Life Cycle Analysis of Run-of River Small Hydro Power Plants in India

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Abstract: For 7-8% growth rate that India is aspiringfor, its energy needs will increase correspondingly. The challenge is to provide desired quality power in a sustainable manner and at reasonable cost. Small hydropower has the potential of about 15000 MW in India and considered to be a reliable source of electricity generation. Three run-of river small hydropower projects in India has been identified and their Life Cycle Analysis has been carried out by using the economic input-output (EIO) technique. The energy use, greenhouse gas (GHG) emissions and energy pay-back period (EPBT) were quantified for these small hydro power plants.

1. INTRODUCTION

Small Hydropower (SHP) is one of the earliest known renewable energy source. The technology was initially used in Himalayan villages in the form of water wheels to provide motive power to run devices like grinders. SHP technology was introduced in India shortly after the commissioning of the world's first hydro power plant at Appleton USA in

There is no international consensus on the definition of SHP. The general practice all over the world is to define SHP by power output. Different countries follow different norms keeping the upper limit ranging from 5 to 50 MW [2]. In India, SHP schemes are classified by Central Electricity Authority (CEA) [3]. Table **1** shows the International definition of SHP whereas Table **2** shows the classification of SHP

Table 1. International Definition of Small Hydro

S. No.	Country	Power (MW)
1.	UK(NFFO)	< 5
2.	UNIDO	<10
3.	Sweden	< 15
4.	Australia	< 20
5.	India	< 25
6.	China	< 25
7.	USA	< 30
8.	Brazil	< 30
9.	Philippines	< 50
10.	New Zealand	< 50

1882. The 130 kW plant at Darjeeling in the year 1897 was the first SHP plant in the country. Few other power houses belonging to that period such as Shivasundaram in Mysore (2 MW, 1902), Galogi in Mussoorie (3 MW, 1907), Chaba (1.75 MW, 1914) and Jubbal (50 kW, 1930) near Shimla are still working properly [1].

in India. In recent years small hydro electrical power has received great deal of attention from many points of view (i) as a sizeable and easily utilizable source of renewable energy and (ii) as a moderate investment method for providing electricity to under developed areas. Minimising the environmental impacts is one of the most significant technical and political challenges, energy sector is facing today. In India, rising electricity demands and rural development schemes has been continuously advocated for the development of SHP for the electricity generation as well as rural electrifica-

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Table 2. Classification of Small Hydropower in India

S. No.	Type	Station Capacity (kW)	Unit Rating (kW)
1.	Micro	Upto 100	Upto 100
2.	Mini	101 to 2000	101 to 1000
3.	Small	2001 to 25000	1001 to 5000

Table 3. Description of Small Hydropower Stations Selected for the Study

S. No.	Name of Project	Year of Project	Capacity (kW)	Net Head (m)
1.	Karmi micro hydro	2005	2×25	55.0
2.	Jakhna micro hydro	2005	2×50	48.24
3.	Rayat small hydro	1996	3×1000	88.0

tion. These projects have received worldwide concern in terms of their economic sustainability and issues of environment protection.

Life Cycle Analysis (LCA) is a tool for evaluating the environment impacts of a product or system through out its entire life span, usually from raw material extraction to final disposal. The LCA can be applied to assess the impact of electricity generation on the environment and will allow producers to make better decisions pertaining to environmental protection [4]. The two primary approaches for LCA are commonly used, one is based on Process Chain Analysis (PCA) and the second approach is based on Economic Input-Output (EIO) model.

Although only few references on hydropower are available yet, previous LCA studies and comparisons of various energy options have reported superior environmental performance for hydropower projects in terms of energy consumption and Global Warming Potential (GWP) [5]. These study reports give an overall life cycle results only which makes it difficult to distinguish exactly what is included and what assumptions are made in the study. Several studies have explicitly mentioned that emissions from the reservoir were considered [6,7].

