Life-Cycle Value Assessment of a Wind Turbine

Alberta, Canada

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February 2000

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 another office in Ottawa, and research associates in Edmonton, Calgary, and other locations across Canada.

The Pembina Institute's Eco-efficient Technologies Program is a response to the growing need to evaluate society's technology choices and to advocate for appropriate energy and waste management alternatives. The Program identifies and advocates the removal of policy barriers, actively markets appropriate technologies, and provides networking opportunities for technology providers and potential customers. Staff work closely with the Institute's other program areas to aid in the adoption of appropriate technologies leading to more sustainable industrial, residential and transportation systems. An earlier version of this paper was presented at the North Sun Conference in Edmonton, Alberta in August 1999.

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1.0 Introduction

Climate change due to rising levels of greenhouse gases is one of the most noteworthy issues facing the global economy in the 21st century. While greenhouse gas emissions come from many sectors, electricity generation is a substantial source. In 1995, the electricity generation sector produced 103 megatonnes (Mt) of greenhouse gases, or 16.6 percent of Canada's total. [1]

This paper compares the life-cycle emissions produced by generating electricity from wind power with emissions produced from the use of coal (Alberta Inter-connected System) and natural gas in Alberta. The life-cycle analysis quantifies the potential amount of greenhouse gas emissions that could be offset by using wind power rather than coal or gas to generate electricity, and it assesses the potential environmental benefits from reducing emissions of acid rain precursors and ground level ozone precursors.

Burning coal and natural gas to generate electricity in Alberta contributes 47 percent of Canada's total greenhouse gases from the electricity sector. [1] This dependency on coal and natural gas puts Alberta in a position where less environmentally destructive alternatives need to be seriously considered. In 1998, wind power provided less than two percent of Alberta's total electricity supply, indicating sizeable room for expanding the wind generation option [3].

A Life-Cycle Value Assessment (LCVA) has been used to encourage the increased application of wind power. This study provides an overview of the LCVA process to illustrate how potential impacts were evaluated for the three systems identified above. The results of the analysis are then described with reference to the LCVA methodology.

1.1 Life-Cycle Value Assessment: An Overview

The Pembina Institute's Life-Cycle Value Assessment process typically incorporates both environmental and economic considerations. It can be used as a comparative analysis tool, as a product or process design improvement tool, and to aid in purchasing decisions. It gives decision makers a detailed assessment of the environmental and economic performance of a product or process to allow for sound and informed decisions. The life-cycle analysis performed in this paper does not include an economic assessment, but does compare the overall impacts of three electricity generation systems:

i) Wind power;
ii) Alberta Inter-connected System (AIS) grid (energy sources for the AIS are 89 percent coal, 8 percent gas, 3 percent hydro);[3]
iii) Natural gas power in Alberta.

The LCVA methodology has six steps: Goal Definition; Scoping; Inventory Assessment; Impact Assessment; Design Improvement; and Reporting (see Figure 1). These steps are described briefly below.

The **goal definition** stage clearly defines the decisions to be made, the questions to be answered and the actual products or production systems to be analyzed and compared on the basis of equivalent provision of service to the consumer.

Scoping consists of clearly mapping out the life-cycle flow of activities involved in production, use and disposal, and organizing these activities into discrete and convenient units of analysis, referred to as unit processes.

Inventory assessment involves collecting and validating data to quantify the inputs and outputs within the life-cycle stages selected for analysis. The data are compiled and modeled to provide aggregated results for various scenarios and systems to answer the key questions outlined in the LCVA goal definition.

