Journal of Cleaner Production 19 (2011) 1582–1589

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

The water footprint of hydroelectricity: a methodological comparison from a case study in New Zealand

Indika Herath [a,b,*], Markus Deurer [a,c], David Horne [b], Ranvir Singh [b], Brent Clothier [a,c]

[a] The New Zealand Institute for Plant & Food Research Limited, PB 11-600, Palmerston North 4442, New Zealand
[b] Institute of Natural Resources, Massey University, Private Bag 11222, Palmerston North 4442, New Zealand
[c] New Zealand Life Cycle Management Centre, Massey University, PB 11222, Palmerston North 4442, New Zealand

ARTICLE INFO

Article history:
Received 16 December 2010
Received in revised form
13 May 2011
Accepted 13 May 2011
Available online 25 May 2011

Keywords:
Water-energy nexus
Hydropower
Hydroelectric dams
Renewable energy
Virtual water
Ecosystem services
Hydrology

ABSTRACT

Hydroelectricity has been rated to have a large water footprint (WF) on global average. We assessed the WF of hydroelectricity by three different methods using New Zealand as a case study. The first (WF-1) and second (WF-2) methods only consider the consumptive water use of the hydroelectricity generation system, while our third method (WF-3) accounts for the net water balance. Irrespective of the method, the WF of New Zealand's hydroelectricity was found much smaller than the commonly cited international value of 22 m^3 GJ^{-1}. Depending on the method, the national WF ranged from 1.55 m^3 GJ^{-1} (WF-3) to 6.05 m^3 GJ^{-1} (WF-1). The WF- 3 considers the net water balance including rainfall, which is the key driver for replenishing water resources. It provides meaningful information that helps our understanding of the differences of the WF in locations, which are diverse in terms of water resource availability. We highlight the effects of local climatic differences and the structural specifics of a hydroelectricity scheme on the WF. The large variation in the WF of hydropower across New Zealand illustrates the inappropriateness of using global average values. Local values, calculated using our hydrologically rational method, must be used.

1. Introduction

Water and energy are two critical necessities for modern civilizations. Freshwater is one of the planet's most valuable resources, being an essential life-sustaining element that cannot be substituted for (Koehler, 2008). At the same time, freshwater is increasingly becoming a scarce resource. Across the globe, there are ominous hydrological signs, such as ground water depletion, lowering of river flows, and the deterioration of water quality. This indicates that current levels of water use exceed sustainable limits in many parts of the world (Postel, 2000). Furthermore, companies which produce water-intensive products and services around the world are facing significant water-related risks (Lambooy, 2011). Energy is considered to be the life-blood of technology and development (Khan and Hanjra, 2009). As the world's population grows, the demand for both freshwater and energy is increasing faster than ever. Competition for freshwater and energy will become one of the defining issues of this century (IEEE, 2010). According to Beddington (2009), by 2030 we will need to be producing 50% more food. At the same time, we will need 50% more energy, and 30% more freshwater (Beddington, 2009). The challenge is to meet these additional food, energy and freshwater demands in a way that does not affect natural capital stocks and the ecosystem services that flow from them.

Energy and freshwater resources are intricately and intimately connected. Energy is required to operate modern water-supply systems and purification facilities. Without the input of substantial amounts of energy, shifting large quantities of water from water-rich to water-poor regions, desalinization of brackish or seawater, and the pumping of ground water aquifers and surface water for irrigation would all be impossible (Gleick, 1994). On the other hand, the production and use of energy often requires significant quantities of water. In almost every type of power plant, water is a major hidden input. Water cools the hot steam of thermal plants, and it turns the hydroelectric turbines. It is a vital ingredient in biofuel crops, and brings geothermal energy as steam from the depths of the earth (IEEE, 2010). With increasing frequency, we will need to assess energy production with reference to water protection, whilst also considering our urgent need to reduce greenhouse gas emissions.

Environmental footprints have been widely used in recent years as indicators of resource consumption and waste creation

* Corresponding author. The New Zealand Institute for Plant & Food Research Limited, PB 11-600, Palmerston North 4442, New Zealand. Tel.: +64 69537690.
E-mail address: I.K.Herath@massey.ac.nz (I. Herath).

0959-6526/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jclepro.2011.05.007

(Hammond, 2006), or in other words, they provide measures of the impacts of human activity on the environment. The water footprint has attracted interest as a metric that indicates the use of freshwater resources and its impacts. In the current methodology, the water footprint is defined as the volume of freshwater used directly, or indirectly, in the production of a good or service (Hoekstra and Chapagain, 2007). The term 'used' considers two facets: the water consumed (evaporated) and the water polluted throughout the production.

Among different sources of energy, hydropower is very attractive because of its low CO_2 emissions (Herpaasen et al., 2001), and its renewable nature. Sims (2004) has shown that hydropower can save 229 g C/kWh (63.61 kg C/GJ) carbon emissions compared with a conventional coal-fired power. But hydropower has been claimed that has a large water footprint per unit energy, relative to other sources of energy (Gerbens-Leenes et al., 2009). However, there has not been a detailed systematic assessment of the water footprint of hydroelectricity to substantiate this claim.

