Synapse
Energy Economics, Inc.

Hydropower Greenhouse Gas Emissions

State of the Research

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1. Introduction

A. Purpose and Scope

Hydroelectric generation of electricity (hydropower) is commonly thought of as renewable, sustainable, and lacking in emission of atmospheric pollutants; however, these assumed benefits are rarely evaluated critically in the context of policymaking, as new reservoirs and dams are rarely proposed in North America, outside of Québec and Labrador.

This report reviews the state of information regarding one key policy consideration: how hydropower stacks up against other technologies with respect to greenhouse gas (GHG) emissions—including the life cycle emissions from the construction and operation of generating capacity. An important aspect of the analysis is a comparison of not only the "typical" amount of GHG emissions from each technology, but a presentation of the range of values that may be observed. The report also discusses concerns about the way GHG emissions are measured, especially in the case of hydropower, and best practices for doing so. Finally, the report discusses a specific policy consideration: the relative trade-off (from a GHG emission perspective) of Canadian hydropower imports versus other energy options for New England.

This report approaches GHG emission estimates by critically considering a variety of primary sources for the various technologies. Section 2 provides a brief review of hydropower's role in the electric industry in North America; a discussion of the types of GHG emissions from hydropower and other electric generation technologies; and an explanation of GHG measurement concepts. Section 3 presents the range of estimates of GHG emissions from existing hydropower facilities and compares those emissions to those from facilities using other technologies, including oil, natural gas, and coal. Section 4 discusses various issues that arise in the consideration and understanding of the GHG emission results and the methodologies used in the literature, including certain important caveats that apply to those results. Section 5 offers recommendations for use in policy-making contexts, including planning around additional Canadian hydropower imports. Section 6 lists the primary source material used.

B. Key Findings

Based on the literature reviewed, we find that hydropower development does emit greenhouse gases (GHGs), but the *rate* of emissions per unit of electric generation from hydropower (excluding tropical reservoirs) is much lower than for fossil fuel technologies.[1] This conclusion is discussed in more detail in Sections 3 and 4.

Lifecycle GHG emission ranges for hydropower and fossil fuel technologies are presented in Table 1 below.

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[1] Tropical reservoir issues will be revisited below, but unless otherwise specifically stated, this report will discuss non-tropical reservoir hydropower.

Table 1. Approximate Lifecycle GHG emission rate ranges by fuel type for electricity generation[2]

Technology	GHG emissions rates (kg CO_2eq/MWh)
Hydroelectric facility (run of river or non-tropical reservoir)	0.5 – 152
Hydroelectric facility (newly flooded reservoir only, boreal)	160 – 250
Hydroelectric facility (tropical reservoirs)	1300 – 3000
Natural gas-fired power plant	400 – 500
Oil-fired power plant	790 – 900
Coal-fired power plant	900 – 1200

The largest sources of GHG emissions for hydropower are the construction of the facilities, and biomass decomposition from reservoir flooding. In addition, there are ongoing net differences between the carbon uptake and respiration of the pre-flooding and post-flooding biomes and water columns. Along with methodological disparities, biomass decomposition is the largest source of uncertainty in the GHG emission estimates; the rate of decomposition is also highly dependent not only on the climate zone (e.g., tropical, boreal, etc.), but also on the specifics of the flooded biome (e.g., old river, wetlands, forest, etc.). Emission uncertainties from biomass decomposition may remain large—and site dependent—as the relevant modeling is complex.

For fossil fuel technologies, the main sources of variability relate to potential carbon capture / sequestration technologies (for new facilities), whose efficiency, effectiveness, and infrastructure requirements are speculative, and a variety of operational issues that affect the amount of electricity produced over a plant's lifetime for a given amount of construction / decommissioning emissions and for a given amount of fuel burned.

Overall, life cycle GHG emissions per unit of electric energy production are lower for hydropower than for fossil fuel sources (though in some cases net hydro emission ranges may be nearly 2/3 those for a natural gas power plant), and may be in the same range as other renewable sources and nuclear (though reservoir hydro emission ranges are likely higher than those for at least some other renewable options, depending on the specific site and the level of indirect emissions, which are not included in Table 1 above).

Recent studies have further shown that, during the first several years after reservoir creation, hydro GHG emissions may be higher than annual emissions for some fossil fuel sources. This is surprising, given the lower GHG emission ranges reported in earlier studies. The ultimate level to which newly flooded reservoir emissions decline over time is uncertain.

An important GHG policy question in comparing potential new generating facilities or imports is "but for the new facility or import, what emissions would have occurred?" This requires consideration of what generators (existing or new, within or without the regions in question) will not

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[2] Note that ranges for all technologies except "hydroelectric facility (tropical reservoirs)" and "hydroelectric facility (newly flooded reservoir only, boreal)" are estimates based on figures in Raadal et al. (2011). Raadal et al. (2011) does not contain a thorough review of tropical hydro emission rates; for this emission source, Weisser (2006) and Demarty and Bastien (2011) were used. Estimates for a newly flooded boreal reservoir were derived by Synapse based on data contained in Teodoru *et al*. (2010) and are explained further below. The units used (kg CO_2eq per MWh) are explained below.

be built or will run less often if the facility under consideration is built. One approach is to examine displaced or avoided generation by looking at the marginal emissions in the affected region or regions. Due to their high fuel cost and the ability of some of them to ramp up and down fairly quickly, natural gas generators are typically the last to be dispatched in any given hour in both New England and New York. Therefore, marginal emissions in both regions are about the same as for natural gas generators. However, one study found, ". . . increased export of hydroelectricity by Hydro Québec to the United States likely was a contributor to increased generation from fossil-fuel-fired sources in other regions in Canada."[3]

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[3] Steenhof, Paul, and C.J. Weber, 2011, An assessment of factors impacting Canada's electricity sector's GHG emissions, *Energy Policy* 39, 4089–4096.

2. Background

A. Hydroelectric Generation

With global demand for electric energy expected to grow steadily over the next 25 years, hydropower is being looked to as an important source of global energy production.[4]

Demarty and Bastien (2011) note that the increase in energy demand worldwide, in addition to raising concerns about GHG emissions, "have put hydroelectricity in the forefront of green energies. Indeed, according to Bates *et al*., 2008, hydroelectricity is the only non-intermittent renewable energy and could therefore sustain the development of other renewable energies."[5]

Hydropower has several special features that affect its role in the generation mix, beyond its energy output and capacity. For example, it does not necessarily rely on outside sources or fossil fuels to restart after an outage, making its existence, even in small amounts, quite valuable as part a utility's plan for recovering from a blackout (its "black start plan"). Hydropower can start up on short notice, as it does not depend on gently warming up boilers or turbines, and can ramp up or down in output quite rapidly. Hydropower facilities with ponding (i.e., not run of river units) can serve an energy banking function, helping to level load and price spikes. Hydropower sources with ponding are typically energy limited rather than capacity limited. That is, the amount of energy produced in a time period, say a year, depends on the amount of water available, not just the size of the unit. These factors all affect the value, economically and from an engineering standpoint, of hydropower.

