Climate Change

CANDU Reactors and Greenhouse Gas Emissions

S. Andseta
M. J. Thompson
Sheridan College, Mississauga, Ontario

J. P. Jarrell
Cameco Corporation, Saskatoon, Saskatchewan

D. R. Pendergast
Atomic Energy of Canada Limited

Abstract

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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 life cycle studies of several different kinds of power plants. Greenhouse gases generated by fossil fuels during the preparation of fuel and heavy water used by operating CANDU power plants are estimated. The total greenhouse gas emissions from CANDU nuclear plants, per unit of electricity ultimately produced, are very small in comparison with emissions from most other types of power plants.

Introduction

Greenhouse gases are generated during the preparation of materials used to build and operate nuclear and other types of power plants. The construction and decommissioning of plants will consume energy, some of which will be from sources that generate greenhouse gases. In order to demonstrate the 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 depends on the source of energy used to support the various phases of the life cycle. An ultimate electricity production system, from the greenhouse gas emission viewpoint, is one that derives all it's 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 ubiquitous and is 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 that go into the construction and operation of a nuclear plant. Each component of a plant also has a life cycle, which depended 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. The separation of heavy water, a material component of heavy water reactors, from the light water with which it is mixed in nature provides a simple example. The separation can be achieved using a heat source. At one extreme the heat could be derived from fossil fuels such as coal or oil. Another extreme would derive the heat 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 now obtained by using nuclear energy to supply heat.

As time goes on sources of materials will vary in quality as rich ore bodies are depleted. New materials will be introduced by new technology. 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 that may result from man's quest for energy.

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 which 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 consumptive process (enrichment of uranium) and introduces another (separation of heavy water) to the light water moderated nuclear electricity systems evaluated previously. 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 lifecycle emissions from the CANDU fuel cycle, based on this 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 of greenhouse gases emitted 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 a very wide variation in quantities of materials to construct power plants of equal energy generating capacity. Electricity technologies based on low energy intensity sources require a large amount of material to collect the energy. The comparison provided will not be static as improvements in efficiency of the systems presented here are expected. Carbon dioxide emissions for construction of these systems is expected to be roughly proportional to the amounts of materials used. Additional quantitative information on CO_2 emissions from the preparation and transport and erection of materials is needed to continue the life cycle analysis.

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

Generation Technology	Steel	Concrete	Other Metals	Glass	Silicon
Coal - Electric	1500	5500	30	-	-
Coal - Synfuel	600	*	30	-	-
CANDU 900Mwe (1995)	1600	14000	*	-	-
LWR	2500	15000	125	-	-
CANDU 600Mwe (1995)	1400	18000	*	-	-
Solar - Photo	20000	210000	30000	12000	1800
Hydro	3500	60000	200	-	-
Wind	8000	35000	1000	-	-
Biomass	4500	12000	*	-	-

* Data not available
- Negligible

Many estimates of CO_2 releases just from the operation of various types of power plants have been undertaken. A typical study (Science Concepts, 1990) shows CO_2 releases varying from 40 to 1070 kt/TWh based on 1000 Mwe plants assumed operating at 63% capacity factor. The study also included natural gas, oil, and wood power plants. They produced CO_2 emissions of 600, 870 and 870 kt/TWh, 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.

A German lifecycle study (Weis, et al) found that the contribution to CO2 emissions from enrichment amounted to only about 0.5% that of a coal plant. The great difference relative to the previously cited study is attributed (Uranium Institute) to differing enrichment processes. Most enrichment in the United States utilizes the gas diffusion process whereas centrifuge enrichment is predominant in Germany. The order of magnitude difference emphasizes the importance of process efficiency in overall determination of CO2 releases per unit electrical energy output.

A recent study in Britain (Proops) provides an integrated lifecycle assessment of several pollutants from eight alternate electrical generating systems. Emissions of CO2 during construction, operation and decommissioning are included. Changes in levels of emissions, which would result by replacing "old coal" power, with the alternate technology are established. Table 2 summarizes the results for emissions of CO2. Examination of the data reveals, however, that the CO2 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 replacement plants are being considered. The data also reveals that the CO2 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 CO2 generated during construction, by all systems, is small compared with the savings resulting from operation. The CO2 emission reduction from the non-fossil plants during operation overwhelmingly counters the CO2 expenditure in construction and decommissioning. The solar plants, which require the greatest CO2 expenditure, release only 1/26 times as much CO2 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

SXC4	1.00	2.22	-1117.38	0.61
Tide	2.45	5.45	-1129.18	0.00
Wave	8.66	19.22	-1129.21	0.28
Wind	15.54	34.51	-1130.20	0.21
Solar	19.69	43.71	-1149.61	0.48

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

A Swedish lifecycle study (Vattenfall) provides comparative data for power systems operating or considered for installation as part Sweden's electricity supply system. The studies are based on the operation of Vattenfall's hydro power, nuclear power, oil condensing, gas turbine, biofuelled heat and power, wind power and a hypothetical natural gas fueled combined cycle plant. The total CO2 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 from nuclear power than the Science Concepts study (30kt/TWh) and is about equal to the Table 2 results (2.83kt/TWh) from Britain which do not include CO2 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 waterpower is an input source than would be the case in England. The studies all indicate that the CO2 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 1/3 of the world's uranium. In 1996, which is the reference year for this fuel cycle inventory, approximately 95 % came 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 is 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 t in 1996.

