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Life cycle environmental balance and greenhouse gas mitigation potential of micro-hydropower energy recovery in the water industry

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ABSTRACT

Micro-hydropower (MHP) presents new opportunities to generate electricity from within existing water infrastructure. This paper quantifies the environmental impacts of electricity generation from three MHP case studies (15–140 kW) in the water industry, using a life cycle assessment approach. Environmental burdens were calculated per kWh electricity generated over nominal turbine operational lifespans. Compared with marginal UK grid electricity generation in combined cycle turbine natural gas power plants, normalised life cycle environmental burdens for MHP electricity were reduced by: >99% for global warming potential (GWP); >98% for fossil resource depletion potential; >93% for acidification potential; 50–62% for human toxicity potential. However, the burden for abiotic resource depletion potential was 251–353% higher for MHP than marginal grid-electricity. Different quantities of raw materials and installation practices led to a range in GWP burdens from 2.14 to 4.36 g CO_2 eq./kWh. One case benefitted from very low site preparation requirements while others required substantial excavation works and material quantities. Carbon payback times ranged from 0.16 to 0.31 years, extending to 0.19–0.40 years for worst-case scenarios examined as part of a sensitivity analysis. The carbon payback period for future MHP installations was estimated to increase by 1% annually, as the carbon intensity of marginal grid electricity is predicted to decline. This study demonstrates that MHP installations in the water industry have a strongly positive environmental balance.

1. Introduction

The water industry is the 4th largest energy intensive sector in both the UK and Ireland (Gaius-obaseki, 2010). Most of the electricity used to treat and supply water is sourced from fossil fuels, with an average carbon footprint of 483 g CO_2 equivalent per kWh (g CO_2 eq./kWh) consumed (Defra, 2013). Overall, the UK water industry is responsible for 5 million tonnes of CO_2 emissions annually (EA, 2009), and reducing the demand for fossil-based electricity is a key sustainability objective in terms of economics, resource efficiency and environmental responsibility.

Water companies often have to respond to government regulations that state that utility suppliers must monitor and reduce greenhouse gas (GHG) emissions (Rothausen and Conway, 2011). For example, Dŵr Cymru Welsh Water are targeting a 25% reduction of their GHG emissions by 2015, and 50% by 2035 (Dŵr Cymru Welsh Water, 2007). Renewable energy can provide one solution to help water companies meet their GHG emission targets and provide long-term sources of energy for water treatment and supply. In Europe, hydropower is considered the most suitable technology for the water sector to adopt for generating electricity (Flury and Frischknecht, 2012).

Micro-hydropower (MHP) installations have recently been identified as an area of growing interest for water companies as they consider energy recovery from within water infrastructure (McNabola et al., 2014b). These sites are located throughout the water infrastructure where excess pressure exists and sites can generate between 5 and 300 kW. In addition to generating electricity, the MHP installations can help optimise a network by acting as a mechanism for flow control, pressure management and subsequently reducing water losses through leakage (Corcoran et al., 2013; McNabola et al., 2014a). Locations for energy recovery exist throughout water infrastructure, from water treatment works, break pressure tanks, pressure reducing valves and wastewater treatment plants. The recovered energy may be used on-site to reduce net electricity demand by the water company, or be

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exported to the national grid. In either case, according to carbon footprinting rules (BSI, 2011), the carbon footprint of the industry is reduced.

Life cycle assessment (LCA) has previously been used to assess the environmental impacts of renewable energy systems (Guezuraga et al., 2012; Pascale et al., 2011; Raadal et al., 2011; Rule et al., 2009). However, the PAS 2050 carbon footprint guidelines state that it is not required to report the embodied carbon in capital goods for a renewable energy project (BSI, 2011). Guidelines have been developed to calculate the embodied carbon for the water industry (UKWIR, 2008); however, carbon and other environmental burdens of MHP installations in water infrastructure are not reported. In cases where areas of land are flooded for hydro installations, previous LCA studies have yielded high levels of GHG emissions due to vegetation decay (Donnelly et al., 2010; Gagnon and van de Vate, 1997). The results noted by Raadal et al. (2011) demonstrated a very large variation in GHG emissions of between 0.2 and 152 g CO_2 eq./kWh. This study provides evidence relating to both the environmental impacts of MHP specific to the water industry and outlines the life cycle results for applications of the technology in water infrastructure.

