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Carbon footprint analysis of two different types of hydropower schemes: comparing earth-rockfill dams and concrete gravity dams using hybrid life cycle assessment

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ABSTRACT

Different types of hydropower schemes utilize different construction methods and have different carbon footprints. However, differences in carbon footprints between different schemes have been largely ignored when comparing environmental impacts for decision making. Thus, this paper aims to study and compare the carbon footprints of two types of Nuozhadu hydropower schemes with the same scale: an earth-core rockfill dam (ECRD) and a concrete gravity dam (CGD). The hybrid life cycle assessment (LCA) method combines the completeness of economic input–output LCA (EIO-LCA) and the specificity of process-based LCA (PA-LCA). It was applied to quantify the carbon footprint over the whole life cycle of the hydropower system. The evaluation of the carbon footprint considered the emissions from material production, transportation, construction, and the operation and maintenance phases for a period of 44 years. All relevant materials and energy consumption were included. It was found that the ECRD reduced CO_2 emissions by approximately 24.7% compared to the CGD. With respect to each stage of the life cycle, the ECRD decreased CO_2 emissions by 46.1% for material production, 16.5% for transportation and 9.0% for operation and maintenance but increased emissions by 6.6% for construction due to the heavy workload. Operational maintenance was the greatest contributor to CO_2 emissions, followed by the production, construction and transportation stages. These results indicate that ECRDs are more environmentally responsible throughout its life cycle. This knowledge could help decision makers in the design phase looking to choose the appropriate type of hydropower system.

1. Introduction

Global climate change has become a major threat to the environment and the economic development of the world. In order to address the problem, environmental factors must be considered in a number of different types of decisions made by businesses, individuals, and public administrations and policymakers (Finnveden et al., 2009). Although they utilize renewable water resources without consuming fossil fuels, resulting in little air pollution during their operation, hydropower plants have also caused worldwide concern with regard to environmental protection issues (Zhang et al., 2007). As a consequence, environmental assessments that include the natural environment (e.g., landscape change and impacts on territorial and aquatic habitats) and social environment (e.g., population migration and settlement) are recognized as important factors for making decisions regarding hydropower projects. However, greenhouse gas (GHG) emissions are often portrayed as nonexistent and have largely been ignored in the comparison of environmental impacts between different types of hydroelectric systems (Pacca, 2007). However, life cycle assessments of some hydroelectric plants show that GHG emissions occur at all phases in a power plant's life (Steinhurst et al., 2012).

Life cycle thinking tools, in particular the carbon footprint (CF) related to the quantification of life cycle impact indicators for the global warming midpoint category, are becoming popular for assessing the GHG emissions associated with goods and services (Rugani et al., 2013; El Hanandeh, 2013). ISO.DIN 2 14067 (International Organization for Standardization, 2012) defines PCF (a product's actual carbon footprint) as the sum of GHG emissions and removals in a product system, expressed as the carbon dioxide

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equivalent (CO_2e) and based on a life cycle assessment. CF could be a valid parameter for comparing the impact of different products (Weidema et al., 2008).

The environmental performance of hydroelectric projects has been investigated using life cycle thinking tools. Several studies have focused on GHG emissions from biomass decay in reservoirs (Coltro et al., 2003; Pacca, 2003; Kim and Dale, 2005). Other research has claimed that GHG emissions due to dam decommissioning are notable (Pacca, 2007). With respect to the project scale, carbon emissions over the life cycle of small hydroelectric plants have received much attention (Pascale et al., 2011; Suwanit and Gheewala, 2011; Prakash and Bhat, 2012), while larger hydropower projects have performed better than smaller ones in terms of energy efficiency and GHG emissions (Zhang et al., 2007). Furthermore, different construction methods for concrete dams have different environmental impacts (Liu et al., 2013). However, research to date only relates to the concrete dam body and innovative dam construction methods. Few studies have been performed to study the environmental impacts of other construction methods, including the earth and rockfill dam, which is the most common dam type. It is necessary to extend the scope of study to the whole hydropower system and more common dam types, which is of great practical significance.

The objective of this paper is to estimate, with the aid of a hybrid LCA method, the CF over a dam's lifetime and to compare the global warming potential of two different types of large hydropower schemes: the ECRD and CGD systems of the Nuozhadu project. The hybrid LCA model combines the completeness of environmental input–output LCA (EIO-LCA) and the specificity of process-based LCA (PA-LCA). It is used to quantify the CF of the whole system. In this research, all relevant materials and equipment are considered. In addition, the energy consumption of all of the structures is considered throughout the life cycle, including material production, transportation, construction and operation. The results of this analysis could provide valuable information for decision makers in order to select more environmentally responsible types of hydropower systems.

