Greenhouse Gas Emissions and the Decommissioning of Hydroelectric Dams

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Abstract Greenhouse gas (GHG) emissions from hydroelectric dams are often portrayed as nonexistent by the hydropower industry and have been largely ignored in global comparisons of various sources of electricity. This work examines the role of decommissioning hydroelectric dams in GHG emissions. Accumulated sediments in reservoirs contain elevated levels of carbon, which may be released to the environment as CO_2 and CH_4 upon decommissioning of the dam. The sediment accumulation rate and the volume of sediment are estimated for six of the ten largest hydroelectric reservoirs in the United States. The carbon content of the sediments is estimated and calculated in terms of the global warming potential (GWP) of the sediments per kWh of power produced by the plant in its lifetime. The estimated potential warming effects of each of the eight power plants ranged from 3.57gC/kWh to 10.95gC/kWh. A table is presented comparing these potential global warming effects to those of other sources of electricity. This comparison demonstrates that GHG emissions from the decommissioning of hydroelectric dams are significant compared to emissions from other phases of the lifecycle. The amount of greenhouse gases emitted by the sediments upon decommissioning of the dam should not be ignored, and should be taken into account when considering the construction and relicensing of hydroelectric dams. Hydroelectricity is viewed as a clean, renewable source of energy. It is important, however, that the GHG emissions at the decommissioning of the dam be included in these views, and hydroelectricity be treated as another precursor for climate change.

Introduction

Currently the Intergovernmental Panel on Climate Change (IPCC) maintains that 38% of worldwide greenhouse gas emissions are from electricity generation alone. [Metz 2001]. This figure does not include any potential emissions from hydroelectric reservoirs, which can be a significant omission. The contribution of reservoirs as a source of carbon emissions has become an object of investigation for researchers concerned with the comparison between hydroelectric plants and fossil fueled power plants as competing electricity supply options (Rudd 1993, Gagnon 1993, Rosa 1994, Dones 1998, Tahara 1997). Until the end of the last decade, energy planners have claimed that hydroelectric plants were clean technologies, because they produced fewer greenhouse gas emissions than thermal power plants. Recent studies have shown, however, that there are many other possible sources of increased carbon emissions from hydroelectric plants, including that in the sediments at the time of the decommissioning of the dam.

The construction of large dams has been known to cause considerable social and environmental problems, such as displacement and disruption of local communities, and effects on the river downstream of the dam, such as river incision, disturbance of river habitat. (Patrick McCully 1996) My work, however, will focus on the relationship between GHG production and environmental effects of decommissioning of large dams and sediment deposition. Sediment accumulates behind dams as water flow velocities decrease as the river flows enter the reservoir area, which allows increased particle deposition and lowers the turbidity of the water, in turn, increasing light penetration. (Klumpp, 2003) Thus, the primary productivity in reservoirs tends to be high, which contributes to the fixation of organic carbon. The increased particle deposition rate and the augmented decomposition rate, lead to a build-up of sediment, and thus, carbon, above the dam persisting throughout the life of the dam.

These carbon deposits are most prevalent at the beginning of the power plant’s life, during the formation of the reservoir. Greenhouse gas emissions from electricity generation plants are most often studied in terms of a Life Cycle Assessment (LCA). An LCA takes into account all stages in the lifespan of the power plant. The manufacturing of the construction materials, the actual construction of the dam, the operation of the plant, and the decommissioning of the plant at the end of its life are some various stages of the LCA. The figures for the construction of the dam include the flooding of the accumulation basin of the reservoir, which inhibits activities that depend on oxygen consumption. This leads to the death of the vegetation. Therefore, carbon that was stored in biomass and soil is subject to decomposition by bacteria underwater. Research has already produced data for carbon emissions for the construction of the dam (European Commission) and the operation of the plant itself (Pacca, 2002). There has not yet been any published research studying the greenhouse gas emissions upon decommissioning of the dam. This sediment problem can be compared to the responsibility of nuclear power plants for spent fuel rods when their power generating capacity has been exhausted. The hydropower industry is responsible for the sediments built up in the same way. Over 300 dams have been removed in the United States as dams become old enough to require Federal Energy Regulatory Agency relicensing, and as costs of repairs and maintenance outweigh the benefits. (Hotchkiss, 2001)

The decommissioning of a dam can progress three different ways; 1) No action; 2) Partial dam removal; 3) Full dam removal. (Hotchkiss, 2001) None of the dams removed in the United States have taken into account potential negative impacts from the release of built up sediments. These negative impacts have not been extensively researched, but may include downstream fish kills, filling-in of riffle-pool habitats, blockage of upstream navigational channels, increased downstream deposition, and destabilization of stream banks. A few case studies have been done to address sedimentation issues, but these studies have mainly focused on sediment overloading to a rectangular channel with uniform sediments, which is not a very accurate scenario. Most studies which observe the sedimentation issues at decommissioning have only looked at what will happen if the sediments are allowed to travel downstream, not if they are dredged out or controlled by other methods.