Today, hydropower is the most common form of renewable energy, accounting for 16.3% of global energy production due its long history of development and exploitation compared to other types of renewable generation. In Canada, 59% of electricity generated in the country came from hydroelectric sources in 2008, although that is down from 62% in 1990.[6] In the U.S., data indicates that 6.6% and 22.8% of electricity generated in New England and New York, respectively, came from hydroelectric sources. (See Table 2, below.)

Table 2. 2010 Net Generation (MWh)[7]

	New England	New York
Hydroelectric	8,025,563	25,471,697
Non-hydroelectric	121,702,164	111,489,957
% Hydroelectric	6.6%	22.8%

According to the EIA, about 19% of hydropower's potential has been developed, globally. The *World Energy Council (WEC), Survey of Energy Resources 2007*, estimates the overall technical

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[4] IEA. *International Energy Outlook – Highlights*. Report #DOE/EIA-0484 (2010). http://www.eia.gov/oiaf/ieo/highlights.html.

[5] Of course, this is not strictly correct. Geothermal generation, for example, is not necessarily intermittent, and intermittent sources can be firmed up with storage as with molten salt solar thermal facilities. The point of the quotation, however, bears thought.

[6] Steenhof and Weber, 2011, *op. cit.*

[7] EIA Form 923 2010, 2010 December EIA-923 Monthly Time Series File, Page 1, "Generation and Fuel Data." New York is the host for several very large hydropower projects on the U.S. side of the St. Lawrence River.

potential for hydropower to be more than 16,400 TWh/yr; in 2008, global hydropower production totaled just 3,288 TWh.[8] The five countries with the highest potential include China, the United States, Russia, Brazil, and Canada.[9]

While there is clearly room for hydropower to grow (from a technical standpoint), its benefits and risks are rarely evaluated critically in the context of policymaking, as new reservoirs and dams are rarely proposed in North America, outside of Québec and Labrador. One reason is that most locations on North American rivers that were economically viable in comparison to fossil fuel generation (or energy efficiency) have already been developed. In fact, some that were developed before the large, international trade in oil have been decommissioned. Remaining undeveloped sites tend to be environmentally sensitive or costly to develop for the expected output.[10] Environmental pressures, especially regarding restoration of aquatic habitat, have also limited the political viability of new hydropower and even led to the decommissioning of a small number of hydropower sites in the U.S.

As noted above, Québec and Labrador are exceptions. Both have extensive untapped hydropower potential at sites that provincial utilities intend to develop.[11] While many of those sites are in remote areas, transmission technologies advanced between 1960 and 1980 to the point where it has become technically and economically feasible to move thousands of megawatts of hydropower from such remote locations to urban load centers in the northeastern U.S. and in Canada. As a result, exports of power from far northern Québec and Labrador to southern Québec and the U.S., as well as between British Columbia and California, became a routine commercial activity.

Measuring Electrical Output

All electric generating units, including hydropower facilities, measure their electrical output in two different but related ways. Amounts of electric energy used or produced (e.g., in a year) are measured in megawatt-hours (MWh). When discussing an amount of electric energy produced (e.g., the number of MWh produced in a given year), the terms “generation,” “generated,” or “electric output” will be used. The amount of electric power produced or consumed at a given moment will be referred to as “load” or “demand,” respectively, while the amount that *can be* produced at a given moment will be referred to as “capacity.” Capacity is measured in kilowatts (kW) or megawatts (MW). The amount of energy that *is* produced by a generator in a given period is often compared to the amount it *could* have produced if running at full capacity 100 percent of the time. That ratio, expressed as a percent or as a number between zero and one, is called the plant’s capacity factor (CF).[12]

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[8] IEA. *Renewable Energy Essentials: Hydropower*. http://www.iea.org/papers/2010/Hydropower_Essentials.pdf, (2010). Worldwide hydropower produced 3,288 TWh in 2008, yet has the potential to produce > 16,400 TWh/yr.

[9] Ibid.

[10] See Section 4.C for options in this regard.

[11] Province of Québec. (2011, May 6). *BUILDING NORTHERN QUÉBEC TOGETHER. The Project of a Generation*. Retrieved from http://www.plannord.gouv.qc.ca/english/documents/action-plan.pdf.
Hydro Quebec. (2009). Strategic Plan (2009 – 2013). Retrieved from: http://www.hydroquebec.com/publications/en/strategic_plan/pdf/plan-strategique-2009-2013.pdf
Nalcor Energy website. Accessed December 2011. http://nalcor.ca/lower-churchill-project.asp

[12] W. Steinhurst, (2008), *The Electric Industry at a Glance*. National Regulatory Research Inst. Available at http://www.synapse-energy.com/Downloads/SynapseReport.2011-01.0.Elec-Industry-Overview.10-076.pdf

B. Greenhouse Gas Emissions

There are numerous substances that act as a GHG when emitted into the air.[13] Due to the volume of their emission in energy production, the two of primary concern are carbon dioxide and methane, CO_2 and CH_4 (the main constituent of natural gas), respectively. CO_2 is emitted by the development and operation of fossil fired generators, as well as hydropower, and some CH_4 is emitted by some fossil fuel technologies. Both are also products of biomass decomposition at hydropower facilities.[14]

Each GHG has a different, quantitative effectiveness in trapping heat at the earth's surface; that effectiveness is referred to as the substance's global warming potential (GWP). In addition, each GHG degrades chemically over time in the atmosphere or is gradually absorbed by the ocean or another terrestrial geochemical cycle. Thus, GWP must be defined for a specific point in time after the emission of the GHG, similar to forecasting the economic value of an inventory of perishable goods. For example, during the first year after emission, a ton of CH_4 emitted into the atmosphere has 72 times the GWP as a ton of CO_2 emitted at the same time, while it has only 21 times the GWP of CO_2 over a 100-year period after emission. This is because CH_4 cycles out of the atmosphere faster than CO_2. Over 500 years, the ratio is 7.6.[15]

While GWP has shortcomings for short-lived GHGs, it is useful for comparing the potential climate change associated with emissions of different greenhouse gases. According to the IPCC, "The Global Warming Potential (GWP) is a useful metric for comparing the potential climate impact of the emissions of different LLGHGs [long-lived GHGs]…. Global Warming Potentials compare the integrated radiative forcing [heat trapping effectiveness] over a specified period, say 100 years, from a unit mass pulse emission and are a way of comparing the potential climate change associated with emissions of different greenhouse gases."[16] A 100-year time period is often used to compare the GWP of a mix of GHGs in policy discussions.

Using a chosen time period and the resulting GWP values, it is possible to determine the GWP of a mix of gases emitted by a power plant or its fuel cycle and to convert that total to a so-called CO_2 equivalent (CO_2eq or CO_2e). CO_2 equivalent is a measure used to compare the emissions from various greenhouse gases based upon their global warming potential (GWP). CO_2 equivalent for a given amount of a gas is derived by multiplying the weight of the gas emitted by that gas's GWP. For example, with a time period of 100 years, a ton of CH_4 has a CO_2eq as follows:

$$CO_2\text{eq of } CH_4 = (\text{weight of } CH_4) * (\text{the GWP of } CH_4)$$

or,

$$CO_2\text{eq of 1 ton of } CH_4 = 1 \text{ ton } CH_4 * 21$$

$$= 21 \text{ tons.}$$

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[13] For a list of those of concern to the United Nations, see, for example, Figure TS.5 and Table TS.2, in Solomon, S., D. Qin, M. Manning, *et al.*, 2007: Technical Summary. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, *et al.,* (eds.)]. Cambridge Univ. Press, Cambridge, UK, and New York, NY, USA.

