Docket No. _____
Exh. TDI-SGP-13

LEVITAN & ASSOCIATES, INC.

To: File
From: E.G Cool, S.G. Parker, A.J Mattfolk
Re: Hydroelectric Reservoir GHG Emissions
Date: December 1, 2014

This memo reviews the results of a study of the greenhouse gas (GHG) impact of a hydroelectric reservoir, and discusses how the results of that study may be used to estimate a net CO_2eq emission rate for hydroelectric power.[1] The study, "The Net Carbon Footprint of a Newly Created Boreal Hydroelectric Reservoir" by Cristian R. Teodoru *et al*, was published in the June 2012 *Global Geophysical Cycles*, Volume 26 (Teodoru Study). The Teodoru Study analyzed measurements of carbon dioxide (CO_2) and methane (CH_4) releases and uptakes from terrestrial and aquatic ecosystems before and after the flooding of the Eastmain-1 reservoir in northern Quebec. This peer-reviewed study was conducted over a seven-year period, 2003 to 2009, and includes four years of post-flooding measurements.[2]

The authors collected field measurements and made other estimates of carbon releases (as CO_2 and methane gas) and deposition (as carbon in sediments and forest biomass) at over 100 sites across the 602.9 km^2 reservoir ecosystem. The difference between the post-flooding measurements and the pre-flooding measurements was used to calculate the overall ecosystem carbon budget and the average net flux of carbon over the reservoir, expressed in units of carbon per square meter per day (mg C m^{-2} d^{-1}). The Teodoru Study converted the average net carbon flux across the reservoir basin to a carbon emission rate per GWh (in terms of the carbon component in CO_2eq) by multiplying by the area of the reservoir (602.9 km^2) and dividing by the expected annual generation of the Eastmain-1 hydroelectric plant (2.7 GWh).[1]

The Teodoru Study found that net carbon emissions were high in the early years following flooding and then declined steeply. The values reported in the Teodoru study shown in the table below have been converted to kg CO_2eq/MWh.

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[1] By convention, CO_2 has a greenhouse warming potential of 1. Other GHGs, such as methane, have different greenhouse warming potentials. To express all GHGs in terms of CO_2-equivalent (CO_2eq), all other GHGs are converted to the quantity of CO_2 which would have the equivalent greenhouse warming potential.

[2] We have inquired if field data collection has continued since 2009, but have not yet received a response from the authors.

Teodoru Study – Net Carbon Emissions by Year

Year	metric tons C-CO_2eq/GWh	kg CO_2eq/MWh
2006	183	671
2007	119	436
2008	84	308
2009	65	238

The Teodoru Study also compiled carbon flux rate data from existing reservoirs elsewhere in Quebec from other studies, and assumed that the pre-flooding conditions and carbon budgets would have been similar to the ecosystem beneath the Eastmain-1 reservoir The post-flooding measurements, less the assumed pre-flooding estimates for these other reservoirs, were used to extrapolate the empirical data from Eastmain-1 out 100 years. The Teodoru Study concluded that over time, the net carbon emission rate for similar reservoirs did not become zero, but appeared to level out. Using curve-fitting techniques, the Teodoru Study estimated the long-term average net carbon emission flux rate over a 100-year lifecycle, and converted it to a carbon emission rate per GWh by using the annual hydroelectric generation for Eastmain-1. This value was 43 metric tons of carbon (C-CO_2eq) per GWh, equivalent to 158 kg CO_2eq/MWh. Importantly, the study notes that this per GWh rate would decrease to 17 metric tons of carbon (C-CO_2eq) per GWh (equivalent to 62 kg CO_2eq/MWh) when the Eastmain-1 capacity is expanded and annual energy output increases to 6.9 GWh, assuming no change in the reservoir.

The Teodoru Study tried to minimize uncertainties regarding measurement techniques and calculations. The Teodoru Study utilized a "sampling strategy… to obtain an extensive coverage of the reservoir surface reducing the uncertainties around mean values of measured variables and to take into account the spatial heterogeneity in surface fluxes that is related to the former landscape types." In addition, the authors "…bracketed our best estimates (the mean value) of net reservoir C footprint, with likely upper and lower limits, by creating two contrasting extreme scenarios: 1) a low emission scenario that combines the lowest reservoir fluxes and highest pre-flood emissions; and 2) a high-emission scenario that combines the highest reservoir fluxes plus the highest pre-flood sinks (or minus the lowest pre-flood emissions). This approach intrinsically provides wider confidence intervals than standard error propagation calculations would yield and we are thus confident that the uncertainty in our projected emissions are both conservative and robust."