My research will be concerned with how these sedimentary deposits may affect the environment upon the decommissioning of the dam. The amount of sediment and its carbon content, at the moment of the decommissioning of the dam, (assumed to be 100 years after the first operation of the dam), is my relevant data. The carbon released is partitioned into CO_2 and CH_4 emissions and converted to CO_2 equivalent emissions using the GWP method. (Liikanen 2002) The global warming effect (GWE) due to decommissioning the reservoirs is normalized to the total electricity produced over the lifetime of each power plant. The addition of this global warming potential to a hydroelectric plant’s total emissions, when compared to the energy output of the hydroelectric plant over its lifetime, may demonstrate that hydroelectricity is less efficient than previously thought.

Methods

Data on sediment accumulation was collected by contacting personnel from the operating agencies of our six case study dams, which are six of the ten largest hydroelectric dam-created reservoirs in the country. These six are all operated by either the US Bureau of Reclamation or the Army Corps of Engineers. The latest reservoir survey or most recent sediment data for Garrison, Oahe, Fort Peck, and Fort Randall Dams came from the USACE (1997). Sediment Data from Hoover Dam was obtained from Dendy (1975). Glen Canyon sediment data was obtained from USBR (2004). Yearly power production data was obtained for Garrison, Oahe, Fort Peck, and Fort Randall Dams from USACE (2004). Power production data for Hoover Dam and Glen Canyon Dam was obtained from USBR (2004). The resulting data was entered in a spreadsheet (Appendix A) including the Fort Peck Dam on the Upper Missouri River in Montana, completed in 1938; Garrison Dam on the Missouri in North Dakota, completed in 1953, Oahe Dam on the Missouri River in South Dakota, completed in 1958; Fort Randall Dam on the Missouri River in South Dakota, completed in 1953; Hoover Dam on the Colorado River between Arizona and Nevada, completed in 1935; Glen Canyon Dam on the Colorado River in Arizona, completed in 1963.

The data is analyzed as follows:

1. The total sediment volume at the end of the plant's life is estimated from a time series of the two most recent sediment data points available. An alternative potential final sediment amount is estimated using a linear regression including all of the data points in our information. Except for Hoover Dam and Glen Canyon Dam, since sediment information for both included only two data points. These sedimentation rates will be used to predict the volume of sediments present one hundred years after the initiation of operation of the plant.

2. The total organic carbon (TOC) present in these sediments will be estimated by multiplying the total volume of sediments by an average sediment density. Several studies have been done to find an average sediment density of U.S. reservoirs. One study done by Lara and Pemberton in 1963 took 1129 samples from 101 U.S. reservoirs and calculated the sediment densities. They found a range from .3-1.88 metric tons per cubic meter. A later survey done with samples from 800 U.S. reservoirs found an average sediment density of .96 metric tons per cubic meter. (Dendy and Bolton, 1976) For this study, the sediment density will be estimated to range

from .3 to 1.88 metric tons per cubic meter, with a most likely value of .96 metric tons per cubic meter. This mass of sediment is then multiplied by the carbon density in the sediment to find the TOC present. Carbon density in reservoirs has been estimated to vary from 1% up to 18% with most hovering between 1-3%. (Bastviken 2003, Campbell 2000)

3. The greenhouse gas emissions will then be estimated looking at the amount of carbon present as methane and the amount of carbon present as carbon dioxide. (Liikanen 2002)

Total methane emissions = TOC x % share of anaerobic decomposition

Total carbon dioxide emissions = TOC x % share of aerobic decomposition

The % share of each type of decomposition varies from 7% anaerobic in natural conditions up to 97% anaerobic in shaken laboratory samples. (Dannenberg 1997) A study performed in Australia found that sediment beds with certain types of bacterial organisms converted as much as 60% of SOC to CH_4. (Boom 1995) Reservoir conditions tend towards undisturbed sediments, and bacteria levels are unknown, so the numbers used for our analysis will vary only from 7% to 15%. (Liikanen 2002)

4. To analyze both compounds, they will be converted to carbon dioxide equivalents, using the global warming potential (GWP) method. Because of the concern with the potential impact of GHG releases from sediments over time, we convert CH_4 emissions to CO_2 equivalents using GWP. This allows for the comparison of overall impacts without two forms of carbon to consider. The time interval selected to calculate the GWP for methane defines the value of the GWP. For example the IPCC publishes the GWP for 20 years, 100 years, and 500 years, which correspond to 62, 23, and 7 respectively (Houghton 2001). In the case of decommissioning of dams it makes sense to use a GWP for 20 years, corresponding to 62, to convert the CH_4. The power plant stops producing electricity upon decommissioning and all of the CH_4 in sediments is released and converted to CO_2 equivalent in a relatively short period of time, on the order of magnitude of 20 years.

