*While some of the wood waste produced by the forest industry in British Columbia is used to cogenerate process steam and electricity in pulp and paper mills, substantial excess quantities of this material are burned with no attempt to capture energy released during incineration. If 50% of the current wood waste surplus were instead used to produce electricity from condensing turbines, approximately 4280 gigawatt hours per year of electricity could be obtained. If the electricity were exported to the United States and thereby prevented the construction of a fossil fuel burning thermal electricity plant in the US, the results would include direct economic benefits to British Columbia as well as global environmental benefits.*

*Bien qu'une certaine quantité des déchets de bois produits par l'industrie forestière en Colombie Britannique soit dirigée vers la cogénération de la vapeur et de l'électricité dans les usines de pâte et de papier, un surplus considérable de ces matériaux est brûlé sans aucune tentative de capter l'énergie libérée au cours de l'incinération. Si 50% du surplus actuel des déchets de bois étaient plutôt utilisés pour produire de l'électricité avec des turbines à condensateur, à peu près 4280 gigawatt-heures d'électricité pourraient être obtenues chaque année. Si on exportait cette électricité aux Etats-Unis, empêchant ainsi dans ce pays la construction d'une usine d'électricité thermale qui brûle un combustible fossile, parmi les résultats figureraient des avantages économiques directs pour la Colombie Britannique ainsi que pour l'écologie mondiale.*

Mark Jaccard is Assistant Professor and Timo Makinen and John Nyboer are graduate students in the Natural Resources Management Program, Simon Fraser University, Vancouver, BC.

# Electricity from Wood Waste: Integrating Energy and Environmental Analysis in British Columbia

MARK JACCARD, TIMO MAKINEN and JOHN NYBOER

Wood waste (also called hog fuel) is combustible wood residue in mechanically shredded form. In British Columbia vast quantities are produced as a byproduct of the wood products industry, sawmills being the primary source. Considerable amounts of wood waste are burned for the production of steam and some electricity in pulp and paper mills and sawmills. However, more than half the annual production of wood waste in BC is disposed of through combustion in beehive and teepee burners.

When energy prices rose in the 1970s, researchers at the University of British Columbia assessed the economics of increasing the use of wood waste for the production of electricity at BC's pulp and paper mills (Margolick and Helliwell, 1981). Although this research succeeded in demonstrating an economic interest in further utilization of wood waste, a number of factors over the past decade have prevented this from occurring to any significant degree:
(1) excess productive capacity for electricity in BC and in potential export markets in the US;
(2) institutional barriers in BC discouraging investments to utilize wood waste for energy production; and
(3) declining energy prices, which reduced the economic interest in the use of wood waste as an energy source.



Energy Studies Review Vol. 1, No. 2, 1989 Printed in Canada

While energy prices have still not recovered in real terms, other conditions have changed considerably in recent years. First, the excess electricity capacity in BC and potential US markets has largely been absorbed. Electric utilities in both jurisdictions are once again assessing various options for investment in expanded capacity.

Second, the BC government is now actively exploring the potential for electricity exports to the US. Without electricity imports, many of the target market areas in the US face new investments in electricity production based on the burning of fossil fuels.

Third, several of the institutional barriers to electricity production from wood wastes have been removed. For example, BC Hydro now exhibits an interest in all potential energy sources and a willingness to purchase electricity from independent producers.

Fourth, the environmental consequences of energy production and use have emerged as a central concern of scientists, politicians and the public. Thermal electricity plants are responsible for considerable emissions of atmospheric pollutants. Since excess wood waste is already disposed of via combustion, applying the energy thereby released to the production of electricity would have environmental benefits if it supplanted thermal electricity from fossil fuels.

The objective of this study is to assess the economic and environmental impacts of harnessing the unutilized energy referred to above in order to produce electricity. Quantifying these impacts requires a number of plausible assumptions concerning the market for the electricity to be produced and the electricity producing technology that it would replace. It also implies the need for evaluative techniques which are capable of considering more than one objective and of assessing factors which may not be measurable in the dollar terms normally used to account for costs and benefits.