Teodoru Study Figure 4a – Net Carbon Emissions over Time

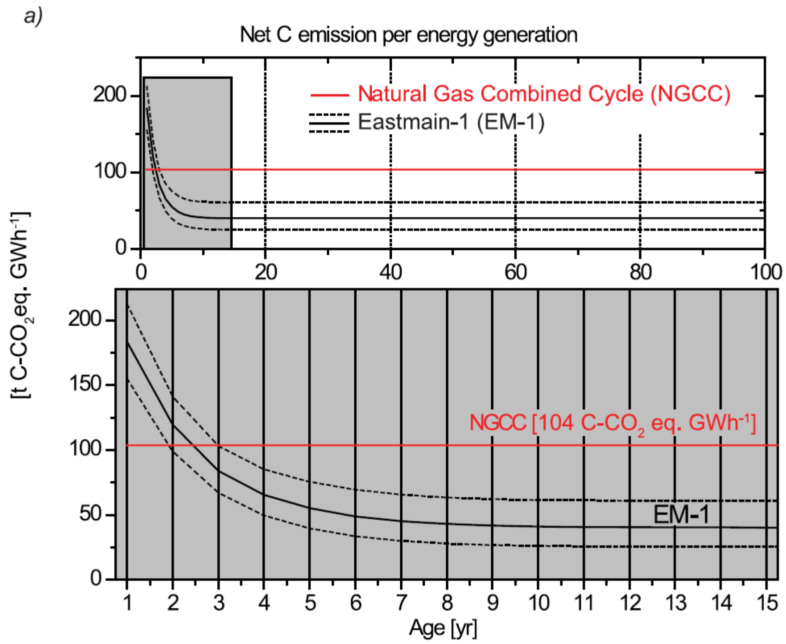


Figure 4a from the Teodoru Study illustrating the estimated decline in the net carbon emission rate over time is provided above. This figure includes (i) an uncertainty band bracketing the measured and projected carbon emission rate (per GWh), (ii) the estimated emission rate from a natural gas-fired combined cycle plant, and (iii) an expanded view of the chart for the first fifteen years.

Based on the chart data, we estimated the average emission rate over the first 10 years of a newly developed hydroelectric reservoir, the average emission rate over a 100-year lifetime of a hydroelectric reservoir, and the high and low average values using the uncertainty bands provided in the chart. These results are shown in the table below.

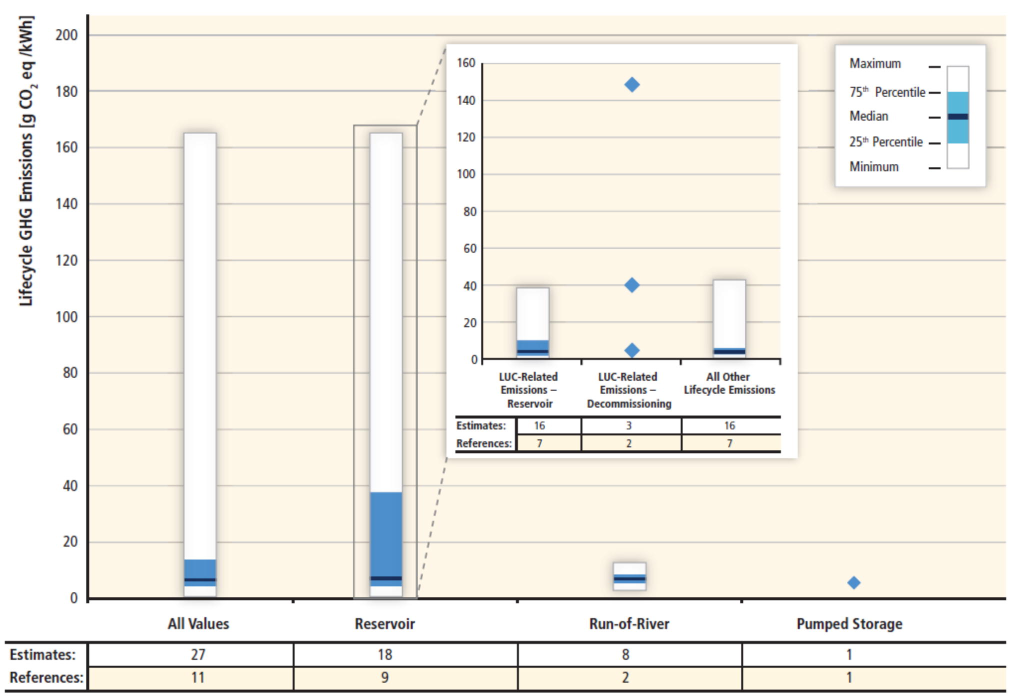
Teodoru Study – Average Emissions Rate (kg CO_2/MWh)