5. The last step is to estimate the carbon intensity for the hydroelectric plant's total global warming potential per life cycle energy production of the power plant. For most of the power plants, the only available power production data is the installed capacity of the plant, which is not the same as the amount of energy produced in a year. Therefore research was done to determine a capacity factor and find what percent of capacity the average hydroelectric plant runs at. Values for this capacity factor were found as low as 23% for the Hoover Dam, up to a

general average of 60% (USACE 2004). The final answer will be in units of grams of CO2 equivalent/kWh. This presents the efficiency of hydroelectric power plants in terms of greenhouse gas emissions.

All of these estimated ranges for the sediment volume after 100 years of operation, sediment density, organic carbon percentage, and capacity factor will be analyzed using the Monte Carlo method. 10,000 simulations were run using Crystal Ball Software by Decisioneering. The variable distributions are as listed in Table 1. As final values, I selected the statistical mean from each simulation.

Variable	Type of Distribution	Min. value	Most likely value	Max. value
Sediment Volume	Triangular	Lower Potential Sed. Volume	Average of Two Potential Sed. Volumes	Higher Potential Sed. Volume
Sediment Density	Triangular	.30Mg/m^3	.96Mg/m^3	.88Mg/m^3
Capacity Factor	Triangular	.25	.50	.66
Methane Conversion Factor	Triangular	.07	.12	.15
O.C. %	Gamma	Loc: 1.0%	Scale: 1.25%	Shape: 2

Table 1 – Probability Distributions Used

Results

Figures 1a-d show the two potential final sediment volumes after 100 years of operation for the four dams with multiple sediment data points. Hoover Dam and Glen Canyon Dam only had two data points, so they are not included here. The pink dotted line is the projection using a linear regression including all data points. The blue dotted line is a projection using a linear regression including only the two most recent data points. This was done to test the sensitivity of our model by running simulations with this as a range for sediment volume.

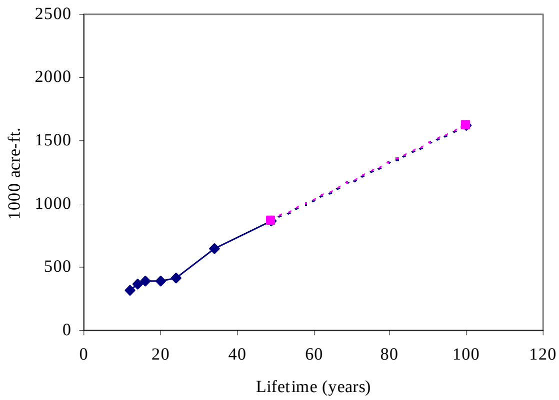

Figure 1a. Fort Peck Dam

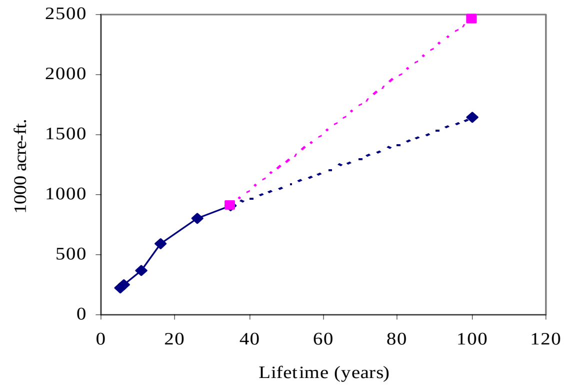

Figure 1b. Garrison Dam

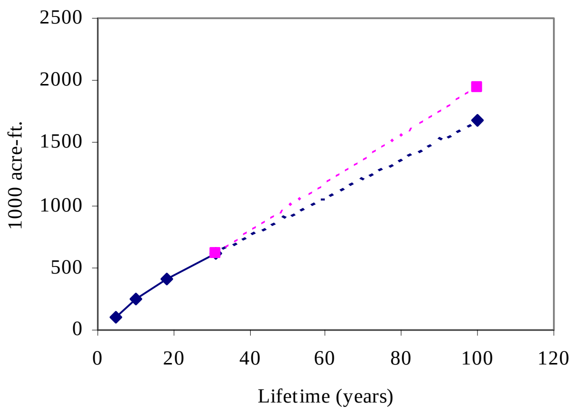

Figure 1c. Oahe Dam

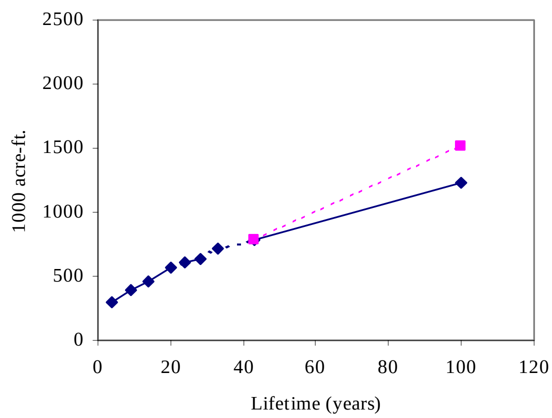

Figure 1d. Fort Randall Dam

Using the results of sedimentation above, and completion of steps 2-5 in the methods, Table 2 summarizes my results of projected sediment volume, projected mass of organic carbon, and the mean values of global warming effect for each dam.