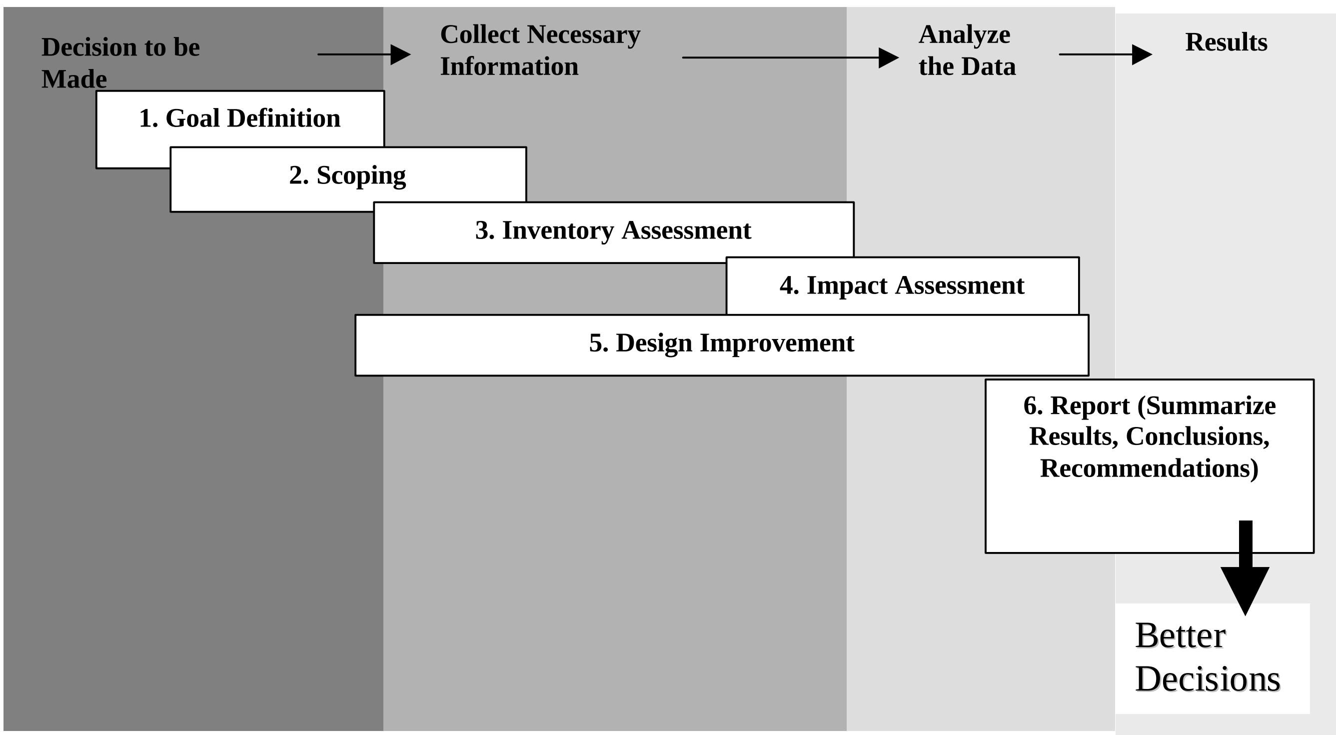
The **impact assessment stage** involves assessing the results in terms of their environmental and financial impacts and significance. This step considers the relative change in total environmental loadings and the sensitivity of exposed areas, along with capital and operational costs.

Design improvement is a series of steps taken in tandem with the four main analysis stages. Done fully, it ensures that a systematic and serious effort is made to find opportunities to reduce the financial and environmental impacts of various technologies, process activities and material supply choices across the full life cycle. Much of the thinking and techniques of "total quality management", "pollution prevention" and "design for environment" can be deployed in LCVAs that are committed to a full design improvement stage. Design improvements were not considered in this particular study.

Report preparation includes the synthesis and summary of results, along with development of conclusions and recommendations. These are compiled in a report or presentation to the decision makers responsible for project approval, selecting options, or making any other decisions that triggered the LCVA in the first place.

This paper follows the general format of the LCVA process to compare the provision of electricity from wind with electricity produced by the Alberta Interconnected System and by stand-alone natural gas systems. The comparison includes the production, construction, and maintenance of a wind turbine, but does not consider the environmental impacts associated with the construction or maintenance of existing coal or natural gas plants.

Figure 1. The LCVA Process



2.0 Goal Definition

2.1 Objective

This study was undertaken to assess and quantify the potential environmental benefits provided by wind power. It particularly examined the life-cycle emissions of greenhouse gases, acid rain precursors, and ground level ozone precursors from wind power, and compared them with the emissions from fossil-fuel power sources.

2.2 System Description

Table 1 below identifies and briefly describes the three electricity-generating systems that were compared in this LCVA: wind, the coal-based AIS, and natural gas combustion.

