Life-Cycle Inventory of Energy Use and Greenhouse Gas Emissions for Two Hydropower Projects in China

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Abstract: Two different sized hydropower projects in China, one with a capacity of 44 MW and the other of 3,600 MW, were examined through life-cycle assessment (LCA) from the perspective of both sustainability and environmental impact and the influence of project scale. Using the economic input-output based LCA approach, energy use and greenhouse gas (GHG) emissions were quantified. The resulting energy payback ratios were found to be 7 and 48, whereas the normalized GHG emissions were 44 and 6 g CO_2 equivalent per kW h of electricity production, both in favor of the larger project. Compared with published data on other renewable and nonrenewable options, temperate hydropower, particularly large hydropower, is indicated as an efficient electrical source with relatively low GHG emissions.

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Introduction

Minimizing environmental impacts is one of the most significant technical and political challenges facing the energy sector today, particularly when making investment decisions. Hydroelectric systems, although utilizing renewable flowing water and thus resulting in little air pollution during their operation, have also fallen under considerable scrutiny, particularly due to hydrological and ecological concerns associated with water impoundments and dams. Of course, no power development is without significant environmental costs. Thus, a pressing issue is whether hydropower is an "environmentally responsible," sustainable or green energy alternative. Moreover, does this environmental designation depend on the scale of the project? With these and other concerns, more effort is needed to evaluate the sustainability of all energy generation options, not only using profit and financial considerations, but also using quantitative environmental assessment tools based on multidisciplinary insights and a broad professional knowledge (Kozak 2004; Bernhard et al. 2000).

In China, due to rising electrical demands and rapid economic growth, hydroengineering has been continuously advocated and several megaprojects are currently under construction or planned. Such projects have caused worldwide concern in terms of their economic sustainability and issues of environmental protection (Easterbrook 2004). A systematic, detailed and quantitative assessment of these matters is clearly called for. To this end, two hydroprojects in China, of quite different sizes, are herein studied and compared.

Assessment of power systems, such as comparing hydro and thermal energy sources, involves an interesting interaction between capital and operating energy requirements. For example, hydropower may require less nonrenewable energy during the operation stage as opposed to the construction stage. In such cases, life-cycle assessment (LCA) is widely recognized as a systematic approach that considers not only the resource usage and environmental discharges associated with each project stage, but also the potentially significant shifts of these loads between stages.

Although only a few references focus on hydropower, previous LCA studies and comparisons of various energy options reported superior environmental performance for hydropower projects in terms of air pollution and global warming potential (Gagnon et al. 2002; Meier 2002; Goralczyk 2002; USNEI 2005; Hydro Quebec 2001; IEA & OECA 1998). Unfortunately, these studies report the overall life-cycle results only, thus making it difficult to distinguish exactly what is included and what assumptions are made. Several studies explicitly mention that emissions from the reservoir only were considered (CHA 2002; Coltro et al. 2003; Kim 2004). A report prepared by Stanley Rhodes et al. (SCS 2000) endeavored to develop a uniform approach to broadly assess environmental impacts, but lacks a solid database for its inventory study. A LCA case study of greenhouse gas (GHG) emissions from the Glen Canyon Hydropower Project (a U.S. project upgraded between 1984 and 1987 by 338–1296 MW) was carried out (Pacca and Horvath 2002). However, this study did not include the GHG emissions due to routine operation and maintenance or due to decommissioning. The global warming effects over different analysis periods (20, 30, and 40 years after construction) were assessed by integrating LCA and global warming potential.

Certainly LCA has been widely exploited in recent years

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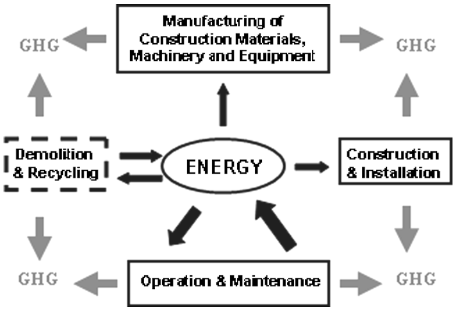

Fig. 1. Note: (1) energy use for raw material extraction is included in the manufacturing stage; (2) distinction between the arrows hints at the relative amounts of energy required and expended during each life-cycle stage of a hydroproject

for the evaluation of energy generation alternatives (Meier 2002; Coltro et al. 2003; May and Brennan 2003; Lee et al. 2004; Benetto et al. 2004; Lombardi 2003). Although there are few published studies on hydropower projects, in the few that have appeared LCA has been advocated as a useful framework for sustainability assessments. Moreover, substantial surveys related to reservoir emissions are available (Gagnon et al. 2002; IEA & OECA 1998; CHA 2002; USNHA 2000; McCully 2004). However, further research into LCA for hydropower would assist in making more informed choices from available energy alternatives.

