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"Decision-making in Electricity Generation Based on Global Warming Potential and Life-cycle Assessment for Climate Change"

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FINAL REPORT

University of California Energy Institute
California Energy Studies Program
July 2003 - June 2004

Project title: **Decision-making in Electricity Generation Based on Global Warming Potential and Life-cycle Assessment for Climate Change**

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1 INTRODUCTION

The use of an indicator that is based on global climate change effects is important to support decision-makers committed to sustainable development. Our project demonstrated the use of life-cycle assessment (LCA) as a systematic approach to analyzing the construction and upgrade, operation, maintenance, and ultimate decommissioning of electric power plants. A case study of a hydroelectric power plant (Glen Canyon) was completed, including sensitivity analysis.

The LCA performed in this research quantified emissions during different phases of the life of a power plant. The emissions of greenhouse gases (GHGs) were then characterized using the global warming potential (GWP) method. GWP is a method to compare the global climate change effects of different GHGs to that of CO_2. It provides a relative assessment of impacts based on selection of specific time frames. However, because the GWP compares the potential impacts of any GHG to the potency of CO_2, we decided to use a different name for our indicator that assesses the potential impact of electricity generation technologies. The global warming effect (GWE) combines LCA and GWP, and was used in comparative assessments of electricity generation technologies.

2 RESULTS

The results of this project are divided into analytical methods and tools, and quantitative results.

2.1 Analytical methods and tools

The GWE analysis consists of quantification of life-cycle emissions of different electricity generation alternatives, and translation of climate change impacts into a universal, comparable unit. We also discussed uncertainties in the GWE method. There are three major uncertainty sources: power plant characterization uncertainties, LCA uncertainties, GWP uncertainties.

To estimate the energy input into the manufacturing and installation of power plants, LCA was employed. The economic input-output analysis-based LCA (EIO-LCA) model (www.eiolca.net) was used to estimate GHG emissions (CO_2, CH_4, N_2O) from constructing and operating power

plants. The construction assessment included material (extraction, processing, and transportation) and energy (extraction/generation, processing, transportation) inputs, and equipment use in construction processes (combustion of fuel). For the operations stage of the power plants, fuel use is quantified over the service life, and air emissions are estimated from the extraction, transportation and combustion phases. Using the total amounts and costs of the materials and energy inputs, the EIO-LCA outputs are scaled to their actual values for a given power plant type based on the following formula:

$$GWE = \sum \frac{m_i \times p_i \times g_{ij}}{1{,}000{,}000}$$

Where:

m_i is the mass of material or energy input "i" (in metric tons or m^3)

p_i is the price of material or energy "i" (in $/metric ton or m^3)

g_{ij} is the emission of greenhouse gas "j" from manufacturing $1 million of a commodity from sector "i"

Quantification of emissions through LCA is more comprehensive than emissions accounting only for the operation of power plants. Although the interpretation of aggregated emissions from power plants needs to be done carefully because of the spatial variations of local or regional impacts, meaningful results are obtained when precursors to global problems are at stake. In the case of global climate change, the location of GHG emissions does not affect potential impacts, which is more a function of the timing of the releases. Using a function to compare the airborne fraction of CO_2 emissions and the relative impacts of other GHGs over time, it is possible to compare various electricity generation options over different analytical periods and their relative impact on global climate change. This approach attempts to assess the technologies over time.

In the case of hydroelectric plants, besides construction, an important emission source relates to the loss of ecosystems displaced by reservoirs. We also looked at the impact of sediments trapped in reservoirs and potential GHG emissions during the decommissioning of hydroelectric power plants.

Although hydroelectric plants do not consume fossil fuels during their operation, they emit GHGs from biomass decay in the reservoir. An exponential function may represent the decay of

biomass in the reservoir, and the rate of decay depends on the mean annual temperature (MAT). The decay rate is the inverse of the residence time; therefore the carbon fraction mineralized (CFM) every year as a function of time (t), in years, and residence time (τ) is calculated as:

$$CFM = \frac{C_0}{\tau} * e^{-\frac{t}{\tau}} \qquad (1)$$

Colder climates have slower decay rates, and thus lower annual emissions [Gagnon 1997]. The residence time for the biomass in the reservoir is calculated as [Sanderman 2002, Lloyd 1994]:

$$\tau = 42.8 \times e^{-1921\left(\frac{1}{283.15\ -139.4} - \frac{1}{MAT\ -139.4}\right)} \qquad (2)$$

The value C_0 depends on the carbon stored in the ecosystem, which is a function of the ecosystem type (Table 1).