2. ABOUT THE PROJECTS: CASE STUDY

Karmi-III micro hydro power project is located 36 km from Bageshwar town in district of Bageshwar Uttarakhand (India) by road upto Godiyadhar village and followed 8 km by foot track. This project envisages diversion of water from KARM GAD which is tributary of river Saryu through a semi permanent weir by 93 m long, 0.275 m diameter steel pipe and utilising 55.0 m of net head. Two hydraulic turbines of 25 kW each with synchronous generators are installed and power is transmitted through 11 kV lines to 5 villages (Dobar, Topania, Munar, Thalidar and Khalidar). The area falls in the humid temperate zone of higher Himalaya.The maximum temperature is in the range of 30°C to 0°C during summer and winter respectively. Karmi micro hydro plant is located in zone (V) of the seismic zone map of India, accordingly the basic seismic coefficient for the site is to be selected [8].

Jakhna Micro hydro power project is at the remote hilly area of Bhilangana block of Tehri Garwhal district of Uttarakhand (India). This area receives all its supplies from Gansali, which is about 44 km from the site. The temperature in the project area is generally between 3°C to 30°C and humidity between 30 to 85%. The gross head (H) of the plant is 52.74 m while net head is 48.24 m. The design discharge is 0.28 m^3/s and the installed capacity of the plant is 100 kW (2×50) [9]. This scheme electrifies villages of Jakhna, Bhaildgaon and Toli with a total population of nearly 260 families. The population is generally poor and the literacy rate is nearly 50-55%. Village Jakhna, Toli and Bhaildgaon are situated on the banks of river Balganga in Thati valley of Bhilangana block. An attempt to draw power from the Grid will be costlier and may involve deforestation at large scale. It was observed that irrigation canal exists in the area which passes just above the village Jakhna. Local enquiry has revealed that the water of this canal is used for 15-20 days in a year otherwise it lies unutilized hence this existing canal is used as power channel.

Rayat small hydro power project is located at a distance of about 12 km from Kempty falls in the District of Tehri Garwhal in Uttarakhand near village Nautha. The project utilizes perennial water of Aglar river for power generation without affecting the environment. The maximum and minimum temeperature are in the range of 35°C to 5°C during the summer and winter respectively. This project is located in earthquake zone (IV) of the seismic zone map of India, and the basic seismic coefficient for the site is selected as 0.05. The available net head is 88.0 m and the installed capacity of the plant is 3000 kW (3×1000) [10]. Table **3** shows the description of the hydropower stations selected for the study.

3. METHODOLOGY

LCA is a tool for evaluating the environmental impacts of a product or project through its entire life span, usually from raw material extraction to its final disposal (cradle to grave). Of the two primary approaches for LCA, EIO based LCA approach has been adopted in the present study. The 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 envi-

Table 4. Inventory of Energy Use and GHG Emissions in Civil Works

S. No.	Component	Cost in Rs 2004-05 (10⁶)			Cost in US $ (1997) (10⁶)			Energy Use (TJ)			GHG Emission (MgCO$_{2eq}$)		
		1	2	3	1	2	3	1	2	3	1	2	3
1.	Construction	2.891	2.126	65.845	0.266995	0.196344	6.081043	2.087902	1.535413	47.55375	160.7311	118.1993	3660.788
2.	Erection	0.313	0.588	10.59	0.028907	0.054304	0.978028	0.226051	0.424658	7.648178	17.40188	32.69106	588.7728
3.	Penstock	0.418	0.689	4.971	0.038604	0.063632	0.459091	0.579059	0.954478	6.886369	52.11531	85.90298	619.7732
	Total	**3.622**	**3.403**	**81.406**	**0.3345**	**0.3143**	**7.518**	**2.893**	**2.915**	**62.088**	**230.248**	**236.79**	**4869.33**