2.3 Limitations and Boundaries

i) In comparing the systems described in Table 1, the system boundaries (see section 4.1, Inventory Assessment, System Boundary Selection) used in this LCVA include unit production for the wind system (i.e., the wind turbine), but do not include the construction or expansion of either the coal- or gas-powered facilities. This results in a conservative evaluation of the benefits of the wind system.

ii) Information on emissions resulting from the production of the wind turbine was obtained from a single source, and thus may not represent the emissions associated with other wind turbines that differ in size and technology.

iii) Data on emissions associated with the processes described in this paper came from a variety of sources and, in the opinion of the Pembina Institute, are currently the best available public data sources. However, a degree of uncertainty will still exist, given differences in location, time, and process technology.

iv) The assessment of the life-cycle impacts of the wind turbine does not include the manufacturing (parts assembly) of the turbine or tower.

Other limitations:

- This paper does not include a life-cycle assessment of costs and revenues.
- Data sources have not been externally reviewed by a second party.
- Maintenance of AIS infrastructure facilities (including natural gas) are not considered.
- Decommissioning of neither wind nor AIS facilities is considered.
- Potential solid and water pollutants are not included.

These limitations are not considered to have a significant influence on the overall results of this study.

Table 1: System Identification and Description

System	Description
Case 1: Electricity provided by a horizontal axis Vestas® wind turbine	The provision of electricity over a 25-year period from a 600kW Vestas® horizontal axis wind turbine. This includes the extraction and processing of the raw materials, transportation to the site, and on-site assembly and maintenance. The manufacturing, or parts assembly, of the turbine is not included in this study, given limited energy input. A 20% capacity factor is applied. [4]
Case 2: The Alberta Inter-connected System (AIS) representing the grid average	The provision of electricity over a 25-year period from a system whose electrical generation make-up is approximately 89% coal, 8% natural gas, and 3% hydro.[3] Coal and natural gas extraction and transmission are included. Coal-fired plant is reported to be 32% efficient, gas-fired plant at 29% efficiency. [3]
Case 3: Electricity provided by combustion of natural gas	The provision of electricity over a 25-year period from natural gas plants. Assume simple cycle. 29% efficiency reported. [3] Gas extraction and processing included.

3.0 Scoping

3.1 Functional Unit

The production of 1,000 kWh of electricity was used as the functional unit to compare each system. The wind system was initially modeled for the total amount of electricity a wind turbine could provide over the span of 25 years (as provided by Vision Quest Windelectric Inc.), but for ease of presentation, results are reported for 1,000 kWh. Distribution losses are considered within the functional unit.

3.2 Environmental Stressor Categories

Table 2 presents the three environmental stressor categories selected for analysis in this LCVA. Since much of the interest in wind power arises from greenhouse gas emissions, it is reasonable to focus on the differences in air pollutant emissions for the systems being considered. Three stressor categories—greenhouse gases, acid rain precursors, and ground level ozone precursors—provide an indication of the relevant environmental performance of different technologies. The contributing factors to each stressor category are shown in Table 3. Each stressor category has two or more contributing pollutants, each with a weighting factor that allows the results to be reported in "stressor equivalents."

Table 2. Selected Environmental Stressor Categories

Stressor Category	Discussion
Greenhouse Gases	Potential impact is climate change through enhanced greenhouse effect. Canada has agreed to reduce emissions to 6% below 1990 levels through the Kyoto Protocol of the United Nations Framework Convention on Climate Change.
Acid Rain Precursors	Acid forming emissions lead to regional acid deposition with potential impacts on flora and fauna due to a low pH in soils and water. In 1994, Canada set a national annual cap of 3.2 million tonnes of SO_2 by the year 2000.
Ground Level Ozone Precursors	Ground level ozone, or smog, is considered to have a negative impact on human health (respiratory problems) and plant growth. Several Canadian municipalities, including Vancouver, have limitations on these emissions to protect local air quality. In Alberta, a 24-hour average guideline of 110 ppb for NO_2 exists.

Table 3. Contributing Factors to each Environmental Stressor Category

Stressor Category	Stressor Category Units	Contributing Factors	Weighting of Factor
Greenhouse Gases	Kg CO_2-Equivalent	CO_2 CH_4 N_2O	1 21 320
Acid Rain Precursors	Kg SO_2 -Equivalent	SO_2 NO_x	1 0.70
Ground Level Ozone	Kg (VOC[1] + NO_x)	VOCs NO_x	1 1

[1] VOC = volatile organic compounds

4.0 Inventory Assessment

4.1 System Boundary Selection

The three process-flow diagrams presented below (Figures 2 to 4) illustrate the unit process considered for each system. The shaded areas in each diagram indicate those unit processes that were not scoped and whose environmental impacts thus were not quantified.

