Ecological Indicators 38 (2014) 81–88

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Emergy analysis of a small hydropower plant in southwestern China

Li-Xiao Zhang*, Ming-Yue Pang, Chang-Bo Wang

State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China

ARTICLE INFO

Article history:
Received 21 July 2013
Received in revised form
27 September 2013
Accepted 29 September 2013

Keywords:
Small hydropower
Emergy analysis
Environmental performance
Unstable operation

ABSTRACT

Although its environmental performance and sustainability remain unclear, small hydropower (SHP) has undergone rapid expansion in China. Through emergy analysis, this study aimed to assess the environmental impact and relative sustainability of a small hydroelectric plant in Guizhou Province, which is located in southwestern China, in 2010. The analysis included a comparison with similar evaluations that were conducted for large hydroelectric projects: two hydropower dams on the Mekong River in Thailand, one multipurpose dam in Korea, and the Three Gorges Dam in China. As indicated by the emergy yield ratio (EYR), environmental loading ratio (ELR), and emergy sustainability index (ESI), the overall environmental performance of the SHP system examined in this research surpassed the environmental performance of large dams. However, environmentally sensible designs do not automatically imply a promising future. The case-study SHP is on the verge of bankruptcy due to financial losses, which can be attributed to the current grid-connected cost of electricity of 0.23 CNY/kWh. The emergy exchange ratio (EER) quantitatively demonstrates that the fair price of electricity from the perspective of emergy balance is 0.4 CNY/kWh. The sensitivity analysis reveals that the inherent defect of unstable operation, which is exhibited by the SHP system, greatly affects the environmental performance of a SHP plant.

1. Introduction

Large and small hydropower, which is the most critical form of "renewable" energy for electrical power production, has been vigorously pursued by the Chinese government to alleviate the energy crisis and environmental issues created by fossil fuels (NDRC, 2011). In China, hydropower plants with installed capacities less than 50 MW are currently referred to as *small hydropower* (SHP) plants. China possesses abundant SHP resources that are economically feasible for exploration. A check of state water resources shows that the exploitable part of China's rural SHP resources using current techniques is 1.28×10^8 kW, which ranks first in the world (CWSY, 2009). Although this resource is widely distributed throughout the entire country, it is predominantly available in the central and western mountainous regions, which have 81.5% of the total resources (Ding et al., 2011; Zhou et al., 2009). Due to rural economic growth and governmental support, SHP has developed rapidly in China. By the end of 2010, SHP plants achieved an installed capacity of 0.59×10^8 kW with an annual average generation of 2.0×10^{11} kWh, which was approximately 38.7% of the total annual hydropower generation capacity (Tian, 2011). More than 45,000 SHP plants have been constructed, and the percentage of rural household with access to electricity has increased to 99.6% (Li, 2012). The rapid expansion of SHP projects in China elicits a series of concerns, such as ecological impacts, the unfair grid-connected cost of hydroelectricity, and the inherent defect of unstable operation (Cheng and Zhu, 2009; Fu et al., 2008; Zhang, 2010). These issues, which threaten the sustainable development of SHP, cause members of the public to question whether SHP is a cost-effective and environmentally sensible technology.

The use of energy analysis to assess transactions between nature and human society was initially based on the work of Lotka (1925) and gained prominence in the 1970s (Lefroy and Rydberg, 2003; Zhang et al., 2007, 2009a). Odum's ecological and dynamic analysis in ecological economics, which is based on systems ecology and contributed to a unified evaluation of environmental resource exploration associated with an ecological economic system, represented a major development in energy analysis methods (Cai et al., 2009). The theoretical and conceptual basis for the emergy methodology is grounded in energetics and general systems ecology (Odum, 1971, 1988, 1996). One of the main strengths of emergy analysis is the potential and capacity to evaluate resources and services in ecological economic systems on a common energy basis and to internalize the external costs that are typically considered free of charge. Using embodied solar energy as a measurement base, emergy is defined as the quantity of solar energy that is consumed, directly and indirectly, to obtain a final product or service (Odum, 1996; Ulgiati and Brown, 2009). The units of solar transformity consist of solar emJoules J^{-1} (seJ J^{-1}). Other unit emergy

* Corresponding author. Tel.: +86 10 59893229.
E-mail address: zhanglixiao@bnu.edu.cn (L.-X. Zhang).

1470-160X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ecolind.2013.09.037

