Journal of Cleaner Production xxx (2013) 1–8

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Embodied carbon budget accounting system for calculating carbon footprint of large hydropower project

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A R T I C L E I N F O

Article history:
Received 10 July 2013
Received in revised form
26 October 2013
Accepted 28 October 2013
Available online xxx

Keywords:
Carbon-related behavior
Embodied carbon
Large hydropower project
Tibet

A B S T R A C T

Large hydropower project (LHP) is now the most important renewable and low-carbon source for electricity generation, carbon footprint calculation is crucial for it. We established an embodied carbon budget accounting system for LHP to calculate its actual carbon footprint. In additional to traditional carbon emission from plant construction, the accounting system included two new items in the carbon footprint of a hydropower project: carbon reductions due to the provision of extra services, and carbon emissions due to the decrease in adjacent ecosystem services. We classified these three items into main products and by-products for LHP in its lifecycle, formed a carbon footprint inventory, then quantified the direct and indirect emissions and reductions embodied in these products. This approach leads to a relatively complete carbon footprint assessment. According to this approach, embodied carbon emissions and reductions for the Zhikong hydropower project (Tibet, China) were 3.98×10^{12} and 6.89×10^{9} g CO_2 equivalents (CO_2-e), respectively. Therefore, the total carbon footprint is 3.97×10^{12} g CO_2-e, equivalent to a carbon emission intensity of 195 g CO_2-e kWh^{-1}. This is 111.17% higher than the traditional carbon footprint for this project. The results indicate that the low-carbon status of LHP may be overestimated at present, and could help in preventing the blind enthusiasm on LHP in low-carbon energy choice.

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1. Introduction

A carbon footprint is defined as the sum of greenhouse gas (GHG) emissions caused by an organization, event, or product and is expressed in terms of CO_2 equivalents (CO_2-e) (Chakraborty and Roy, 2013). Transition to low-carbon energy is often an efficient approach to reduce the carbon footprint of products, organizations, and cities (Dong et al., 2013; Perry et al., 2008; Vázquez-Rowe et al., 2012; Wang et al., 2011). Hydropower is widely recognized as low-carbon energy because direct consumption of fossil fuel is not involved in this form of power generation (Cheng et al., 2012; Hondo, 2005; Kosnik, 2008), and thus carbon mitigation often plays an important role in licensing of LHP (Madani, 2011). In the context of mitigating climate change, LHP plays an increasingly important role in meeting global low-carbon energy demands (Frey and Linke, 2002). More than 17% of the world electricity is supplied by hydropower, mainly generated by LHP (Yüksel, 2007). However, the present method for calculating the carbon footprint of LHP is not satisfactory.

The boundaries for estimating the carbon footprint of a product or enterprise include three scopes (on-site direct emission, on-site indirect emission and off-site indirect emission) and four classes for GHG activity, which include energy consumption, material production, service provision and land appropriation (Table 1). If a product involves one or more of the four activity classes, then it has carbon-related behavior. Products include both goods and services.

Hydropower plants generate electricity without direct fuel combustion or indirect energy consumption. Therefore, their carbon footprint is usually calculated according to indirect emissions from the supply chain, mainly CO_2-e emissions due to material and energy consumption during plant construction (Pascale et al., 2011). This traditional approach only considers hydroelectricity production, which limits the carbon footprint to GHG activity classes (1) and (2). However, in addition to the main product of hydroelectricity, there are other products and by-products involved in LHP that fall into GHG activity classes (3) and (4).

Dams are constructed to form artificial reservoirs for hydropower. Together with electricity generation, new reservoirs increase services in terms of water regulation, flood control, and shipping facilitation (Yüksel, 2010), all are main products for LHP. However, dam construction also causes environmental pollution and soil erosion, blocks sediment transportation, floods vegetation,

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0959-6526/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jclepro.2013.10.060

Please cite this article in press as: Zhang, J., Xu, L., Embodied carbon budget accounting system for calculating carbon footprint of large hydropower project, Journal of Cleaner Production (2013), http://dx.doi.org/10.1016/j.jclepro.2013.10.060

Table 1
Classification of GHG emission scope and activity.

Item	Classification	
GHG emission scope[a]	On-site	Direct emissions from combustion or another process
		Indirect emissions from electricity, heat and steam consumption
	Off-site	Other indirect emissions upstream and downstream of the supply chain
GHG activity[b]	(1) Energy, fuel, and electricity consumption	
	(2) Material production	
	(3) Service provision	
	(4) Land appropriation	

[a] Adapted from Huang et al. (2009) and Matthews et al. (2008).
[b] Adapted from ISO (2006) and Scipioni et al. (2012).

and destroys habitats around the reservoir (Klaver et al., 2007; Kummu and Varis, 2007). This can have negative issues on aquatic biodiversity and riparian vegetation and can lead to wetland shrinkage downstream (Asaeda and Rashid, 2012; Franssen et al., 2007; Gordon and Meentemeyer, 2006; Manyari and de Carvalho Jr., 2007; Tomsic et al., 2007; Zhou et al., 2009). All of these negative issues are by-products of LHP. Although negative downstream issues can be reduced or may be acceptable if environmental flow requirements are met, they still affect adjacent ecosystem services in the vicinity of the reservoir, such as environmental decontamination, soil conservation, water regulation, and habitat support.