[14] Robert Dones, *et al. Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries,* Ecoinvent Data V2.0.,103 (2007).

[15] Table TS.2 cited in footnote 13.

[16] IPCC, *Climate Change 2007: The Physical Science Basis*, p. 31 ff.

By definition, the GWP of carbon dioxide is 1.

When considering GHG emissions and emission rates, it is crucial to distinguish between different units of weight as well as between gases with different GWPs. There are two aspects to this. First, there is a difference between tons (2000 U.S. pounds, sometimes called a short ton) and tonnes (1000 kilograms, or about 2204 U.S. pounds, sometimes called a metric ton).[17] European scholarly works and UN and IPCC publications typically report in tonnes. U.S. scholarly and government publications vary in which unit they use. Second, data may be reported in terms of tons (or tonnes) of CO_2 or of carbon. A ton of CO_2 gas contains about 0.273 tons of carbon. (1 g C = 0.083 mole CO_2 = 3.664 g CO_2)[18] There seems to be a trend to standardize in tonnes of CO_2 for reporting total amounts, but it is important to check units on every comparison. Similarly, units for emission rates must be verified, but kg CO_2eq per MWh appear to be gaining ground over pounds per MWh.

C. Life Cycle Analysis (LCA) of Emissions

Life cycle emissions for an electric generation facility include emissions associated with the construction and eventual decommissioning of the facility (often called indirect emissions), as well as any emissions resulting from the facility's operation (often called direct emissions). Ideally, life cycle GHG emissions for a generating facility are calculated over a long enough interval to address all effects stemming from the facility and its fuel cycle, and, in the case of hydropower, for the entire watershed. With respect to residence times, a 100-year interval was recommended by the IPCC (and has been adopted by the UNFCCC) as a standard time horizon for the comparison of greenhouse gas emissions.[19] Note, however, that this report did not verify the extent to which life cycle analyses in the reviewed literature employed the 100-year interval.

Best practices dictate that a plant's emissions be analyzed according to a life cycle analysis (LCA) approach. LCA evaluates the sum of emissions from the complete energy chain (including the entire life cycle of the plant and its fuel), and allows for standardized comparisons. Dones et al. (2007) shows explicit examples of the energy use and non-energy emissions resulting from each

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[17] A long ton, sometimes called an Imperial ton, is defined as 2,240 pounds and is no longer used except for measuring the capacity of ships.

[18] *Glossary: Carbon Dioxide and Climate*, 1990. ORNL/CDIAC-39, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Third Edition. Edited by: Fred O'Hara Jr. Also available at http://cdiac.ornl.gov/pns/convert.html.

[19] IPCC. *Climate change: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the IPCC*. New York: Cambridge University Press (2006).
UNESCO-IHA. *The UNESCO-IHA measurement specification guidance for evaluating the GHG status of man-made freshwater reservoirs*. IHP/GHG-WG/5, 15 (June 4, 2009) (http://unesdoc.unesco.org/images/0018/001831/183167e.pdf). Recommending net GHG emissions from hydropower be calculated over 100 years in accordance with the IPCC.
IPCC, Task Force on National Greenhouse Gas Inventories. *Frequently Asked Questions*, Q1-2-4, Q1-2-11. http://www.ipcc-nggip.iges.or.jp/faq/faq.html. Q1-2-4. "How can you compare emissions of different gases? A: The radiative impact of a single GHG depends on the amount emitted and its specific properties. Currently, in reporting to the UNFCCC, Parties are asked to weigh their emissions by the "Global Warming Potential" (GWP). The GWP are calculated as the ratio of the radiative forcing of one kilogramme greenhouse gas emitted to the atmosphere to that from one kilogramme CO_2 over a period of time. The precise numbers to be used are laid down by the UNFCCC and at present they are for a 100 year time horizon. More recent estimates of GWP are given in the IPCC's third and fourth assessment reports."

stage in the construction and operation of facilities, as well as the extraction, refinement, transportation, and combustion of fuel used at the facility.

According to a 2007 report, “LCA studies systematically and adequately address the environmental aspects of product systems, from raw material acquisition to final disposal (from ‘cradle to grave’).[20] The International Organisation for Standardisation published international standards on LCA (International Organization for Standardization (ISO) 2006a; International Organization for Standardization (ISO) 2006b).” Life Cycle Analysis of emissions applies to all technologies in varying degrees.

The following table identifies the broad categories of LCA emissions.

Table 3. Categories of LCA emissions

Category of Emissions	Emission Sources
Direct emissions (from operation)	Combustion of fuels
	Operational fuel use
	Other emissions from operation (e.g., flooded land)
	Goods and services consumed during operation
Indirect emissions	Infrastructure
	Construction work
	Materials
	Transport
	Decommissioning and waste disposal

As reported below, LCA emission levels for new hydropower facilities are generally less than those from fossil fueled generators, and may be roughly comparable to, or somewhat higher than, various other renewable technologies.

D. Methodology and Sources

In the literature, there are many, occasionally conflicting, ranges for emission rates for hydroelectric and non-hydroelectric sources. Raadal *et al*. (2011) was chosen as the primary source of data in Figure 1 due to its recent publication date, comprehensive review of the literature, and analysis of a variety of emission sources. Raadal *et al*. (2011) does not contain a thorough review of tropical hydroelectric emission rates; for this emission source, Weisser (2006) and Demarty and Bastien (2011) were used. In addition, Teodoru *et al*. (2010) provides detailed field measurements of CO_2 flux for a newly flooded boreal reservoir (Eastmain 1).

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[20] Frischknecht R., Jungbluth N., Althaus H.-J., *et al*. (2007) *Overview and Methodology. Ecoinvent report No. 1*. Swiss Centre for Life Cycle Inventories, Dübendorf, 2007

3. Results

This section presents the range of estimates of GHG emissions from existing facilities, including hydro facilities, other renewables, nuclear, and fossil fuel power plants (oil, natural gas, and coal). While the research shows that hydropower development does lead to greenhouse gas emissions, and while there is some indication that emissions from hydropower facilities in the first ten years may be high, over a plant's life cycle it appears that the rate of GHG emissions per unit of energy produced is lower for non-tropical hydropower than for fossil fuel generation sources.

A. GHG Emissions Ranges for Various Technologies

Until recently, the literature had indicated that hydropower life cycle emissions are relatively low (ranging from 0.5 – 152 kg CO_2eq/MWh)[21] and are comparable to geothermal, nuclear, biomass, wind, and solar photovoltaic (PV) life cycle emissions. As shown in Figure 1 (below), those earlier estimates of hydropower life cycle emissions were much lower than those for fossil fuel sources, such as natural gas, oil, and coal.