For the wind system, most aspects in the production of the turbine have been included. This includes raw material extraction and component production, as well as component transportation. Once the wind turbine has been installed, the only unit process considered to have significant environmental effects, in terms of air emissions, is the ongoing maintenance of the turbine. Maintenance is considered for only one turbine, but routine conditions would have multiple wind turbines maintained during a single visit. Thus any air impacts resulting from maintenance would be overestimated in this study.

For both coal and natural gas power (Figures 3 and 4), the emissions created from upstream activities (resource extraction, processing, and transportation) are included. The transmission of electricity is included as the final life-cycle stage for all systems. Some processes not included in the analysis are listed in Tables 4a, 4b, and 4c.

Figure 2. Wind-Generated Electricity

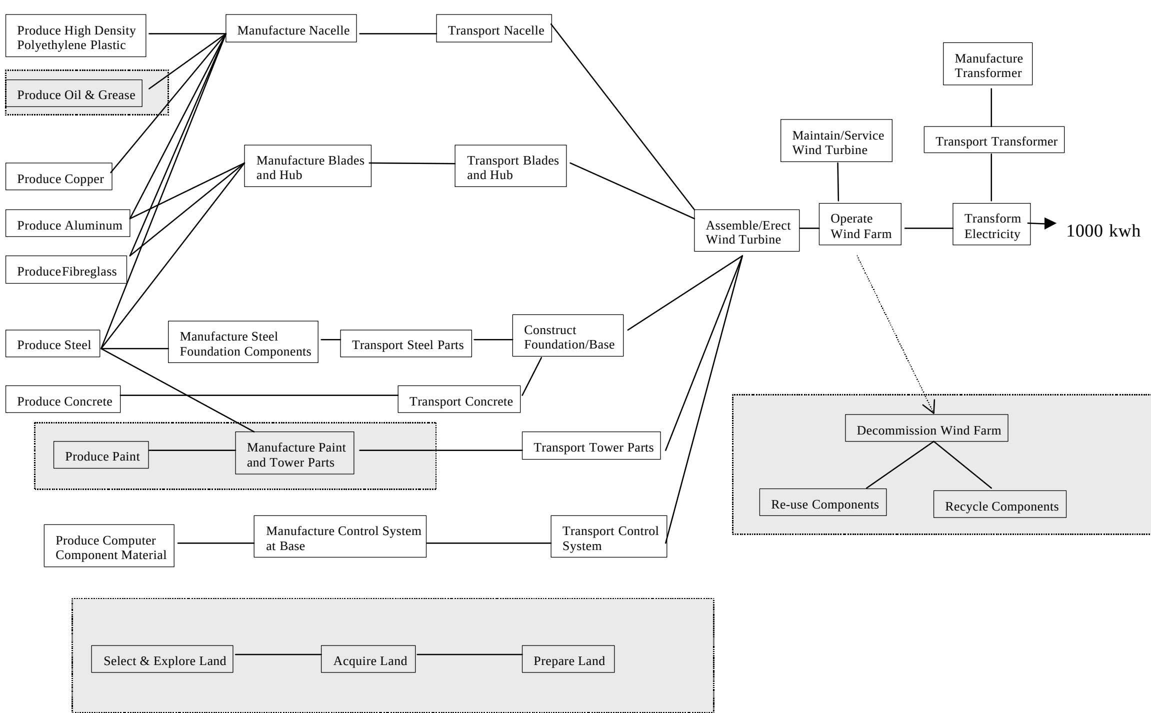


Figure 3. Alberta Inter-connected System

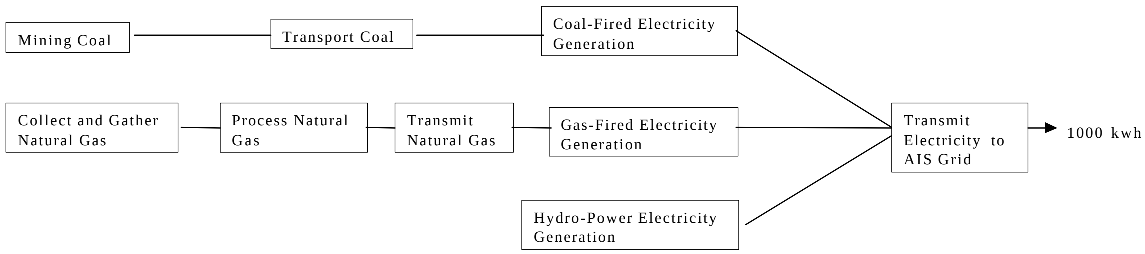


Figure 4. Natural Gas-fired Electricity Production System

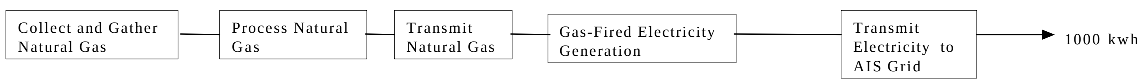


Table 4a. Processes not Quantified in the Wind System

Unit Process	Reason for Exclusion
Manufacture of the wind turbine or tower	These impacts are negligible compared to the extraction and processing of raw materials used in the manufacturing.
Back-up power generation	Power backup is irrelevant in a dynamic spot market such as the AIS grid, as a multitude of buyers and sellers participate in the market and ensure that all loads are met under normal conditions.
Produce oil and grease	Based on proxy data for oil and grease, CO_2 emissions from the production of oil and grease used for a wind turbine were calculated to amount to approximately 0.05% of the total environmental outputs.[5] Thus this process was not considered significant.
Produce paint	At the time of this study, no data were available on the production of paint. However, it is assumed that the emissions associated with the quantity of paint required per turbine would be negligible.
Transportation of *processed* materials (i.e., not final products)	The distance between processing plants and manufacturing plants in Europe is relatively minor compared to transportation distances overseas.
Select/explore, acquire, and prepare land	Wastes associated with these processes are extremely variable and thus difficult to adequately quantify.

Table 4b. Processes not Quantified in the Coal and Natural Gas Systems

Unit Process	Reason for Exclusion
Ongoing plant maintenance	It is assumed that the emissions associated with plant maintenance will not significantly affect overall emissions for either system.

Table 4c. Processes not Quantified in All Systems

Unit Process	Reason for Exclusion
Decommissioning of facility infrastructure	A lack of reliable data and the variability of end uses were the primary reasons for excluding this process. The disposal and recycling of waste material would truly be the final stage in a life-cycle analysis.

