highway is used for millions of trips over its lifetime.

[b] NG in the TransCanada pipeline originates primarily in Alberta, although some gas is sourced from NE British Columbia, Saskatchewan and the NWT. To make a simple estimate of emissions related to compressor station energy use and of land change due to NG extraction, the analysis assumes that NG is supplied exclusively from Alberta. Supply is allocated to different regions within Alberta based on estimates of existing reserves (see Appendix C for more detailed information).

[C] In the case of the TransCanada pipeline, [i] use of existing infrastructure is small on an annual basis: the Simple Cycle scenario would require 1.1% of the Trans Canada pipeline daily throughput (= 6,700 mmcf/day, 2001 average figure)[4] for 30 years, [ii] land change due to the pipeline is minimal, since the Canadian mainline is largely underground, and does not change land use on the surface right-of-way, except at compressor stations (land use above the pipeline is largely agricultural; the right-of-way is 220 ft.)[5] Thus, the mathematical product: "(land change due to the TransCanada pipeline) * (% of land change allocated to the NG scenarios)" is negligible.

Table A3.6 Key Parameters and Assumptions for the Wind Option

ID #	Process	GHG-related Parameter / Assumption	→	Rationale	Land Change-related Parameters / Assumptions	→	Rationale
A1-A3	Planning	(No quantitative analysis conducted)			(No quantitative analysis conducted)		
B1-B7	Produce Building Materials	(See **Appendix 5** for building material quantities)			• Negligible land change	→	Would use only a small fraction of existing industrial infrastructure[a]
B11-B16	Transport Building Materials to Site	(See **Appendix 5** for transportation distances)			• Negligible land change	→	Would use only a small fraction of existing transportation infrastructure[a]
B21	Build Generating Facility	(See **Appendix 5** for fuel consumption quantities)			• Wind turbines located on farmland, arranged in a square grid pattern, with 200 m spacing between turbines	→	Typical arrangement[1]
					• Each turbine foundation replaces 110 m^2 of farmland[1]; the remainder of the land within the farm remains unchanged	→	Changed land area in the wind scenario is simply the combined area of all fifty turbine foundations
					• Access road right-of-way may be needed. No quantification since windfarm location unknown	→	Assumption
B22	Build Transmission Lines	• Negligible land change	→	Only minimal new transmission infrastructure would be required[2]	• Negligible land change	→	Only minimal new transmission infrastructure would be required[2]
C1	Harness Wind	(No direct impact on emissions)			(Land change accounted for elsewhere)	→	Would occur on land already changed during facility construction (B21)
C3	Generate Electricity	(No direct impact on emissions)			(Land change accounted for elsewhere)	→	Generation would occur on land already changed during facility construction (B21)
C4	Maintain Generating Facility	• 750 l gasoline consumed per turbine per year[1]	→	(Land change accounted for elsewhere) →	Land change accounted for elsewhere)	→	Maintenance would occur on land already changed during facility construction (B21)
C5	Transmit Electricity	(No direct impact on GHG emissions)			(Land change accounted for elsewhere)	→	Transmission would occur on land already changed during transmission line construction (B22)
D1	Decommission Generating Facility	(No quantitative analysis conducted)			(No quantitative analysis conducted)		

Data Sources:
[1] Information provided by VisionQuest Wind Electric
[2] Basic operating parameter for the wind scenario (see Table A1.1)

Additional Clarifications:
[a] If the Wind scenario uses x% of a facility, then it is responsible for x% of land change caused by that facility. In many cases, this land change is negligible since the percentage use (x) is negligible. For instance, plant construction may require just a few hundred trips on a highway is used for millions of trips over its lifetime.

