Journal of Cleaner Production 99 (2015) 152–159

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

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

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A R T I C L E I N F O

Article history:
Received 28 June 2014
Received in revised form
1 March 2015
Accepted 2 March 2015
Available online 11 March 2015

Keywords:
Environmental burdens
Carbon footprint
Fossil fuel mitigation
Water infrastructure
Renewable energy

A B S T R A C T

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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http://dx.doi.org/10.1016/j.jclepro.2015.03.011

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)

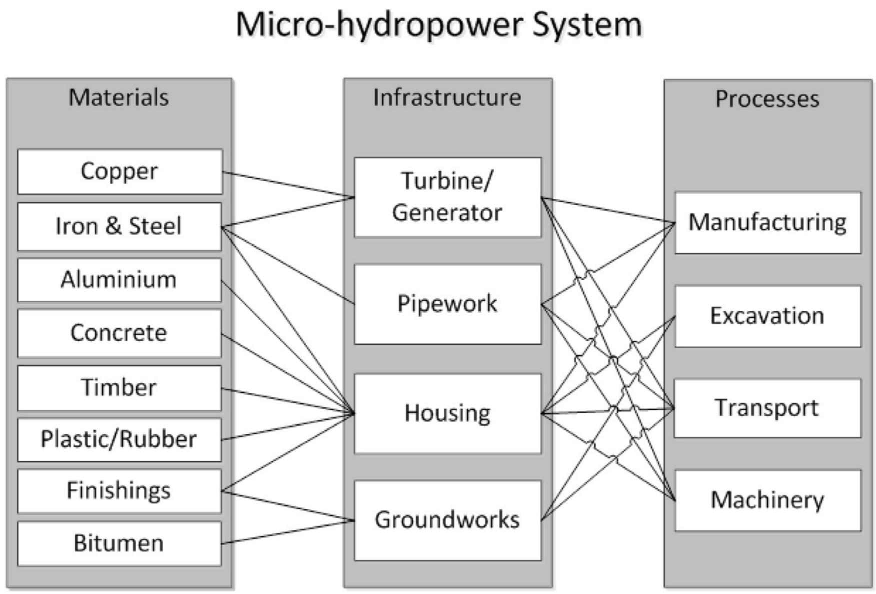
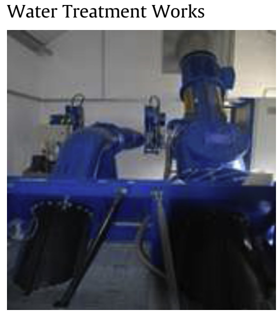
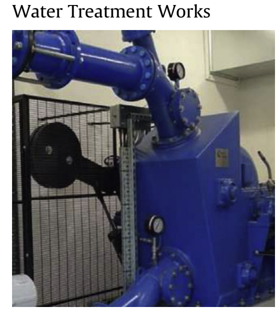


Fig. 1. Primary materials and processes considered within the system boundaries for MHP.

Table 2
Description of MHP case studies for LCA (Dublin City Council, 2013; Dŵr Cymru Welsh Water, 2013; Zeropex, 2013).

15 kW Pen y Cefn Water Treatment Works	90 kW Vartry Reservoir & Water Treatment Works	140 kW Strata Florida Water Treatment Works
		
• Location: Gwynedd, Wales • Dŵr Cymru Welsh Water • Design capacity: 15 kW • Power output: 12.5 kW • Turbine: Zeropex Difgen • Head: 90–105 m • Flow: 10–30 l/s • Existing housing in place • Gravity fed by Llyn Cynwch reservoir • New installation, flow control from Difgen turbine to DAF treatments system	• Location: Wicklow, Ireland • Dublin City Council • Design capacity: 90 kW • Power output: 78 kW • Turbine: Kaplan • Head: 7–16 m • Flow: 580–1200 l/s • Concrete housing constructed • Gravity fed from nearby Vartry reservoir • Replacing outdated Pelton wheel turbine which generated electricity for site since 1940's	• Location: Ceredigion, Wales • Dŵr Cymru Welsh Water • Design capacity: 140 kW • Power output: 110 kW • Turbine: Pelton twin jet • Head: 183–195.5 m • Flow: 100 l/s • GRP kiosk constructed • Fed by Llyn Teifi and Llyn Egnant raw water reservoirs • New installation, existing DAF system on site, 250–300 kW energy consumption on site

SimaPro software to calculate the environmental burdens of the MHP installations. The database generated included the extraction and production of raw materials, manufacturing of the products for each MHP installation, and the transportation and implementation of these products to site.

