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Water-carbon nexus of hydropower: The case of a large hydropower plant in Tibet, China

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ABSTRACT

Under the increasing crisis of a worldwide watershed water shortage and the pressing carbon emission reduction requirement, making clear the water-carbon nexus of hydropower plants will help co-resolve the contradiction in a significant water-carbon related issue. Simulating the water-carbon nexus of a biomass energy plant, this study calculates the water-carbon nexus of a hydropower plant, which represents the water utilization amount per unit greenhouse gas (GHG) reduction. The water utilization of a hydropower plant is composed of absolute water evaporation loss and temporary water storage loss. For the Zhikong hydropower plant in Tibet, 0.704 m^3 of water is utilized when achieves a unit kg GHG reduction, and 0.126 m^3 of water is evaporated when keeps a cubic meter of water in reservoir storage. With regards to the accumulated water-carbon nexus, a biomass energy system is more efficient in achieving a GHG reduction than the Zhikong hydropower plant in the first three years of operation, but thereafter the Zhikong hydropower plant is more efficient. The water-carbon nexus has identified a new direction for allocating watershed water resources to maximize GHG reduction potential, and also can be an indicator against which to manage watershed water resources in an efficient and sustainable way.

1. Introduction

Fossil energy has been a dominant part of the Chinese energy supply mix for decades, and this role will also continue in the future, which makes a positive driving force for the China development (Bloch et al., 2015). However, the negative energy carbon issues caused by fossil energy utilization should not be ignored.

The greenhouse gas (GHG) emission caused by fossil energy consumption is the largest man-made emission in China, fossil energy consumption in industry sector caused the main GHG emission and the related air pollution issues (Wen et al., 2014; Huo et al., 2015). Recently, the co-resolve of fossil energy saving and GHG reduction becomes a hot spot, many industry sectors are exploring the mitigation of energy-carbon related pressure (Wen et al., 2015; Tan and Wen, 2016).

Hydropower has been the largest non-fossil energy resource in China for decades (Li et al., 2015a,b). Actually, watershed hydropower development has been integrated into the Chinese “emission reduction plan” because it reduces carbon emissions when replacing the fossil fuel electricity system. The low carbon emission intensity of hydropower makes this technology one of the ideal alternatives by which to reduce GHG emission or alleviate energy-carbon issues (Zhang et al., 2015).

However, it must be noticed that hydropower also has its own water efficiency problem with the expansion of its scale, which like vegetations who fix carbon with water transpiration loss, hydropower plant contributes GHG reduction with reservoir surface evaporation loss and flow storage. That is to say, hydropower plant reduces GHG at the cost of water utilization. There is a common conflict between hydropower water usage and downstream other water usage, and watershed water allocation must takes the water efficiency into consideration (Kadigi et al., 2008).

Therefore, before concluding that hydropower is the perfect alternative for resolving the energy-carbon issues of fossil energy, the water-carbon nexus of hydropower must be determined. This study is conducted to make a systematic analysis of the water utilization process and GHG reduction process of hydropower. Based on this analysis, the water-carbon nexus for hydropower is established, which identifies the cost of water resource utilization when achieves GHG reduction, and facilitates comparisons of the water-carbon nexus among other renewable alternatives as a guide to increase the watershed water utilization efficiency when reduces GHG emission.

2. Materials and methods

2.1. Water utilization process of hydropower

Hydropower plant as an energy converter, it transfers the hydraulic

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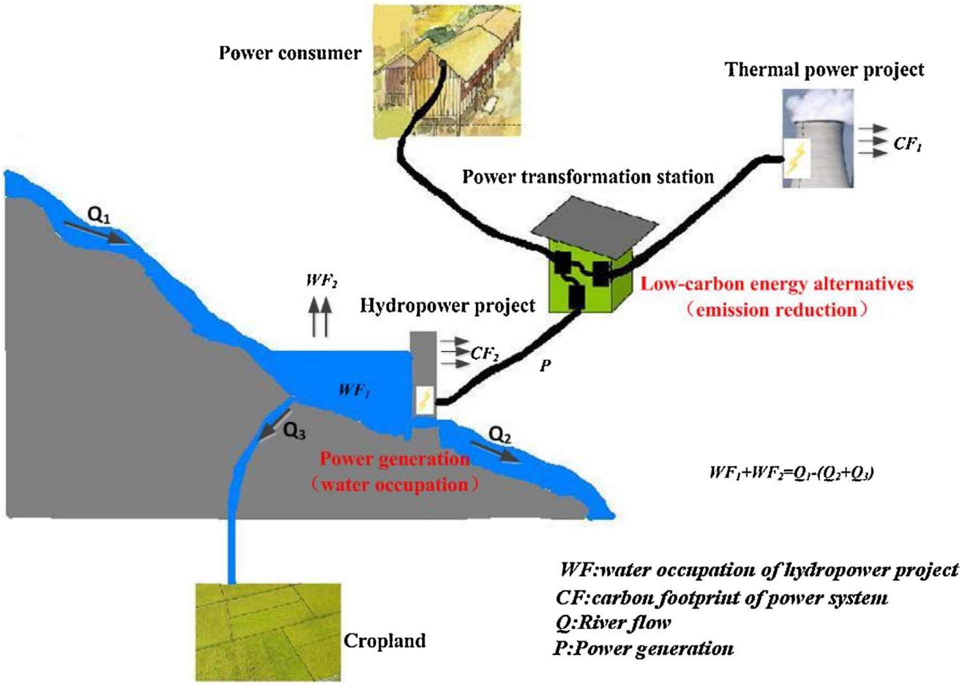