Case	10-year	100-year
High	353	247
Mid	267	158
Low	208	113

The 10-year average rate is applicable for estimating the incremental emissions ascribable to a newly constructed reservoir for only the first ten years after impoundment. The 100-year average is customarily reported as a life-cycle emission rate, and is applicable to the long-term operation of a hydroelectric plant. In either case, it is important to note that these results are site-specific for the particular ecosystem of the Eastmain-1 reservoir basin, and sensitive to the annual energy production of the Eastmain-1 plant. Thus, these rates may not readily be generalized to all hydroelectric generation facilities.

The Teodoru Study is the most recent empirical analysis of GHG emission rates for a hydroelectric facility in a boreal environment in Quebec; there have been other studies using different approaches and for other locations internationally. A systematic review and analysis of life cycle assessments of various power generation technologies conducted between 1980 and 2010 was undertaken by the National Renewable Energy Laboratory (NREL), using a methodology set forth by the International Panel on Climate Change (IPCC).[3] NREL is funded by the U.S. Department of Energy and is the primary laboratory for renewable energy and energy efficiency research and development in the U.S. IPCC is a scientific intergovernmental body under the auspices of the United Nations and is an international accepted authority on climate change. The rigorous analysis of published studies involved "harmonization" of the life cycle assessment data so that they could be represented on an "apples to apples" basis, and to screen out data not meeting IPCC quality standards. The results are presented as a statistical range, recognizing the variability of the measurements. NREL's results for hydropower life cycle assessment data are reproduced in the figure below. The second bar illustrates values from 9 references and 18 estimates for reservoirs, comparable to the Teodoru Study.

NREL Life Cycle Greenhouse Gas Emissions of Hydropower Technologies – Figure 5.15



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[3] From: Kumar, A., T. Schei, A. Ahenkorah, R. Caceres Rodriguez, J.M. Devernay, M. Freitas, D. Hall, Å. Killingtveit, Z. Liu, 2011: Hydropower. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press. Figure 5.15 and found at: http://www.nrel.gov/analysis/sustain_lca_hydro.html

IPCC's statistical analysis of the reservoir data, provided in the table below, indicates that the Teodoru Study long term average value of 158 kg CO_2eq / MWh (equal to 158 g CO_2eq/kWh) based on the current Eastmain-1 annual energy output is significantly above the high end of the data range.[4] However, the estimated long term average value when the Eastmain-1 expansion is constructed, 62 kg CO_2eq/MWh (equal to 62 g CO_2eq/kWh) is closer to, but still somewhat above the maximum value for reservoirs reported NREL notes that the higher values tend to be associated with land use change (LUC) assessments pre- and post-flooding, such as captured in the Teodoru Study. LUC assessments associated with hydropower reservoirs continue to be an area of active research.

IPCC's Statistical Analysis of the NREL Data[5]

Value	kg CO_2eq/MWh
Minimum	0
25th percentile	3
50th percentile	4
75th percentile	7
Maximum	43

[4] Moomaw, W. et al, Annex II: Methodology, in IPCC Special Report (Ibid.).

[5] Note that the outliers (the blue diamonds in the NREL figure inset), which show reservoir hydropower lifecycle estimates of over 150 kg CO_2eq/MWh, are based on only a few data points related to LUC during reservoir decommissioning, and do not appear to be included in the IPCC statistical analysis.

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