Table 1: Carbon content per m^2 of different ecosystems (Harte 1988).

Ecosystem type	kg of C/m^2
tropical forests	18.8
temperate forests	14.6
boreal forests	9
woodland and shrubland	2.7
grassland	0.7
desert scrub	0.3

More accurate values for various ecosystem types all around the world, including carbon stored in the litterfall and soils can be found in the Good Practice Guidance for Land Use, Land-Use Change and Forestry report published by the IPCC (Penman et all 2003).

The displacement of any terrestrial ecosystem also leads to the disruption of carbon exchanges between the ecosystem and the atmosphere. The net ecosystem production (NEP) measures the amount of carbon uptake by terrestrial ecosystems, and is the difference between Net Primary Productivity (NPP), which accounts for carbon absorbed from the atmosphere, and heterotrophic respiration in the absence of disturbances, which accounts for carbon releases to the atmosphere. NEP is calculated as:

$$NEP = NPP - \frac{C}{\tau} \qquad (3)$$

where:

C is the amount of carbon stored in the terrestrial ecosystem

τ is the average turnover time, which is calculated using equation 2.

A comprehensive list of NEP values for different ecosystems and soil types can be found in the Good Practice Guidance for Land Use, Land-Use Change and Forestry report published by the IPCC (Penman et all 2003).

Most of the CO_2 emissions from fossil fueled power plants are from annual fuel combustion. Usually, this amount depends on the annual electricity output of each power plant and is assumed to be constant; therefore, it is possible to make a parallel between the amount emitted by a fossil fuel plant and the amount corresponding to the forgone NEP due to the footprint of a land-use-

intensive alternative such as a hydroelectric plant or a massive solar photovoltaic (PV) installation. In this case, the NEP is also assumed to be constant even if it depends on the exact ecosystem type, which varies spatially, and climatic conditions of a specific year.

Another effect associated with the ecosystem that needs to be considered is the fate of carbon buried in the sediments accumulated in the reservoir during its operation. The two major sources of carbon in a reservoir are erosion and phytoplankton. They both contribute to the accumulation of carbon that is buried in the sediments (Figure 1). After the decommissioning and draining of the reservoir, the sediments may be mineralized and released to the atmosphere.

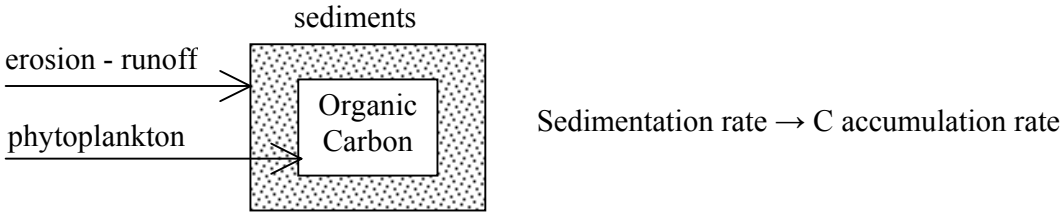

Figure 1: Schematic for Carbon Accumulation in the Reservoir's Sediments

Part of the carbon mineralized is released as CH_4 and part is oxidized and released as CO_2. Emissions from biomass decay and NEP are comparable to GHG emissions from a fossil fueled power plant.

One of the outcomes of this project is the development of an MS Excel spreadsheet that can be used to calculate the GWP over different time frames. Figure 2 shows a screen shot of the GWP tool.