## Method

Politicians have responded to rekindled public concerns about environmental degradation by claiming that, henceforth, environmental costs and benefits will be incorporated in private and public investment decision making. In theory, the standard techniques of cost-benefit analysis (CBA) allow for this, but their practical application runs into several problems. Simpson and Walker (1987) draw attention to three major limitations of CBA which seem particularly relevant when the investment in question concerns energy and the environment. They note that there are problems in using CBA to deal with:

- **intangibles** — costs and benefits which are difficult or impossible to express in monetary terms;
- **uncertainty** — which exists because future costs and benefits may be very difficult to estimate with any degree of confidence; and,
- **intergenerational equity** — because there tends to be bias against future generations resulting from conventional ways of incorporating time preference or capital productivity (i.e., the discounting of future costs and benefits).

Simpson and Walker recommend that, instead of trying to amalgamate each of these aspects into a single quantitative CBA result, the energy analyst better serves the decision maker by explicitly setting up multiple accounts (or dimensions) and providing evaluative information for each in turn.

This study provides a practical context in which to apply their approach. Certain air pollutants, such as excessive $CO_2$ emissions, create problems in CBA because: (1) many of the costs are difficult to quantify (the problem of intangibles); (2) those that are quantifiable will occur decades into the future and are thus extremely difficult to estimate precisely (the problem of uncertainty); and (3) the costs will be incurred far enough into the future such that the practice of discounting biases the evaluation against the interests of future generations (the problem of intergenerational equity).

The investment proposal considered in this study is evaluated in two dimensions. The first dimension is restricted to tangible, relatively certain and near-term costs and benefits, which are evaluated in the conventional manner. The second dimension assumes that society recognizes a benefit — however intangible, uncertain and far into the future — to reducing atmospheric emissions in the present. In this dimension, the evaluation technique switches from CBA to **cost effectiveness.** Benefits are quantified in physical terms and set in a ratio to the costs of achieving them (e.g., cost per tonne of $CO_2$ emission reduction). This allows for the comparison of alternative investments that will achieve the same objective.

The problem of uncertainty is also treated in accordance with the guidelines of Simpson and Walker (1987). Some of the uncertainty is associated with the tangible data used in the economic analysis. Wherever possible, this uncertainty is dealt with through the common practice of sensitivity analysis: a range of probable values for uncertain variables is tested to see if changes in them significantly affect the results. On the other hand, uncertainty related to variables already judged to be intangible and difficult to estimate, such as the costs borne by a society due to excessive $CO_2$ emissions, must be omitted from the sensitivity analysis because they are not evaluated in dollar terms at all. Indeed, the very need for an intangible component arises in part because the variables involved in it are more uncertain than the tangible variables. Thus one can say that uncertainty in the intangible variables is dealt with merely by accepting the non-monetary objectives established for that part of the analysis, in this case the reduction of various atmospheric emissions.

The analysis proceeds as follows. First, the magnitude and cost of electricity potentially available from wood waste in BC are calculated. Next, an export price is used to estimate the revenues from the sale of the electricity in long term contracts to the US. Then, because this export of electricity could supplant electricity produced in fossil fuel burning plants in the US, estimates are made of the net reduction in the emissions of airborne pollutants which would result.

## Data

The basic assumption of this study is that at least 50% of BC's annual production of wood waste, an amount equal to 2.2 million tonnes per year (Reid, Collins and Associates, 1987), could be made available as a long run renewable energy source for thermal electricity production. The 50% figure was chosen in order to account conservatively for future unavailability of at least some of the wood waste. This may occur due to: (1) other emerging uses, such as the production of particle board; (2) the difficulty of bringing some of the wood waste to an efficient location for combustion; (3) variations in annual production of wood waste due to cyclical fluctuations in forest industry output; and (4) the possibility that the total cut of the forest industry may decrease due to future shortages of timber supply.

Over the period from 1976 to 1986 the provincial surplus of hog fuel increased by 2%, even though the utilization of wood waste increased by 81% (Reid, Collins and Assoc., 1987). Thus, although some variations in regional supply are to be expected, no major shortfall in the province-wide supply of hog fuel is likely, given the 50% buffer assumed in this study.

