Renewable Energy 99 (2016) 711–720

Contents lists available at ScienceDirect

Renewable Energy

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

Global water footprint assessment of hydropower

Laura Scherer*, Stephan Pfister

Institute of Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 13 September 2015
Received in revised form
31 May 2016
Accepted 11 July 2016

Keywords:
Renewable energy
Water scarcity
Environmental flow requirements
Life cycle assessment

ABSTRACT

Hydropower is an important renewable energy source, but it can consume a lot of water due to evaporation from the reservoir surface, which may contribute to water scarcity. Previous studies mostly used a gross evaporation approach for water footprint assessment where all the evaporation is attributed to hydropower. They fail to consider both evapotranspiration before the dam construction, which should be deducted from the footprint, and the seasonal storage dynamics of water. These considerations are critical for assessing reservoir impacts on water scarcity using temporally explicit water stress indices. This study seeks to fill this gap: we calculate the water footprints of ~1500 hydropower plants which cover 43% of the global annual hydroelectricity generation. Apart from reduced water availability, alterations of the flow regime can also adversely affect ecosystems. Therefore, environmental flow requirements are also analysed.

This novel approach for the water footprint assessment of hydropower indicates that previous studies mostly overrated the impacts of hydropower on water scarcity, often because reservoirs store water in periods of low scarcity and release water during months of high water scarcity. By contrast, flow alterations generally affect the environment more than water consumption. Since impacts vary broadly among plants, plant-specific evaluations are necessary.

1. Introduction

Electricity generation, the greatest share of which is produced by combusting fossil fuels [1], constitutes the single largest anthropogenic greenhouse gas emissions source. Considering the global challenges we face with regard to climate change as well as the depleting stocks of fossil fuels, it is evident that we need a shift to clean and renewable energy [1,2]. Hydropower is currently the largest source of renewable electricity. While it only provided 2.4% of the world's primary energy in 2012, it generated 16.2% of the global electricity. China, Brazil, Canada and the United States alone already produce more than 50% of this electricity [3]. In Europe, 75% of the feasible capacity is already exploited, but there is great potential for growth, especially in Asia and Africa [1]. Worldwide, it is estimated that the capacity could still triple [1,4] or even quadruple [5,6]; however, the construction of new dams has slowed down due to the controversy associated with them regarding socio-economic and environmental impacts [2].

Hydropower has been identified as the most sustainable renewable energy after wind power [7]. It entails both many benefits and many drawbacks for people as well as the environment. On the one hand, it is renewable, as it uses the energy of flowing water without depleting it, and it supports other renewables by its operational flexibility. Since other renewables such as wind and solar energy are highly intermittent and often unpredictable, they require back-up technologies to fill gaps and hydropower very much suits this purpose. At the same time, hydropower is able to respond rapidly to changing loads and meet peak demands, thereby ensuring electric grid reliability [2,4,5]. It also has one of the highest energy conversion efficiencies at about 90% [2,5]. Furthermore, it is cost-efficient, contributes to social and economic development, emits very few greenhouse gases and other air pollutants, and the reservoirs of hydropower plants provide additional beneficial services such as freshwater storage, flood control, navigation services and recreational facilities [4,5].

On the other hand, hydropower might cause severe social and environmental impacts. By the year 2000, 40–80 million people were relocated due to dam constructions [8]. Many large hydroelectric dams have been built since then, including the Three Gorges dam for which alone over 1 million people were displaced [9]. Such resettlements can lead to social disruptions, especially if indigenous people with traditional social structures are affected

* Corresponding author.
E-mail address: scherer@ifu.baug.ethz.ch (L. Scherer).

http://dx.doi.org/10.1016/j.renene.2016.07.021

[10], whose livelihoods can rarely be restored [8,10]. In the Three Gorges area, for example, fertile farmlands were submerged and numerous factories were closed, which resulted in declines in income and increased unemployment [9]. The livelihoods of downstream dwellers were also adversely affected, especially those dependent on natural floodplain functions and fisheries [8]. On top of that, many of the displaced people were not compensated and for those who were, the remuneration was often insufficient [8].

Environmental impacts from hydropower are also diverse and complex [11] and the growing literature on the topic reveal an increasing concern about the affected ecosystems, in particular the aquatic ones [12,13]. While the total greenhouse gas emissions of hydropower are minor in comparison to the total anthropogenic emissions [14], in extreme cases emissions per unit electricity generated can be as high as for thermal power plants [11,15]. The reservoirs of hydropower plants also require large land areas [2,16], whose impact can be significant, since terrestrial habitat destruction is the main driver for biodiversity loss [17]. In addition, dams might change water quality [18] with consequent impacts on aquatic biodiversity [19,20]. Possible quality alterations caused by hydropower include changes in suspended sediments [21], dissolved oxygen, pH, organic carbon, nutrients [18,19] and the thermal regime [20]. The alteration of flow regimes [22] and the river fragmentation by dams [23] also lead to biodiversity loss, as a dynamic flow regime is essential to provide diverse ecological functions critical at different life periods of aquatic species [24] and their migration is obstructed by the dam [23].