Appendix 4: Construction Materials and Transportation Distances

Table A4.1: Construction Materials and Transportation Distances – Wuskwatim Hydro Option

	Building Materia					Building Material Transportation Distances - Average by Material (km)					Fuel use during Construction (l)
	Cement	Steel & St	Lumber	Aluminum	Other	Concrete, by Truck (km)	Steel & Steel Parts, by Truck	Lumber, by Truck	Aluminum, by Truck	Other, by Truck	Diesel
Wuskwatim Hydro[1]	32,500	28,000	4,400	1,500	5,400	1,380	2,710	820	3,300	880	17,500,000

Table A4.2: Construction Materials and Transportation Distances – Carbon Fuel–based Options

Electricity Supply Option	Building Material Quantities (t)[a]		Building Material Transportation Distances - Average by Material (km)			Fuel use during Construction (l)		
	Concrete	Steel & Steel	Concrete, by Truck	Steel & Steel Parts, by Truck	Steel & Steel Parts, by Ship	Diesel	Gasoline	Propane
Pulverized Coal[2]	18,700	4,710	15	1,850	4,500	665,500	0	47,000
IGCC[2]	26,730	6,770	15	1,850	4,500	948,500	153,000	67,000
Biomass[2]	1,	290	100	1,950	4,500	41,500		3,000
NG Simple Cycle[2]	7,320	1,840	15	1,850	4,500	260,000		18,500
NG Combined Cycle[2]	7,320	1,840	15	1,850	4,500	260,000		18,500

Table A4.3: Construction Materials and Transportation Distances – Wind Option

	Building Material Quantities (t)							Building Material Transportation Distances - Average by Material (km)				Fuel use during Construction (l)
	Concrete	Steel &	Specialized Parts (Blades, Hubs and Nacelles), comprising:					Concrete, by Truck	Steel & Steel Parts, by Truck	Specialized Parts, by Truck	Specialized Parts, by Ship	Diesel
			Steel	Aluminum	Fibreglass	Copper	Other					
Wind[3]	6,500	6,730	2,150	950	980	150	45	100	2,400	2,800	14,000	187,500

Data Sources:

[1] Information provided by Manitoba Hydro based on the current Wuskwatim Hydro proposal

[2] Information for the NG Simple Cycle option is based on data from a Single Cycle NG power plant built by Manitoba Hydro at Brandon in 2002 . Information for other scenarios is derived from these figures as follows:

- NG Combined Cycle: material quantities and fuel consumption are assumed to be the same as in the NG Simple Cycle case. In reality, the material requirements for a combined cycle plant may be slightly higher than requirements for a simple cycle plant of identical capacity. However, given the relatively minor contribution of construction-related emissions to the overall total for Natural Gas-fired technologies, this distinction is considered to be insignificant.
- Pulverized coal: material quantities and fuel consumption are adjusted for higher capacity (multiplying factor 400 MW/250 MW = 1.6) and greater complexity (multiplying factor = 1.6)[b] of the coal plant. Transportation distances are identical (same proposed site).
- IGCC: material quantities and fuel consumption are adjusted for higher capacity (multiplying factor 570 MW/250 MW = 2.3) and greater complexity (multiplying factor = 1.6)[b] of the plant. Transportation distances are identical (same proposed site).
- Biomass: material quantities and fuel consumption are adjusted for lower capacity (multiplying factory = 25 MW/250 MW = 0.1) and greater complexity (multiplying factor = 1.6)[b] of the plant. Transportation distances are adjusted for a hypothetical site 100 km from Brandon.

[3] Information derived from data on a wind farm in Pincher Creek, Alberta provided by VisionQuest Wind Electric. Material quantities have been adjusted to account for a larger turbine size (1.65 MW vs 660 kW in the original data, multiplying factor per turbine = 5 provided by VisionQuest). Transportation distances have been adjusted for a hypothetical site 100 km from Brandon.

Additional Clarifications:

[a] Other building materials (e.g. iron, aluminum) are not included as they account for less than 1% of the total building mass.

[b] The complexity multiplying factor is derived from a comparison of plant material quantities in two reports by the National Renewable Energy Laboratory (NREL): [i] Spath, Pamela et al. *Life Cycle Analysis of Coal-fired Power Production*. Golden, Colorado: NREL. 1999. [ii] Spath, Pamela et al. *Life Cycle Analysis of a Natural Gas Combined Cycle Power Generation System*. Golden, Colorado: NREL. 2000.