Using the hog fuel to generate steam and running the steam through condensing turbines[1] would produce 15.4 PJ (4280 GWh) of electricity per year.[2] This is equivalent to the amount of power produced by a thermal plant of 542 MW capacity. Condensing electricity produces roughly twice the electricity per unit of fuel as does the cogeneration of steam and electricity. As no potential currently exists to utilize steam from the excess wood waste in BC, it is assumed

1 / In a condensing turbine high pressure steam is used to drive the turbine but, unlike cogeneration, no use is made of the exhaust steam.

2 / Hog fuel has an estimated heat content of 20 MJ/kg (Batelle Pacific Northwest Laboratory, 1984):

$20\ MJ/kg \times 2.2 \times 10^9$ kg of hog fuel burned/yr = 44 PJ/yr.

Using a thermal efficiency of 35% for condensing turbine electricity generation yields 44 PJ/yr x 0.35 = 15.4 PJ/yr.

that it would be most economical to generate the maximum amount of electricity possible, rather than cogenerate steam and electricity.

Transmission losses during delivery of the electricity to the US are assumed to be 7.5% for a market such as California (Northwest Power Planning Council, 1988). This leaves a total of 14.25 PJ (3959 GWh) to be purchased by the US importer.

For the environmental account, it is necessary to estimate the size and location of a US plant that would not have to be built because of this incremental purchase of electricity from BC. A plausible alternative to the extra imported electricity would be a coal burning plant at the US coal fields on the east side of the Rocky Mountains. Such a plant would also suffer transmission losses were it producing for a market such as California, but, since the distance to market is less, we assume that it would only incur losses of 3.75%. Thus, the 542 MW of thermal electricity generation capacity in BC would supplant a thermal plant of approximately 520 MW in the US.

It is difficult to produce an estimate for the export price of the electricity. It is assumed for this project that it will be negotiated in long term contracts, with a formula based on the costs avoided by not building a generating plant in the US.[3] Given that the cost to American utilities of producing electricity with a medium-sized coal-fired thermal plant is currently estimated at \$.06/kWh (1988 Canadian dollars) (Lee, 1988), a selling price of \$.03/kWh appears to be a conservative estimate. This is assumed to be the price received by the BC electricity producer net of wheeling charges for transmitting the electricity through the BC Hydro and US delivery networks.[4] At a price of \$.03/kWh the electricity sales would generate annual gross revenues of \$119 million.[5]

Since expenditures are already incurred to dispose of hog fuel, only the incremental capital, operating and transport costs associated with this electricity generation proposal are included. These are itemized below, with all costs in 1988 Canadian dollars.

Because the province's supply of hog fuel is relatively dispersed, it would be more practical and less costly overall if a number of small power generation facilities were constructed. These would be strategically located in regions of the province having the greatest supply of hog fuel (most notably the Prince George, Cariboo and Mackenzie regions) and near existing utility grids in order to minimize transportation and handling costs. Largely because of the widespread development of small scale independent electricity production in the US in recent years, the cost of **packaged turbines** is lower than a decade ago. Turbines rated at 20 MW and greater are estimated to cost in the order of \$1250 per kW of installed capacity. This cost includes state-of-the-art particulate emission control systems and high efficiency burner designs for wood waste boilers[6] (Jagerlund, 1981). The installed capital cost for the total number of required small scale electricity plants is estimated to be \$678 million.[7]

Annual operating and maintenance costs are typically 2 to 6% of the installed capital cost of a plant (Peters and Timmerhaus, 1980). However, the addition of the new facilities will primarily replace labour already employed at existing wood waste incineration facilities. For this reason, the lowest value of the above range is used to account for any additional labour the hog fuel-fired electricity generation facilities may re-

---

3/ This is similar to precedents set in contracts between Manitoba Hydro and Quebec Hydro for long term electricity sales to the US.

4/ In a recent short-term electricity export sale by BC Hydro, wheeling charges were approximately \$.002/kWh.

5/ 14.25 PJ/yr x 1 kWh/3.6 MJ x \$0.03/kWh = \$118,750,000.

6/ The latest hog fuel boiler designs allow wood waste of 60-70% moisture to be burned without fossil fuel supplement. While negligible amounts of fossil fuel may be required for boiler start-up, no incremental fossil fuel costs are anticipated.