2. Differences between ECRDs and CGDs

High dams have been and continue to be constructed on rivers around the world to respond to the increasing demand for clean energy and water in developing countries. From the statistics of the International Commission on Large Dams (ICOLD) in 1995, rockfill dams constituted over 33% of the large dams (higher than 150 m) under construction in the world. ECRDs are a type of rockfill dam designed to optimize the use of available natural materials by placing them in the best zones of the dam body. ECRDs are very common and constitute one of the most frequent solutions in the domain of rockfill dams (das Neves, 1991). The percentage of CGDs higher than 150 m under construction in 1995 was approximately 24%, followed by earth dams, buttress dams and arch dams, each at 14%. The figures have certainly changed from when these studies were performed; however, ECRDs and CGDs are still two common choices when a new high dam is built due to their strong adaptability to the topography and geological conditions as well as their mature construction technology.

There are significant differences in the layout, cross-section, materials, and construction technologies between ECRDs and CGDs. Embankment dams are constructed of either earth fill or a combination of earth and rock fill. An ECRD is zoned with central impervious soil materials for the core wall flanked by pervious shells. The cross-section is generally trapezoidal. The majority of materials used in ECRDs are locally sourced, including clay, sand, gravels, pebbles, block stones and decayed rocks. The key links in ECRD construction are the layered and zoned filling and rolling of earth and rock materials. It is necessary to construct a spillway on a side of the dam body that cannot overflow as well as a water diversion and power generation system. This type of dam does not use many high-emission building materials such as steel, cement and timber. Furthermore, it reduces long-distance transport; however, a disadvantage is the high degree of engineering required.

Gravity dams depend entirely on their own weight to resist the tremendous force of stored water. The cross-section of a gravity dam is triangular. The most heavily consumed construction material in CGDs is concrete, in which cement is an important component. The production of cement is an energy-intensive process during which large amounts of CO_2 are emitted. Constructing concrete formwork, placing concrete, compacting concrete, and curing concrete are the main construction processes. Spillway and inlet structures are located on the dam body in order to produce a compact layout. The amount of engineering required for a CGD is less than that of an ECRD with the same scale. However, CGDs require a large number of high-emission building materials that require long-distance transport.

3. Methodology

3.1. Project description

Nuozhadu Power Station in China, the largest in Asia and the third largest in the world, is used as a case study. In order to make the two different schemes comparable, ECRD and CGD systems were designed separately for the same 5850 MW plant in the planning phase. The ECRD system was composed of a clay-core rockfill dam with a 258 m height, an open crest spillway, spillway tunnels, bank protection, water diversion and power generation system and diversion construction. The CGD system was composed of a concrete gravity dam with a 265 m height, plunge pool and subsidiary dam, bank protection, water diversion and power generation system and diversion construction. Construction of the Nuozhadu Power Station began in 2004, and it is scheduled to be completed around 2017. However, no studies have been performed on the comparative analysis of the CFs between these two schemes. Fortunately, reliable and detailed data have been obtained through personal contacts with the design institute, HydroChina Kunming Engineering Corporation. Although these reports and data are nominally confidential, it is of significant importance to analyze the CFs of the two contrasting schemes. In this study, the analysis covers a period of 44 years, including 14 years for the construction phase (including a 3-year period to begin production) and 30 years for the production phase. Therefore, the operation period is 33 years.

3.2. Carbon footprint analysis method

CF arises as a potential parameter for decision making in companies due to the use of a life cycle approach and its popularity, even though it provides a limited view of environmental performance because global warming is the only impact category assessed (Iribarren et al., 2010). The task of calculating CF can be approached methodologically from two different directions: bottom-up, based on PA-LCA, or top-down, based on EIO-LCA (Wiedmann and Minx, 2007). PA-LCA is a tool for evaluating the environmental impacts of a product through its entire lifespan, usually from raw material extraction to final disposal (Zhang et al., 2007). This approach suffers from 'truncation error,' which arises from the inevitable omission of steps and processes to make the task manageable. This can lead to a serious underestimation of the total in most situations (Nässén et al., 2007; Facanha and Horvath,

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