4.1.1 Location

The systems considered in this investigation are for Alberta, Canada. Although the wind turbine is considered for a wind farm in Alberta, its parts are produced and manufactured in Denmark. The regional impacts will depend on land use, ecological sensitivity, climate conditions, and land and water features that exist in the area where the environmental impact occurs. Global impacts from greenhouse gases are independent of location.

As well, emissions created from the production of the wind turbine will depend on the country or countries in which the raw materials are processed and the turbine parts are manufactured. Process technologies in North America may differ from those in Europe, and both areas would most likely have more efficient technologies than any developing countries with the capacity to produce turbine components.

4.1.2 Time and Technology

This LCVA is based on current practices and technologies in the delivery of power. Any changes in technologies utilized over time are not considered. Given that any technological advances should increase the operational efficiency of the systems involved, the life-cycle inventory provided in this study could be considered a worst case scenario when compared with future power generation.

4.2 Data Sources and Assumptions

Wind Power – Case 1

The unit processes and considerations for wind power generation are summarized in Table 5.

4.2.1 Manufacturing of Processed Materials

The quantities of materials required to produce the components for one 600kW Vestas® wind turbine supplied from Denmark were obtained from Vision Quest Windelectric Inc. and directly from the manufacturer. The emissions resulting from the energy inputs to each manufacturing process are not considered in this analysis due to lack of available data. However, masses were provided and applied to transportation-generated air emissions (Table 6).

4.2.2 Transporting Component Parts

Distances traveled in the delivery of all the components and associated wind turbine parts are indicated in Table 7. These distances were estimated assuming a wind farm located at Pincher Creek, Alberta. The total mass of each component is included (data supplied by Vision Quest®). Plant locations differ for each component as noted in the table above.

Transportation by truck and by ship was considered in this investigation. Truck travel amounted to 12,565 km, and 31,000 km were traveled by ship in transporting the wind machine components. It is assumed that all modes of transportation are fueled by diesel. Transportation distances between the production plant (where raw materials are combined to create a processed material) and the manufacturing plant (where processed materials are formed for a specific purpose) are not included.

All air emission data for the combustion of diesel fuel are from the Center for Transportation Research, Argonne National Laboratory, 1998. The amount of fuel consumed was based on energy content factors per tonne-kilometres. These data were supplied by the same organization, for both ships and trucks.