7/ Assuming a 90% utilization factor and using the energy flows calculated in footnote 2, above, the total rated capacity required would be:
44 PJ/yr x 1 yr/8760 h x 1 h/3600s x 0.35 x 1/0.9 = 542 MW.
Thus the capital cost = \$1250/kW x 542,000 kW
= \$677,500,000.

quire. Thus, annual operating and maintenance costs are estimated at $13.2 million over and above the current costs of wood waste disposal. Ash disposal costs are assumed to be unchanged from the present situation.

Because of the large provincial surplus of hog fuel, and because of a limited number of alternative uses for the wood waste, the cost of the hog fuel currently burned as waste is essentially a function of transportation distance and the degree of handling. Strategic placement of the power generation facilities will minimize transport costs. Estimating a cost for hog fuel is difficult given the lack of external markets and the wide variation in transport opportunities,[8] but the best estimates available indicate that an average cost of $10 per tonne is reasonable (Reid, Collins and Assoc., 1987). Thus, annual handling and transportation costs can be estimated at $22 million.[9]

In this study the exported electricity is assumed to supplant an equivalent amount of coal-derived electricity in the US. This assumption was chosen for several reasons. First, it appears that conservation currently offers the best economic return to electricity investments in BC, so that little or no investment in electricity supply is presently justifiable in this province. Second, utilities in the US, even in the resource-rich Pacific Northwest, still include coal as a key component in their long range portfolio of future electricity sources (Northwest Power Planning Council, 1989). Even if the demand for electricity did not grow at all, new facilities, many of which burn coal, are continually required to replace thermal plants as they are decommissioned. It is therefore a realistic assumption that the exported electricity could prevent the installation in the US of 520 MW of coal-fired electricity production capacity.

The combustion of coal and other fossil fuels is associated with an array of atmospheric pollutants. Although particulates, unburned hydrocarbons and carbon monoxide are significant byproducts of this combustion, the key pollutants are sulphur dioxide ($SO_2$) and nitrogen oxides ($NO_x$), the precursors to acid rain, and carbon dioxide ($CO_2$), the primary greenhouse gas.

If one assumes that the avoided coal plant would be built to meet the emission standards of the US Environmental Protection Agency, and that it would operate at roughly the same thermal efficiency as the wood-fired plants (35%), the following annual reductions in emissions would result: 22,022 tonnes of $SO_2$, 11,011 tonnes of $NO_x$, and 3.71 million tonnes of carbon dioxide. (See Appendix A for detailed calculations.)

In addition to the reductions in US emissions, there would be improved air quality in BC. Burning wood waste in state-of-the-art furnaces in order to produce electricity would result in reduced emissions of fly-ash and other particulates in comparison to combustion with beehive and teepee burners. Improved combustion can be expected to reduce the amounts of carbon monoxide and $NO_x$ produced as well. Unfortunately, no data have been found to allow quantification of this benefit.

The data inputs for the CBA are summarized in Table 1. Uncertainty associated with capital cost, the export price and the discount rate are dealt with by testing alternative values for these three inputs. Capital costs range from $1000 to $1500 per kW of installed capacity. The export price for electricity ranges from $.04/kWh to $.05/kWh. The discount rate ranges from 6% to 10%. The base case values for these three inputs are $1250/kW, $.045/kWh and 8% respectively.[10]

## Results and Discussion

*Economic Dimension*

Table 2 presents the results of the CBA for the

8/ We are assuming that 50% utilization of the current surplus will leave hog fuel as an essentially free good (except for transport costs). As more hog fuel is demanded it may be necessary to alter this assumption and estimate supply and demand curves for hog fuel that would enable the calculation of an equilibrium price.

9/ $2.2 \times 10^6$ t burned/yr x $10/t = $22 \times 10^6$

10/ This is the base discount rate currently used by BC Hydro to evaluate alternative investments.