Scope and Objectives

Fig. 1 divides the life cycle of a hydroproject into four stages: (1) the manufacturing of construction materials, installed machinery and equipment, including the extraction of raw materials (M.M.); (2) construction and equipment installation (Constr. and Inst.); (3) operation and maintenance (O&M); and (4) facility demolition and recycling. As decommissioning a large dam is rare (Isambert and Crepon 2004; UNEP-DDP 2006) and reference data unavailable, the last stage is excluded from this life-cycle study and differentiated with dotted lines in Fig. 1. However, the O&M stage does consider the replacement and upgrading of machinery and equipment. Fig. 1 indicates that each life-cycle stage consumes energy and produces GHGs. Yet what makes the kind of project shown in Fig. 1 interesting is the dual role that electrical energy plays: Not only is electrical energy the chief product during the O&M stage, but also the primary distinguishing factor and comparator in the assessment of energy generation projects relative to other infrastructure projects.

This study uses LCA to quantify the energy efficiency and GHG emissions of two hydroprojects, both of which are primarily intended for electricity generation. Project A, designed for a 50 year lifespan, has a 44 MW plant, an 88.8 m high rock-fill concrete dam, and was constructed between 1993 and 1998 (ZHDI-1 1992; ZHDI-2 1992). Project B has a capacity of 3,600 MW, is designed for 100 years, and utilizes a 305 m high double arch concrete dam; it has been planned for decades and construction is expected to start soon (SWHDI 2003).

Methodology and Data Sources

LCA is a tool for evaluating the environmental impacts of a product or project through its entire lifespan, usually from raw material extraction to final disposal. Of the two primary approaches for LCA, one is based on process models and was formalized in the 1990s by the U.S. Environmental Protection Agency and the Society of Environmental Toxicology and Chemistry (USEPA 1993; SETAC 1991). The second approach is based on the economic input-output (EIO) method. The so-called EIO-LCA approach consists of a matrix of economic data (representing the inputs from all sectors of the economy into all other sectors and the distribution of each sector's output throughout the economy) and a matrix of sector level environmental coefficients. The EIO-LCA approach enables an estimation of the economy-wide direct and indirect economic and environmental impacts (e.g., total energy use across the supply chain) of a production decision. An EIO-based model of the U.S. economy is maintained by the Green Design Institute at Carnegie Mellon University (CMU—Green Design Institute 2005). In this study, the process model approach is utilized for the overall life-cycle inventory, whereas the EIO-LCA model is utilized to account for the energy input and GHG emissions associated with the manufacturing of major materials and equipment used in the projects. Since no EIO-LCA model is yet available for China, the Carnegie Mellon EIO-LCA model (1992 economic matrix) is used provisionally here. Since Project A was built in 1992, it is reasonable to use the 1992 version of EIO-LCA model rather than the most recent (1997) version. To run the model, each cost in Chinese currency (RMB) is converted to equivalent U.S. dollars by using the Purchasing Power Parity (PPP) in the corresponding year, and then further adjusted to 1992 U.S. dollars using the U.S. Consumer Price Index (CPI). The applicability of the U.S. model for this study is discussed in the next section.

This study utilizes a functional unit of 1 kW h of net electricity production. However, some life-cycle data are also presented on a per project basis. GHG emissions are normalized to an equivalent of CO_2 mass (gram) emissions per kW h of net electricity production based on IPCC 100 year global warming potentials (IPCC 1996), the so-called GHG emission factor. Following Meier (2002), the energy efficiency is indicated by the energy payback ratio (EPR), defined as the ratio of total net electricity product (energy output) to total energy consumption (energy input) over the lifespan of a project. That is

$$\mathrm{EPR} = \frac{\mathrm{output}}{\sum_{i=1}^{4} \mathrm{input}_i} \tag{1}$$

where input_i=total energy consumed during each of the four LC stages. In particular, input_3 is total lifetime energy associated with project operation and maintenance, but excludes the usual considerations of fuel (in this case, the "fuel" is the energy provided naturally through the flowing water). Finally, input_4=total energy consumed for project decommissioning, but is also excluded here. All these energy terms are expressed here in joules (1 kW h =3.6 MJ).

The material inputs and monetary costs are extracted from project-specific Budgetary Estimate Reports (ZHDI-1 1992; ZHDI-2 1992; SWHDI 2003). These budget reports were obtained through personal contacts in China with the design institutes. Although these data are nominally confidential, there is a strong sense of the importance of this research, and the conviction that the data should be self-explanatory, rather than depending on the guesswork or intuition of decision makers. Since Project A was constructed before this study, the material and equipment costs used in the analysis are closely tied to purchase contracts.