	Year Completed	Projected sediment volume (km3)	Projected mass of organic carbon (tons)	Power Production	Global Warming Effect gCO2/kWh
Hoover	1935	3.395	93,321,250	4.09TWh	3.95
Glen Canyon	1963	4.65	128,067,739	3.5TWh	6.24
Garrison	1953	2.53	69,668,555	2.73TWh	5.69
Oahe	1958	2.23	61,388,415	3.81TWh	3.57
Fort Peck	1938	2.00	55,008,635	1.12TWh	10.95
Fort Randall	1953	1.69	46.524.885	1.93TWh	5.36

Table 2 – Results from six case-study dams

To estimate the mean global warming effects for each dam, I used the results of sedimentation in Figures 1a-d, and completion of steps 2-5 in the methods. Figures 2a-f. show the resulting probability distributions of CO_2 emissions per kWh produced over 100 years. Each probability distribution was run for the six dams through a 10,000-Monte Carlo simulation, using the variables as specified in the methods section. The mean values of gCO_2/kWh that were used for calculations in the discussion are shown for each dam, and are found in Table 2.

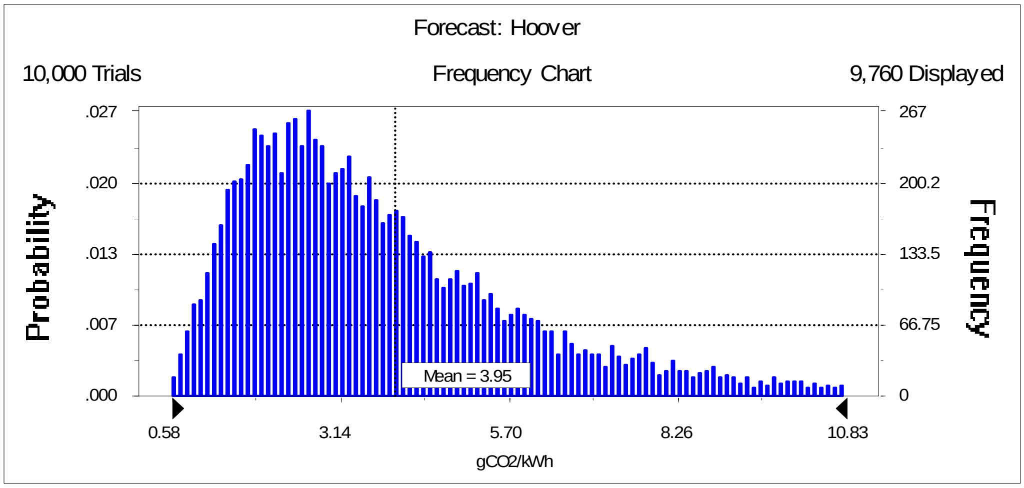

Figure 2a. Hoover Dam Probability Distribution

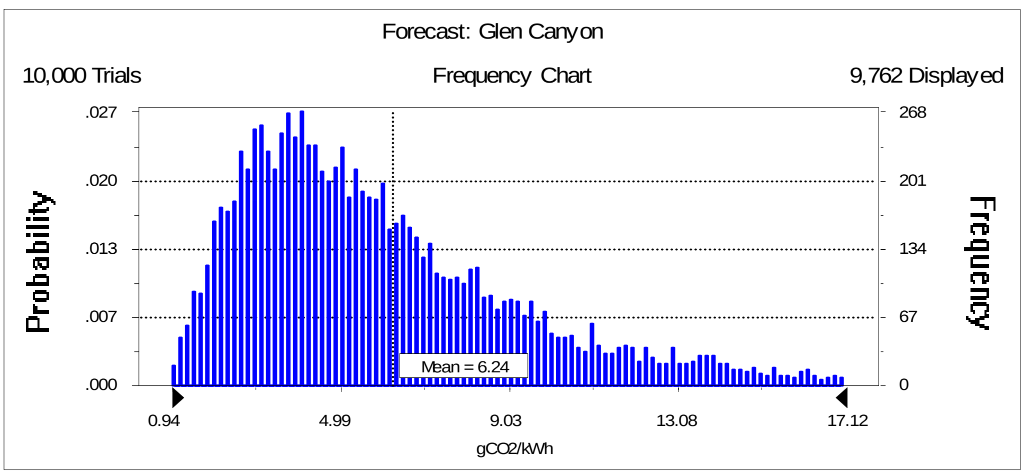

Figure 2b. Glen Canyon Dam Probability Distribution

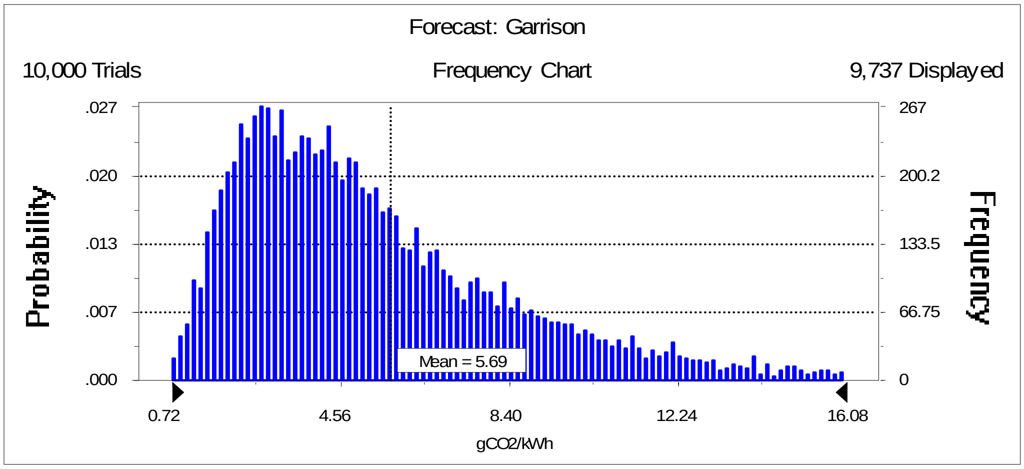

Figure 2c. Garrison Dam Probability Distribution

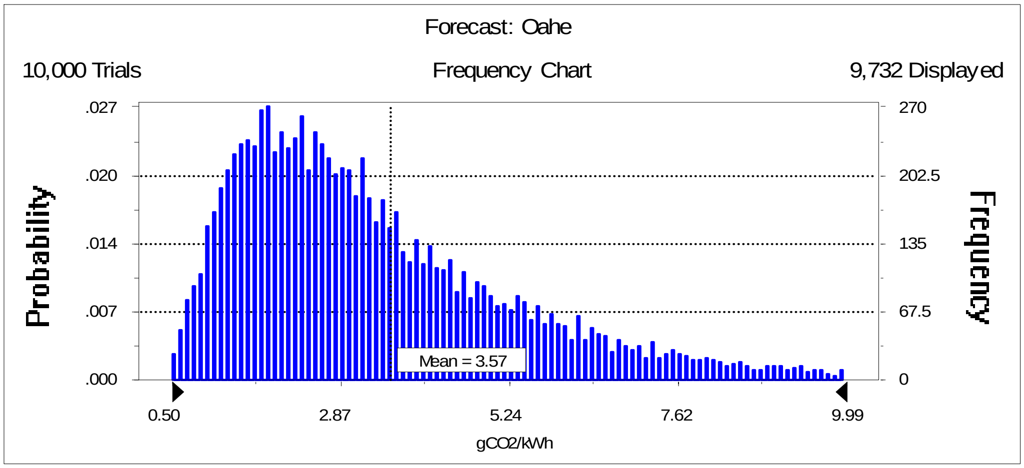

Figure 2d. Oahe Dam Probability Distribution

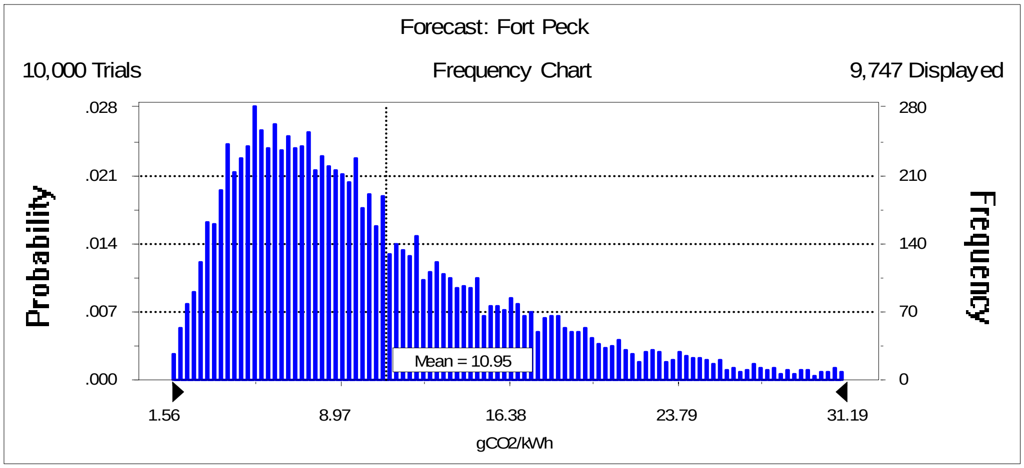

Figure 2e. Fort Peck Probability Distribution

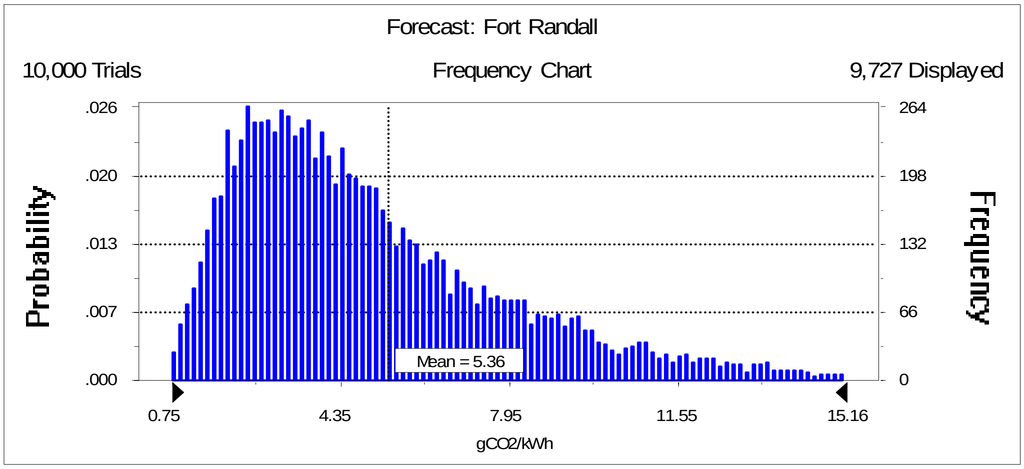

Figure 2f. Fort Randall Probability Distribution

Figure 3 compares previous research studies on Global Warming Effect, or CO_2 equivalent emissions during the pre-decommissioning phases (construction and operation) to my results of CO_2 equivalent emissions at decommissioning for Oahe Dam and Fort Peck Dam. I chose Oahe Dam and Fort Peck Dam because they represented the lowest and the highest results of