**Table 1:** Data for Cost Benefit Analysis* (All monetary values in 1988 $)

| | |
|---|---|
| Capital Costs | = $1000, $1250, $1500 per kW capacity |
| Operating Costs | = 2% of capital cost |
| Installed Capacity | = 542 MW |
| Electricity at at Bdr (GWh) | = 3959 (4280 GWh/yr with 7.5% transmission loss) |
| Electricity Revenue | = $0.04, $0.045, $0.05 /kWh |
| Capacity Factor | = 90% (uptime of plants) |
| Hog Fuel (t/yr) | = 2,200,000 (4,400,000 tonnes available, 50% used) |
| Transportation & Handling | = $10.00 per tonne |
| Discount Rate | = 6.0%, 8.0%, 10.0% |

* The base case includes the following conditions: $1250/kW capacity, $0.045/kWh, 8% discount rate.

**Table 2:** Cost Benefit Analysis Results: Extreme Values of Sensitivity Analysis

| Electricity Price ($/kWh) | Discount Rate (%) | Capital Cost ($/kW) | NPV ($x10$^6$) |
|---|---|---|---|
| .03 | 8 | 1250 | 239* |
| .01 | 6 | 1500 | -728 |
| .05 | 6 | 1000 | 1684 |

*Base case

extreme values of the sensitivity analysis in which capital cost, export price and discount rate are varied. In the base case, the investment yields a net present value (NPV) of $239 million over its 40-year life. That is, an investment of $678 million with annual operating and fuel costs of $35.2 million and annual revenues of $119 million would yield, when discounted to present value using a rate of 8%, net benefits of $239 million.

The investment is unprofitable at the extremely low electricity price of $.01/kWh (NPV = -$728 million), but this is to be expected. This low price was included primarily for the purpose of demonstrating a low return to electricity production from wood waste that society might be willing to accept in order to meet certain environmental objectives. We return to this issue in the next section.

At the other extreme, the project could produce a NPV of $1684 million. The probability of this outcome is considered to be higher than that of the negative outcome described above, given current electricity prices in North America.

With the base case values, the cost of electricity from wood waste-fired plants in BC is in the order of $0.017/kWh.[11] It is interesting to note that this cost is just over a third of the estimated $0.045/kWh for electricity from BC Hydro's next potential hydroelectric project, the Site C dam on the Peace River. This surprising result suggests that if one were to relax the assumption that the wood waste-generated electricity be exported, it may be competitive as the next source of electricity for domestic requirements. Indeed, even if there are additional costs overlooked in this study, a thorough evaluation of the wood waste option should be conducted prior to any decision to build the Site C dam for export or domestic requirements.

Finally, the cost of acquiring wood waste, additional to the cost of the current disposal method, was adjusted in order to find the level to which it could rise without rendering the project unprofitable. For base case conditions, the break-even cost of acquiring, handling and transporting wood waste is $21/tonne. Moreover, this cost could rise to $46/tonne before the electricity from wood waste equalled the cost of electricity from the Site C dam.

*Environmental Dimension*

Evidence suggests that human activity is responsible for the significant increase in atmospheric

11/ Average cost per kWh is calculated by compounding forward the capital cost to the first year of operation (year three), then annualizing capital cost using a capital recovery factor. Annualized capital cost is then added to operating and wood waste costs, then divided by annual electricity production.

levels of certain gases, such as the three mentioned here. It is less certain that these increased levels will result in climate change over the next 50 years, but increasingly that likelihood is leading decision makers to see benefits from investments that reduce emissions of these gases or, at least, that prevent the addition of new emission sources. (See, for instance, Government of Canada (1989).) Since the costs of climate change are extremely uncertain, often intangible and assumed to be primarily in the distant future, it makes little sense to try to quantify these in monetary terms in order to incorporate them in a CBA.

Instead, the assumption taken in this study is that reduction or prevention of these emissions is seen as providing a social benefit, however unmeasurable. In this situation one can conduct a cost-effectiveness analysis, in which investments are compared on the basis of the costs required to achieve the same objective.

The objective in this case is to reduce or prevent the emission of $CO_2$, $SO_2$ and $NO_x$. Ratios can be developed, for comparison with alternative investments, of the cost per tonne of gas emission reduced.

Table 3 presents the cost effectiveness results for reducing $CO_2$ emissions for the extreme values of the sensitivity analysis. Similar ratios can be calculated for $SO_2$ and $NO_x$. The middle row of the table shows that if the price received for electricity from wood waste were only $.01/kWh, the project implies a cost of $5.20 for each tonne of $CO_2$ reduced. This ratio can then be compared with other investments intended to reduce $CO_2$ emissions.