The most serious damages of hydroelectricity on the environment are caused by water consumption [25]. The operational water consumption by far exceeds that of most other electricity generating technologies [26,27]. The only exception is bioelectricity, which has a lower water consumption, but still in the same order of magnitude [27]. The water consumption of hydropower is caused by evaporation from the reservoir lake, which varies greatly depending on the surface area and local climate [28]. Several studies have attempted to estimate global ranges and averages of hydropower water consumption mostly by applying a simplified approach of dividing the gross evaporation by the annual power production. Sathaye et al. provided a range of 0–58 m^3/GJ based on US plants only [26], whereas Mekonnen et al. provided a range of 0.3–850 m^3/GJ [27]. Mekonnen et al. used the GLWD database, which comprises a few hundred hydroelectric reservoirs [29]. They divided the total actual evaporation of an incomplete set of reservoirs within a country by the national hydroelectricity generation [27]. Global estimates of water consumption per unit of generated electricity also vary a lot. Mekonnen and Hoekstra determined the locally specific water consumption for 35 globally distributed plants with an average of 68 m^3/GJ [28]. Gerbens-Leenes et al. divided literature values of global evaporation from artificial surface water reservoirs by the global hydroelectricity generation, which resulted in a value of 22 m^3/GJ [30]. Pfister et al. performed linear regressions of known net water consumption of US power plants with potential evapotranspiration and aridity which yielded an average of 7 m^3/GJ [25]. A case study in New Zealand demonstrated the deviations in estimates when applying different methods including a gross evaporation approach, a net evaporation approach and a simple water balance approach [31]. All these studies are based on annual data, while a recent review identified temporal dynamics as the most important aspect to include in an enhanced impact assessment of hydropower [32].

This study aims at improving the methodology to quantify water consumption of hydropower and at translating it to water footprints. Water footprints evaluate the impacts that water consumption of a product (here: hydropower) has on water resources throughout its life cycle [33]. Since the water consumption of hydropower infrastructure is marginal [25], it is only analysed for the operational phase. With ~1500 plants, this work is based on a much larger sample than all previous studies and takes into account net evaporation, allocation between multiple reservoir purposes, monthly water balances, and water stress. Water stress can refer to water scarcity which is typically based on the consumption-to-availability ratio [34] and relates anthropogenic water requirements to water availability, or it can refer to environmental water stress by not meeting environmental flow requirements. Like temporal storage dynamics, the consideration of monthly and environmental water stress is a novel aspect for sustainability assessments of hydropower and allows the quantification of the additional environmental impact of flow regime change on top of water consumption.

2. Methodology

2.1. Data on hydropower plants

The characteristics of the reservoirs and dams of hydropower plants (HPPs) were obtained from the Global Reservoir and Dam (GRanD) Database [35]. It includes information on the dam location, reservoir surface area and primary and secondary purposes of the reservoir. The annual electricity generation (AEG) of each HPP was provided by the CARMA database [36] on all types of power plants for the years 2004 and 2009. The coordinates of the plants in the CARMA database entail high uncertainties so an automatic spatial matching of the two databases was not feasible. Instead, the databases were matched manually considering the locations, the names, the lack of greenhouse gas emissions and online searches for alternative names. This resulted in 1473 HPPs that could be matched and analysed in this study (Fig. 1). They are distributed over 108 countries and, with more than 1500 TWh in 2009, cover ~43% of global hydroelectricity. The values of AEG range from 76 MWh to 92 TWh per HPP. Ten HPPs were selected for demonstrating the results and their major characteristics are compiled in Table 1. They include the HPPs with the highest AEG in each continent and the HPPs with the largest reservoir surface area (Davis Bor), the highest dam (Nurek), and the largest (Burnt) and smallest area to electricity ratio (Guangzhou). Regional plant characteristics are compiled in Table S1 (S1).

For two of the reservoirs (Laxiwa and Les Cedres), the area was not given and was approximated by dividing the reservoir capacity by half the dam height. Validation against the remaining 1451 reservoirs for which area, capacity and dam height were available showed that on average the area was overestimated by only 2%, whereas the area of two thirds of the reservoirs was still underestimated.

2.2. Reservoir water balance

Firstly, the annual outflow (OF_a) of the reservoir is derived from its annual water balance [38]:

$$OF_a = IF_a + P_a - PET_a - SP_a \quad (1)$$

where IF is the inflow, P is precipitation, PET is potential evapotranspiration and SP is seepage.

Monthly river discharges are obtained from the global hydrological model WaterGAP3 as simulated for the Earth2Observe project [39]. To ensure unaltered river flows into the reservoir, the river discharge one cell upstream of the dam is taken as inflow.

Monthly precipitation data based on ECMWF are also provided by the Earth2Observe project [39].

PET is obtained from Mu et al. [40]. Where there are data gaps at