CO_2 equivalent emissions in my study (respectively: 3.57gCO_2/kWh, and 10.95gCO_2/kWh). Figure 3 helps to visualize the relative proportion of CO_2 equivalent emissions pre and post decommissioning.

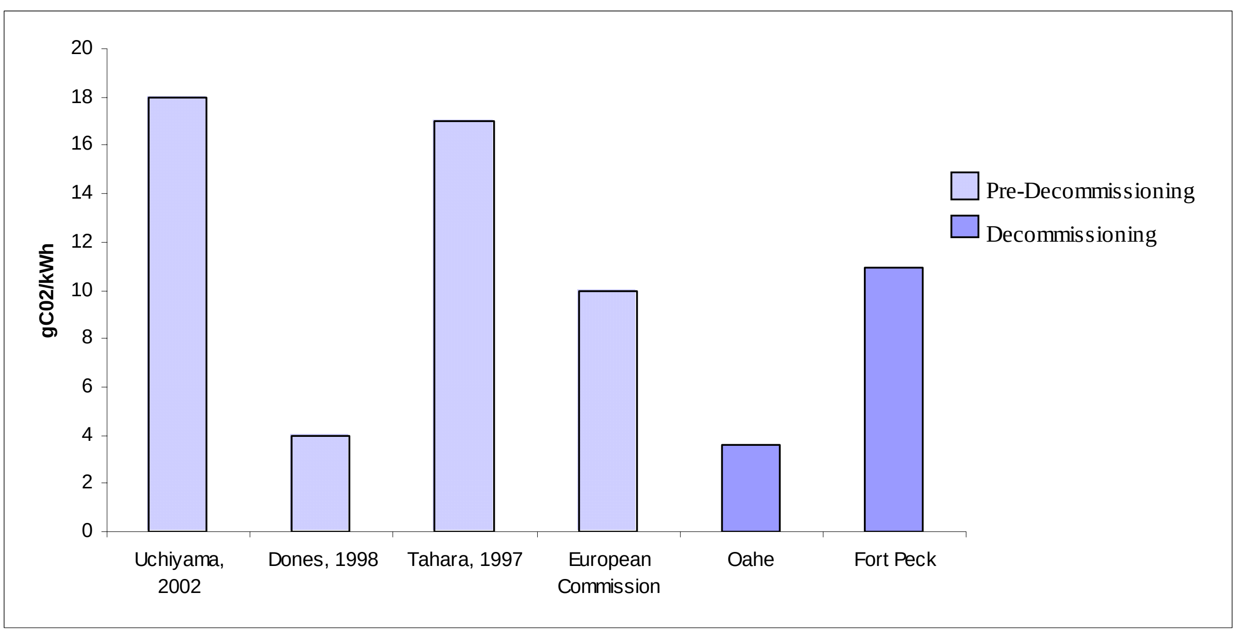

Figure 3 – Comparison of hydroelectric emissions from different sources

Figure 4 shows a comparison of hydroelectricity total CO_2 equivalent emissions to CO_2 equivalent emissions from wind, photo-voltaic, natural gas, and coal electricity generation options. The number for hydro was obtained by adding together the highest value found for pre-decommissioning emissions, and the lowest number obtained from my decommissioning studies. This number could range from 8gCO_2/kWh up to 28.95gCO_2/kWh. I selected a value for this figure near the median of these possibilities, because it is representative of the possibilities, and demonstrates the potential of hydro to be on the same scale as wind power.