The cost effectiveness results for the first and third rows of Table 3 indicate that in the base case and the optimistic case the project has the fortunate characteristic of being both economically viable and environmentally desirable. The negative values indicate that the proposal to export electricity from wood waste in order to supplant coal-generated electricity produces $1.70 of NPV per tonne of $CO_2$ reduced in the base case and $11.90 per tonne of $CO_2$ reduced in the optimistic case.

Since the quantities of $SO_2$ and $NO_x$ emissions are much smaller than that of $CO_2$, the base case cost effectiveness analysis reveals extremely high benefits per tonne of emissions reduction. The proposed investment generates $286 of NPV per tonne of emission reduction of $SO_2$ and $572 of NPV per tonne of emission reduction of $NO_x$.[12]

**Table 3:** Cost Effectiveness Analysis Results: Extreme Values of Sensitivity Analysis for $CO_2$ Reduction

| Electricity Price ($/kWh) | Discount Rate (%) | Capital Cost ($/kW) | Cost Effectiveness ($/tonne) |
|---|---|---|---|
| .03 | 8 | 1250 | - 1.7* |
| .01 | 6 | 1500 | 5.2 |
| .05 | 6 | 1000 | -11.9 |

*Base case

Although these are unconventional results for a cost effectiveness analysis, they nonetheless provide an important signal that should not be overlooked. These ratios suggest that the investment project considered in this paper would allow us to have our cake and eat it too. Perhaps there are other such investments. Some have suggested, for example, that numerous conservation investments will produce similar results; i.e., a combination of economic and environmental benefits.[13] Multiple objective studies, similar to this one, will hopefully assist decision makers in assessing investments that seek to meet, or perhaps trade off, more than one objective.

12/ Economists and engineers in the US have devoted considerable research effort to identifying cost effective measures to reduce $SO_2$ emissions, ranging from scrubber technologies to low sulphur coal. Few, if any, of these proposals provide the luxury of generating both economic and environmental benefits.

13/ A study conducted for the Federal/Provincial/Territorial Task Force on Energy and the Environment (Government of Canada, 1989) identified an array of conservation and fuel switching investments to reduce $CO_2$ emissions; those investments providing economic benefits (at a discount rate of 7%) were estimated to achieve almost half of the target $CO_2$ reduction goal of 20% of 1988 Canadian $CO_2$ emission levels by the year 2005.

## Conclusion

A project to utilize the energy from the combustion of wood waste in BC in order to produce electricity for export to the US has been shown to be financially viable. The proposed project would also reduce North American emissions of $SO_2$, $NO_x$ and $CO_2$ by eliminating the need for a medium-sized, fossil fuel-burning electricity plant. Regional air quality improvements within BC would also occur.

In spite of these significant social benefits, this project does not appear to be under serious consideration by the relevant private or public agencies in BC. The reasons for this are diverse, but clearly work is still required to remove several barriers. Public decision makers must explicitly incorporate environmental objectives (via cost effectiveness analysis or other means) in their assessment of the social benefits of alternative investments and encourage those which are found to be beneficial but which are not initiated in the private sector. In the case of wood waste this might involve the following actions.

- Steps could be taken to ensure security of wood waste supply at a fair price for the investor, be that BC Hydro or some other private or public agent. This may require an initiative by government (e.g., the BC Ministry of Forests) to reduce some of the transaction costs of wood waste acquisition and to ensure security of wood waste supply.
- If the investor is not BC Hydro, there must be guaranteed access to the BC Hydro transmission grid at a price that reflects the contribution to system costs incurred by the wood waste project involved. Again, third party intervention may be required, perhaps from the BC Utilities Commission.
- Access to US customers, through the Bonneville Power Administration's intertie between the Pacific Northwest and California, must be ensured. The Canada-US free trade agreement has already improved BC Hydro's access rights to this intertie (Government of Canada, 1988), but negotiations are required if the new capacity necessary for substantial exports is to be added. This is perhaps the greatest obstacle to the export component of this proposal. It does not preclude, however, the production of wood waste electricity for domestic consumption.