Appendix 5: Fuel and Combustion Data for Carbon Fuel–based Scenarios

Table A5.1: Fuel and Combustion Data for Carbon Fuel–based Scenarios

Electricity Supply Option	Fuel	Net Heat Rate of Generating Plant – HHV basis (BTU / kWh)	Fuel Heating Value – HHV basis (BTU / lb)	Emissions Factors		
				Carbon Dioxide - CO_2 (kg / t fuel)	Methane - CH_4 (kg / t fuel)	Nitrogen Oxide – N_2O (kg / t fuel)
Pulverized Coal	Sub-bituminous Coal	9,294[1]	9,350[2]	2,046[3]	0.02[3]	0.1[3]
IGCC			9,350[2]	2,046[3]	0.02[3]	0.1[3]
Biomass	Flax Straw	13,600[1]	7,300[4]	0[5]	0.15[6]	0.16[6]
NG Simple Cycle	Natural Gas	11,500[1]	23,000[7]	2,691[7]	0.32[7]	0[7]
NG Combined Cycle	Natural Gas	7,000[1]	23,000[7]	2,691[7]	0.32[7]	0[7]

Data Sources & Additional Clarifications:

[1] Basic operating parameters for each scenario

[2] Figure is an average value for coal from the Spring Creek mine (assumed source of coal, see Tables A3.2 and A3.3). Information provided by Kennecott Energy Company, in: *Guide to Coal Mines served by Burlington Northern and Santa Fe Railway*. Fort Worth: Coal Business Unit, BNSF railway.

[3] CO_2 and CH_4 factors are average for sub-bituminous coal. N_2O factor is the minimum of a range of values (0.1-2.11 kg / t) for sub-bituminous coal. Source: *Canada's Energy Outlook 1996-2020*. Ottawa: Natural Resources Canada. 1997.

[4] Figure is for flax straw containing 15% moisture by weight. LHV heating value obtained from: *Research Update #719*. Humboldt, Saskatchewan: Prairie Agricultural Machinery Institute. 1995. Adjusted to HHV heating value based on flax straw hydrogen content of 6.2 %, obtained from: Hörnell, Christina. *Thermochemical and Catalytic Upgrading in a fuel context: Peat, Biomass and Alkenes* (Dissertation). Stockholm: Royal Institute of Technology. 2001.

[5] Net emissions of CO_2 are 0 for flax fuel (and other biofuels). During combustion, CO_2 is emitted to the atmosphere, however an equivalent amount of CO_2 was removed from the atmosphere by the growing flax plant. Thus, over the life-cycle of growth and combustion, no net CO_2 is released.

[6] Factors are for wood / wood waste (best data available). Source: *Canada's Greenhouse Gas Inventory – 1997 Emissions and Removals with Trends*. Ottawa: Environment Canada. 1999.

[7] Factors are for a typical sample of NG containing 94.4% methane, 3.1% ethane, 0.5% propane, 1.1% N_2, 0.5% CO_2, and 0.4% other hydrocarbons. Source: Spath, Pamela et al. *Life Cycle Analysis of a Natural Gas Combined Cycle Power Generation System*. Golden, Colorado: National Renewable Energy Laboratory (NREL). 2000.

Table A5.2 Material and Transportation Fuel Emission Factors

Activity	Greenhouse Gas Emissions Factors ($kg\ CO_2e / m^3$ or $kg\ CO_2e / t$)
Gasoline Comb n (3 1	2,360
Diesel Combustion (m^3)[1]	2,730
Steel Production (	3,200
Concrete Production (m^3)[3]	1,080
Aluminum Pro on (t)[2]	8,000

Data Sources
1 – "Trends in Canada's Greenhouse Gas Emissions 1990 - 1995", A. Jaques, F. Neitzert, P.Boileau. 1997. A report for Environment Canada.
2 - "Life Cycle Inventories for Packaging", Vol 1, Swiss Agency for Environment, Forests, and Landscape, (SAEFL) 1998.
3 – U.S. EPA AP-42 series, Fifth edition, Chapter 11, Mineral Products Industry, section 11.12. 1995.