In New Zealand, the major portion of electricity is generated by hydropower (Fig. 1, left), which has been the mainstay of New Zealand's energy system for over 100 years. In 2009, 57% of total energy generation in New Zealand (Fig. 1 right) was from hydroelectricity (EDF, 2010). The current recommendation is to include the water footprint of energy in the assessment of the total water footprint of products and services if they are sourced from biofuel, or hydropower (Hoekstra et al., 2009). For accurate water footprint assessments of many of New Zealand products and services, accounting for the water footprint of hydropower is very important. As many of New Zealand's export products are marketed using a 'clean green' image, the water footprint of hydroelectricity will have ramifications for the competitive advantage of New Zealand's export products.

The objectives of this study were threefold. Firstly, we aimed to assess the impact of hydroelectricity generation on water resources by using a water footprint concept considering New Zealand as a case study. In addition to the water footprint assessment based on consumptive water use (WF-1 and WF-2), we attempted to develop a hydrologically rational water footprint assessment for hydroelectricity generation (WF-3). Secondly, we sought to quantify the influences of regional climatic conditions and structural variables (e.g. reservoir surface area) on the WF of hydroelectricity. Thirdly, we attempted to estimate the WF of a unit of New Zealand hydroelectricity as delivered to the national grid and compare this with reported values.

2. Methodology

2.1. Description of New Zealand hydroelectric power plants

In this study, all major hydroelectric power plants in New Zealand (Fig. 2) were considered. These power plants account for more than 95% of hydropower generated in the country (EDF, 2010). Fig. 2 shows the geographical locations of the plants. The hydropower stations in the North Island are clustered together in the central part of the island, while the plants in the South Island are more widely scattered.

2.2. Three methods to quantify the water footprint of hydroelectricity

The science of water footprinting is still in its infancy, and methodologies are still being developed and revised. There is no well-documented and accepted methodology yet to quantify the WF of hydroelectricity. In this study, we considered three different methods to assess and discuss the water footprint of hydroelectricity.

2.2.1. WF-1: consumptive water use

In the first method, we follow the definition of the water footprint given by Hoekstra and Chapagain (2007). This essentially accounts for the water consumed in the process under consideration. For hydropower generation, the water footprint (WF-1) (m^3/GJ) can be calculated as the evaporative water loss from the surface of the reservoir divided by the energy produced by that hydropower plant,

$$WF\text{-}1 = E_0/P$$

Here, E_0 is the annual open-water evaporative loss from the reservoir (m^3) and P is the annual energy production of the power plant (GJ). This definition has been used by Gerbens-Leenes et al. (2009) to estimate the WF of hydropower on a global average basis.

2.2.2. WF-2: net consumptive use

The second approach also considers consumptive water use, but it compares the consequences of land use changes created by the dam. Building of a dam results in the replacement of vegetation by a free-water surface (Fig. 3). Thus, evapotranspiration from the vegetation is replaced by open-water evaporation from the reservoir. Taking this into account, the WF-2 (m^3/GJ) considers the net evaporative water loss from the area occupied by the reservoir,

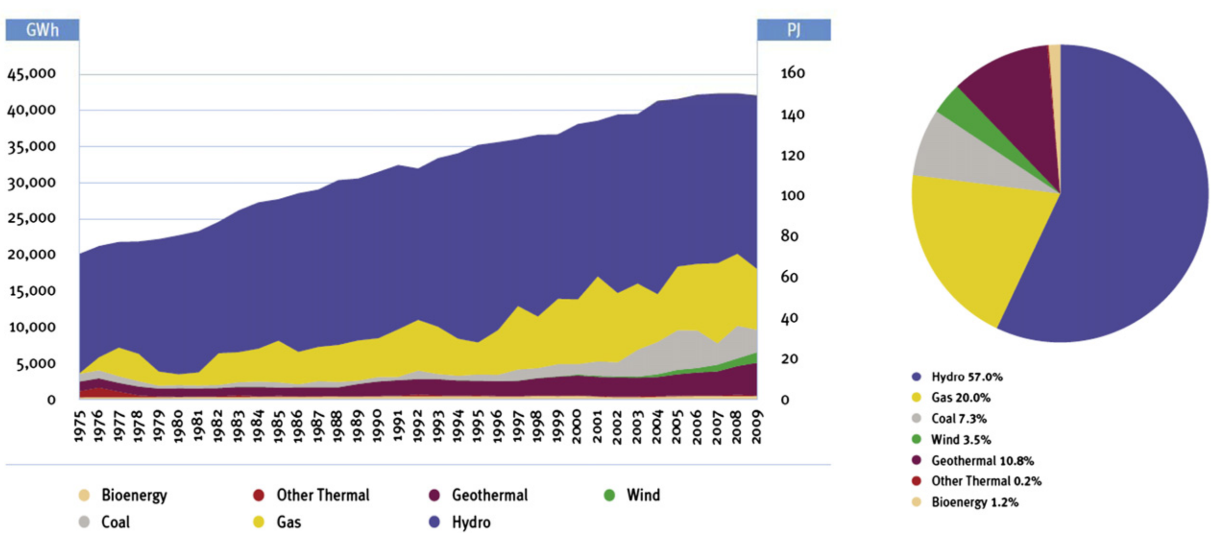

Fig. 1. New Zealand's electricity generation by fuel type: for the past 34 years (left) and for 2009 (right).