Table 5. Inventory of Energy Use and GHG Emissions in E&M Equipment

S. No.	Component	Cost in Rs 2004-05 (10⁶)			Cost in US $ (1997) (10⁶)			Energy Use (TJ)			GHG Emission (MgCO$_{2eq}$)		
		1	2	3	1	2	3	1	2	3	1	2	3
1.	Turbine & Generator	1.75	2.5	60.982	0.161619	0.230885	5.631926	1.048909	1.498442	36.5512	85.49663	122.138	2979.289
2.	Control Panel	0.5	1.6	18.79	0.046177	0.147766	1.73533	0.192558	0.616185	7.236325	15.88487	50.83159	596.9535
3.	Station Auxiliary	0.44	0.55	13.58	0.0406	0.0508	1.254	0.2947	.372	8.452	24.457	30.638	685.809
4.	Transformer & Switch Yard	0.3	0.48	10.505	0.0277	0.0443	0.970	0.275	0.44	9.634	22.359	35.774	782.933
	Total	**2.99**	**5.13**	**103.857**	**0.2761**	**0.4738**	**9.592**	**1.812**	**2.927**	**61.873**	**148.197**	**239.38**	**5044.98**

ronmental coefficients [11]. EIO based software of the U.S. economy is developed by the Green Design Institute at Carnegie Mellon University. In this study EIO-LCA model is used to account for the energy input and GHG emissions associated with the manufacturing of major materials and equipment used in these projects. Since no EIO-LCA model has been developed for India, the Carnegie Mellon EIO-LCA software (US Deptt of Commerce 1997 Industry Benchmark) is used in the present study [12]. The cost estimates of these projects pertain to different years. These costs have been inflated using inflation table of India to bring all the costs at par at the level of year 2004-05 in Indian Rs. Further the costs are converted into equivalent U.S. dollars by using the purchase power parity (PPP) in that year (2004). Further U.S. dollar has been adjusted for the year 1997 by using the U.S. Consumer price index (CPI) (see appendix 1) [13-14].

In this study, a functional unit is taken as 1kWh of net electricity produced by small hydro power. GHG emissions are normalised to an equivalent of CO_2 (gm) (see appendix 2) emissions per kWh of net electricity production based on IPCC 100 year Global Warming Potentials (GWP) [15]. The material input and monetary costs are extracted from detailed project report (DPRs) of the projects and visiting the site. Fig (**1**) shows a schematic diagram of run-of river small hydropower layout. Life cycle of a small hydro project is divided into four stages: (i) Civil works (ii) Electro-mechanical equipment (E&M) (iii) Operation and Maintenance (O&M) (iv) and Decommissioning.

$$EPBT = \frac{Energy\ input\ in\ all\ stages\ (J)}{Output\ energy\ per\ year\ (J\ /\ yr)} \tag{1}$$

4. LIFE CYCLE INVENTORY ANALYSIS

4.1. Civil Works

The inventory of civil works estimated in these projects are summarized in Table **4**, which accounts for major construction material in the components such as diversion, channel, forebay tank, penstock and transportation, erection etc. The total energy use and Greenhouse gas (GHG) emissions for each item is obtained from the EIO-LCA software. The inputs associated with the extraction of raw materials through the manufacturing of the material and equipment has been included in the EIO-LCA software.

4.2. Electro-Mechanical Equipment

The inventory of E&M equipment used in these projects are summarized in Table **5**, which accounts for the major electro-mechanical equipments, control structures, transformer and switchyard and station auxiliaries (valves, battery, PVC cables etc). The total energy use and GHG emissions for each item is obtained from the EIO-LCA software. The inputs associated with all processes from extraction of raw materials to manufacturing of the materials and equipments are included in the EIO-LCA software.

Table 6. Inventory of Energy Use and GHG Emissions in Annual O&M

S. No.	Component	Cost in Rs 2004-05 (10^6)			Cost in US $ (1997) (10^6)			Energy Use (TJ)			GHG Emission ($MgCO_{2eq}$)		
		1	2	3	1	2	3	1	2	3	1	2	3
1.	Civil works	0.10866	0.10209	2.44218	0.010035	0.009429	0.22554	0.08679	0.08745	1.86264	6.90744	7.1037	146.0799
2.	E&M works	0.0897	0.1539	3.11571	0.008283	0.014214	0.28776	0.05436	0.08781	1.85619	4.44591	7.1814	151.3494
3.	Others	0.02	0.15	1.71	0.001847	0.013844	0.157925	0.011193	0.083896	0.899527	0.957027	6.742175	76.90956
	Total	**0.21836**	**0.40599**	**7.26789**	**0.020165**	**0.037487**	**0.671225**	**0.152343**	**0.259156**	**4.618357**	**12.31038**	**21.02728**	**374.3389**