Uncertainties were noted during data collation and used to inform the sensitivity analyses, to provide transparent and representative results for these case studies (Cellura et al., 2011). A cut-off threshold of 0.5% of life cycle GWP was applied to omit minor components from the LCA. This was a lower cut-off threshold than the 1% suggested by PAS2050 and applied by Rule et al. (2009).

2.4. Reference system and carbon payback time

NG-CCT power stations operating at 50% conversion efficiency represent marginal electricity generation in the UK that is avoided by energy saving and renewable energy measures (DECC, 2012). Therefore, 1 kWh of NG-CCT-generated electricity was taken as the reference system for comparison with 1 kWh MHP-generated electricity. The carbon payback time was calculated as the operational time required for the MHP to offset a quantity of marginal grid electricity GHG emissions equivalent to GHG emissions arising over the life cycle of MHP system manufacture, installation and

Table 3
Assumptions made for LCA of MHP Projects.

Assumptions	Details
Boundary conditions	Grid losses and some external infrastructure details omitted in calculations of carbon payback for MHP installations.
Project lifespan	30-year lifespan for turbines[a], 100-year lifespan for housing, 10-year lifespan for paint (further details in Supplementary information).
Raw materials, manufacturing & transportation	Impact category data for raw materials (e.g. steel, concrete, etc.), manufacturing (e.g. steel product manufacturing) and transportation (e.g. freight transport) were sourced from Ecoinvent v.3 database via SimaPro8 (Ecoinvent, 2014). The environmental impact of soil excavation was omitted.
Products	Estimations for the mass of raw materials contained in turbines and generators were based on consultation with manufacturers (Dublin City Council, 2013; Dŵr Cymru Welsh Water, 2013).
Electricity generation	The power generated by the turbines is based on several years of historical data and the average power generated is assumed to be maintained over the 30-year project lifespan.
Operations & maintenance, decommissioning	Few data exist on turbine and generator maintenance burdens, which are considered trivial compared with manufacturing and installation burdens and therefore omitted from the LCA process, as for similar renewable generation LCA studies (D'Souza et al., 2011).

[a] Conservative nominal lifespan used as it varies in literature: 20 years (Guezuraga et al., 2012; Pascale et al., 2011), 25–30 years (Varun et al., 2009), 50 years (Suwanit and Gheewala, 2011), 100 years (Rule et al., 2009).

operation. However, Sleeswijk et al. (2008) outlined how LCA results may not truly reflect the environmental balance of a product over its lifetime, owing to temporal trends in the environmental burdens of contributory or counterfactual processes. A dynamic analysis was therefore applied to forecast the potential cumulative GHG mitigation potential of MHP installations based on future emission projections for marginal grid electricity generation (DECC, 2012).

2.5. Interpretation and sensitivity analysis

To enable a comparison of relative contributions to the five environmental burdens considered at the European scale, EU25 annual loading data for those impact categories were taken from CML (2010) and expressed per capita, assuming a population of 465 million people. Environmental burdens per kWh were then divided by per capita loading, enabling a visual comparison of impact category contributions.

Sensitivity analyses were undertaken in relation to manufacturing and transport for each MHP installation, as the most substantial level of uncertainty was noted for these project components. The following scenarios were assessed in which the environmental burdens attributable to uncertain components were varied by ±50%.

- Scenario 1 – Manufacturing of turbine/generator
- Scenario 2 – Manufacturing of pipework
- Scenario 3 – Manufacturing & construction of housing
- Scenario 4 – Transportation of materials

A sensitivity analysis was also undertaken for lifetime GHG mitigation potential for each of the MHP schemes, by considering avoidance of UK grid average electricity, and avoidance of coal power generation operating at 40% efficiency (DECC, 2012). The latter scenario does not reflect current market trends but represents the high potential GHG avoidance that could be achieved if future policy measures prioritised the removal of the most carbon-intensive electricity from the grid as new low-carbon generation is introduced.

3. Results & discussion

3.1. