CANDU REACTORS AND GREENHOUSE GAS EMISSIONS

S. Andseta, M. J. Thompson
Sheridan College, Canada

J. P. Jarrell
Cameco Corporation, Canada

D. R. Pendergast
Atomic Energy of Canada Limited, Canada

ABSTRACT

It is sometimes stated that nuclear power plants can supply electricity with zero emissions of greenhouse gases. In fact, consideration of the entire fuel cycle indicates that some greenhouse gases are generated during their construction and decommissioning and by the preparation of fuel and other materials required for their operation. This follows from the use of fossil fuels in the preparation of materials and during the construction and decommissioning of the plants. This paper reviews some complete life cycle studies of power plants. Greenhouse gases generated by fossil fuels during the preparation of fuel and heavy water used by operating CANDU power plants is estimated. We conclude that greenhouse gas emission from this activity, per unit of electricity ultimately produced, is very small in comparison with emissions from power plants completely dependent on fossil fuel as an energy source. Nuclear power plants can thus greatly extend the energy supplies which can be derived from fossil fuel supplies while reducing greenhouse gas output.

INTRODUCTION

Greenhouse gases may be generated during the preparation of materials used in the construction and during the erection of nuclear and other types of power plants. They may also be generated from the mining and processing of fuel materials. Finally, the decommissioning of plants will also consume energy, some of which may be from sources which generate greenhouse gases. In order to demonstrate relative reductions of greenhouse gases through deployment of nuclear power plants, a complete and comparative accounting of greenhouse gas emissions for the entire life cycle of electricity production systems is needed.
Greenhouse gas generation per unit power output also depends completely on the source of energy used to support the various phases of the life cycle. An ultimate electricity production system, from the greenhouse gas reduction point of view, is one which derives all its input energy from emission free sources. Although this is conceptually possible, it is unlikely that any such system exists at present as the use of fossil fuel as an energy source is all pervasive and may be of fundamental importance to some material preparation processes.

The estimation of precise quantities of greenhouse gases produced is an enormous, if not impossible, task because of the vast number of integrated operations which go into the construction and operation of a nuclear plant. Each component of a plant also has a life cycle that depends to some degree on fossil fuels. The complexity is compounded by the differing choices of processes and energy sources used to undertake a particular operation. These processes may vary dramatically in their energy efficiency per unit output and the primary energy source that drives them.

As time goes on sources of materials vary in quality and new materials may be introduced. The implication of possible long term declining quality of uranium ores and resultant increasing energy consumption (Mortimer) to provide nuclear fuel has been considered. Similar considerations apply to other commonly used construction materials and to the extraction of fossil fuel energy resources. This time component introduces additional uncertainty in the long term to the quantity of greenhouse gases which may result from our quest for energy.

As a simple example, consider the separation of heavy water, a material component of heavy water reactors, from the light water with which it is mixed in nature. The separation can be achieved using a heat source. At one extreme the energy source could be derived from fossil fuels such as coal or oil. Another extreme would derive the heat source from a nuclear power plant. This approach greatly reduces the amount of carbon dioxide (CO_2) generated per unit of the heavy water reactor component. Heavy water for CANDU reactors is, in fact, now obtained by using nuclear energy to supply heat.

This paper begins with a historical review of estimates of CO_2 emissions from nuclear and other electricity generation systems. The information reviewed gives an indication of the relative magnitude of greenhouse gas generation during the construction and operation of nuclear electricity systems based on the critical assumptions made about the individual processes that make up the systems. CANDU reactors differ from other nuclear power systems as they are based on the use of natural uranium as fuel made possible by the use of heavy water as a moderator. This eliminates one energy intensive process (enrichment of uranium) and introduces another (separation of heavy water) to the overall nuclear electricity generating processes evaluated to date. The paper then proceeds to evaluate Canadian experience with greenhouse gases generated by fossil fuels during the preparation of fuel and heavy water used by CANDU power plants. An estimate of the life-cycle emissions from the CANDU fuel cycle, based on these data, is provided.

REVIEW

Early studies focused on the quantities of materials used by various power sources. Although the context was to evaluate constraints on power generation arising from possible shortages of materials, the information developed provides a basis for qualitative comparisons of CO_2 emissions during construction of power plants. Table 1 combines data from such a study (Rose) with recent data from CANDU reactors to provide a comparison of material requirements for several energy sources. The CANDU data is based on 80% capacity factor. Table 1 indicates very wide variation in quantities of materials to construct power plants of equal energy generating capacity. The trend toward greater material requirements for energy technologies based on low energy intensity sources is expected. The comparison provided here is not expected to be static as differing improvements in efficiency of the systems presented here may be expected in the future. Carbon dioxide emissions for construction materials of these systems are expected to be roughly proportional to the amounts of materials used. Missing from this comparison is any basis for comparing CO_2 emissions during the construction phase with those incurred during operation of the plant.

Table 1 Material quantities for construction of selected electricity generation technologies circa 1983.(Thousands of tonnes per EJ per year)

Energy Source	Steel	Concrete	Other Metals	Glass	Silicon
Coal - Electric	1,500	5,500	30	-	-
Coal - Synfuel	600	*	30	-	-
CANDU 900Mwe (1995)	1,600	14,000	*	-	-
LWR	2,500	15,000	125	-	-
CANDU 600Mwe (1995)	1,400	1,8000	*	-	-
Solar - Photo	20,000	210,000	30,000	12,000	1,800
Hydro	3,500	60,000	200	-	-
Wind	8,000	35,000	1,000	-	-
Biomass	4,500	12,000	*	-	-

* Data not available
- Negligible

Many evaluations of CO_2 releases from the operation of power plants utilizing different primary energy sources have been undertaken. A typical study (Science Concepts, 1990) shows CO_2 releases varying from 55,000 to 1,450,000 tonnes of carbon per year from light water nuclear and coal plants respectively, each of 1000 MW electrical capacity. The study included natural gas, oil, and wood generated CO_2 emissions of 820,000, 1,180,000, and 1,180,000 tonnes of carbon respectively. The electrical energy required to enrich the uranium fuel accounts for the CO_2 emissions by the nuclear plant. The electricity used for enrichment was generated from a mix of coal, gas and nuclear generation. The CO_2 emitted by the nuclear plant on this basis is on the order of 4% of that from an equivalently sized coal plant.

Another study in Germany (Weis, V.M et al, 1990) found that the contribution to CO_2 emissions from enrichment amounted to only about 0.5% of that of a coal plant. The great difference relative to the previously cited study is attributed (Uranium Institute, The) to differing enrichment processes. Most enrichment in the United States utilizes the gas diffusion process whereas centrifuges are the predominant process applied in Germany. The order of magnitude difference emphasizes the importance of process efficiency in overall determination of CO_2 releases per unit electrical energy output.

A recent study in Britain (Proops) provides an integrated life-cycle assessment of several pollution implications of various types of electrical generating systems. Emissions of CO_2 during construction, operation and decommissioning of eight types of systems are included. Changes of emissions that would result by substitution of the systems for “old coal” technology are established. Table 2 summarizes the results. Close examination of the data reveals that the CO_2 contributions resulting from the construction of the “old coal” plant are neglected. This is justifiable on the grounds that the release has already occurred so that only changes resulting from new plants are being considered. The data also reveals that the CO_2 resulting from the preparation of nuclear fuel is neglected. This follows from a decision not to include the effects of imported goods.

An important point, derived from the data of Table 2 is that the amount of CO_2 generated during construction, by all systems, is small compared with the savings resulting from operation. The CO_2 emission reduction from the non-fossil plants during operation overwhelmingly counters the CO_2 investment in construction and decommissioning. The solar plants, which require the greatest CO_2 investment, release only 1/26 times as much CO_2 when compared to “old coal” technology.

Table 2 Carbon Dioxide emission changes relative to "old coal" technology (kT/TWh)

Type	*Construction*[0]	Construction	Operations	Decommissioning
CCGT[1]	*0.43*	0.95	-711.21	0.09
IGCC[2]	*0.50*	1.10	-344.32	0.03
SUPC[3]	*0.67*	1.49	-320.95	0.03
SXC[4]	*1.00*	2.22	-1,117.38	0.61
Tide	*2.45*	5.45	-1,129.18	0.00
Wave	*8.66*	19.22	-1,129.21	0.28
Wind	*15.54*	34.51	-1,130.20	0.12
Solar	*19.69*	43.71	-1,149.61	0.48

[0] *Relative to the nuclear plant - SXC*
[1] Combined Cycle Gas Turbine
[2] Integrated Gasifier Combined Cycle
[3] Super Critical Coal
[4] PWR Nuclear(Sizewell C)

A life-cycle study started in Sweden in 1993 (Vattenfall) provides comparative data for power systems operating or considered for installation as part Sweden's electricity supply system. The studies are representative of the operation of Vattenfall's hydro, nuclear, oil, condensing gas turbine, biofuelled heat and power, wind power and a hypothetical natural gas fueled combined cycle plant. The total CO_2 releases from fueling, construction, operation and eventual decommissioning of the nuclear plants for 1995 is estimated to be 2.85 kT/TWh. This comprehensive study indicates substantially lower releases (an order of magnitude) from nuclear power than the Science Concepts study and is about equal to the results from Britain that do not include CO_2 resulting from the preparation of fuel.

The reasons for the large differences in results of these three studies are not immediately apparent, but may be attributable to differing assumptions as to the components and details of the life cycle accounted for in the studies. In particular, one of the authors of the Vattenfall study (Bodlund) suggests that much more electricity derived from water power is an input source than would be the case in England. The studies all indicate that the CO_2 burden per unit electrical output from the complete nuclear power cycle is very small and nearly negligible compared with the savings relative to fossil fuel systems.

CARBON DIOXIDE EMISSIONS FROM CANADA'S URANIUM MINING AND MILLING

Canada currently produces about one third of the world's uranium. Approximately 95 % of this comes from three mines in the province of Saskatchewan: Key Lake, Rabbit Lake and Cluff Lake. Since this uranium is the source of the natural uranium used to fuel Canada's CANDU reactors, data from these mines are reviewed to establish CO_2 emission per unit of uranium mined, milled and refined to produce the UO_2 which forms CANDU fuel elements. A "snapshot" is taken based on data from Canada's major uranium producer (Cogema, CAMECO) operations reports for 1996. Production of uranium at the mines totaled 11,321 tonnes in 1996.

These three mines and associated mills obtain ore from relatively near the surface, averaging approximately 1.5% uranium. The ore is mined using a combination of open pit and underground mining. Approximately 75% *(check*) of the ore is derived from the open pit operation. The mills associated with the mines extract uranium in the form of U_3O_8 as their final product. Fossil fuel derived energy is used at the mine sites for earth moving, transportation, heating, and steam production. Two of the mines use electricity from the grid which is derived from water power. The third mine site is more remote and generates needed electricity using diesel generators. These operations consumed 45,000 tonnes of fossil fuel, consisting of 50% propane, 47% diesel fuel and 3% gasoline. Combustion of these fuels released about 138,000 tonnes of CO_2. It is worth noting that, had all of the electricity been generated using fossil fuels the additional CO_2 generated would have been on the order of 98,000 tonnes

Organic substances are also used in explosives and as solvents. The carbon content of these has not been precisely analyzed. It is reasonable to assume that the carbon content is similar to that of the fossil fuels. If it is all released as CO_2 this source of about 2000 tonnes would contribute another 6000 tonnes of CO_2.

Some of the components and chemicals used in the refining process have potential to release small amounts of CO_2 as a result of reaction. A first order assessment indicates this is insignificant compared with that generated from fossil fuel use. No attempt is made to include this in the total.

It is concluded from the above data that the fossil fuels, explosives, and solvents used to produce U_3O_8 from Canadian mines in 1996 released 12.1 mass units of CO_2/unit of uranium. Had fossil fuel, based on the use of diesel generators, been the sole source of primary energy the release factor would have been 20.7

The next two stages of the refining process are conducted at Blind River, Ontario and Port Hope Ontario, some 4000 kilometers from the mines. At 0.025 litres/tonne-km, typical of modern diesel transport (Volvo), another 0.26 mass units of CO_2/unit of uranium is released by the trip.

The Blind River facility converts the U_3O_8 from Saskatchewan into UO_3. Natural gas is the major fossil fuel input and is used primarily to generate steam. Electricity, derived primarily from water or nuclear energy, is a major energy input. A small amount of fuel oil is used as backup for steam production. Minor quantities of propane and gasoline also contribute to fossil fuel energy input. The total CO_2 release attributed to fossil energy use is 1.33 units CO_2 per unit mass of uranium. Had diesel generators been the source of electricity this factor would rise to 2.80. Some chemicals used in the conversion process also release CO_2. Organic solvents, with a carbon content similar to diesel fuel are also used. Accounting for these sources contributes 0.04 mass units of CO_2/unit uranium.

At Port Hope, the process differs. Some of the UO_3 is converted to UO_2 for use by CANDU reactors while the remainder is converted to UF_6 for ultimate enrichment as a fuel source for light water reactors. Again, electricity is a major energy source and natural gas, fuel oil, propane and gasoline are also used for energy. Some commercial liquid CO_2 (~ 50 tonnes) is used for cooling and minor quantities of CO_2 are generated by chemicals used to neutralize acid (~3 tonnes) in the process. These sources are neglected here as the quantity is negligibly small and mostly originates as a by-product of combustion for other purposes.

Conversion to UO_2 contributes 2.80 mass units of CO_2 per unit of uranium (4.84 if electricity were derived from hypothetical diesel generators). The corresponding ratios are 2.14 and 6.78 for actual CO_2 release and hypothetical CO_2 release, for the production of UF_6.

HEAVY WATER PRODUCTION

The CANDU reactor differs most significantly from other reactor technologies in its reliance on the heavy water moderator necessary to achieve a nuclear reaction with its natural uranium fuel. Heavy water is present in only small quantities in natural water (1 part in 7000). Large chemical plants processing large quantities of natural water using substantial quantities of energy are required for production of heavy water in the quantities needed to provide the initial charge and makeup for CANDU reactors. A history of heavy water production in Canada (Rae, 1991) indicates that energy equivalent to 1 to 5 barrels of heavy oil/ kg heavy water is needed, depending on the efficiency of the chosen separation process.

The actual generation of CO_2 from Canada's heavy water production is difficult to trace. Some of the early production was based on the use of fossil fuels. The first major Canadian plant used coal as a source of energy. The second used steam from a back pressure turbine of the Nova Scotia Power Corporation in a cogeneration mode. Subsequently, two larger plants derived energy directly from steam provided by the Bruce Nuclear Power Development in Ontario. These plants have been the source of all heavy water supplied by Canada for several years. The heavy water currently available for CANDU reactors is thus essentially CO_2 free.

We establish the energy associated with heavy water production from 1973 to 1993 based on the records (Witzke) of the Bruce heavy water plants. These records provide heavy water production (15,000 tonnes), electricity consumption and steam consumption expressed as electricity production foregone based on the 31% efficiency (145,000 GWh thermal energy) of the CANDU station. We then estimate hypothetical CO_2 release (2571 tonnes CO_2/tonne U) had fuel oil, releasing 74 tonnes of CO_2/TJ (NRCan), been used as the energy source for heavy water production. Initial charges of heavy water and makeup to account for losses (COG) are used to estimate the amounts of heavy water needed per unit of net electrical production in 1995 as representative of current CANDU performance. Twenty four CANDU reactors with a total rating of 17,000 MWe charged with 15,000 tonnes of D_2O produced a net electrical output of 100 TWh in 1995. Energy derived from the uranium fuel used in 1994 (Cox) exceeded 180 MWh thermal /kg U. The average uranium consumption can thus be expressed as 18 tonnes uranium/TWh at 31% thermal efficiency.

Should fuel oil have been used as a primary energy source make up of heavy water losses would have averaged 2.26 kT CO_2/TWh. Since the initial heavy water charge can be recycled on decommissioning, the contribution from the initial charge ultimately becomes vanishingly small over a long time span. Assuming only a 40 year life, corresponding to the expected reactor life, for the initial charge results in an additional release of 9.6 kT CO_2/TWh.

CARBON DIOXIDE RELEASE ATTRIBUTABLE TO CANDU REACTOR OPERATION

The major contributors to CO_2 release from CANDU reactors have been established quantitatively. Some components are missing requiring estimates to establish the total. Construction and decommissioning , in particular have not been studied. The information on major material inputs provided in Table 1 and the basic similarity of light water reactors to CANDU reactors suggests that there is sufficient correlation that the data for from Table 2 is applicable.