Appendix 6: Fuel Extraction-Related Land Change for NG Simple Cycle & Combined Cycle Scenarios

This appendix covers the calculation of land changes associated with NG extraction.
Detailed calculations are provided in Tables A6.1 and A6.2 for the Simple Cycle and Combined Cycle scenarios respectively.
In addition, two overall assumptions should be noted:

NG is supplied from the Trans-Canada Pipeline (TCPL), and is a mixture of gas from all of the wells that supply TCPL. For the simple cycle scenario, 77 mmcf/day NG is needed. TCPL transports ~ 6,700 mmcf/day through its Canadian mainline which would supply the Brandon plant. Thus, the NG Simple Cycle scenario accounts for ~ 1.1% of total TCPL throughput.

To evaluate land change, a modelling assumption is made that dedicated wells would supply the generating facility. I.e. rather than allocating 1.1% of the impact of **all** wells supplying TCPL to the project, the number of wells needed to supply 77 mmcf/day for 30 years (= 843 bcf) is calculated, and the entire impact of these wells is allocated to the project.

The number of 'dedicated' wells is calculated as:
(the number of **new** wells needed each year to **maintain** a production of 77 mmcf/day) * (30 years), using initial production and decline data for wells[1].

All NG is assumed to come from Alberta where some wells are in forested areas, and others in farmland area.

In forested areas, land is cleared for exploration: seismic surveys, drilling and access roads. When exploration is complete, some of the cleared land is still required to operate successful wells: well-pads, access roads, and collection pipelines. Land change in forested areas is defined as the total of initially **cleared** land, since clearing involves a non-temporary change (restoration may take 30-50 years or more)[2].

In farmland areas, exploration does not involve any change of land type. Changes are only associated with developed wells: well-pads, access roads, and collection pipelines, which occupy land that can no longer be used for agriculture. Thus, land change in farmland areas is defined as the total of **occupied** land.

[1] An equivalent result can be obtained using life-time production data for wells. The number of 'dedicated' wells is equal to: (843 bcf) / (lifetime production per well)
[2] MacFarlane, Arin. *Revegetation of Wellsites and Seismic Lines in the Boreal Forest* (Dissertation). Edmonton: University of Alberta. 1999.

Table A6.1 Land Change Calculations for the NG Simple Cycle Scenario

Overall Parameters

45.6 mmcf/day NG supplied from Alberta for 30 years[a]

Assessment of Alberta NG reserves in 2001: 82% in NE+NW+SW quadrants (largely forested), 18% in SE quadrant (largely farmland)[b].

∴ Estimate that 80 % of supply will come from forest in NE+NW+SW and 20 % from farm areas in SE.

FORESTED AREAS (80% of total supply)

Number of Wells Required

Forest production required: 36.5 mmcf/day
Well initial production (average): 0.7 mmcf/day[b]
Well annual decline rate (average): 20%[b]

∴ 10.4 new wells / year needed to maintain production.
∴ 310 wells developed to supply project over 30 yrs.

Type of Land Change

- One-time forest clearing for drilling, seismic surveys and to install roads and pipelines.
- Part of cleared land then occupied by infrastructure (wellhead, roads, pipelines) throughout life of well. Remainder of cleared land (seismic, drillpad) allowed to begin regenerating.

∴ Forest → Cleared land, partially occupied by infrastructure

Area of Cleared Land and Occupied Land

1.7 drills / developed well[c]
1 ha cleared / drill[d]
0.04 ha occupied / developed well[e]

10.4 km seismic right-of-way / developed well[f]
6 m width cleared for seismic right-of-way[f]
0 m width occupied by seismic

0.8 km road & pipeline right-of-way / developed well[g]
30 m width cleared for road & pipeline right-of-way[e]
10 m width occupied by road & pipeline[e]

∴ 10.4 ha cleared / well
∴ 0.86 ha occupied / well

Density of Wells

1.4 developed wells / section of land[h]

∴ 0.7 section of land / developed well
∴ 180 ha land / developed well

Forest Sub-Total over the Project Life (30 years)

∴ 310 wells and 3,250 ha changed land (= cleared land)
∴ 310 wells spread out over 57,000 ha area

FARMLAND AREAS (20% of total supply)

Number of Wells Required

Farmland production required: 9.1 mmcf/day
Well initial production (average): 0.14 mmcf/day[b]
Well annual decline rate (average): 20%[b]

∴ 13 new wells / year needed to maintain production.
∴ 390 wells developed to supply project over 30 yrs.