Recently, detailed multi-year field measurement of the CO_2 emissions from a newly flooded boreal reservoir (Eastmain 1 in Quebec) has provided a slightly different perspective. Teodoru *et al*. (2010) presents measured CO_2 net fluxes for that reservoir as indicated in Table 4.

Table 4. Measured CO_2 fluxes at Eastmain 1

Year post flooding	kg CO_2eq/MWh
1	671
2	436
3	308
4	238

Teodoru *et al.* (2010) concludes that the rate at which emissions after Year 4 will decline is uncertain. For the purposes of this study, we assume a project lifetime of 100 years and two sets of emission rates after year 4: one set of high values representing no further decline (238 kg CO_2eq/MWh in all years beginning in Year 4), and a low-range set of values that declines linearly from the Year 4 value to a low of 147 kg CO_2eq/MWh in Year 14 and remains flat at 147 kg CO_2eq/MWh thereafter. Combining these data for CO_2 emission rates with the Eastmain 1 project's anticipated output of 2,700 GWh/year, we obtain a lifecycle average emission rate that ranges from about 160 to about 250 kg CO_2eq/MWh. This indicates that newly flooded boreal reservoirs, over their lifetime, may have CO_2 emission rates from about 1/3 to nearly 2/3 that of a natural gas combined-cycle plant.

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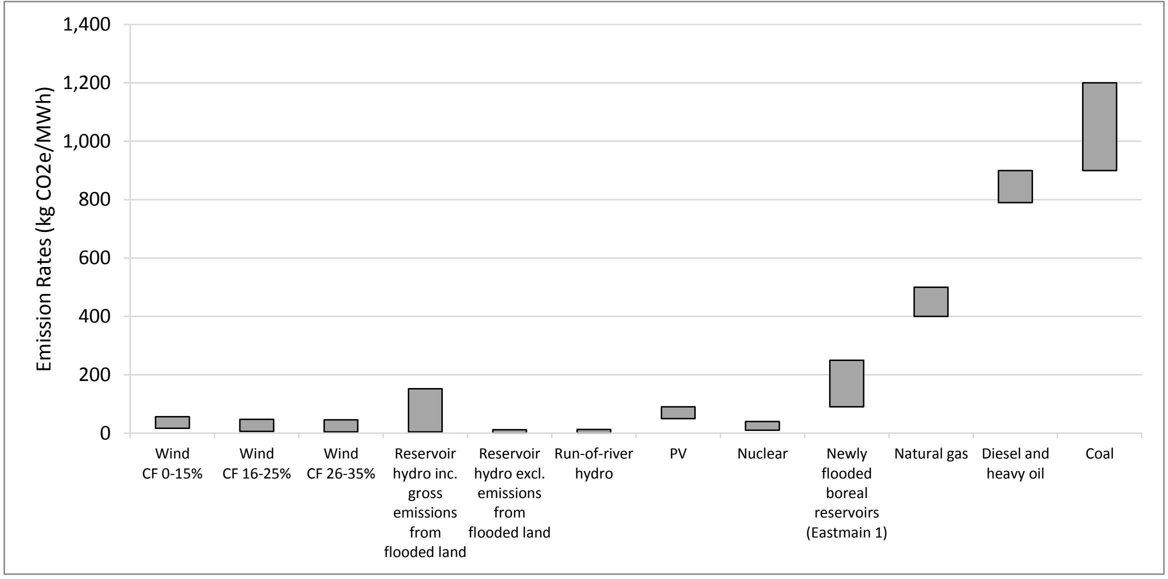
[21] Excluding tropical reservoirs.

Figure 1. GHG emission ranges for various technologies[22]



Source: Raadal, H.L., *et al*. (2011). For newly flooded boreal reservoirs, Teodoru *et al*. (2010).

The ranges provided in Figure 1 indicate that (excluding tropical reservoirs), even the *highest* emitting hydropower GHG emission rates are less than the *lowest* emitting oil, coal, and natural gas sources.

For equal electric energy outputs, the Eastmain 1 data suggest that, in addition to any indirect emissions from facility construction, newly flooded boreal reservoirs may emit CO_2 at a rate close to 32 to 63% that of the least emitting natural gas plant. In contrast, the least emitting oil- and coal-fired facilities emit more than 3 times as much GHGs than the highest emitting hydropower facility.

Not included in the hydropower emissions estimate in Figure 1 are emissions from tropical reservoirs. Tropical reservoirs are those reservoirs in the latitudes between the Tropic of Cancer and the Tropic of Capricorn.[23] Analysis by Weisser (2006) indicates that reservoirs in tropical regions emit up to 20 times the amount of GHGs as do reservoirs in boreal regions, due to higher rates of biodegradation. As analysis by Raadal, *et al*. (2011) estimates reservoirs in boreal regions to be 0.5 – 152 kg CO_2eq/MWh, the emissions factor for tropical reservoirs can be then estimated to be about 3,000 kg CO_2e/MWh. Similarly, analysis by Demarty and Bastien (2011) shows that multiple-year studies of tropical reservoirs indicate emissions factors between 1,308 – 2,222 kg

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[22] Note that ranges displayed in Figure 1 are estimates based on figures in Raadal *et al*. (2011), with the exception of newly flooded boreal reservoirs, which was based on Teodoru *et al*. (2010). Ranges in Figure 1 indicate the full ranges of maximum and minimum rates of emissions as analyzed in Raadal *et al*. (2011). Ranges for GHG emissions in this figure exclude emissions from grid losses, infrastructure related to the grid, and any backup power required for grid integration. Grid losses typically range from 5% to 20% at the retail meter, depending on service voltage, time of year, and customer density. The long distance transmission losses are a relatively small portion of the losses. Dones *et al.* (2007) provide some estimates of the energy requirement and emissions from transmission and distribution infrastructure in their section 15, but not in a manner readily interpretable for comparing remote generation options to more local ones. Additionally, the ranges indicating GHG emissions from wind power in Figure 1 combine data from studies with results for single wind turbines, studies with average data over a number of wind turbines, and studies that use average data from more than one study.

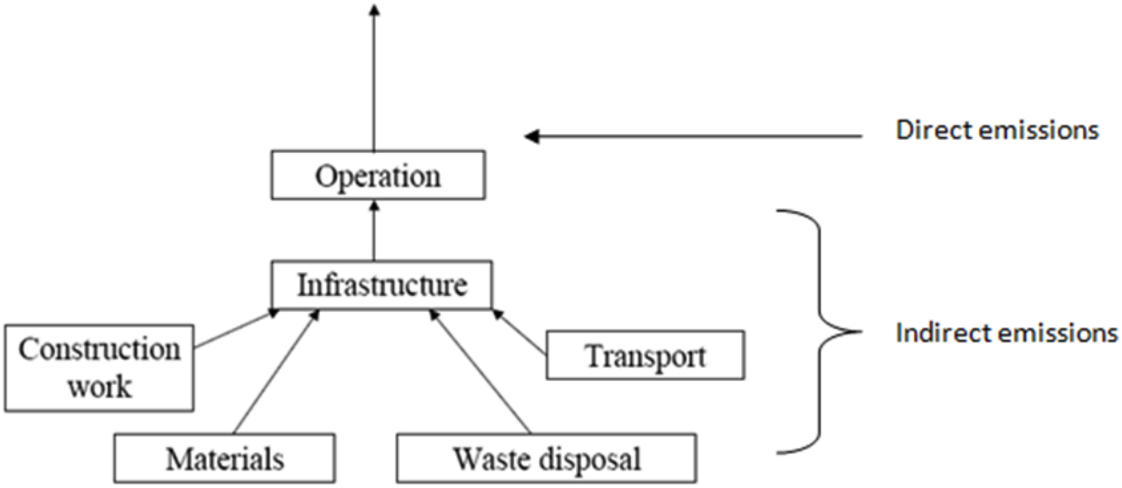
[23] This is the band of latitudes from approximately 23.5º N to 23.5º S, respectively, extending roughly from Egypt, Bangladesh, and the Bahamas on the north and Madagascar, Queensland, and southern Brazil on the south.