Table 1. Inventory of Energy Use and GHG Emissions during Manufacturing Stage for Projects A and B

	Total cost (10^6 RMB)		Total cost (10^6 \$ 1992)		Electricity use (MkW h)		Energy use (TJ)		GHG emissions ($MgCO_2$ eq.)	
Category	A (92)	B (03)	A	B	A	B	A	B	A	B
Main construction materials	17.1	1,590	14.3	675	24.3	1,245	536	22,700	40,400	1,711,000
Machinery and equipment	23.3	2,140	19.4	906	11.1	537	183	9,100	13,500	672,000
Structural metals and devices	4.1	210	3.4	88	3.2	81	66	1,700	4,700	120,000
Total	44	3,900	37	1,670	38	1,860	785	33,500	58,600	2,500,000

Note: For Project A, the total costs in RMB (1992 Chinese dollar values) are converted into the total costs in US$ for the same year (1992) using Purchasing Power Parity (PPP). The PPP conversion factor is 1.2 for 1992. For Project B, the total costs in RMB (2003 Chinese dollar values) are first converted to the total costs in US$ in 2003 by the PPP factor (PPP=1.8 in 2003) (The World Bank 2004) and then further converted to the values in 1992 ($) by Consumer Price Index (CPI). CPI=0.713 for 1992; and CPI=0.544 for 2003 (US Census Bureau 2005).

Project B uses prospective budget data which certainly brings greater uncertainty, but probably no more than is typical in decision-making and planning activities. Published values are used for other data regarding O&M of hydroplants and economic indices (PPP, CPI, etc.).

Life-Cycle Inventory Analysis

Manufacturing Life-Cycle Stage

The inventory of materials used in both projects is included in Table 1, which accounts for major construction materials, the mechanical and electrical equipment including turbine-generator sets and transformers, and the metal structures for items such as the control gates, devices, and pipes. The total electricity usage and GHG emissions for each item are obtained from the EIO-LCA model. The inputs and discharges associated with the extraction of raw materials up through the manufacture of the materials and equipment are automatically included in the EIO-LCA model.

To partially explore the applicability of the U.S. EIO-LCA model for a hydroproject in China, the energy required to produce 1 Mg of hot-roll steel bar was investigated. The steel price in the 1992 China market was around 1,747 RMB/Mg (ZHDI-2 1992), which is equivalent to $1,456/Mg by the PPP conversion (PPP=1.2 in 1992) (The World Bank 2004). This value is then input into the U.S. EIO-LCA model, resulting in energy use of 23.8 GJ for the manufacture of 1 Mg of steel bar. Reassuringly, this energy estimate is within the range of 20–25 GJ/Mg reported for steel production in Shanghai, China (Dhakal 2004).

By contrast, if the actual cost in the 1992 U.S. market is used to run the EIO-LCA model, the resulting energy required for steel bar production is unrealistically low. For example, using an annual average price of hot-rolled steel bar of $385/Mg in the 1992 U.S. market (Fenton 1998), and rerunning the U.S. EIO-LCA model, results in an energy input of only 6.3 GJ/Mg, which is about one-fourth of the estimated energy consumption in China.

This comparison demonstrates that dollar costs converted by the PPP factor is a reasonable way to use the U.S. EIO-LCA model with Chinese monetary cost data, although this point comparison does not answer all objections, and the use of U.S. data is clearly one of the limitations of the current study. However, the example does demonstrate that the actual U.S. market prices should not be used for commodities produced and consumed in China; the economic structure and industry energy efficiencies are, not surprisingly, quite different in the two countries. Due to the often significant impact of the environmental performance of the electricity generation mix on results of life-cycle studies, we examined the Chinese and U.S. mixes. Interestingly, based on the available data sources in 2000, the mixes in the two countries are actually quite similar: For example, fossil fuel supplies 70% in the United States versus 81% in China, nuclear supplies 20% versus 1%; and 11% versus 18% from hydro and other renewables (EIA 2001; Yang 2003). Thus, these differences are likely not significant enough to strongly impact the overall energy use and emission factors, and are certainly less significant than the impact of sector level aggregated data used in the EIO-LCA model.

Construction and Installation Life-Cycle Stage

The construction and installation stage is the most complex one in the life of a hydroproject. This stage involves a series of procedures (such as excavation, drainage, pavement, concrete mixing,

Table 2. Inventory of Energy Use and GHG Emissions during Construction and Installation Stage for Projects A and B

		Quantity (10^3)		Unit cost (RMB /unit)		Electricity use (MkW h)		Energy use (TJ)		GHG emissions ($MgCO_2$ eq.)	
Const. material	Unit	A	B	A (92)	B (03)	A	B	A	B	A	B
Diesel	Mg	2.4	69.2	2,700	4,100	5.4	120.7	148	3,290	17,000	430,000
Electricity	kW h	7,940	240,000	0.42	0.56	0.4	8.6	259	7,350	38,600	792,000
Total	—					6	129	407	10,600	55,600	1,222,000

Note: The quantities of diesel and electricity are those energy amounts immediately consumed during the construction and installation stage. The quantity of GHG emissions results from diesel production (obtained from the petroleum refining sector through the use of the EIO-LCA model) and use (combustion during vehicle/equipment operation, which is estimated using a fuel emission factor). As the diesel is mainly used by heavy construction machinery (heavy-duty diesel vehicles, HDDVs) in the construction stage, the CO_2 emission factor for HDDVs 2,730 g/L (Environment Canada 2004), i.e., around 3,200 kg CO_2 eq. per Mg of diesel, is used to estimate these GHG emissions.