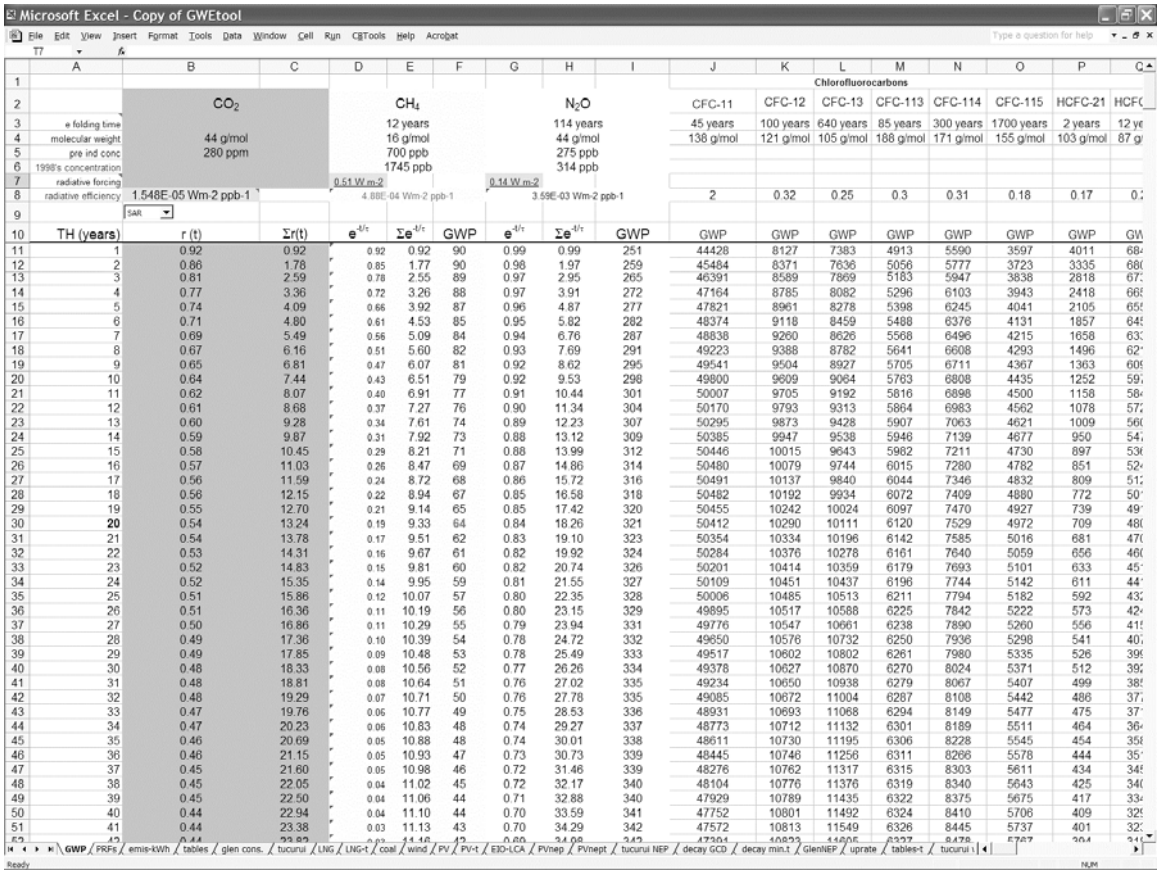

Figure 2: An example screen capture of the MS Excel spreadsheet with the GWP calculations used in GWE framework

2.2 Quantitative Results

The electricity supply mix in California is diversified: 22.35% of the energy is imported, and 9.84% of the electricity is produced in coal fired power plants outside of the state. The contribution of electricity produced by hydroelectric power plants in California is 11.17% [CEC 2004]. However, if imported electricity is also taken into account, the amount of hydroelectricity in the state mix amounts to 16.2%. In the same vein, the amount of electricity generation from coal in 2003 corresponded to 21.3%. Therefore, hydropower, coal, and natural gas were the major electricity supply sources for California in 2003.

Because the location of coal and natural gas power plants are not driven by the same type of natural constraints as the construction of hydroelectric power plants, we decided to carry out a case study based on a hydroelectric power plant that supplies energy to the U.S. Southwest grid. The Glen Canyon power plant (GC) on the Colorado River is the second largest power plant

operated by U.S. Bureau of Reclamation (USBR). The reservoir, Lake Powell, is formed by a concrete arch dam with 3,750,000 m^3 of embedded concrete. The power house has 8 turbine generator sets; five are presently rated at 165 MW each, and three are rated at 157 MW each. The total electricity produced for the fiscal year 2003 was 3.5 TWh [USBR 2004].

We compared the GHG emissions associated with electricity produced by GC with electricity produced by similarly sized coal and natural gas fueled power plants, and by two renewable sources: solar photovoltaics and wind. Figure 3 shows the results normalized by energy output. If the GHG intensity of electricity generation technologies varies, the contribution of a given life-cycle phase in the overall emissions is also variable. In the case of hydroelectric plants, the flooding of the reservoirs and the displacement of the natural ecosystem is a source of emissions.

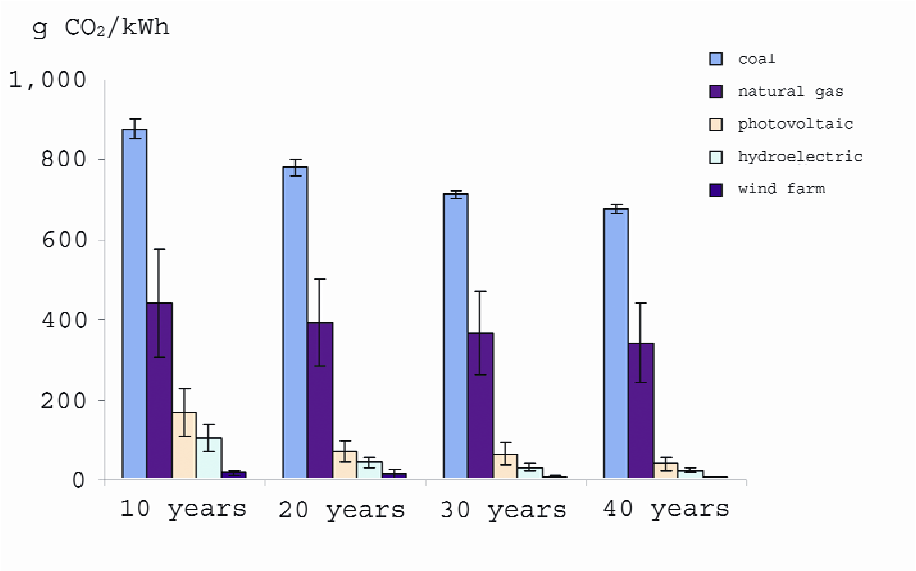

Figure 3: Comparative LCA of Electricity Generation Options for CA

In the case of GC, it is assumed that the mean annual temperature (MAT) of the water in the reservoir is 286 K (13ºC) [Hueftle 2001]. Therefore τ equals 33 years. Other assumptions made were: (1) the area of the flooded land is similar to the surface area of the reservoir, Lake Powell (653,130,000 m^2), (2) originally the land was covered by desert scrub that has a carbon density of 0.3 kg C/m^2 [Harte 1988], and (3) 10-30% of the carbon was subject to anaerobic decomposition and released as CH_4 [Rosa 1995].

Consequently, emissions from flooded biomass are estimated to be 920,000–2,700,000 $MgCO_2Eq$, depending on how much carbon is converted to CH_4. Emissions due to the forgone carbon uptake of the flooded area is 700,000 $MgCO_2Eq$ (measured after 20 years of operation). These values are also part of the results shown in Figure 3.

A sensitivity of the GC analysis assuming that the same project is built on different ecosystems led to the following GWE normalized by electricity output (Table 2). These results show that the location of the hydroelectric plant and the carbon density of the ecosystem affects the environmental performance of this technology.

Table 2: Sensitivity analysis of GWE of GCD due to different ecosystem types.

Ecosystem type	g of CO_2/kWh
tropical forests	2,696
temperate forests	2,053
boreal forests	1,296
woodland and shrubland	370
grassland	99
desert scrub	49

Another life-cycle phase of power plants that is usually ignored during environmental assessment is the end-of-life. Impacts during the decommissioning of power plants may be significant especially in the case of nuclear plants [Wald 2003, OECD 2003]. In this study we also considered the impacts of decommissioning large hydroelectric plants. Potential impacts from the decommissioning of hydroelectric power plants may be associated with the sediments accumulated in the reservoir during the operation of the power plant.

In the case of GC, a 1986 report from the USBR determined that the average sediment deposition rate over the 22 years of operation of the reservoir was 45,603,741 $m^3\ yr^{-1}$, which corresponds to an average accumulation of 7 cm yr^{-1} [Ferrari 1988]. Such accumulation rate is more than three times the average sedimentation rate for reservoirs worldwide (2 cm yr^{-1}) [Mulholland 1982]. Assuming an average bulk density of 1 Mg m^{-3} and 2% of carbon [Dean 1998], the carbon accumulation rate equals to 910,000 Mg per year, which corresponds to 3,300,000 $MgCO_2Eq$. This calculation assumes an average carbon percentage in sediments; however, the climate of the upper Colorado watershed is classified as semiarid, and the lower part of the basin is sparsely

vegetated because of inadequate rainfall and poor soil conditions [Ferrari 1988]. Thus, the carbon content in the sediments is likely to be less. If all carbon accumulated over the life-cycle of the GC hydroelectric plant is released to the atmosphere and 30% is converted to CH_4, this would amount to an additional 4.6 grams of CO_2Eq./kWh. In this calculation a 20-year GWP is used to covert CH_4 emissions to CO_2Eq.

Leaving aside the effects from decommissioning and summing up the two GHG emission sources (construction of the dam and biomass decay from the reservoir), and the forgone NEP, the total GWE of the Glen Canyon Dam after 20 years of operation (at the time of the upgrade) is estimated at 2,400,000–4,300,000 MgCO_2Eq. The reason for the variability is the percentage of carbon emitted as CH_4.

Solar photovoltaic modules and wind power are amongst the technologies that would substitute for electricity produced by hydroelectric plants and fossil fueled power plants and minimize the global warming effect associated with electricity generation. Although the design of these technologies is not dictated by the local natural conditions like in the case of dams there are different types of technologies within the two renewable energy classes an the performance of such systems also depend on the availability of natural resources.

Within a specific generation technology such as PV, for example, there are different subtypes that affect the overall performance of the system with respect to GHG emissions. Conversion efficiency and manufacturing characteristics are some examples that should be carefully described in the analysis but not confused with uncertainties. Instead they should be characterized as simple choices made by the proponent of the alternative. Figure 4 shows a comparison between multicrystalline PV technology and thin film PV technology. Of course, the performance of solar photovoltaic systems is affected by the amount of solar radiation available.

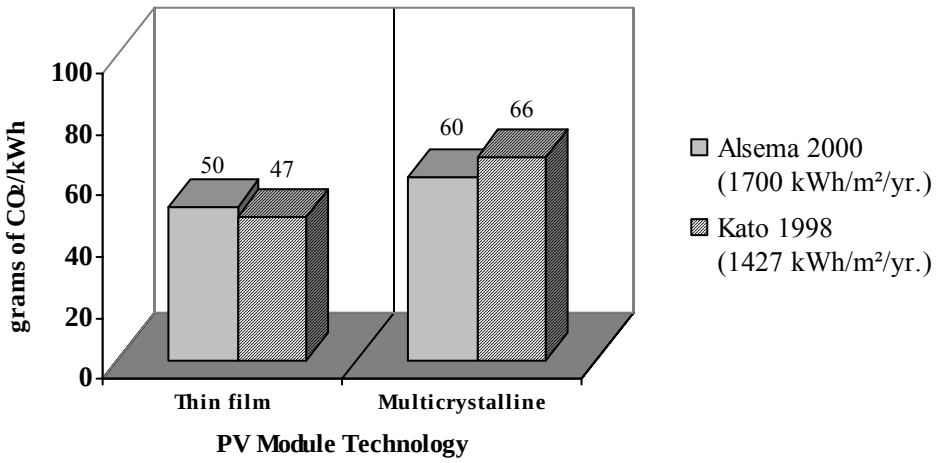

Figure 4: Environmental performance of thin film and multicrystalline PV systems

The environmental performance of wind farms is also driven by natural conditions such as the availability of wind resources. Other factors such as the energy type and intensity during the manufacturing of the turbines and their lifetime, which are not a function of the location of the turbine also affect the performance of this technology. Table 4 shows CO_2 emissions and characteristics of large wind turbines.