CO_2eq/MWh. The bottom of the resulting range (about 1300 to 3000 kg CO_2e/MWh) begins about at the level of the most emitting coal facilities and its high end is markedly higher than any other resource studied in the literature we examined. Demarty and Bastien (2011) note, however, that "to our knowledge, GHG emissions have been measured for only 18 of the 741 large dams…listed in the tropics." They further conclude that, because of the limited scientific information available, "at this time, no global position can be taken regarding the importance and extent of GHG emissions in warm latitudes."

B. Sources of Emissions and Variability

Life cycle emissions for hydropower include both indirect and direct emissions. The following figure distinguishes between the two.

Figure 2. Schematic overview of the electricity production chain for hydropower



Source: Robert Dones *et al*. *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries*. Ecoinvent Data V2.0 (2007).

Indirect Emissions

Sources of indirect emissions for hydropower include emissions from development of infrastructure (e.g., roads and transmission lines), from construction work on the facility itself, from manufacturing of materials and equipment used in building the facility, from transportation of materials and workers, and from waste disposal and decommissioning. According to Dones *et al*. (2007), the major sources of GHG emissions for hydropower within these categories include cement and steel production, and the use of diesel and electricity.[24] Raadal *et al*. (2011) states that "the major contributing factors to the infrastructure GHG emissions are concrete production and the transportation of rocks in the construction of dams and tunnels."

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[24] Robert Dones, *et al*. *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries,* Ecoinvent Data V2.0.,103 (2007). CH stands for Switzerland, FI for Finland. Reservoirs in Finland can flood large areas of peat, which is very high in organic material compared to other biomes.

Indirect emissions can account for a sizeable portion of a facility's total GHG emissions, possibly representing:[25]

- ≤ 20% of cumulative emissions for fossil fuel technology, and
- > 90% of cumulative emissions for renewable resources and nuclear.

For boreal hydropower, however, Figure 1 suggests that indirect emissions probably represent a small portion of overall emissions.

Direct Emissions

Direct emissions include emissions due to facility operation. For fossil fueled generators, this is largely from the combustion of fuel, plus the rest of the fuel cycle including extraction, refinement, and delivery, plus disposal of fuel waste and other operational waste. For hydropower facilities, decay of biomass in the soil and biome of land newly flooded by the facility's reservoir emits GHGs that diffuse up through the reservoir's water and into the atmosphere. That release of GHGs due to biomass decomposition is the largest source of direct GHG emissions for hydropower.[26]

Unlike for indirect emissions, the range of variability for direct emissions is quite large. Raadal *et al*. (2011) note that:

> "The large variations in GHG emissions from reservoir hydro power can for the most part be explained by differences in GHG emissions from flooded land… Recent research [38] shows that this data can be misleading, as the reported emissions may not represent the 'net' emissions for which reservoirs are responsible. Most LCAs report 'gross' emissions from reservoirs, as measured fluxes over reservoirs. However, there is now consensus that most natural lakes and rivers are also major sources of GHGs, as they return to the atmosphere the carbon flushed into water ways from surrounding ecosystems."

Yet another source of variability in direct emissions stems from a lack of scientific consensus on methods for estimating GHG emissions from hydropower. This issue is discussed more in Section 4.

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[25] Daniel Weisser, 2007. *op. cit*.

[26] Raadal, H., Luc Gagnon, Ingunn Saur Modahl, & Ole Jørgen Hanssen. *Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power*, *Renewable and Sustainable Energy Rev*., 15(7), 3417-3422 (September 2011) (quoting Gagnon, L, van de Vate, J.F. Greenhouse gas emissions from hydropower: the state of research in 1996, *Energy Policy* 25, 7-13 (January 1, 1997)). The other major source of GHG emission is indirect emissions from construction activities.
Alain Tremblay, *et al*. *Net Greenhouse Gas Emissions at Eastmain 1 Reservoir, Quebec, Canada*, 13 (2010). CO_2 emissions from a boreal reservoir studied in Quebec were dominated by diffusive emissions (> 99% of total emissions); degassing and bubbling represented <1% of total emissions.
IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Agriculture, Forestry and Other Land Use. Possible Approach for Estimating CO_2 Emissions from Lands Converted to Permanently Flooded Land: Basis for Future Methodological Development*, 4 (Ap 2) (2006) http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_p_Ap2_WetlandsCO2.pdf. IPCC's most simplistic formula (Equation 2A.1) for calculating CO_2 emissions from land converted to flooded land only uses diffusion rates, not degassing or bubbling.

Outside of the variances caused by inconsistent methodology, one of the largest sources of uncertainty in measuring direct hydropower emissions is the rate of decomposition.[27] Variables that impact a reservoir's decomposition rate include:

- Temperature[28]
- Water residence time, reservoir shape and volume, and amount and type of vegetation flooded[29]
- Depth[30]
- Geographic location[31]
- Reservoir age[32, 33]

In particular, reservoir age and the amount and type of vegetation play a major role in decomposition rates.[34] Teodoru *et al.* (2010) have shown that GHG emissions can increase dramatically immediately after reservoir creation, tend to fall off over a few years, and that further declines in emission rates are uncertain.

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[27] IPCC, 2006, *op. cit*.

[28] Robert Dones, *et al*. (2007), *op. cit*.
Daniel Weisser, 2007, *op. cit.*, (quoting R. Dones, T. Heck,& S. Hirschberg, (2004), *op. cit.*). Weisser estimated average GHG emission factors of 10–60 kg CO_2 eq/MWh for boreal and temperate reservoirs; 200–3000 kg CO_2 eq/MWh for tropical reservoirs.

[29] Alain Tremblay, *et al*., 2010, *op. cit.* Teodoru *et al.* (2010).

[30] Robert Dones, *et al*., 2007, *op. cit.*.

[31] IPCC, 2006, *op. cit.* P. Lee, R. Cheng, M. Hanneman & C. Scheeler. *Hydropower Development in Canada: Greenhouse Gas Emissions, Energy Outputs and Review of Environmental Impacts (Hydropower Report #2)*. Global Forest Watch Canada 10th Anniversary Publication #7. Edmonton, Alberta, 17-18 (2010) (quoting D.M. Rosenberg et al. *Large-scale impacts of hydroelectric development*. Environ. Rev. 5, 27–54 (1997) http://www.environmental-expert.com/Files%5C6455%5Carticles%5C7571%5C18sep18-A97-001.pdf.