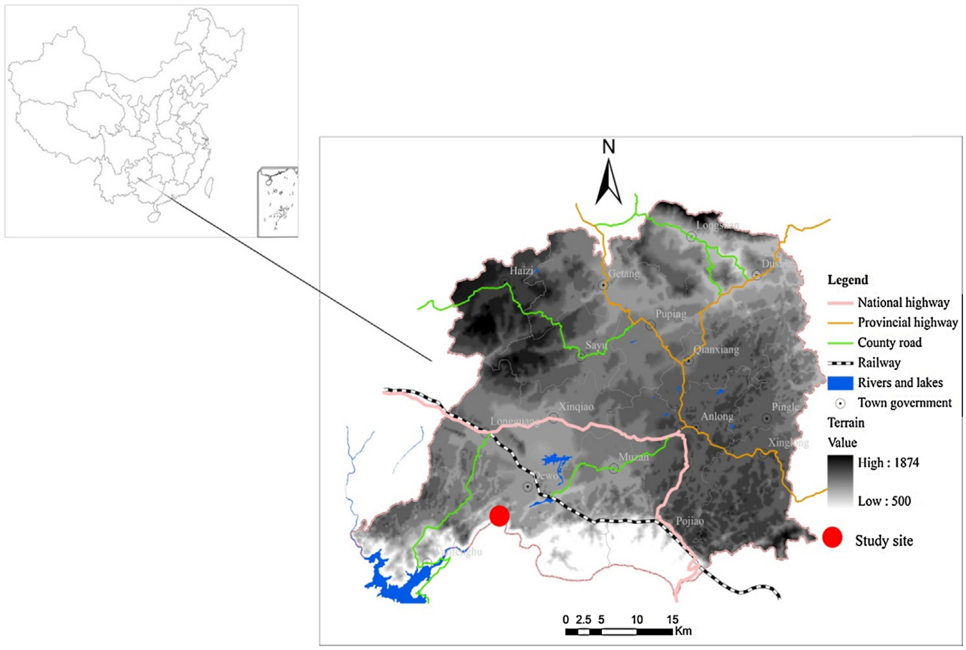

Fig. 1. Location of Hongyan SHP station in Anlong County of Guizhou Province.

values (UEVs) include the specific emergy, which is expressed in solar emJoules kg^{-1} (seJ kg^{-1}), and the emergy-to-money ratio.

By applying emergy concepts to an ecological economy as a system comprised of nature and society, in which it can be shown that energy and resource management maximizes economic vitality, society may improve its industrial efficacy, innovate with less trial and error, and adapt to environmental and social changes more rapidly. Emergy analysis has been effectively used to evaluate several dam and hydropower projects (Brown, 1986; Brown and McClanahan, 1996; Kang and Park, 2002; Yang et al., 2012). The rapid development of SHP plants in China highlights the need for a more objective and comprehensive approach to quantify their impacts on the environment and society with regard to long-term sustainable development.

This study presents an emergy assessment of a SHP plant in southwestern Guizhou Province in China. The main objectives of this paper are as follows: (1) to measure the environmental sustainability of a SHP system and to compare it with large hydroelectric dams, (2) to calculate the fair price of hydroelectricity from SHP plants in terms of ecological energy balance, and (3) to explore the sensitivity of the environmental performance of SHP plants to the inherent defect of an unstable operation due to seasonal variations in water flow.

2. Location and study site

As mentioned previously, China's SHP plants are primarily located in the remote central and western mountainous areas, particularly in the Yunnan, Sichuan, and Guizhou provinces. The case project, which involves the Hongyan SHP plant, is located in Anlong County in southwestern Guizhou Province (N24°59′44.52″, E105°11′55.68″), as shown in Fig. 1. This area is situated in the subtropical monsoon climate region, which is characterized by uneven intra-annual and inter-annual rainfall distributions (Fig. 2). The average precipitation in Anlong County is 1084.0 mm, of which about 2/3 occurs between May and October. Therefore, Anlong County possesses abundant rural hydropower resources and a long history of SHP development. In this remote county in China, approximately 20 SHP plants have been constructed; all are currently in operation.

The Hongyan SHP plant was built in 2003 and is a diversion-type plant, with no dam or water-storage reservoir. The water source for electricity generation is channeled from the Dewo River, which also provides water to nearby agricultural irrigation systems as needed. Water is diverted from the river through an intake structure in a man-made weir. A continuous flow of water passes through the man-made smooth channel to stabilize the water level before it reaches the forebay. In the forebay, suspended particles, such as stones, wood, or man-made litter can be settled out to prevent damage to the turbine; subsequently, water is distributed to the pressure pipe. Through the pressure pipe, the water descends to the turbine (a Pelton turbine). The hydro-turbine converts the gravitational potential energy of water into mechanical energy, which drives the electricity generator. All diverted water returns to the river below the power house, and the power is connected to the grid after voltage transformation.

Although the average flow rate is only 2.06 m^3/s, the water head is significantly high with a maximum height of 496 m (Table 1). The plant is equipped with 2 hydro-turbine generating units; each has a rated capacity of 4 MW with a total installed capacity of 8 MW. Unlike large hydroelectric plants, SHP plants typically suffer

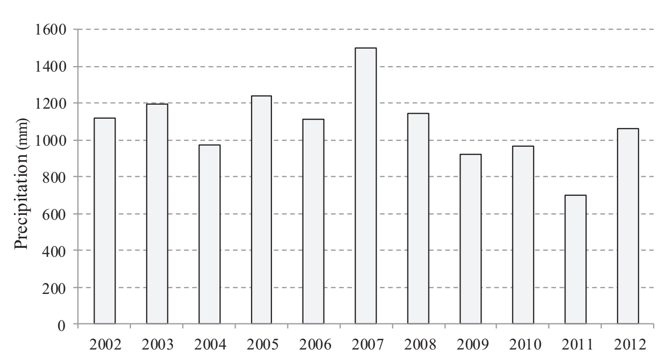

Fig. 2. Annual variation of rainfall in Anlong County of Guizhou Province.