Table 7. Total Life Cycle Inventory of Energy Use and GHG Emissions of Projects

S. No.	Component	Cost in Rs 2004-05 (10^6)			Cost in US $ (1997) (10^6)			Energy Use (TJ)			GHG Emission ($MgCO_{2eq}$)		
		1	2	3	1	2	3	1	2	3	1	2	3
1.	Civil works	3.622	3.403	81.406	0.3345	0.3143	7.518	2.893	2.915	62.088	230.248	236.79	4869.33
2.	E&M works	2.99	5.13	103.857	0.2761	.4738	9.592	1.812	2.927	61.873	148.197	239.38	5044.98
3.	O&M*	6.5508	12.1797	218.0367	0.60495	1.12461	20.13675	4.57029	7.77468	138.5507	369.3114	630.8184	11230.17
	Total	**13.1628**	**20.7127**	**403.2997**	**1.21555**	**1.91271**	**37.24675**	**9.27529**	**13.61668**	**262.5117**	**747.7564**	**1106.988**	**21144.48**

*for 30 years life

Table 8. Energy Pay-Back Period and GHG Emissions of Small Hydro Power Houses

S. No.	Name of Power House	Capacity (kW)	Energy Generated (kWh_e/year)	EPBT (years)	GHG Emissions (gCO_{2eq}/kWh_e)
1.	Karmi-III	50	332880	2.71	74.88
2.	Jakhna	100	665760	1.99	55.42
3.	Rayat	3000	19972800	1.28	35.29

4.3. Operation and Maintenance

The general estimates for the energy use and GHG emissions are based on the annual maintenance cost and use of machine tools etc. Based on the project scale, the annual maintenance cost is taken as 3% of the total civil works and 3% of electro-mechanical equipment. Annual plant electricity usage is estimated as 5% of the annual electricity output. 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 [16], whereas the carbon content of different ecosystems varies from 18.8 kg of CO_{2eq}/m^2 for tropical forests to 0.3 kg of CO_{2eq}/m^2 for desert shrub. In the SHP scheme studied, there is no storage of water, henceno change in terrestrial ecosystem is considered. Table **6** shows annual energy use and annual GHG emissions in the operation and maintenance stage.

4.4. Decommissioning

The major components used in the power house are expected to last for 20-35 years. The energy consumption and GHG emissions for replacement and maintenance have been averaged and included in the operation and maintenance stage. Ideally decommissioning stage is also very important in accounting the total inventory of energy use and GHG emissions. However, the practice of demolition of small hydro power structures and components are very uncommon for the reason of renovation, modernization and uprating of the existing power house. As a power house completes its life, it goes for renovation, modernization and uprating. So there is no need to demolish the existing power house, but only to modify as per the condition of project site at that particular time. Table **7** summarizes the life cycle inventory of these projects.