[32] IPCC, 2006*, op. cit.* "[T]he age of reservoirs has a significant influence on CO_2 fluxes during the first 10 years. . ." (citing Huttunen, J.T., *et al*., Fluxes of methane, carbon dioxide and nitrous oxide in boreal lakes and potential anthropogenic effects on the aquatic greenhouse gas emissions, *Chemosphere*, 52, 609-612 (2003); Huttunen, J.T., *et a*l., Fluxes of CH_4, CO_2 and N_2O in hydroelectric reservoir Lokka and Porttipahta in the northern boreal zone in Finland, *Global Biogeochemical Cycles*, 16(1), doi:10.1029/2000GB001316; Soumis, N., *et al*., "Hydroelectric reservoirs as anthropogenic sources of greenhouse gases," *Water Encyclopedia*, v. 3: *Surface and agricultural water*, sous la dir. De J.H. Lehr et J. Keeley. p. 203-210. Hoboken, NJ: John Wiley & Sons; Therrien, J., Tremblay, A. and Jacques. R. (2005). "CO_2 Emissions from Semi-arid Reservoirs and Natural Aquatic Ecosystems," *In* Tremblay, A., L. Varfalvy, C. Roehm and M. Garneau (Eds.), *Greenhouse Gas Emissions: Fluxes and Processes, Hydroelectric Reservoirs and Natural Environments*, Environmental Science Series, Springer, Berlin, Heidelberg, New York, pp. 233-250; Tremblay, A., Therrien, J., Hamlin, B., Wichmann, E. and LeDrew, L. (2005). "GHG Emissions from Boreal Reservoirs and Natural Aquatic Ecosystems", *In* Tremblay, A., L. Varfalvy, C. Roehm and M. Garneau (Eds.), 2005, *op. cit.*

[33] IPCC, 2006, *op. cit.* "The rate of the post-flooding decrease in emissions may depend on the region in which the reservoir is located, but seems to vary in about a 10-year period." (citing Delmas, R. *et al.* (2005). *Long Term Greenhouse Gas Emissions from the Hydroelectric Reservoir of Petit Saut (French Guiana) and Potential Impacts*. *In* Tremblay, A., L. Varfalvy, C. Roehm and M. Garneau (Eds.), *op. cit.*, pp. 293-312; Abril, G. *et al* (2005). Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit-Saut, French Guiana*)*, *Global Biogeochemical Cycle* (in press); Tremblay, A., Therrien, J., Hamlin, B., Wichmann, E. and LeDrew, L. (2005). GHG Emissions from Boreal Reservoirs and Natural Aquatic Ecosystems," *In* Tremblay, A., L. Varfalvy, C. Roehm and M. Garneau (Eds.), 2005, *op. cit.*
Alain Tremblay, *et al*., 2010, *op. cit.*. Pre-flood net 3,200 C-CO_2/year within surface area of reservoir later flooded rose to 500,000 C-CO_2/year within one year of reservoir creation, but were expected to stabilize to 100,000 C-CO_2/year within ten years.

[34] IPCC, 2006, *op. cit.*; Alain Tremblay, *et al*., 2010, *op. cit.*

Research done at Hydro-Québec's Eastmain 1 reservoir showed that net GHG emission rates within one year of reservoir creation increased from 3,200 to 500,000 tonnes of carbon, a 156-fold increase, over pre-flooded conditions.[35] This carbon increase at Eastmain 1, calculated as a rate per unit of energy output, suggests that hydropower from the reservoir produced more GHG emissions than a natural gas combined-cycle facility each year for three years after impoundment. This is surprising, given previously reported ranges of GHG emissions for hydropower reservoirs in non-tropical areas, which were much lower.

It is noteworthy that several other studies reviewed for this report reveal similar decomposition trends as the Eastmain 1 study (GHG emissions decline with reservoir age), but the methods used were substantially less rigorous, and the hydropower emission rates were not as high. This includes three studies published in a 2005 monograph also focused on Canadian boreal reservoirs.[36]

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[35] Alain Tremblay, *et al*., 2010, *op. cit.*

[36] Alain Tremblay *et al*. (eds.). *Greenhouse Gas Emissions: Fluxes and Processes, Hydroelectric Reservoirs and Natural Env'ts*. Envtl. Sci. Series, Springer (2005).

4. Discussion

A. Best Practices for Estimating GHG Emission from Hydropower

Considerable effort has been invested in developing best practices for comparing the emission profiles of different generating technologies in ways that reflect life cycle emissions in a comparable manner and on a level playing field. It is noteworthy that there is not yet scientific consensus on methods for estimating GHG emissions from hydropower. To take one simple example, the proper atmospheric "dwell time" for various GHG emissions affects the global warming potential (GWP) values to be used in comparing GHG mixes. At times, certain utilities have proposed using a financial-type discount rate to compare GHG emissions at various times during the life cycles of technologies, even though that technique does not help policymakers determine the true environmental effects of the emissions. Yet without standards, there is always room for well-meaning disagreements, not to mention cherry picking results to favor one technology over another.

The UNFCCC and Kyoto Protocol monitoring, reporting, and review guidelines for national inventories incorporate the methodological Good Practice Guidance developed by the IPCC, which stipulate how emission estimates are to be prepared and what is to be included in annual inventory reports.[37] The IPCC guidelines for reporting GHG emission from hydropower, however, appear to be limited. For carbon, they provide specific guidance only regarding the carbon emissions resulting from the loss of biomass on flooded land. For estimating methane from hydropower, they note that "available information on CH_4 emissions is provided [in the IPCC document]," but "it is not possible, at present, to recommend a default methodology. Countries seeking to report CH_4 emissions from flooded lands should, where feasible, develop domestic emission factors."[38]

The lack of consensus appears to be fundamental, not just rhetorical. More research is needed and concepts need to be clarified. This has resulted in varying degrees of accuracy and precision. As noted by Raadal, *et al*., "The wide ranging results [of GHG emissions from hydro power] indicate a need for stricter standardised rules and requirements for life-cycle assessments, in order to differentiate between variations due to methodological disparities and those due to real differences in performance of the plants."[39] This is despite the adoption of directives by the European Union (EU Electricity Directive 2004/53/EG, art. 3), guidelines set out by the Society of Environmental Toxicology And Chemistry (SETAC), and an ISO Standard (ISO-14044), all addressing the issue.[40]

Newly flooded reservoirs release GHGs due to the decomposition of biomass covered by the flooded reservoir as explained above. In addition, when considering new reservoirs, there is an additional GHG effect that should be considered. That effect is the elimination of a terrestrial biological community and its replacement by an aquatic biological community. Since each

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[37] Env't Can. 2010. Nat'l Inventory Report: *1990-2008: Greenhouse Gas Sources and Sinks in Can., Part I*. The Canadian Gov'ts Submission to the UN Framework Convention on Climate Change.