Table 3. Inventory of Energy Use and GHG Emissions during O&M Stage for Projects A and B

	Total cost (10^6 RMB)		Total cost (10^6 \$ 1992)		Electricity use/product (MkW h)		Energy use (TJ)		GHG emissions ($MgCO_2$ eq.)	
Category	A (92)	B (03)	A	B	A	B	A	B	A	B
Electricity generation/year					−105.7	−16,620				
Plant self-supply electricity use/year					6.34	997				
Net electricity generation/year					−99.36	−15,620				
Net reservoir emissions/year									110	2,360
Maintenance/year	6.5	367	5.4	156	0.84	24	25	714	1,940	55,810
Annual total									2,050	58,170
Total for O&M stage	325	36,700	270	15,600	42	2,400	1,250	71,400	102,500	5,817,000

Note: Negative values represent the amount of electricity generated or supplied to the power grid.

filling, lining, rolling, etc.) and each component (dam, tunnel, powerhouse, etc.) requires a variety of construction procedures and machinery. Due to the site-specific characteristics of large scale hydroprojects, few components are conventional products or can be directly purchased. Fortunately, data concerning the total quantities and unit costs of diesel and electricity immediately consumed during the construction and installation stage are provided in their respective budget estimate reports. But the (likely relatively small) energy use and emissions corresponding to the production of the construction machinery and equipment, and the corresponding large use of construction labor, are unfortunately neglected, possibly causing some truncation error in this study.

For consistency with other life-cycle stages, the EIO-LCA model is used, utilizing the "petroleum refining" sector for diesel and the "electric services (utilities)" sector for electricity, to obtain the energy use and GHG emissions for producing the diesel and electricity used during construction and installation (Table 2). The GHG emissions from diesel combustion during operation of heavy construction vehicles and equipment are not included in the result of EIO-LCA model for the petroleum refining sector, and thus these were estimated using relevant emission factors from Environment Canada (2004).

Operation and Maintenance Life-Cycle Stage

Little detailed data are available about the O&M stage for a new hydroproject. However, general estimates of the annual cost, plant electricity use, and reservoir GHG emissions for a hydroproject are well established. Depending on the generation capacity and annual electricity production, the average annual cost of a hydropower project is around 3–5% of total initial investment, 50–70% of which results from the annual depreciation of all construction (dam, tunnel and powerhouse, etc.) and equipment, with the remainder arising from overhaul, maintenance, replacement and daily operation including administration, labor payment, and so on (Hohai University et al. 1983). For the purpose of the energy inventory during the O&M stage, the depreciation of all construction and equipment is rightly excluded because the associated resources, energy inputs, and GHG emissions have already been taken into account within either the material manufacturing stage or the construction and installation stage. Therefore, conservatively, 2 to 3% of the total initial project investment is estimated as the annual O&M cost, and it is further assumed that annual cost is a reasonable surrogate for the associated mechanical and electrical maintenance requirements. Based on the project scale, the annual maintenance cost of Project A is estimated as 3% of total initial project investment, which is 6.49 million RMB (1992 value); Project B is estimated as 2% of total initial project investment, 367.4 million RMB (2003 value).

Annual plant electricity use (self-supplied hydroelectricity) is estimated near 6% of the annual electricity output, and good use is usually made of the power produced during lower demand hours (SPIN 2005). The tiny amount of electricity potentially supplied by back-up diesel electricity generation for "dark start-up" is negligible (dark start-up refers to bringing on-line a generation unit without operational electricity supply from the power grid, such as during a blackout). In addition, the power losses in the transformer and during transmission are beyond the system boundaries of this research. Therefore, the GHG emission factors refer to g/kW h of net electricity produced only, exclusive of electrical delivery issues (which invariably vary project to project, and may or may not include economies of scale on a per kW h basis).

The reservoir, replacing as it does terrestrial ecosystems and natural lakes, is considered to be one of the major GHG emission sources during the operation stage. These GHG emissions depend on the area of the reservoir, and the characteristics of both the flooded soils and vegetation, and of the upstream watershed (carbon dissolved or suspended in rivers flowing into the reservoir).

Table 4. Overall Life-Cycle Inventory of Projects A and B

	Total cost (10^6 RMB)		Total cost (10^6 \$ 1992)		Electricity use (MkW h)		Energy use (TJ)		GHG emissions ($MgCO_2$ eq.)	
Category	A (92)	B (03)	A	B	A	B	A	B	A	B
Total of M. M. Stage	44	3,900	37	1,670	38	1,860	785	33,500	58,600	2,500,000
Total of Constr. and Inst. stage	106	11,560	89	4,900	6	129	407	10,600	55,600	1,222,000
Total of O&M stage	325	36,700	270	15,600	359	102,100	1,250	71,400	102,500	5,817,000
Life-cycle total	475	52,240	396	22,100	403	104,000	2,400	115,500	216,700	9,543,000

Note: Totals may not add due to rounding. Total cost includes labor, rental cost of construction equipment, etc., as well as capital plus O&M.

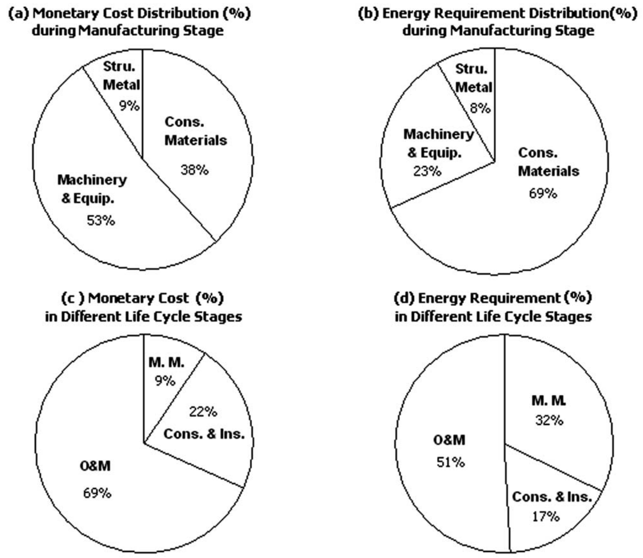

Fig. 2. Distribution of energy requirement versus distribution of monetary cost (Project A)

The amount of flooded biomass per unit of reservoir area can vary from 500 Mg/ha for tropical forest to 100 Mg/ha for a boreal climate (Gagnon et al. 2002), whereas the carbon content of different ecosystems varies from 18.8 kg of $\mathrm{C/m^2}$ for tropical forests to 0.3 kg of $\mathrm{C/m^2}$ for desert scrub (Horvath 2005).

Research on GHG emissions from hydroreservoirs has been carried out since the early 1990s in Canada, Finland, and South America. The types of reservoirs investigated range from deep storage pools in cold mountainous regions with little flooded vegetation, to warm, shallow tropical reservoirs with large quantities of flooded vegetation. Based on the measurements from nine tropical hydropower reservoirs in Brazil (McCully 2004), the GHG emission rate ranged from 240 to 10,000 Mg carbon per year per $\mathrm{km^2}$ (i.e., 880–36,700 Mg $\mathrm{CO_2}$ eq./year/$\mathrm{km^2}$). However, measurement in Canadian hydroelectric reservoirs shows good consistency, and the net GHG emission rate is around 250 Mg $\mathrm{CO_2}$ eq./year/$\mathrm{km^2}$, which includes the reduction of GHG absorption by the original vegetation on the replaced land (CHA 2002).

As both of the current projects are located in the boreal mountains in mid-China, the water surface temperatures are expected to be similar to, but slightly higher than, those in Canada. Thus, using the average measurement of GHG emissions from Canadian sites is likely reasonable but might slightly underestimate the annual reservoir GHG emissions. Yet a sensitivity analysis has shown that the annual reservoir GHG emissions, even when assumed to be significantly higher than our baseline value, have insignificant impact on the final LC GHG factor. The reservoir areas of Projects A and B are 0.44 and 9.44 $\mathrm{km^2}$, respectively, and the annual reservoir emissions are estimated to be 110 Mg $\mathrm{CO_2}$ eq. for Project A and 2360 Mg $\mathrm{CO_2}$ eq. for Project B.

The final inventories of energy use and GHG emissions during the O&M stage are summarized in Table 3 for Projects A and B.

Demolition and Recycling Life-Cycle Stage

The major machinery and equipment installed at a hydroplant are expected to last 15–30 years, shorter than the lifespan of the main construction components (dam, concrete foundation, etc.). The energy consumption and GHG emissions for replacing and recycling the machinery and equipment have been averaged and included here in the annual maintenance cost.

