Resources, Conservation and Recycling 105 (2015) 11–17

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

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

Making green technology greener: Achieving a balance between carbon and resource savings through ecodesign in hydropower systems

John Gallagher[a,*], David Styles[a], Aonghus McNabola[b], A. Prysor Williams[a]

[a] School of Environment, Natural Resources & Geography, Bangor University, Wales, United Kingdom
[b] Department of Civil, Structural & Environmental Engineering, Trinity College Dublin, Ireland

ARTICLE INFO

Article history:
Received 15 May 2015
Received in revised form 8 October 2015
Accepted 13 October 2015
Available online 29 October 2015

Keywords:
Life cycle assessment
Global warming potential
Abiotic resource depletion
Environmental burdens
Ecodesign
Cradle-to-operation

ABSTRACT

Renewable energy systems reduce the greenhouse gas (GHG) emissions associated with energy generation. However, we live in a world with depleting reserves of natural resources, and significant quantities of raw materials are often embodied within renewable energy infrastructure. This paper examines the potential for ecodesign measures to improve the GHG and resource balance of five small-scale hydropower case studies (50–650 kW). A life cycle assessment (LCA) approach compares two specific environmental impact categories: global warming potential (GWP) and abiotic resource depletion potential (ARDP). A number of ecodesign measures were examined for each installation: powerhouse structure, concrete selection, roofing materials, excavation work and transportation. Ecodesign led to cumulative savings of between 2.1% and 10.4% for GWP, and ARDP savings of between 0.1% and 2.6%, for the hydropower installations. Small savings were made with each ecodesign measure applied in all case studies. Furthermore, applying a 1% materiality threshold as outlined by LCA standards was shown to under-estimate the total project burdens, and to neglect opportunities for burden savings through ecodesign. Ecodesign can promote the use of locally sourced materials and some measures can lead to time savings during the construction process. The findings demonstrate the potential for ecodesign to modestly improve the carbon and resource efficiency of hydropower projects.

1. Introduction

Renewable energy systems contribute an increasing fraction of global electricity supply (REN21, 2014). The International Energy Agency (IEA) have recognized this growth, with generation almost trebling between 1973 and 2011 to 3566 TWh, and to further double to 7000 by 2035 (IEA, 2014). For this sector to continue to expand, significant quantities of raw materials and energy will be used to manufacture these technologies. In a recent review by Asdrubali et al. (2015), the reported environmental impacts of renewable energy systems varied significantly between technologies, with wind and hydro providing the best results, while geothermal and photovoltaics (PV) generated significantly higher impacts. The majority of the environmental burdens for renewable technologies are associated with the infrastructural phase of the project life cycle, as opposed to the high contributions of emissions during the operational phase for fossil-fuel systems (Turconi et al., 2013). Overall, the environmental burdens (e.g. greenhouse gas emissions) of electricity generation from renewables over their life cycle are significantly lower than fossil-fuel systems, except in a number of cases for the abiotic resource depletion impact category (Gallagher et al., 2015a).

In comparison to other renewable technologies, hydropower infrastructure has the longest lifespan, and therefore could represent a highly effective method of investing our depleting natural resources (Asdrubali et al., 2015). Hydropower (HP) is currently the largest contributor of renewable energy to global electricity production, providing over 16% of global electricity demands, which helps mitigate substantial greenhouse gas (GHG) emissions from fossil fuel combustion (REN21, 2014). The IEA (2014) report states that there is significant potential for further HP developments, with the Intergovernmental Panel on Climate Change (IPCC) stating that hydropower offers significant potential for carbon emission reductions (Kumar et al., 2011).

A recent paper by Bódis et al. (2014) suggested that 28,000 unexploited HP sites remain in Europe. Following this, Gallagher et al. (2015a) estimated the total potential as 7.35 TWh of additional generation which could offset 2.96 Mt of CO_2 from fossil fuel savings

* Corresponding author.
E-mail address: j.gallagher@bangor.ac.uk (J. Gallagher).

http://dx.doi.org/10.1016/j.resconrec.2015.10.015

(Gallagher et al., 2015a). Studies have shown that the embodied carbon in HP projects ranges from 0.2 to 152 g CO_2 eq./kWh (Raadal et al., 2011), which is lower than the current average carbon footprint of European grid electricity of 352 g CO_2 eq./kWh (Defra, 2014). Other publications have presented the carbon footprint of different sized HP projects: 15 g CO_2 eq./kWh for a small HP plant (Gagnon and van de Vate, 1997); 35–75 g CO_2 eq./kWh for a range of sizes of HP plants (Varun et al., 2008); 53 g CO_2 eq./kWh for a micro-HP installation (Pascale et al., 2011); 195 g CO_2 eq./kWh for a large HP project (Zhang and Xu, 2015). More recent studies have presented 'cradle-to-operation' results for small- and micro-HP projects installed in water supply infrastructure and run-of-river settings as low as 5–10 g CO_2 eq./kWh (Gallagher et al., 2015a,c).