Table 4: CO_2 emissions and characteristics of large wind turbines [Lenzen 2002].

Year of study	Location	Energy Intensity $(\frac{kWh_{in}}{kWh_{el}})$	CO_2 intensity $(\frac{gCO_2}{kWh_{el}})$	Power rating (kW_{el})	Life time (y)	Load factor (%)	Turbine type	$\varnothing_r$ (m)	H (m)	Rated wind speed (m/s)	Remarks
1997	Denmark[o]	0.020	15.9	400	20	22.8					Excl. imports
1991	Germany[o]	0.048		450	20	20.0	3-bl	35	36	18	AN-Bonus 450
1994	Germany[o]		18.2[e]	500	20	27.4					Incl. factory buildings
1994	Germany[o]	0.068	8.1	500	20	36.5	2/3-bl	39	41		
2000	Denmark[o]	0.033	9.7	500	20	25.1	3-bl		41.5		On-shore farm (18)
2000	Denmark[o]	0.047	16.5	500	20	28.5	3-bl	39	40.5	16	Off-shore farm
2000	Belgium[o]	0.033	9.2[e]	600	20	34.2					
2000	Belgium[o]	0.036	7.9[e]	600	20	34.2					1980 I/O tables
1996	Germany[o]		14[e]	1000	20	18.5	3-bl	54	55		HSW 1000
1996	Germany[o]		22[e]	1000	20	18.5	3-bl	54	55		HSW1000
1996	Germany[c]	0.035	10	1000	20	36.2	3-bl	60	50		
1996	UK[o]		≈25	6600	20	29					System not specified

3 REFERENCES

[CEC 2004] California Major Sources of Energy. http://www.energy.ca.gov/html/energysources.html

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

[Ferrari 1988] Ferrari, Ronald L. 1988. 1986 Lake Powell Survey - 1988. Bureau of Reclamation, Denver Co. U.S. Department of the Interior. 67pp.

[Gagnon 1997] Gagnon, L., and J. van de Vate, "Greenhouse Gas Emissions from Hydropower: The State of Research in 1996", *Energy Policy* 25(1), pp. 7-13. 1997.

[Harte 1988] Harte, J. Consider a spherical cow: a course in environmental problem solving. Los Altos, Calif. W. Kaufmann.

[Hueftle 2001] Hueftle, S.J., Stevens, L.E. "Experimental Flood Effects on the Limnology of Lake Powell Reservoir, Southwestern USA" *Ecological Applications* 11(3), pp. 644-656.

[Lenzen 2002] Lenzen, M. and Munksgaard, J Renewable Energy 26: 339-62.

[Lloyd 1994] Lloyd, J., Taylor, A. "On the Temperature Dependence of Soil Respiration", *Functional Ecology* 8(3) pp. 315-323.

[Mulholland 1982] Mulholland, P. J., and Elwood, J. W., "The Role of Lake and Reservoir Sediments as Sinks in the Perturbed Global Carbon Cycle", *Tellus*, 34, pp. 490–499, 1982.

[OECD 2003] OECD. Decommissioning Nuclear Power Plants: Policies, Strategies, and Costs". Nuclear Energy Agency. Organization for Economic Cooperation and Development. 2003.

[Penman et al. 2003] Good Practice Guidance for Land Use, Land-Use Change and Forestry http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.htm

[Sanderman 2002] Sanderman, J., Amundson, R., Baldocchi, D. University of California, Berkeley, umpublished results.

[USBr 2004] Glen Canyon Powerplant Colorado River Storage Project Glen Canyon Storage Unit. http://www.usbr.gov/power/data/sites/glencany/glencany.pdf

[Wald 2003] Wald, M.L. Dismantling Nuclear Reactors. *Scientific American*. March 2003. 60-9. 2003.