Ideally, decommissioning of construction components should be included in a LCA study. However, the practice of large dam demolition is uncommon except for the reasons of safety when there is severe ecosystem disruption. Dam removal occurs only for small projects (UNEP-DDP 2006); to date, a successful large hydrodam has never been demolished. The average height of removed dams in the United States is 6.5 m (IRN 2005). In reality, many hydropower facilities are still working well even beyond their design lifespan; in some cases, even if the main purpose of a hydroproject has been modified for tourism and recreation, the dam is still kept on site, because the ecosystem and environment have adapted to its presence. Thus, demolishing a large dam after a long term of operation is not only energy intensive but also may damage the already balanced ecosystem (SCS 2000; Isambert and Crepon 2004). Certainly, not including decommissioning might exclude some exceptional situations where integration was problematic or ecosystem restoration necessary. Moreover, technological developments may increase the competitiveness of other sustainable alternatives even while social changes may increasingly cause hydroprojects to be decommissioned. Unfortunately, these possibilities are difficult to integrate into the current assessment and are provisionally excluded in this

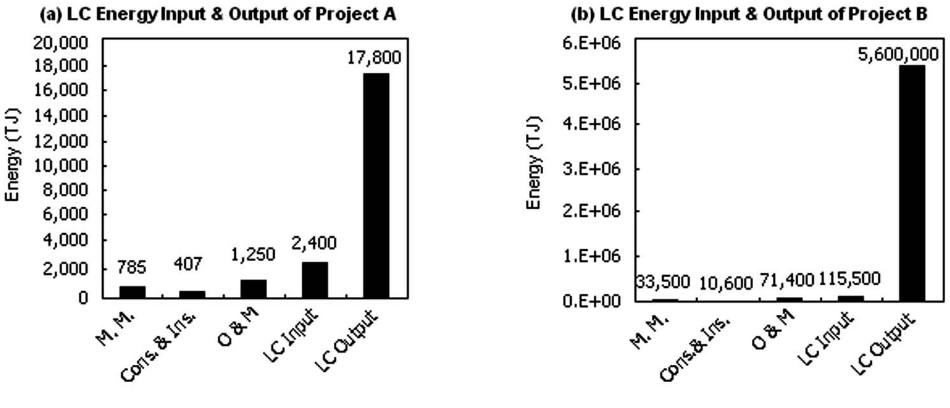

Fig. 3. Summary of net energy analysis for Projects A and B

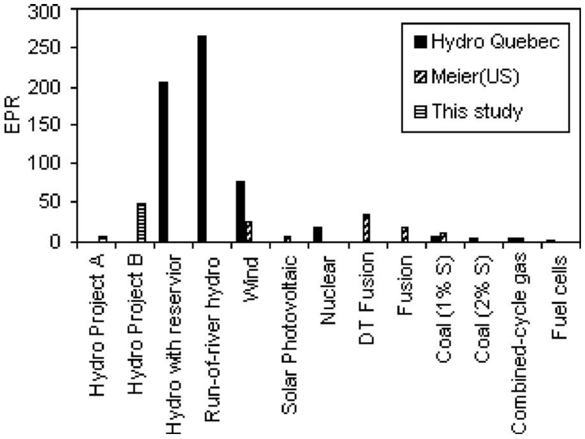

Fig. 4. EPR comparisons with other energy options

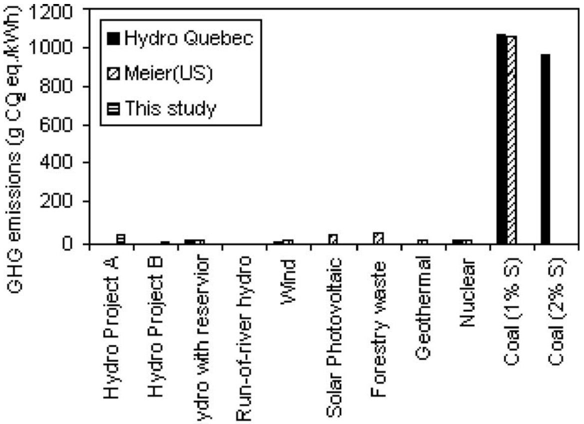

Fig. 6. Comparisons of GHG emission factor with other energy generation options

study. Table 4 summarizes the total monetary cost, electricity use, energy use, and GHG emissions during the life cycles of Projects A and B.

Results and Discussion

Monetary Cost and Energy Consumption

Monetary costs are not directly proportional to the energy use or environmental loads. Energy intensity varies from material to material and construction materials are more energy intensive than mechanical and electrical equipment installed in the studied projects. For Project A, Figs. 2(a and b) reveal that the cost of construction materials (38% of total cost during the manufacturing stage) is much less than that of machinery and equipment (53% of total cost during the manufacturing stage); however, the energy consumed in manufacturing the construction materials (69% of the total energy required for this stage) is considerably higher than that required to produce machinery and equipment (23% of total energy required for this stage). Figs. 2(c and d) illustrate that the energy intensity varies from one life-cycle stage to another. Thus, the monetary cost cannot explicitly represent the energy requirement.