2. Methods

2.1. Goal & scope definitions

The objective of this study is to calculate the life cycle environmental balance of electricity generated by three micro-hydropower installations in the water supply infrastructure. Five relevant environmental impact categories were selected from CML (CML, 2010): global warming potential (GWP), expressed as kg CO_2 eq.; abiotic resource depletion (ARDP), expressed as kg Sb eq.; acidification potential (AP), expressed as kg SO_2 eq.; human toxicity potential (HTP), expressed as kg 1,4-DCBe eq.; fossil resource depletion potential (FRDP), expressed as MJ eq. (Table 1). These categories were chosen as they represent the direct environmental impacts (human health, ecosystem quality and resources) associated with the hydro projects and have been previously presented in literature for renewable projects and water infrastructure projects (Bonton et al., 2012; Flury and Frischknecht, 2012; Goedkoop and Spriensma, 2001).

The functional unit was 1 kWh of electricity generated, for comparison with marginal UK grid electricity generation via a natural gas combined cycle turbine (NG-CCT) power station (DECC, 2012). The system boundaries included raw material extraction, processing, transport and all installation operations, followed by electricity generation over the lifetime of the turbines (Fig. 1).

In addition, sensitivity analysis was used to determine the robustness of the results to uncertainties, and site-specific variations in manufacturing processes, materials and transportation requirements. Future projections for the carbon footprint of marginal electricity were used to predict the cumulative GHG savings over the lifespan of these MHP projects. This work aims to provide an insight into the overlooked issue of embodied carbon in MHP systems, and to provide recommendations for efficiently assessing and reporting the environmental balance of these installations. Although carbon footprinting standards such as PAS 2050 (BSI, 2011) exclude carbon embodied in buildings and capital equipment, the magnitude of these upstream GHG emissions in relation to avoided fossil GHG emissions is critical in determining the net GHG mitigation potential of renewable energy projects (Guezuraga et al., 2012; Raadal et al., 2011).

2.2. Case study descriptions

Details relating to the three case studies examined in this paper are outlined in Table 2. The three MHP projects selected represent a broad range of typical installations that can take place in water infrastructure: a 15 kW installation to control water flow into a new water treatment works, a 90 kW new build installation to replace a dated turbine at a water treatment works, and a 140 kW installation as part of a new water treatment works project.

A conservative nominal turbine and generator lifespan of 30 years was applied. Turbine lifespan values cited in the literature vary considerably, from 20 to 100 years (Guezuraga et al., 2012; Rule et al., 2009). A number of assumptions were made during the LCA study in order to define comparable system boundaries and account for all important contributory processes. These included aspects related to materials used, products, manufacturing processes, transportation contributions, operations/maintenance and decommissioning (Table 3).

2.3. Inventory for LCA case studies

To undertake a detailed LCA of the three case studies, data were collected from water suppliers and/or turbine manufacturers (Dublin City Council, 2013; Dŵr Cymru Welsh Water, 2013; Zeropex, 2013). The data included the size and capacity of the turbine and generator units, the materials and construction details, including information of on-site plant and machinery. This information was extracted from a combination of sources for the purpose of the LCA, project reports, quantities spreadsheets and project design drawings.

This study followed ISO 14040 standards for LCA, and as such accounted for at least 95% of the total mass and 90% of the total energy inputs for each MHP project (ISO, 2006). The LCA process is complex and time consuming (Raadal et al., 2011), thus a database for raw materials and production was generated in MS Excel following extraction from Ecoinvent v.3 (Ecoinvent, 2014) via

Table 1
Life cycle assessment impact categories selected to compare micro-hydropower projects with marginal UK grid electricity generation, descriptions provided (Goedkoop et al., 2008).

Impact category	Abbrev	Units	Information
Global warming potential	GWP	kg CO_2 eq.	GHG emissions contributing to climate change and their effects on ecosystem health, human health and material welfare (measured in equivalents kg CO_2 eq./kWh).
Abiotic resource depletion potential	ARDP	kg Sb eq.	Protection of human welfare, human health and ecosystem health (measurement based on quantity of minerals extracted as a fraction of concentration of global reserves).
Acidification potential	AP	kg SO_2 eq.	Impacts of acidifying substances on soil, surface water, groundwater, organisms, ecosystems and building materials (expressed as equivalent sulphur dioxide concentrations).
Human toxicity potential	HTP	kg 1,4-DCBe eq.	Substances that are toxic to human health, calculated with USES-LCA, describing fate, exposure and effects of these substances (equivalent 1,4-dichlorobenzene).
Fossil resource depletion potential	FRDP	kg kJ eq.	Depletion of energy as fossil fuel deposits used to generate electricity (measured in equivalent kg kilojoules)