Table 5. Unit Processes and Considerations for Wind Power

Unit Process[2]	Considerations
Produce HDPE[6]	European data. This data includes the extraction of resources up to final polymerisation.
Produce Copper[7]	European data. "Cradle-to-gate" analysis.[3] All life-cycle stages up to "gate" are considered.
Produce Aluminum[8]	European data. "Cradle-to-gate" life of an aluminum ingot. Transportation distances of raw materials will differ for national plants, as will energy sources.
Produce Fibreglass[9]	American data. Emissions from resin production are not included. No greenhouse gas emission data available.
Produce Steel[8]	European data. "Cradle-to-gate" analysis for a "tinned" steel sheet. Hot-forming and cold-rolling process should not account for a significant portion of the emissions.
Produce Concrete[10]	American data. Emissions include the production of cement. Fuel source for cement processing not reported.
Operate Turbine	A capacity factor of 20% is used; this may be conservative and thus emissions for a wind turbine may actually be lower than calculated.
Transform Electricity	1% transformation losses are applied.
Transmit Electricity	7% transmission losses are applied.

Table 6. Material Amounts and Manufacturing Locations (kg)

	HDPE	Copper	Aluminum	Fibreglass	Steel	Paint	Concrete	Location
Nacelle	50	1,000	1,600	750	16,350	-	-	Denmark
Blades/Hub	-	-	250	5,750	2,500	-	-	Denmark
Paint and tower parts	-	-	-	-	37,000	250	-	Denmark
Foundation	-	-	-	-	4,735	-	43,230	Alberta, Canada
Transformer	-	-	-	-	3,279	-	-	Oregon, U.S.A.

Table 7. Distances and Unit Masses for Transportation Processes

Unit Process	Assumptions and Considerations
Transport transformer	Distance from Oregon is 1,700 km and mass of transformer is 3,279 kg.
Transport steel	Distance from Calgary and surrounding areas is 300 km to Pincher Creek and mass of steel is 4,735 kg.
Transport concrete	Distance from local suppliers is 100 km and mass of concrete is 43,230 kg.
Transport tower parts	Distance by truck from Louisiana to Pincher Creek is 4,465 km and the mass of the tower is 37,000 kg.
Transport control system	Distance by truck from Halifax to Pincher Creek is 4,900 km and the distance by ship from Denmark to Halifax is 7,000 km. The mass of the control system is 200 kg.
Transport blade and hubs	Distance by truck is from Halifax to Pincher Creek is 4,900 km and distance by ship from Denmark to Pincher Creek is 7,000 km. Total mass is 8,500 kg.
Transport nacelle	Distance by truck is 1,100 km from Vancouver to Pincher Creek and distance by ship is 17,000 km from Denmark to Vancouver. The mass of the nacelle is 20,000 kg.

[2] Each process noted in this table includes the gathering and extraction of raw materials.
[3] "Cradle-to-gate" refers to the time and processes from extraction of raw materials up to and including the processing. The processing plant is the "gate."

Table 8. Other Assumptions

Unit Process	Data Source	Assumptions and Considerations
Operate wind farm	Vision Quest, 1998	A single 600 kW wind turbine will produce 25 million kWh over a 25-year period. A conservative 20% capacity factor is considered in this study. An increased factor would reduce per-unit emission of the turbine. No backup power is considered.
Maintain and service wind turbine	Vision Quest, 1998	Travel distances assumed per wind turbine. Quarterly inspections from Calgary for first two years; quarterly inspections from close proximity (10 km) all remaining years. More than one wind turbine would be serviced at once.

Alberta Inter-connected System – Case 2

These data were collected through a study completed by Monenco Agra Consultants in 1996. It assumes that 89 percent of the AIS grid is supplied with coal-fired electricity, with 8 percent and 3 percent being delivered from natural gas and hydroelectric power respectively. [3]

For coal and natural gas, all upstream exploration and gathering have been taken into account. The transmission and distribution efficiency over the electrical lines is assumed to be 93 percent. [3] Given that the AIS mix has not changed significantly since this study was performed and no real technological advancements have been implemented, this data set is considered to be applicable. The gas turbine considered is reported to have an efficiency of 29 percent, and is assumed to be simple cycle. [3] The coal plant is reported to have an efficiency of 32 percent. [3]