Energy Efficiency

A summary of life-cycle energy use and net energy production is shown in Fig. 3. As the electricity use is mainly contributed by the self-provided internal electricity consumption during the O&M stage, this amount is subtracted from the total electricity produced over the lifetime to obtain the net energy output. The energy efficiency of a power generation system, represented by the EPR of Eq. (1), can be calculated using the data in Fig. 3.

Fig. 4 compares the EPRs of Projects A and B with those of other hydro- and nonhydrogeneration projects. The EPR of Project A is 7, which is close to those of the other renewable and nonrenewable electricity generation systems, but the EPR of Project B is 48, which is higher than other published values for nonhydrorenewable and nonrenewable systems. Thus, the energy performance of both projects is competitive, while the larger one is particularly efficient.

However, the EPR values of both projects are noticeably lower than those reported for a previous hydro-LCA study (Hydro Quebec 2001). The most likely reason is that the energy use during the O&M stage was not included in the Hydro Quebec research. This conjecture is partly supported by the EPR values provided by Hydro Quebec for different types of hydroprojects: Run-of-river hydroprojects have a higher EPR value (267), whereas the hydroprojects with impounded reservoirs have a lower EPR value

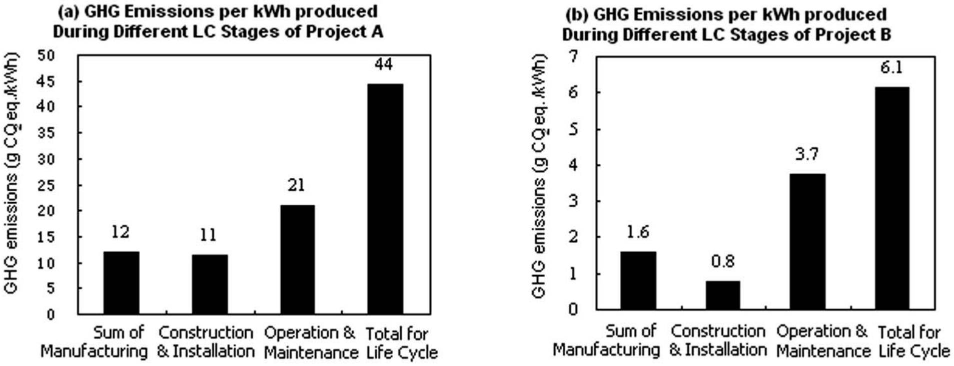

Fig. 5. Life-cycle inventory of GHG emissions for Projects A and B

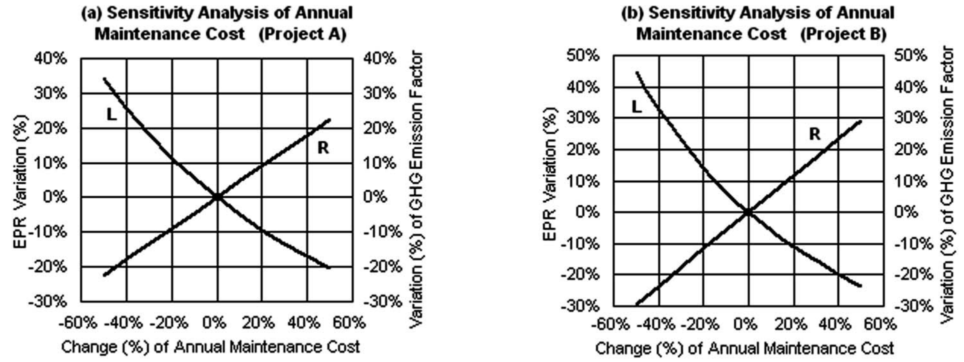

Fig. 7. Sensitivity analysis of annual maintenance cost

(205). When the energy use for O&M is disregarded, EPR comparisons are likely to favor run-of-river hydro (due to their smaller scale, smaller initial investment, and smaller impoundments), which is consistent with those values reported. However, the reality is that all such comparisons must be tentative in any case, owing to the strongly site specific nature of hydrodevelopments.

GHG Emissions

The contributions of GHG emissions from each LC stage and the LC GHG emission factor are presented in Fig. 5. The total GHG emissions are around 0.2 million Mg of CO_2 eq. during the 50 year lifespan of Project A and 9.5 million Mg of CO_2 eq. during Project B's 100 year lifespan. However, the LC emission factor on a per kW h produced basis are 44 and 6 g CO_2 eq./kW h for Projects A and B, respectively, in which the most significant portion is from the O&M stage with construction much less significant. The GHG emission factors of both projects are within the range of other hydropower studies (2–48 g CO_2 eq./kW h; USNEI 2005).

Fig. 6 compares the GHG emission factors of hydroprojects with other electricity generation systems. Not surprisingly, the GHG emissions of both projects are hundreds of times lower than for fossil-fuel generation; even amongst renewables, Project B ranks best. Overall, the larger hydroproject is found to be more environmentally favorable than the smaller one in terms of both energy efficiency and GHG emissions on a per kW h generated basis.