Type of Land Change

- Farmland occupied by infrastructure (wellhead, roads, pipelines) throughout life of well.

∴ Farmland → land occupied by infrastructure

Area of Occupied Land

1.7 drills / developed well[c]
0.04 ha occupied / developed well[e]

8.2 km seismic right-of-way / developed well[f]
0 m width occupied by seismic

1.2 km road & pipeline right-of-way / developed well[g]
10 m width occupied by road & pipeline[e]

∴ 1.3 ha occupied / well

Density of Wells

3.3 developed wells / section of land[h]

∴ 0.3 section of land / developed well
∴ 80 ha land / developed well

Farmland Sub-Total over the Project Life (30 years)

∴ 390 wells and 500 ha changed land (= occupied land)
∴ 390 wells spread out over 30,000 ha area

Total over Project Life (30 years)

∴ 700 wells and 3,750 ha changed land (= cleared or occupied land)
∴ 700 wells spread out over 87,000 ha area

Table A6.2 Land Change Calculations for the NG Combined Cycle Scenario

Overall Parameters

76.6 mmcf/day NG supplied from Alberta for 30 years[a]

Assessment of Alberta NG reserves in 2001: 82% in NE+NW+SW quadrants (largely forested), 18% in SE quadrant (largely farmland)[b].

∴ Estimate that 80 % of supply will come from forest in NE+NW+SW and 20 % from farm areas in SE.

FORESTED AREAS (80% of total supply)

Number of Wells Required

Forest production required: 61.3 mmcf/day
Well initial production (average): 0.7 mmcf/day[b]
Well annual decline rate (average): 20%[b]

∴ 17.5 new wells / year needed to maintain production.
∴ 525 wells developed to supply project over 30 yrs.

Type of Land Change

- One-time forest clearing for drilling, seismic surveys and to install roads and pipelines.
- Part of cleared land then occupied by infrastructure (wellhead, roads, pipelines) throughout life of well. Remainder of cleared land (seismic, drillpad) allowed to begin regenerating.

∴ Forest → Cleared land, partially occupied by infrastructure

Area of Cleared Land and Occupied Land

1.7 drills / developed well[c]
1 ha cleared / drill[d]
0.04 ha occupied / developed well[e]

10.4 km seismic right-of-way / developed well[f]
6 m width cleared for seismic right-of-way[f]
0 m width occupied by seismic

0.8 km road & pipeline right-of-way / developed well[df]
30 m width cleared for road & pipeline right-of-way[e]
10 m width occupied by road & pipeline[e]

∴ 10.4 ha cleared / well
∴ 0.86 ha occupied / well

Density of Wells

1.4 developed wells / section of landh[g]

∴ 0.7 section of land / developed well
∴ 180 ha land / developed well

Forest Sub-Total over the Project Life (30 years)

∴ 525 wells and 5,450 ha changed land (= cleared land)
∴ 525 wells spread out over 95,000 ha area

FARMLAND AREAS (20% of total supply)

Number of Wells Required

Farmland production required: 15.3 mmcf/day
Well initial production (average): 0.14 mmcf/day[b]
Well annual decline rate (average): 20%[b]

∴ 21.9 new wells / year needed to maintain production.
∴ 655 wells developed to supply project over 30 yrs.

Type of Land Change

- Farmland occupied by infrastructure (wellhead, roads, pipelines) throughout life of well.

∴ Farmland → land occupied by infrastructure

Area of Occupied Land

1.7 drills / developed well[c]
0.04 ha occupied / developed well[e]

8.2 km seismic right-of-way / developed well[f]
0 m width occupied by seismic

1.2 km road & pipeline right-of-way / developed well[df]
10 m width occupied by road & pipeline[e]

∴ 1.3 ha occupied / well

Density of Wells

3.3 developed wells / section of land[g]

∴ 0.3 section of land / developed well
∴ 80 ha land / developed well

Farmland Sub-Total over the Project Life (30 years)

∴ 655 wells and 850 ha changed land (= occupied land)
∴ 655 wells spread out over 51,000 ha area

Total over Project Life (30 years)