Natural Gas Fired Electricity – Case 3

These data were extracted from the 1996 Monenco Agra study. [3] Emissions associated with extracting and gathering the natural gas, as well as with the transmission of sweetened natural gas, will vary with time. As mentioned, the gas turbine is reported to have an efficiency of 29 percent and is assumed to be simple cycle. [3] Transmission and distribution efficiency over the electrical lines is assumed to be 93 percent. [3]

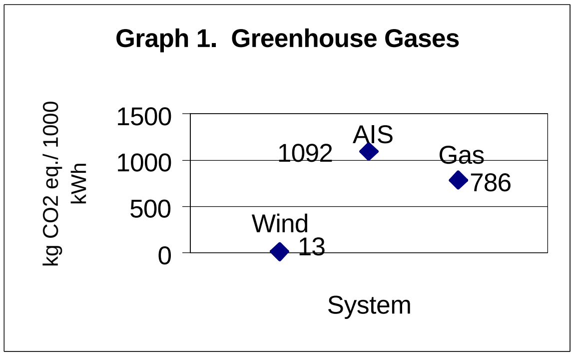
4.3 Uncertainty – All Systems

Due to the lack of time and resources available, an in-depth investigation into the uncertainty for each system was not performed. However, even assuming a 50 percent error margin for all systems, there would be no overlap between the high range of uncertainty for the wind system and low range of uncertainties for the other options. Thus, a high level of confidence exists when comparing the mean results for each system in this study.

5.0 Results and Discussion

5.1 Greenhouse Gases

Graph 1 shows that the greenhouse gases produced by the AIS and by natural gas-generated electricity far exceed those created by the wind turbine. Greenhouse gas emissions from the Wind system are approximately 98.5 percent less than similar emissions from the Gas system and 98.9 percent less than the AIS. Given that this difference is based on the provision of 1,000 kWh of electricity, the difference becomes substantial over time.



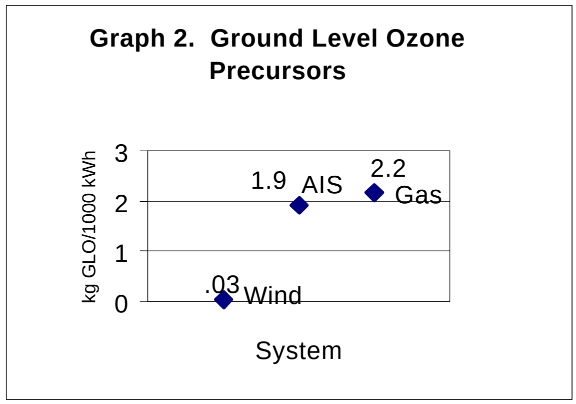
To put this into context, a single 600kW wind turbine producing 1.3 million kWh of electricity annually, offsetting the current AIS grid system, would result in a reduction of approximately 1.4 kilotonnes of CO_2 equivalents per year. Canada's total contribution of greenhouse gases from electricity generation in 1995 was 103 Mt [1] and Alberta accounted for approximately 47 percent of these emissions. [1] Considering that less than two percent of Alberta's electricity was generated from wind in 1998, there is clearly a significant opportunity to avoid these emissions. [3]

In the production of a wind turbine, it was found that 70 percent of the greenhouse gas emissions were generated from the combined production of concrete (including cement), aluminum, and steel. Each of these processes would occur in Denmark, but the greenhouse gas impact would be global.

Numerical amounts of potential greenhouse gas emissions are provided in section 6.0.

5.2 Ground Level Ozone Precursors

Graph 2 displays the relative air emissions of ground level ozone (GLO) precursors in the three systems. GLO precursors generated from the wind system are approximately 98.5 percent less than those produced by the AIS and 98.7 percent less than those created by the Gas system. While more GLO precursors were generated by the Gas system than the AIS, this can be accounted for by the amount of volatile organic compounds (VOCs) reported for the combustion of natural gas. Note that the same data source providing information on both coal and natural gas life cycles only reported VOCs for the gas stream and not for coal.[3] Also, the reported efficiency for the gas turbine (29 percent) is less than that of the coal plant (32 percent).