Parameter Uncertainties and Sensitivity Analysis

As the greatest uncertainty in this study is associated with the O&M stage, a sensitivity study was conducted on the impacts of annual O&M cost and annual reservoir GHG emissions. Fig. 7 shows that the annual maintenance cost is reasonably influential on both the LC GHG emission factor and the energy efficiency (EPR). In fact, this sensitivity is even greater for the larger Project B [see Fig. 7(b)]: A 50% reduction in the annual maintenance cost increases the EPR by 45% (from 48 to 70) and reduces the LC GHG emissions by 30% (from 6 to 4 g CO_2 eq./kW h).

Fig. 8 shows that LC GHG emission values are slightly affected by the variation of annual reservoir GHG emissions: A tenfold increase in annual reservoir emissions increases the LC GHG emission factor in both projects by only around 25%. This insensitivity is not necessarily general to hydroprojects but arises here because both projects have relatively high dams and small flooded areas. Actually, the GHG emissions during the O&M stage contribute more significantly to the LC emission factor. Besides, the natural variation of annual reservoir GHG emissions has no influence on the EPR of the hydrogeneration system, as there is no energy invested/input or gained/output due to the natural process biomass decomposition.

Limitations in Current LCA

Several limitations of the present study need to be specifically acknowledged. The study is illustrative in that it quantifies two

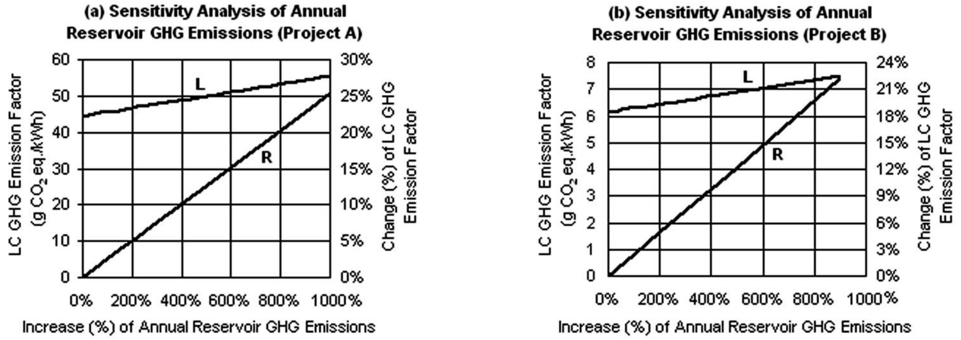

Fig. 8. Sensitivity analysis of annual reservoir GHG emissions

important metrics for hydropower projects on a life-cycle basis. However, additional environmental (e.g., landscape change, impacts on territorial and aquatic habitat), economic (e.g., potential loss or gain of tourism) as well as social (e.g., population migration and settlement) metrics should be examined for all hydroprojects. Other limitations include those related to both the model and data. Key limitations related to the EIO portion of the analysis include those noted in Joshi (2000) as well as that the model was developed for the United States, not for China. There is considerable uncertainty related to the assumptions and estimates made for annual reservoir emissions and annual O&M cost. Other challenges in applying LCA to hydroprojects are recognized as well. In a LCA, it is difficult to consider the multiple functions of a hydroproject (such as flood control and water supply) and the flexibility of hydrooperation in a power grid.

Summary

1. Although monetary costs are difficult to explicitly represent as energy expenditures, this study shows it is feasible to perform, at least in a provisional way, a LCA study for a hydroproject based on engineering budgetary estimates. In fact, given the value of such estimates, the writers recommend that LCA studies become a routine part of hydropower engineering studies in order to better inform decision making and comparisons between power projects.
2. An *a priori* assessment of project scale should not be used uncritically as a criterion for sustainability assessment. Large hydroprojects are not necessarily less environmentally favorable, at least not when evaluated by measures more complex than pure size. Because of their inherent economies of scale, larger hydropower projects often perform better than smaller ones in terms of both energy efficiency and unit GHG emissions.
3. Advanced technologies can influence the LCA of hydroprojects. In recent decades, the optimization of structural design and application of new construction materials and techniques have benefited the environment by reducing construction impacts. For example, the design of a double arch dam in Project B significantly reduces the concrete volume, and thus improves the specific indicators of energy efficiency and GHG emissions.
4. Although no fossil fuel is needed for operation, the energy use and GHG emissions during the O&M stage of a hydroproject are important aspects of a project's assessment. The GHG emissions from routine maintenance and operation, and not the releases from the reservoir (at least, not in cold regions), are key contributors to the total GHG emissions. Moreover, sensitivity analysis shows that variation in annual maintenance costs significantly influences both LC energy efficiency and GHG emissions, and thus it is as environmentally significant to improve the O&M efficiency as it is to advance construction technologies.

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