Detailed information on the energy consumption and nature of fuels used during the final fabrication has not been compiled to date. However the materials of CANDU fuel are similar to light water reactor fuel The total quantity of fuel used in CANDU reactors is about five times greater due to the use of natural uranium. The study undertaken in Germany (Weis) indicated 3 mass units of CO_2 are emitted per mass unit of natural uranium. We estimate fabrication of CANDU fuel will release 5 times as much. We anticipate differences in fuel sources between Germany and Canada could substantially modify this estimate. It is a relatively small CO_2 contributor to the overall process.

These data and those from previous sections is converted and summarized in Table 3 to provide estimates of CO_2 resulting from the CANDU life-cycle using the current Canadian mix of fossil, nuclear and water power sources. This is compared with an upper bound estimate based on the assumption fossil fuels provide the sole operational energy input for fuel and heavy water production.

DISCUSSION

From Table 2 the savings in CO_2 emissions resulting from avoidance of “old coal” technology is about 1120 kT/TWh. The CO_2 cost associated with this saving from construction, operation and decommissioning of CANDU reactors is only 3.4 kT/TWh or 0.31%. Had the energy inputs for operation been derived solely from high carbon fossil fuels, rather than primarily from nuclear and hydro power the CO_2 cost would still be only 15.27 kT/TWh or 1.36%.

A small investment of fossil fuels in the construction and operation of nuclear plants thus provides a tremendous multiplication (~75 to 325 times for the example above) of energy available from the use of the fossil fuel directly as an energy source. This multiplication factor can also vary considerably, depending on the degree nuclear energy is used as an input to materials preparation. The CANDU system's use of nuclear thermal energy for heavy water separation eliminates this potential major component of CO_2 emission.

Table 3 Carbon Dioxide Emission attributable to the CANDU Fuel Cycle

Fuel Cycle Process	Actual 1996 Energy Sources (kT/TWh)	All Fossil Fuel Energy Sources (kT/TWh)	Notes
Construction	2.22	2.22	From Table 2
Heavy Water Charge	0.0	9.64	40 year life, not recycled
Heavy Water Replacement		2.26	
Mining and milling	0.22	0.37	Product is U_3O_8. Includes explosives and solvents
U_3O_8 Transport	0.005	0.005	4000 km
U_3O_8 to UO_3	0.025	0.051	Includes solvents
UO_3 to UO_2	0.050	0.087	Minor amounts from cooling and neutralization neglected
Fuel Fabrication	0.27	0.27	Extrapolated from LWR data
Decommissioning	0.61	0.61	From Table 2
Total	**3.40**	**15.27**	

Some studies(Mortimer) have suggested that nuclear energy would not be an effective means of reducing greenhouse gas emissions for a significant time. Fortunately, they are based on naïve assumptions with respect to the over use of fossil fuel in the nuclear fuel cycle and an underlying assumption that the nuclear fuel will not be reprocessed. There are many other opportunities, beyond the CANDU heavy water extraction example, to feed nuclear energy back into the processes used to prepare materials and to supply energy for other inputs to the nuclear fuel cycle. Electricity, in particular, can be applied to ore extraction and refining and to the processing of metals and other construction materials. Continuing development of the nuclear fuel cycle (Boczar) provides additional potential for sustaining the energy that can be derived from nuclear fission.

This review highlights the fact that nuclear and other alternate energy sources are all dependent to some degree on our fossil fuel sources at present. No doubt it would be possible to completely eliminate this dependence should they be depleted. Perhaps a more rationale approach would be to sustain our fossil supplies for as long as possible by using them prudently as an input to multiply our energy supplies.

CONCLUSION

A review of studies of energy input to the nuclear fuel cycle has been undertaken. An estimate of energy input to the CANDU fuel cycle based on actual Canadian experience with mining and refining of uranium ores and separation of heavy water has been presented. An upper bound estimate based on the assumption all energy input comes from high carbon fossil fuels is calculated for comparison.

Over one hundred times as much energy is derived from the CANDU fuel cycle in Canada than is input, while reducing CO_2 emissions by a similar factor. Even assuming all energy input to the cycle is derived from fossil fuel, the reduction in CO_2 emissions and multiplication factor for energy production overwhelms the energy and CO_2 inputs.

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