5. RESULTS AND DISCUSSIONS

5.1. Energy Pay Back Period

Project costs are not directly proportional to the energy use or environmental loads. For these projects, civil works share is 31.19, 21.41 and 23.65%. E&M equipment share is 19.54, 21.50 and 23.57% and O&M work share is 49.27, 57.09 and 52.78% respectively for the Karmi-III, Jakhna and Rayat power plant respectively. The annual net energy generation for the three power plants at 80% load factor after deducting 5% energy as auxiliary consumption are 3.3288, 6.6576 and 199.728 lac units for Karmi-III, Jakhna and Rayat power plant respectively. The average life of the power plant is assumed to be 30 years. The EPBT for these power plant have been worked out as 2.71, 1.99 and 1.28 years respectively as shown in Table **8**.
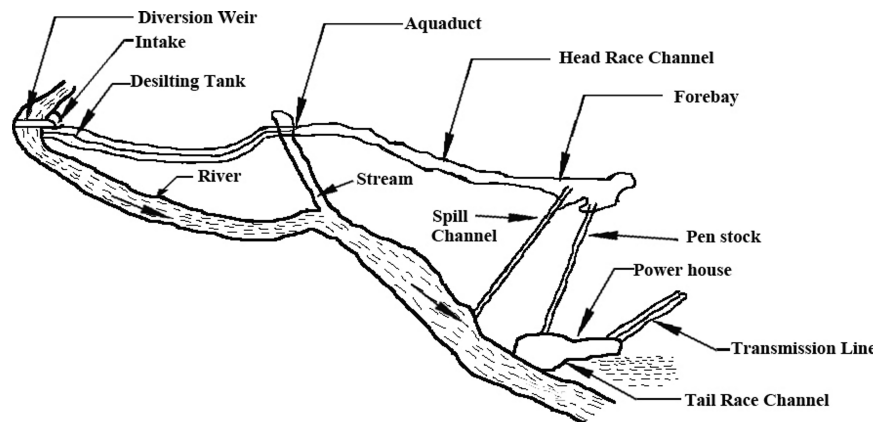
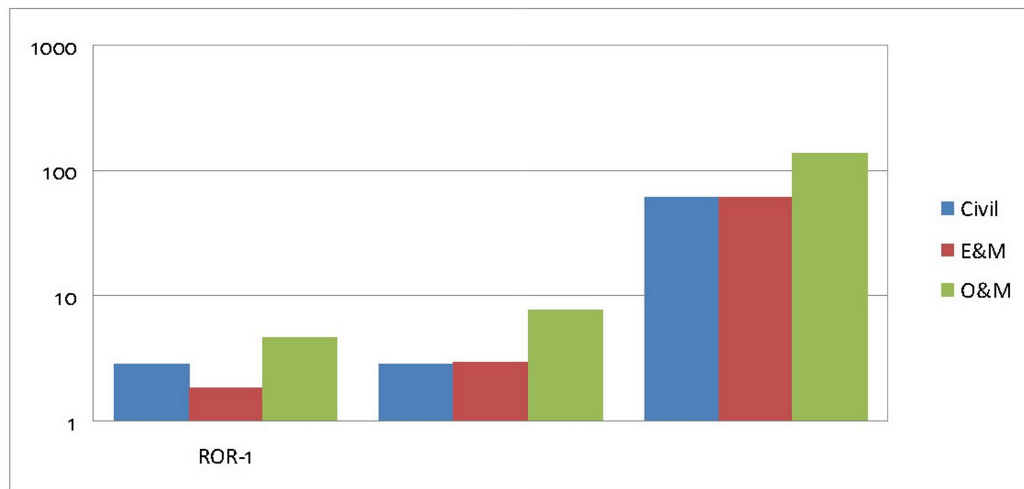**Fig. (1).** Layout of a Run-of-River small hydro power scheme.

Fig. (2). Variation of GHG emissions for different power houses.

5.2. GHG Emissions

The contribution of GHG emissions from each life cycle stages for these three power plant has been evaluated. The GHG emissions shared by civil works are 30.79, 21.39 and 23.03%, E&M equipment shares are 19.82, 21.62 and 23.86% and O&M shares are 49.39, 56.99 and 53.11% respectively for the Karmi-III, Jakhna and Rayat power plant respectively. The total GHG emissions are 747.7564, 1106.988 and 21144.48 $MgCO_{2eq}$ respectively. The GHG emission for power houses are estimated 74.88, 55.42 and 35.29 gCO_{2eq}/kWh_e for the Karmi-III, Jakhna and Rayat power plant respectively as shown in Table **8**. Fig. (**2**) shows the variation of GHG emissions for civil, electromechanical and O&M works share for three different run-of river SHP power plants.

6. CONCLUSIONS

In this study, the LCA of three run-of river small hydro-power plants has been carried out. The EPBT of these power houses varies from 1.28 to 2.71 years and GHG emissions vary from 35.29 to 74.88 gCO_{2eq}/kWh_e. The variation in the EPBT and GHG emissions shows that as the capacity of the power house increases EPBT and GHG emissions decreases. The EPBT and GHG emissions from small hydro power generation system are less as compared to the conventional type of electricity generation systems.

SUPPLEMENTRY MATERIAL

Supplementary material can be viewed at www.bentham.org/open/torej

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