Life cycle assessment (LCA) is a method of quantifying the environmental burdens for a product or service, such as a HP installation, through its life cycle (BSI, 2011). It provides a simple platform for comparison of HP projects with other fossil fuel electricity generation systems (Raadal et al., 2011). However, a detailed database of raw materials and energy processes are required to accurately report the environmental burdens for these projects (Chomkhamsri and Pelletier, 2011; Curran, 2013). Carbon footprinting is considered as a universal method of presenting the environmental impacts of a product or service (BSI, 2011), and has been used as the sole indicator by a number of LCA studies for the construction industry (Kenny et al., 2010; Basbagill et al., 2013). Furthermore, guidelines developed by the Waste and Resource Action Programme (WRAP, 2012) outline carbon as the sole indicator for environmental impacts in material selection for the construction sector. The focus on carbon footprinting risks under- or over-estimating overall life cycle burdens, and savings potentials, when evaluating ecodesign options for renewable energy systems.

Significant quantities of embodied energy are included from raw materials, component manufacturing and construction of HP projects (Rule et al., 2009). However, reporting on the environmental impacts of renewable energy projects has typically focused on carbon. Rule et al. (2009) noted that the use of natural resources and embodied energy, or 'emergy', has not widely been used as an indicator of sustainability. The depletion of abiotic resources has received more interest in recent years as current production and demands for raw materials continues to grow (Muilerman and Blonk, 2001; Yellishetty et al., 2011; Klinglmair et al., 2014). The concept of 'dematerialisation' has been considered to reduce consumption by increasing material efficiency, promoting material shifts and increasing the reuse and recycling of products (van der Voet et al., 2004).

For the majority of LCA studies of HP installations, the focus has been on GHG emissions and the associated carbon footprint of a project. For example, Zhang et al. (2015) compared the carbon footprint of two HP projects, an earth-core rockfill dam (ECRD) and a concrete dam, and demonstrated the potential to reduce CO_2 emissions by almost 25% using the ECRD design. This provides a positive outlook upon alternative construction methods, yet it only presented one environmental burden. It is important to examine a range of categories and taking an ecodesign approach to a project, even for a renewable energy system like a HP installation, as there is a need to examine the quantity of natural resources used in addition to the carbon footprint of materials and manufacturing processes.

The EU Directive 2009/125/EC defines ecodesign as 'the integration of environmental aspects into product design, with the aim of improving the environmental performance of the product throughout its whole life cycle' (EC, 2009). In 2012, the Energy Efficiency Directive demonstrated the commitment of the EU to achieving more energy efficient products (EC, 2015). In product design, ecodesign is presented as one method of minimizing the environmental burdens over a product's lifespan (Zbicinski et al., 2006). Despite being considered in other industries (Sala et al., 2012; Basbagill et al., 2013), ecodesign has only recently been suggested for a renewable energy system (Gallagher et al., 2015a). An ecodesign approach to a renewable energy system, which is made up of a combination of multiple products, can maximize material and energy savings. Assuming ecodesign was applied to all 28,000 technically feasible HP projects identified by Bódis et al. (2014) for Europe, Gallagher et al. (2015a) estimated potential savings of 800,000 tonnes of concrete, 10,000 of steel and 65 million vehicle miles. As the majority of the environmental burdens for a renewable energy system are embodied in the design and construction stages, ecodesign presents a significant opportunity for carbon and resource savings in HP projects (D'Souza et al., 2011; Suwanit and Gheewala, 2011; Guezuraga et al., 2012).

This paper applies LCA to capture the environmental burdens of five small-scale HP projects, representing water supply infrastructure and run-of-river installations. Several potential ecodesign measures are examined for these projects. The results focus on carbon- and resource-based environmental burdens represented by global warming potential (GWP) and abiotic resource depletion potential (ARDP) impact categories, respectively. Finally, the study examines the implications for ecodesign of using the 1% materiality threshold commonly quoted in LCA guidelines for inventory compilation.

2. Methods

2.1. Goal and scope definitions

This paper presents five distinct HP projects in the UK and Ireland, three run-of-river and two water supply network infrastructure projects, each of which required a unique combination of material quantities, manufacturing processes and component transport (Gallagher et al., 2015c). The focus of this paper is to consider ecodesign in the construction of these HP installations; therefore a 'cradle-to-operation' scope was adopted to account for all environmental impacts up to the stage of generating electricity. This scope was considered suitable as the vast majority of burdens are linked to the main project components required in the construction stage (Raadal et al., 2011). In addition, the end-of-life stage for HP installations is difficult to quantify due to typically long, though uncertain, operational lifespans and unknown future materials recycling performance (Haynes, 2010).

Two relevant environmental impact categories were selected from the CML impact assessment method: global warming potential (GWP), expressed as kg CO_2 eq., and abiotic resource depletion (ARDP), expressed as kg Sb eq. (CML, 2010). These categories represent the primary environmental burdens (climate change and resource depletion) associated with hydro projects and grid electricity generation. Thus, the results of eco-design modifications are presented as percentage changes in these environmental burdens for the cradle-to-operation phase of deployment, relative to the standard designs reported in Gallagher et al. (2015a).

2.2. Inventory for LCA case studies

To accurately assess the environmental burdens of all project components, materials and processes, a complete and detailed inventory database was generated from previous life cycle HP investigations (Gallagher et al., 2015a,b,c) and is included in Table SI.1 in the Supplementary Information. The database of environmental burdens relate to raw material extraction, product manufacturing and transport burdens, and was generated in MS Excel. The Ecoinvent v.3 database accessed via SimaPro 8.0 software was used to calculate the environmental burdens of the HP