Fig. 1. Water-carbon nexus framework of a large hydropower plant.

energy into hydroelectricity, and the hydroelectricity generation process doesn't consume water directly. Moreover, the hydroelectricity generation process of a hydropower plant often depends on a dam to form the water head and a reservoir for water storage. Thus, there are two different indirect pathways through which water is utilized for a hydropower-reservoir system.

Water evaporation from a reservoir (WF_2, Fig. 1) is one of the significant water utilization pathways. For a common hydropower reservoir, as the reservoir water level increases so does the reservoir area, and the increased surface area will be matched with the increasing of water loss by evaporation (Herath et al., 2011).

Reservoir occupation (WF_1, Fig. 1) is the other un-ignorable water utilization pathway. Ecosystem protection requires that a particular downstream environment flow (Q_2, Fig. 1) must be maintained for the hydropower plant to protect the river downstream; therefore, Q_2 is the normal water resource requirement for the river itself (Fang et al., 2010; Zhang et al., 2014a,b). Though a reservoir stores water for both hydropower production and agricultural use (Q_3, Fig. 1), this water storages provided at the cost of the dramatic decline of the original Q_2, which can induce unavoidable ecological losses in the downstream river. Therefore, reservoir occupation can be seen as another indirect water utilization pathway of hydropower.

2.2. *GHG reduction process of hydropower*

A typical hydropower plant is actually a GHG emission source that embodies both direct and indirect GHG emission pathways. Directly, a hydropower reservoir creates a certain area of inundation in which the flooded biomass decays and then emits GHG (DelSontro et al., 2010). Direct reservoir GHG emission mainly appears during hydropower plant operation. A hydropower plant in a tropical region has a significant reservoir GHG emission (Demarty and Bastien, 2011). Indirectly, a large amount of materials and energy is consumed during the construction of a hydropower plant; these indirect energy consumptions all contribute to the indirect GHG emission of hydropower (Zhang and Xu, 2015). Indirect emissions mainly appear during hydropower plant construction. It is common to include these indirect emissions in the carbon footprint assessment of hydropower.

Direct and indirect emissions comprise the total GHG emission of a hydropower plant (CF_2, Fig. 1). Though a hydropower plant is a GHG emission source, the GHG emission intensity of a hydropower plant is much lower than that of thermal power plant. Because water is a renewable and alternative energy source, the GHG emission reduction appears when hydroelectricity replaces thermal electricity in the power grid.

2.3. *Water-carbon nexus model of hydropower*

Based on an analysis of the water utilization and GHG reduction process, a water-carbon nexus model of a typical hydropower plant can be calculated as the amount of water consumption per unit CO_2 reduction, which directly shows the relation between water flow and carbon flow of hydropower plant, and demonstrates the hydropower plant reduces GHG at the cost of water utilization. The model is described by the following equations.

$$WCF = \frac{WF}{(CF_1 - CF_2)P} \tag{1}$$

$$WF = WF_1 + WF_2 \tag{2}$$

$$WF_2 = \sum_{i=1}^{n} AE_i \tag{3}$$

$$P = \alpha QH\eta t/\beta \tag{4}$$

In Eqs. (1)–(4), WCF is the water-carbon nexus of a hydropower plant, $m^3\,kg^{-1}$; WF is the average annual water utilization amount of the hydropower plant, m^3; WF_1 is the reservoir occupation loss, which equals water storage capacity, m^3; WF_2 is the water evaporation loss, m^3; CF_1 is the carbon footprint of the substituted thermal power system, for which a commonly cited value of 1100 $gCO_2\,k\,Wh^{-1}$ is used (Wang et al., 2007); CF_2 is the carbon footprint of the hydropower system, $g\,CO_2\,k\,Wh^{-1}$;P is the average annual power generation of the hydropower system, kWh; A_i is the hydropower reservoir area at normal water level, m^2; E_i is the reservoir surface evaporation rate at month i, mm, where $i = 1–3…12$; α is the specific weight of water, 1000 kgm^{-3}; Q is the discharge of the hydropower plant, $m^3\,s^{-1}$; H is the water head of the hydropower plant, m; η is the energy conversion efficiency, for which a value of 0.9 is used according to published data (Kucukali,