[38] IPCC, 2006, *op. cit*.

[39] Raadal, Hanne Lerche, *et al.*, 2011, *op. cit*.

[40] All cited in *ibid.*

biological community has a net GHG effect due to respiration of plants and animals, as well as their natural fixing or releasing of carbon during their growth and decay, there may be a substantial net GHG effect per year from this change in ecology. For example, a tropical rain forest typically fixes and stores a large net GHG amount, while a boreal tundra or forest may store a substantial amount of carbon in slow growing biomass but would have a smaller net fixing rate per year. Most of the literature reviewed does not discuss this effect or is unclear about whether that effect is or is not included in GHG emission estimates. Teodoru *et al.* (2010) provides a valuable example of how such measurements may be made.

In sum, efforts to standardize GHG flux measurements from reservoirs are ongoing.[41] However, given the long-term effects of many GHGs and the long lifetimes of power plants, it seems reasonable that LCAs should cover a minimum time period of 100 years for comparisons of GWP for all projects, as well as requiring a full watershed analysis for hydropower projects, in particular.

Precision, accuracy, and validity of GHG LCA estimates depend on the amount of existing reference data. For example, as wind power technologies progress in size and capacity factor, their LCA emission rates will change, but we do not now know how. Hydropower estimates may be water-body specific, country specific, or climate specific.[42] Hydropower emissions appear to vary markedly over the plant's lifetime as reservoir decomposition regimes evolve.

B. Displaced Generation Issues

An important aspect of GHG policy comparisons for potential new generating facilities is the "but for" question. That is, but for the new facility, what emissions would have occurred. This goes beyond comparing one new generating technology with another. It requires consideration of what generators (existing or new) will not be built or will run less often if the facility under consideration is built. Similarly, for imports, even from existing facilities, this question arises for both the importing and exporting regions. It may even extend to "knock on" effects in neighboring regions, depending on the strength of the electrical interconnections between them. In a policy context, it may also be important to address the bookkeeping aspects for trades in the environmental attributes of power.

One approach to examining displaced or avoided generation is to look at the marginal emissions in the affected region or regions. Marginal emissions are the emissions from the generating plants "at the margin." That means the plants that are the last ones to be run in any given hour. This is usually determined by the total load being experienced; the variable operating costs of the available plants, which is mainly dependent on fuel price and plant efficiency (called heat rate in combustion plants); and the potential need to run some plants out of economic order for reliability reasons.

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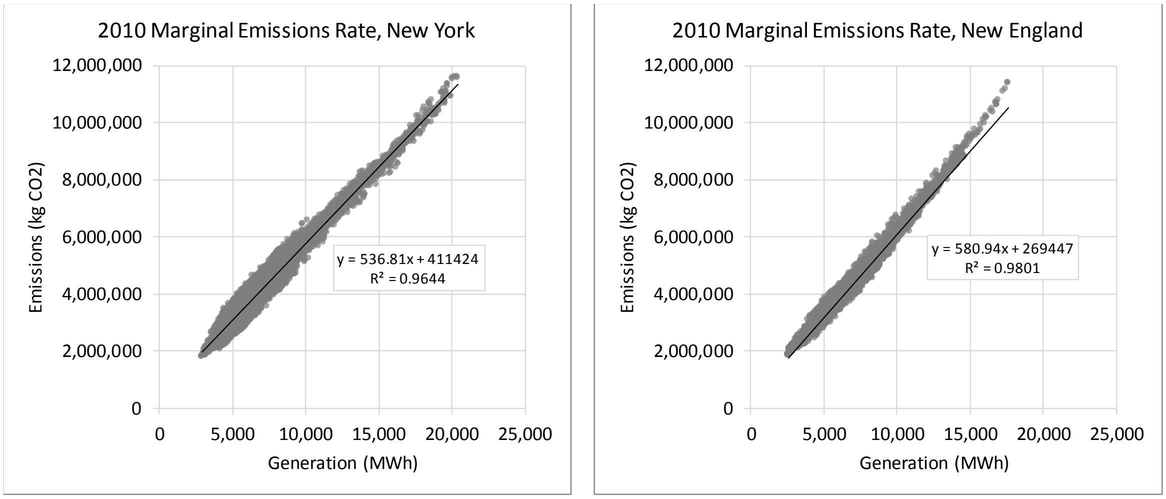
[41] IEA Hydropower. The International Energy Agency Implementing Agreement for Hydropower Technologies and Programmes. *Current* Activities. http://www.ieahydro.org/Hydro___The_Environment6.html, One objective is to standardize GHG flux evaluation methods. The following report was to be issued on March 2011: Annex XII: Hydropower and the Environment; Task 1: Managing the Carbon Balance of Freshwater Reservoirs; Volume 1: Guidelines for the Quantitative Analysis of Net GHG Emissions from Reservoirs.)

[42] IPCC, 2006, *op. cit*.

Figure 3. 2010 Emissions (kg CO_2 / MWh) for fossil fuel units in New York and New England.[43]



The scatter plots in Figure 3, above, indicate the emissions in kg CO_2 per MWh in New York and New England in 2010. By fitting a linear trend to the data points, a slope of marginal emissions was found, indicated in Table 5. Due to their high fuel cost and the ability of some of them to ramp up and down fairly quickly, natural gas generators are typically the last to be dispatched in any given hour in both New England and New York. Therefore, marginal emissions in both regions are about the same as for natural gas generators. Note that the curves both bend upward at high loads, so the estimates of marginal emissions may err on the low side with respect to peak load hours.

Table 5. 2010 Marginal Emissions (kg CO_2 / MWh) derived from scatter plots in Figure 3.

New York	537
New England	581

One study that specifically considered this issue found, “With nearly all of the new capacity brought online in Québec being hydro and with existing fossil-fueled electricity [being] brought offline, emissions over this period [1990 to 2008] actually decreased. Nonetheless, although an increase in generation did not directly contribute to a rise in emissions, increased export of hydroelectricity by Hydro Québec to the United States likely was a contributor to increased generation from fossil-fuel-fired sources in other regions in Canada since exporting this electricity

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[43] Note that Figure 3 only includes emissions from fossil fuel units larger than 25 MW and omits plants run in constrained areas. The actual marginal emissions rate would be lower, once nuclear, hydropower, and other renewable units are taken into account. Data for this figure comes from EPA. Clean Air Markets Dataset. (2011)

to the United States (which is typically a higher-priced market) rather than domestic markets would inadvertently increase the requirements for fossil-fueled electricity within Canada."[44]

C. Redeveloping, Repowering and Upgrading Existing Hydropower Sites

While Section 2 of this report explained that development of major new hydropower facilities is rare in much of North America (excepting Québec and Labrador), there are some additional options for increasing total output of hydropower. Many of the existing hydropower facilities in North America are quite old and may date back to the early twentieth century or even earlier. While dam structures may remain sound, other equipment does wear out eventually, and when it does (or even earlier) it may be cost-effective to install new, more powerful and more efficient turbines, generators, and transformers. Thus, it may be possible to cost-effectively increase the electrical output of older hydropower facilities without increasing their reservoir size or dam height. This can be an attractive tradeoff from a GHG standpoint. Small dams are sometimes fitted with add-ons to the dam top that increase reservoir depth a small amount (often a few feet), but result in increased hydraulic head and controllability, and modest increases in absolute output for a given amount of water flow. Utilities that operate multiple dams on a single river system generally expend considerable effort to coordinate turbine and dam operations to maximize the total output from the river system using the same water and facilities. All of these options may be encouraged.