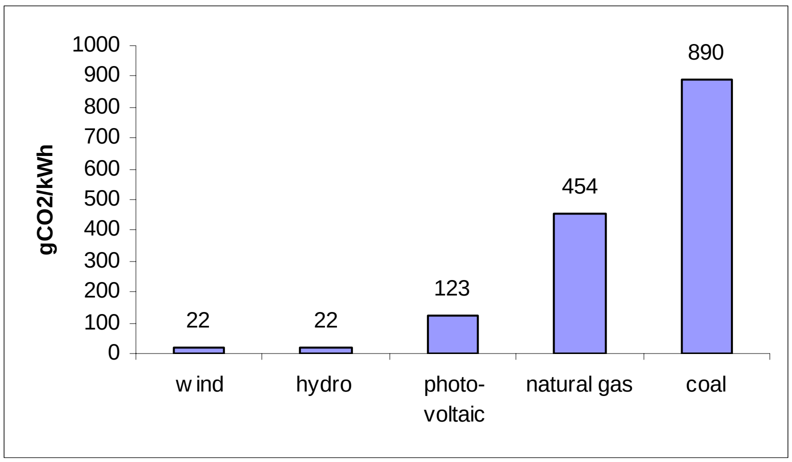

Figure 4 – Comparison to other electricity sources

Values of other electricity source emissions average of published values cited in Pacca, 2003.

Discussion

These results present potential GHG emissions for the decommissioning phase of a hydroelectric dam's life ranging from 3.57 gCO_2/kWh to 10.95 gCO_2/kWh. (Table 2) Compared to previous studies showing pre-decommissioning GHG emissions ranging from 4 gCO_2/kWh to 18 gCO_2/kWh, the addition of decommissioning emissions might more than double perceived GHG emissions.

Compared to other electricity generation options, the total estimated GHG emissions from hydroelectricity still appear favorable. However, the addition of decommissioning emissions shifts hydroelectricity from being the lowest emitter of GHGs, to averaging around the same as wind power.

Within the range of the assumptions made, simulations provided possible values from as low as 0.33gCO_2/kWh, to as high as 90.4gCO_2/kWh. The standard errors of the simulations ranged from 0.02 to 0.08, therefore, these extremes are unlikely, but they did appear from the assumed variable values. In the case of 90.4gCO_2/kWh, 90% of the simulations returned values less than 19.91. If conditions were favorable for GHG production, this value of 90.4gCO_2/kWh could become reality, and would potentially be a major factor in global warming.

These results present an opportunity for the hydropower industry to analyze reservoir's sediments and incorporate results in the impact assessment of reservoirs. When regulators are considering the relicensing and continued operation of a hydroelectric dam, they need to consider impacts from the eventual decommissioning of the dam. The gCO_2/kWh calculated here is estimated for a dam that operates for 100 years. As dams grow older than 100 years, sediments continue to accumulate, and become more saturated with carbon dioxide equivalents. Instead of only taking into account the cost of maintaining or potentially removing the dam, regulators should also be concerned about the costs of properly disposing of sediments when the dam is eventually decommissioned, and the effect that they will have on global warming.

The most influential variable in this model is the methane conversion factor. A small change of 1-2% can have large effects on emissions due to the GWP method of converting methane to carbon dioxide equivalents. This study assumes conversion values ranging from 7-15%, but studies in specific environments have shown methane conversion values as high as 60% in natural conditions. More study is necessary on the specific conditions that may affect methane conversion factors in hydroelectric reservoirs. For future studies using this model, analyzed samples, and/or more detailed studies of the individual case-study dams would be recommend

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References

Bastviken, D., L. Persson, G. Odham, L. Tranvik. 2004. Degradation of Dissolved Organic Matter in Oxic and Anoxic lake water. Limnology and Oceanography 49(1): 109-116.

Boom, P.I., A. Mitchell. 1995. Methanogenesis in the Sediments of an Australian Freshwater Wetland: Comparison with Aerobic Decay, and Factors Controlling Methanogenesis. Microbiology Ecology 18: 175-90.

Campbell, I.D., C. Campbell, D.H. Vitt, L.D. Laird, D. Trew, B. Kotak, D. LeClair, S. Bayley. 2000. A first estimate of organic carbon strorage in Holocene lake sediments in Alberta, Canada. Journal of Paleolimnology, 24: 395-400.

Dannenberg, S., J. Wudler, R. Conrad. 1997. Agitation of anoxic paddy soils slurries affects the performance of the methanogenic microbial community. Microbiology Ecology 22:257-63.

Dean, W.E. and E. Gorham, 1998. Magnitude and Significance of Carbon Burial in Lakes, Reservoirs, and Peatlands. Geology 26(6), pp. 535-538.

Dendy, F.E., W.A. Champion. 1975. Sediment Deposition in U.S. Reservoirs: Summary of Data Reported Through 1975. United States Department of Agriculture. Miscellaneous Publication Number 1362.