These main products and by-products are all carbon-related and the corresponding embodied CO_2-e data can be transformed when using appropriate methods. The aim of this study was to establish a carbon budget accounting system for LHP by quantifying carbon embodied in its main products and by-products. We then applied this accounting system to the Zhikong hydropower project in Tibet in China to calculate its actual carbon footprint. The results have implications for hydropower planning and regional low-carbon strategies.

2. Methodology

By embodied carbon we mean carbon-related behaviors for the whole hydropower supply chain, which includes upstream hydropower plant construction, on-site hydroelectricity production, and downstream hydroelectricity transmission (Fig. 1). As downstream hydroelectricity transmission is very similar to that for other power generation systems, carbon footprint differences for power systems lie in upstream and on-site activities. To avoid double accounting of GHG emissions, we calculated the carbon footprint on the basis of on-site main products and by-products production.

2.1. Carbon budget inventory

We established a carbon budget inventory for a typical LHP (Table 2), considering both main products and by-products, and carbon-related behaviors explained how these corresponding products cause carbon emission or carbon reduction.

The main products include water regulation, flood control, shipping facilitation, microclimate regulation, and hydroelectricity production. A dam and powerhouse has to be constructed for hydroelectricity production. Dam construction creates an artificial reservoir that floods vegetation. Therefore, the construction processes and the decay of flooded vegetation were considered as GHG emission sources in the budget. LHP provides four main products in addition to hydroelectricity without any extra input, so these can be considered as extra services. According to the shadow product approach, these extra services could offset shadow project construction, and then the reduced shadow projects amount can thus be viewed as carbon reductions.

The by-products for LHP include soil erosion, environmental pollution, destruction of fish and human habitats, reservoir sedimentation, and land appropriation. Plant construction and reservoir filling change the original farmland, grassland, woodland and unused land into building land and water areas, so land appropriation decreases the net ecosystem productivity (NEP) at the reservoir. This NEP decrease corresponds to carbon emission. According to the project restoration method, the other four by-products namely soil erosion, environmental pollution, destruction of fish and human habitats, reservoir sedimentation, can be viewed as increases in investment for corresponding restoration projects, and then the increased restoration projects amount can be transformed into carbon emissions.

2.2. Carbon emission transformation

As most carbon emission inventories are embodied off-site indirect emission (Table 2), we transformed these embodied carbon emission into actual CO_2-e emission separately for different inventory.

2.2.1. Hydroelectricity production

Hydropower plant construction is the main emission source for hydroelectricity production. Although there is no direct fuel combustion during power generation, the decay of flooded vegetation is another direct on-site emission source.

We used a specific input–output model to calculate GHG emissions for hydropower plant construction, the 2002 Chinese Economic Input–Output Life Cycle Assessment (EIO-LCA) method developed at Carnegie Mellon University (Hendrickson et al., 2006). The EIO-LCA model has been used to calculate CO_2-e emissions for hydropower projects in India and foreign trade in China (Prakash and Bhat, 2012; Yan and Yang, 2010). For hydropower the input is the producer price and the output is CO_2-e emissions. The producer price can be divided into the civil works price (dam, division tunnel and plant building) and the electromechanical equipment price, for which the industry sectors for carbon emission transformation are listed in Table 3. We summed up the carbon emission of civil works and carbon emission of electromechanical equipment to get the total emission for hydropower plant construction. For more accurate results, we changed the producer price in the target year (initial input) to the corresponding producer price in 2002 (final input) and the CO_2-e emissions obtained in 2002 (initial output) to the CO_2-e emissions in the target year (final output). This transformation model can be described as follows:

$$P_{2002} = P_n \times \frac{\mathrm{PPI}_{2002}}{\mathrm{PPI}_n} \tag{1}$$

$$E_n = E_{2002} \times \frac{I_n}{I_{2002}} \tag{2}$$

where P_{2002} is the constant price based on 2002, P_n is the price in year n, PPI_n is the producer price index in year n based on PPI_{2002}, and E_n and E_{2002} are the CO_2-e emission and I_n and I_{2002} are the CO_2-e emission intensity in year n and 2002, respectively.

Flooded vegetation emits CO_2-e on decaying for which the intensity depends on the local geography and climate (Demarty and Bastien, 2011; Liu et al., 2011; Wang et al., 2011). It is almost impossible to determine this reservoir carbon emission intensity precisely in the absence of long-term field measurements.

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