These three mines and associated mills obtain ore that averages on the order of 1.5% uranium. Approximately 75% of the ore is derived from the open pit operation with the remainder coming from underground mines. 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 utility supplied electricity that is derived from waterpower. The third mine site is more remote and generates needed electricity using diesel generators. These operations consumed 45,000 t of fossil fuel, comprised of 50% propane, 47% diesel fuel and 3% gasoline. Combustion of these fuels released about 138,000 t of CO_2. Had all of the electricity had been generated using fossil fuels the additional CO_2 generated would have been on the order of 98,000 t based on data for diesel fuel consumption. The data indicates CO_2 emissions of approximately 700 kt/TWh for diesel generation.

Organic substances are also used in explosives and as solvents to purify the concentrate. The carbon content of these is variable, however it is reasonable to assume that the carbon content is similar to that of the fossil fuels. If all of the organic materials used ultimately generate CO_2 this source of about 2000 t would contribute another 6000 t of CO_2.

We conclude from the above data that the fossil fuels, explosives, and solvents used to produce uranium concentrate from Canadian mines in 1996 released 12.1 mass units of CO_2 per 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 mass units of CO_2 per unit of uranium produced.

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. The most significant of the secondary sources of CO_2 are the carbonate content of the ore which is subjected to acid leaching to extract the uranium, and the use of lime to neutralize the resulting leached tailings. The 1996 CO_2 releases from one uranium producer (9400 t) associated with the carbonate dissolution are estimated at about 7000 t. Lime is generated from calcium carbonate. About 22000 t of CO_2 is released by production of the lime needed to neutralize the tailings. The total CO_2 associated with chemical treatment of the ore and tailings associated with 9400 t uranium is thus about 30,000 t or 3.2 mass units of CO_2 per unit mass of uranium produced.

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/t-km, typical of modern diesel transport (Volvo), another 0.26 mass units of CO_2 per unit of uranium are released by the truck on such a trip.

The Blind River facility converts the concentrate into UO_3. Natural gas is the major fossil fuel input and is used primarily to generate steam. Electricity, which is derived primarily from water or nuclear energy, is important. 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 processed. 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 per unit uranium.

At Port Hope, the process diverges. 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 used for energy. Some commercial liquid CO_2 (~ 50 t) is used for specialized cooling requirements and minor quantities of CO_2 (~3 t) are generated by chemicals in the process. These sources are neglected here, as the quantity is negligibly small.

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

Most CANDU fuel is fabricated in Ontario. The buildings used for this are heated with natural gas. The fabrication process uses electricity. Data from fuel manufacturers indicates that annual production of 1775 t (uranium content basis) of fuel entailed the combustion of 500,000 m^3 natural gas and consumption of 14500 MWh of electricity circa 1996 - 1997. Most electricity produced in Ontario is from nuclear or hydro sources. The "actual" CO_2 emission is thus based on the natural gas consumption and amounts to 0.010 kt/ TWh. Had the electricity been derived from fossil fuel the associated CO_2 emission is estimated to be 0.11 kt/ TWh.

Heavy Water Production

The CANDU reactor differs most significantly from other reactor technologies in reliance on the heavy water moderator that is necessary to achieve a nuclear reaction with 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/ kgm heavy water is needed, depending on the efficiency of the chosen separation process.

The actual generation of CO2 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 backpressure 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 CO2 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 t), 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 CO2 release (2571 t CO2/t U) had fuel oil that releases 74 t of CO2/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. This is representative of current CANDU performance. Twenty-four CANDU reactors with a total rating of 17,000 MWe charged with 15,000 t of D2O produced a net output of 100 TWh electrical output 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 t 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 CO2/ 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 CO2/ TWh.

Carbon Dioxide Release Attributable to CANDU Reactor Operation

The major contributors to CO2 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 from Table 2 is applicable.

This data and that from previous sections is converted and summarized in Table 3 to provide estimates of CO2 resulting from the CANDU lifecycle 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 CO2 emissions resulting from avoidance of "old coal" technology is about 1120 kt/TWh. The CO2 emission "cost" associated with this saving from construction, operation and decommissioning of CANDU reactors is only 3.2 kt/TWh or 0.3%. Had the energy inputs for operation been derived solely from high carbon fossil fuels, rather than primarily from nuclear and hydropower the CO2 cost is still only 15.41 kt/TWh or 1.4%.

A small investment of fossil fuels in the construction and operation of nuclear plants thus provides a tremendous multiplication (~75 to 350 times for the example above) of energy available from the use of the fossil fuel directly as an energy source, per unit of CO2 released. This multiplication factor can also vary considerably, depending on the degree nuclear energy is used as an input to materials preparation. The CANDU systems use of nuclear thermal energy for heavy water separation eliminates this potential largest component of CANDU CO2 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 9kt/TWh)	Notes
Construction	2.22	2.22	From Table 2
Heavy Water Charge	0.0	9.64	40 year life, not recycled
Heavy Water	0.0	2.26	

Replacement			
Mining and Milling	0.22	0.37	Product is U_3O_8. Includes explosives and solvents
Chemical Treatment	0.06	0.06	Ore and Tailings
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	0.01	0.11	Extrapolated from LWR data
Decommissioning	0.61	0.61	From Table 2
Total	3.20	15.41	

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 rational 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 through construction of nuclear power plants?

Conclusion

A review of studies of CO_2 emissions from the nuclear fuel cycle has been undertaken. An estimate of CO_2 from 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 CO_2 is avoided by deployment of the CANDU fuel cycle in place of coal plants in Canada than is released by CANDU construction, the fuel production process, and decommissioning. The electrical energy output per unit of CO_2 released overwhelms that from the direct use of fossil fuel for electrical energy.

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