∴ 1180 wells and 8,300 ha changed land (= cleared or occupied land)
∴ 1180 wells spread out over 146,000 ha area

Data Sources:
[a] Result follows from basic operating parameters defined for the NG scenarios.
[b] Jamal, Al. *Gas Supply and Demand Update – Markets balanced...but for how long?*. Transcript of a presentation made to the TransCanada 'Inside Track Customer Meeting'. Spring 2002.
[c] Crowfoot, Carol. *Supply and Demand Forecasts for Natural Gas*. Transcript of a presentation made to the Economics Society of Calgary Fall Conference. November 30, 2000.
[d] Schneider, Richard. *The Oil & Gas Industry in Alberta – Practices, Regulations and Environmental Impact.* Edmonton: Alberta Center for Boreal Studies. 2001.
[e] Estimate

[f] Based on Alberta Environment Land and Forest Service data. Source: *The Final Frontier: Protecting Landscape and Biological Diversity within Alberta's Boreal Forest Natural Region, Protected Areas Report #13*. Edmonton: Alberta Environmental Protection. 1998.
[g] Based on AEUB data to year end 1996. Source: *The Final Frontier: Protecting Landscape and Biological Diversity within Alberta's Boreal Forest Natural Region, Protected Areas Report #13*. Edmonton: Alberta Environmental Protection. 1998.
[h] Conservative estimate (lower end of a typical range for developed well density)

Appendix 7: GHG Emissions due to Land Changes in the Wuskwatim Hydro System

This appendix describes how GHG emissions due to land change are estimated for the Wuskwatim Hydro System. Although there are precise estimates of how much land area would be visibly changed by the Wuskwatim project, the nature of these land changes and their impact on eco-system carbon stocks are highly uncertain. As a result, several assumptions are required in order to estimate GHG emissions.

First, the analysis is limited to three types of GHG releases or sequestration:
(i) *Vegetation clearing:* Cleared trees and other vegetation may be used as lumber, left to decay, or burned. If trees are used as lumber, then the carbon in the trees is not released. If trees or vegetation are left to decay, aerobic decomposition releases CO_2. If trees or vegetation are burned, combustion releases CO_2, CH_4 and N_2O.
(ii) *Peat or soil submergence under water*: When organic matter is submerged under water, it will decay partially. Both aerobic and anaerobic decomposition are possible, releasing CO_2 and CH_4 respectively.
(iii *Vegetation growth*: when trees or other vegetation grow, CO_2 is sequestered from the atmosphere through photosynthesis.

Second, the analysis is limited to GHG releases and sequestration that occur *during the construction and operation phases of the project*. Therefore, if land is cleared during construction, kept cleared during operation, and restored *after* project decommissioning, GHG emissions due to clearing are counted, while GHG sequestration due to vegetation re-growth after decommissioning is not counted. By contrast, if land is cleared during construction and restored during operation, both GHG release and sequestration are counted (and assumed to be equivalent) so that net emissions are said to be 0.[1]

Third, assumptions are made about the carbon content of vegetation and soils in order to quantify emissions. These 'organic carbon stock' parameters are listed in Table A7.1, and were provided by Manitoba Hydro based on empirical data.

Finally, specific assumptions are made about which of the processes (i) through (iii) above will occur during the Wuskwatim project, and on what timescale. Calculations have been made for a likely scenario, presented in Table A7.2. Since the assumptions have a strong influence on the estimate of net GHG emissions, the effect of changing various assumptions is also sketched out in the table.

[1] In fact, the transfer of carbon to the atmosphere is non-zero, but temporary in both cases. If restoration occurs *after* decommissioning, the carbon remains in the atmosphere for a relatively longer time (and has a greater impact on climate) than if restoration occurs *during* operation. Thus, a more accurate analysis might consider ton-years of carbon temporarily transferred to the atmosphere. Given the broad assumptions made in the remainder of the calculation, however, this level of detail is unwarranted and could not supported by sufficiently accurate data.