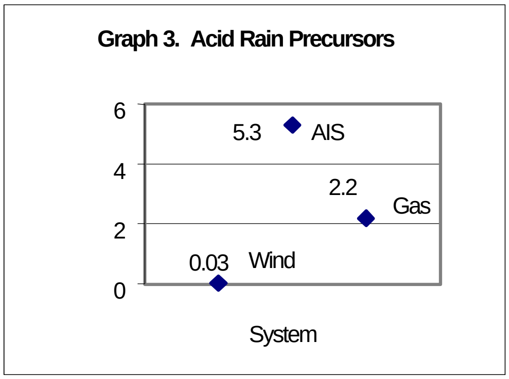


Although the Gas system creates noticeably more GLO precursors than the AIS, both systems generate far more GLO emissions than the wind system. Emissions of ground level ozone precursors have the potential to affect both human health and agricultural crops on regional basis. Given Alberta's agricultural productivity, a shift to wind power would be the most environmentally considerate option.

5.3 Acid Rain Precursors

Graph 3 illustrates the relative emissions of Acid Rain Precursors (ARP) generated by each of the three systems. The AIS is the largest contributor of ARPs, which is to be expected given that the fuel source is predominantly coal. ARP emissions from the wind system are 99.4 percent less than the AIS, and 98.7 percent less than the Gas system.

The regional ARP emissions from both the AIS and Gas system would occur throughout different areas of Alberta.



5.4 Overall Comparison of Systems

When the stressor categories are compared across the three generating systems, not only is wind consistently a more environmentally benign choice, but its life-cycle impact is also far smaller than the other two systems. As well, the cumulative impacts of expanding electrical generating capacity of a system could be significant. For example, each unit amount of electricity generation added to the AIS will cause greenhouse gases to continue to accumulate in the atmosphere; if wind power were used instead, these emissions would remain negligible.

When dealing with effects on local ecosystems, sometimes the amount of environmental loading is less important than how close the ecosystem is to its environmental load limit. For stressors such as acid rain precursors, particulate matter, or hazardous air pollutants, for example, certain environments may already be heavily loaded with a mix of these stressors and any additional stress could have drastic impacts. Therefore, despite the obvious benefits of wind power generation, the application of these results must take into account the geographic location of the various life-cycle stages and the associated loading limits of the surroundings.

A detailed analysis of the three systems clearly shows the environmental benefits of a wind-powered system over traditional fuels.

6.0 Quantification of Potential Co_2eq Offsets from Choosing Wind-Generated Electricity

Having analyzed the amount of greenhouse gases generated by each of the three systems in this study, it is possible to measure the amount of emissions reductions that could be achieved by using wind-generated electricity. The predominant greenhouse gases, in addition to carbon dioxide (CO_2), are methane (CH_4) and nitrous oxide (N_2O). The greenhouse gas impacts of both these compounds are given a weight relative to the impact of CO_2. Thus, the total offsets are reported in CO_2 equivalents (CO_2eq).

Greenhouse Gas Offsets Calculations

The offsets calculated here are based on the functional unit of 1,000 kWh of electricity provided, and thus give a basis for the actual amount of electricity that is to be provided by a single wind turbine.

Greenhouse gas (GHG) emissions per system:

GHG emissions for AIS = 1092 kg CO_2eq
GHG emissions for Natural Gas system = 786 kg CO_2eq
GHG emissions for Wind system = 13 kg CO_2eq
Difference in greenhouse gas emissions per system compared to wind:

[AIS] – [WIND] = 1092 kg CO_2eq – 13 kg CO_2eq
= 1079 kg CO_2eq

[NG] – [WIND] = 786 kg CO_2eq – 13 kg CO_2eq
= 773 kg CO_2eq

To obtain total potential offsets, these offsets will be multiplied by whatever multiple of 1,000 kWh actually is produced by the wind system. For example, if 2,000 kWh of electricity are generated by a wind system instead of the AIS, the offset would amount to 2 x 1079 kg CO_2eq.

Greenhouse gas emission reduction credits are currently being sold and traded in Canada and internationally. The value of these reduction credits varies, ranging from less than $5 per tonne of CO_2 equivalent to as much as $60 per tonne. [11]

7.0 Conclusion

The potential air emissions created through the life of all three systems compared in this study show that wind power is by far the most environmentally benign option of the three. Choosing wind power over coal or natural gas could potentially provide approximately 1,080 kg CO_2eq or 775 kg CO_2eq worth of greenhouse gas offset credits respectively, per 1,000 kWh.

The total offset that could be realized will depend on the type of fuel with which wind is compared, as well as on the conditions of the wind site location. The design of emerging greenhouse gas offset mechanisms may affect any potential greenhouse gas emission reduction credits to be captured.

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