Dendy, F.E., and Bolton, G.C. 1976. Sediment Yield-Runoff-Drainage Area Relationships in the United States. Soil and Water Conservation 31 (6): 274-266.

Dones R, Frischknecht. 1998. Life-cycle Assessment of Photovoltaic Systems: Results of Swiss Studies on Energy Chains. Prog. Photovolt. Res. Appl. 6: 117-125.

Economic Input-Output Life Cycle Assessment 2003, Carnegie Mellon University, Green Design Initiative, http://www.eiolca.net, Accessed March 2004.

European Commission Directorate-General for Energy "Wind Energy – The Facts" Volume 4 The environment. [Unknown Year]

Fearnside, P.M. 2002. Greenhouse Gas Emissions from a Hydroelectric Reservoir (Brazil's Tucurui Dam) and the Energy Policy Implications. Water, Air, and Soil Pollution 133: 69-96.

Gagnon, L., and J. van de Vate. 1997. Greenhouse gas emissions from hydropower: The state of research in 1996. Energy Policy 25(1): 7-13.

Gagnon, L., C. Bélanger, Y. Uchiyama. 2002. Life-cycle Assessment of Electricity generation options: The status of research in year 2001. Energy Policy 30(14): 1267–1278.

Gagnon, L., A. Chamberland. 1993. Emissions from Hydroelectric Reservoirs and Comparison of Hydroelectricity, Natural-Gas and Oil. Ambio 22(8): 568-569.

Hotchkiss, M., M. Barber, E. Wohl. 2001. Dam Decommissioning: Decisions and Unresolved Sediment Transport Issues. Proceedings of the Seventh Federal Interagency Sedimentation Conference, March, 2001.

Houghton, J. T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, C.A. Johnson. 2001. Climate Change 2001: the scientific basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernamental Panel on Climate Change (IPCC), Cambridge University Press, New York.

International Energy Agency (IEA), "Benign Energy? The Environmental Implications of Renewables", International Energy Agency, Paris, 1998, http://www.iea.org/pubs/studies/files/benign/full/00-bene.htm, Accessed March 2004.

Klumpp, C., J. Bountry, B. Greimann. 2003. Case Studies in Dam Decommissioning at the Bureau of Reclamation. World Water and Environmental Resources Congress.

Koch, F.H. 2002. Hydropower – the politics of water and energy: Introduction and Overview. Energy Policy 30: 1207-1213.

Lara, J.M., and E.L. Pemberton.. 1963. Initial Weight of Deposited Sediments. Proc. Federal Interagency Sedimentation Conference. USDA-ARS Misc. Publ. 970. pp.818-845.

Liikanen, A. L. Flojt, P. Martikainen. 2002. Gas Dynamics in Eutrophic Lake Sediments Affected by Oxygen, Nitrate, and Sulfate. Journal of Environmental Quality 31: 338-49.

McCully, P. 1996. Silenced Rivers: The ecology and politics of large dams. New Jersey USA, Zed Books.

Metz, B., D. Ogunlade, R. Swart, J. Pan. 2001. Climate Change 2001: Mitigation. Intergovernamental Panel on Climate Change, Cambridge University Press, New York, NY, p. 752.

Pacca, S. 2003. Global Warming Effect Applied to Electricity Generation Techniques. Dissertation in the Graduate Division, University of California, Berkeley.

Pacca, S. and A. Horvath. 2002. Greenhouse Gas Emissions from Building and Operating Electric Power Plants in the Upper Colorado River Basin. Environmental Science and Technology 36: 3194-3200.

Rosa, L.P. and R. Schaeffer. 1994. Greenhouse-Gas Emissions From Hydroelectric Reservoirs. Ambio. 23(2): 164-165,

RTO West Filing Utilities' Questions on SMD NOPR for Boise Industry Briefing. August, 2002. http://www.rtowest.com/Doc/BoiseQuestions-16Aug2002.pdf, Accessed April 2004.

Rudd, J.W.M., R. Harris, C.A. Kelly, R.E. Hecky. 1993. Are Hydroelectric Reservoirs Significant Sources of Greenhouse Gases? Ambio 22(4): 246-248.

Tahara, K., T. Kojima, A. Inaba. 1997. Evaluation of CO2 Payback Time of Power Plants by LCA. Energy Conversion and Management 38. S615-20.

Uchiyama, Y. 2002. Present efforts of saving energy and future energy demand/supply in Japan. Energy Conversion and Management. 43: 1123-1131.

US Army Corps of Engineers. 1997?. Summary of Reservoir Surveys and Storage Changes-Missouri River Main Stem. (Sent by Informant) Online Publication.

US Army Corps of Engineers. 2004. Hydroelectric Design Center Corps Hydropower Projects. Portland District. https://www.nwp.usace.army.mil/hdc/projects.htm, Accessed April 2004.

U.S. Bureau of Reclamation. 2004. Glen Canyon Dam Facts. U.S. Bureau of Reclamation, http://www.uc.usbr.gov/information/gcdfacts.html, Accessed March 2004.