Table A7.1: Carbon Content of Vegetation and Soil

	Forest Land				Non-forest Vegetation			Peat Bogs	
	Area of Land Change (ha)	Carbon Content			Area of Land Change (ha)	Carbon Content		Area of Land Change (ha)	Carbon Content
		Original Forest Vegetation	Soil	Shrub Re-growth During Operation		Original Vegetation	Shrub re-growth During Operation		Peat
Generating Station & Construction Areas	383	55.6							
Access Road Right-of-way	324	55.6		8	158	8	8		
Flooded Area	34	55.6	125					5	891
Transmission Line Right-of-Way	850	52.5		8	680	8	8		

Table A7.2: GHG Releases & Sequestration from a Likely Emissions Scenario

Area of Land Change	GHG-releasing and GHG-sequestering Activities		Assumed GHG Emissions due to Construction & Operation Activities	Notes
	During Construction	During Operation		
Generating Station	▪ All vegetation cleared, *Note - Built infrastructure (concrete, asphalt etc.) covers entire land area*		100 % of carbon in vegetation (trees+shrub) released as CO_2	used as lumber (rather than being left to decay) GHG emissions may be higher if vegetation is burned[1].
Construction Area & Borrow Pits	▪ Some vegetation cleared, ▪ Some soil removed *Note – No built infrastructure*	▪ All vegetation re-grows ▪ All soil replaced	No net emissions (Trees, shrubs and soil are completely restored during operation, resulting in 0 net emissions)	.
Flooded Area	▪ All vegetation cleared ▪ Remaining peat and soil completely submerged under water *Note – No built infrastructure*	▪ No restoration	100% of carbon in cleared vegetation (trees+shrub) released as CO_2 60 % of carbon in submerged peat and soil released, of which 7% is CH_4 (anaerobic decay), 93% is CO_2. (aerobic decay)	Actual GHG emissions may be lower if a lesser proportion of submerged soil & peat decay, and if aerobic decay predominates. GHG emissions may be higher if a greater proportion of soil & peat decays, and if anaerobic decay is more common.
Access Road Right-of-Way	▪ All vegetation cleared *Note – Built infrastructure (road bed) covers fraction of total right-of-way*	▪ Shrubs re-grow ▪ No trees re-grow	100% of carbon in trees released as CO_2 (Shrubs are cleared during construction, but re-grow during operation, resulting in 0 net emissions).	Actual GHG emissions will be lower if trees are re-used as lumber (rather than being left to decay) GHG emissions may be higher if vegetation is burned[1].
Transmission Line Right-of-Way	▪ All vegetation cleared *Note – Built infrastructure (concrete tower foundations) covers fraction of total right-of-way*	▪ Shrubs re-grow ▪ No trees re-grow	100% of carbon in trees released as CO_2 (Shrubs are cleared during construction, but re-grow during operation, resulting in 0 net emissions).	Actual GHG emissions will be lower if trees are re-used as lumber (rather than being left to decay) GHG emissions may be higher if vegetation is burned[1].

[1] GHG emissions are higher if vegetation is burned since N_2O is produced. Some carbon may also be released to the atmosphere as CH_4 rather than CO_2 increasing the CO_2e value of overall emissions.

Appendix 8: Note on Units and Conventions Used in the Report

Units used in the analysis and in the presentation of results are given wherever figures are reported. Three general points may also be noted:

1. Masses are generally reported in **metric** tons (t). Where exceptions occur, these are denoted by the unit 'tons (US)'.

2. Greenhouse gas emissions are always reported in terms of 'carbon dioxide equivalents' or CO_2e. This measure takes into account the fact that different greenhouse gases have a different degree of effect on global warming. In particular, CH_4 and N_2O respectively have global warming factors of 21 and 310 times that of CO_2. Thus, quantities of CH_4 are multiplied by 21, before being added to the CO_2e total for a given system, and likewise for N_2O.

3. Fuel heating values (BTU/lb or BTU/m^3) and combustion efficiencies (kWh generated / BTU fuel) are always reported in terms of the Higher Heating Value (HHV) of fuel. The HHV gives the amount of energy that is released when a fuel at 25°C is (i) completely combusted to carbon dioxide (CO_2) and water (H_2O) and (ii) these products are cooled to 25°C. Any heat value and efficiency data that was expressed in other terms has been converted to HHV in this report, ensuring the full consistency of all calculations.