Finally, while this study is limited to a specific investment proposal in one region of Canada, its results have a much broader relevance. Significant quantities of wood waste are burned in several regions of the country. With increasing concerns over greenhouse gas emissions, wood waste represents an energy source that might, if logged areas are successfully replanted, involve no significant net change in atmospheric levels of $CO_2$. This aspect of the proposed wood waste program requires further study.

# Appendix A

Calculations of Emissions Reductions

### $SO_2$

The EPA-permitted emission level for electric utility steam generating units constructed after 1978 is 520 ng/J (1.20 lb/million Btu).

The heating value of the coal must equal that of the hog fuel, less the additional transmission losses of the BC-produced electricity (3.75%). The annual reduction in $SO_2$ emissions is:

$$42.35 \times 10^{15}\ \text{J/yr} \times 520 \times 10^{-12}\ \text{kg/J} \times 1\ \text{tonne}/1000\ \text{kg}$$
$$= 22{,}022\ \text{tonnes/yr}$$

### $NO_x$

The EPA-permitted emission level is 260 ng/J (for furnaces fired by lignite, bituminous anthracite and other coal fuels).

The annual reduction in $NO_x$ emissions is therefore:

$$42.35 \times 10^{15}\ \text{J/yr} \times 260 \times 10^{-12}\ \text{kg/J} \times 1\ \text{tonne}/1000\ \text{kg}$$
$$= 11{,}011\ \text{tonnes/yr}$$

### $CO_2$

A typical heating value for bituminous coal is 29.3 GJ/T (Energy, Mines and Resources Canada). A typical analysis shows coal to be 70% carbon by weight (Himmelblau, 1982). From chemical stoichiometry, 44 mass units of carbon dioxide are produced for each unit of carbon burned. (Note that this assumes complete conversion of carbon to $CO_2$; the amount of carbon monoxide produced is assumed to be negligible.)

Therefore, the annual reduction in $CO_2$ emissions is:

$$42.35 \times 10^{15}\ \text{J/yr} \times 1\ \text{tonne}/29.3 \times 10^{9}\ \text{J} \times 0.70 \times 44/12$$
$$= 3.71 \times 10^{6}\ \text{tonnes/yr}$$

## References


BC Hydro (1988) *Proceedings — First Annual Electric Energy Forum* (Vancouver: BC Hydro).

Government of Canada (1988) *The Canada-US Free Trade Agreement and Energy: An Assessment* (Ottawa: Government of Canada).

Government of Canada (1989) *Report of the Federal/Provincial/Territorial Task Force on Energy and the Environment* (Ottawa: Government of Canada).

Himmelblau, D.M. (1982) *Basic Principles and Calculations in Chemical Engineering* (Englewood Cliffs, New Jersey: Prentice-Hall).

Jagerlund, R. (1981) 'Efficient Firing of Wet Bark and Wood,' Technical Paper presented to the Forest Products Research Society, New Orleans.

Lee, G. (1988) 'Is the Planet Baking? — How Might the Greenhouse Effect Affect the Northwest's Energy Picture?' *Northwest Energy News* (Nov/Dec).

Margolick, M. and J. Helliwell (1981) 'Electricity from Wood Waste in British Columbia,' (Vancouver: Department of Economics, University of British Columbia).

Northwest Power Planning Council (1988) 'Cost and Availability of New Generating Resources,' Staff Issue Paper 88-14 (Portland, Oregon: Northwest Power Planning Council).

Northwest Power Planning Council (1989) *Supplement to the Northwest Conservation and Electric Power Plan, Vol I* (Portland, Oregon: Northwest Power Planning Council).

Peters, M. and K. Timmerhaus (1980) *Plant Design and Economics for Chemical Engineers* (Toronto: McGraw Hill).

Reid, Collins and Associates Ltd. (1987) *1986 Hog Fuel Availability Study — North Coastal and Interior Regions of BC* (Vancouver: Reid, Collins and Associates Ltd.).

Simpson, D. and J. Walker (1987) 'Extending Cost-Benefit Analysis for Energy Investment Choices,' *Energy Policy* June:217-227.

United States Environmental Protection Agency (1989) Seattle, Washington Office. Personal communication.