After an initial flourishing of privately owned industrial hydropower in the late 19th and early 20th centuries, most industries sold their dams to utilities or decommissioned them and relied on purchased electricity. Thus, there are abandoned hydropower sites around the U.S., particularly in the East and Midwest. Efforts were made after the enactment of PURPA in the 1970s to inventory and assess such sites. A modest number of them were redeveloped as qualifying facilities (QFs) under PURPA, even without any monetizing of the economic value of avoided GHG emissions, but many were not. Policy makers may wish to consider the merits of a renewed effort in that direction.

D. How Conclusive Is Current Research in Estimating GHG emissions for Hydropower Compared to Other Energy Sectors?

For reasons noted above, it is difficult to firmly answer this question. Estimates for hydropower present challenges not present for other technologies, challenges which remain unresolved. However, we believe that the literature results set out above are conclusive enough to reasonably state that hydropower (excluding tropical reservoirs) emits substantially less GHGs per unit of electrical output than do fossil fuel sources over a plant's life cycle.

While existing approaches and LCA models are mostly appropriate for use in policy discussions, specific values for hydropower sites already studied may not be generalizable to other sites and should be considered as first approximations. Site-specific variables might vary greatly between

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[44] Steenhof, Paul, and C.J. Weber, 2011, An assessment of factors impacting Canada's electricity sector's GHG emissions, *Energy Policy* 39, 4089–4096.

facilities.[45] Such uncertainty may possibly be reduced with site-specific studies,[46] but they are not widely performed due to complexity of estimation methods, requirements for extensive collection of field data, and cost to utilities.[47] Even the most intensive and extensive studies may contain both “known” and “unknown” sources of uncertainty.

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[45] Robert Dones, *et al*., 2007, *op. cit.* LCA models are most appropriately used as first approximations, as site specific variables might vary greatly between plants.

[46] IPCC, 2006, *op. cit*. “[E]mission factors from the various pathways (diffusive, bubble and degassing)” represents one of the two “largest sources of uncertainty in the estimation of greenhouse gas emissions from reservoirs . . . . CO_2 diffusive emissions . . . vary by one to two orders of magnitude in boreal and temperate regions, and by one to three in tropical regions. Therefore, the use of any emission factor derived from Table 2a.2 will result in high uncertainty. Since the age of reservoirs has a significant influence on CO_2 fluxes during the first 10 years, the method may result in an underestimation of CO_2 emissions. . . To reduce the uncertainties on emissions factors, countries should develop appropriate, statistically valid sampling strategies that take into account factors underlying the temporal and spatial variability of the ecosystem studied.”

[47] Alain Tremblay, *et al*., 2010, *op. cit.*

5. Conclusions and Recommendations

Life cycle analysis (LCA) is clearly the current best practice for comparing the GHG emissions of generating facilities. With respect to imported power, consideration of displaced emissions in the importing region, exporting region, *and* neighboring regions electrically interconnected with either may be necessary to form a true picture of GHG effects.

The largest sources of GHGs for newly constructed hydropower are biomass decomposition from reservoir flooding and construction of the facility. Along with methodological disparities, biomass decomposition is the largest source of uncertainty in the GHG emission estimates for hydropower. Emission uncertainties from biomass decomposition may remain large, as the relevant modeling is complex. Further research, both theoretical studies and field measurements, should be considered prior to new construction decisions.[48] Site-specific assessments will be particularly valuable.

For fossil fuel technologies, the main sources of variability relate to potential carbon capture and sequestration technologies (for new facilities), whose efficiency, effectiveness, infrastructure requirements, and decommissioning/waste disposal and cleanup needs remain speculative. Also, a variety of operational issues that affect the amount of electricity produced over a plant's lifetime for a given amount of construction/decommissioning emissions and for a given amount of fuel burned remain to be seen. A wide range of uncertainty should be considered, perhaps via scenario analysis, prior to new construction decisions.

New hydropower development emits greenhouse gases (GHGs), but newly flooded hydropower emission rates per unit of energy produced (excluding tropical reservoirs) are much lower than for oil and coal, and are somewhat lower than natural gas combined cycle generation. Run-of-river hydropower emission rates may be roughly comparable to other renewable resources and nuclear power (assuming prompt decommissioning and permanent high level waste disposal); however, newly flooded boreal reservoirs have life cycle emissions that likely exceed those of other renewable sources. (See Figure 1 in Section 3.) Hydropower GHG emissions during the first years after reservoir creation appear to be even higher than for a natural gas combined-cycle facility, so ongoing, long- term measurement should be pursued for a variety of reservoir types.

Also noteworthy is the fact that there is not yet scientific consensus on methods for estimating GHG emissions from hydropower. This has resulted in varying degrees of accuracy and precision, despite adoption of international standards. As noted by Raadal, *et al.*, "The wide ranging results [of GHG emissions from hydro power] indicate a need for stricter standardised rules and requirements for life-cycle assessments, in order to differentiate between variations due to methodological disparities and those due to real differences in performance of the plants."[49] Teodoru *et al.* (2009) and Teodoru *et al.* (2010) provide examples of how such assessments may be grounded in field data collection before and after construction.

In light of these conclusions, we recommend that future policy decisions be supported by the following:

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[48] See, for example, Teodoru *et al*. (2009).

[49] Raadal, Hanne Lerche, *et al.*, 2011, *op. cit*.

1) Continued documentation of both short- and long-term values of diffusion rate estimates and the LCA emission rates for hydropower development, especially:
    a. The immediate net GHG emission increases from reservoir creation, and
    b. The long-term net GHG emission rate decreases after reservoir creation. This should include rates from Annex I countries, as reported in their UNFCCC submissions.

   Any deviations from the ranges presented in this report should raise red flags.

2) Consideration of the net effect of replacing terrestrial biome with an aquatic biome in the case of new flooding in estimating long-term net GHG emission rates.
3) Encouragement and monitoring of IEA's progress toward issuing guidelines for quantifying net GHG emissions from reservoirs.[50]
4) Adoption by regulators, researchers, and utilities of best practices for estimating GHG emissions from all types of generators, including full life cycle analysis, in general, and full watershed evaluation for hydropower, in particular.
5) Adoption by regulators, researchers, ISOs/RTOs, and utilities of best practices for the assessment of displaced emissions attributed to new resources, including displaced or increased emissions in regions electrically interconnected with exporting and importing regions and environmental attribute accounting.
6) Resource policymaking based on best practices and life cycle analysis that reflect GHG emissions.
7) Review in all policy fora of evidence proffered in support of new construction, exports, or imports for consistency with the above recommendations. Emission claims that differ markedly from the values given here may or may not be warranted, but they may also be driven by analysis not conforming with best practice.

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[50] See footnote 41.

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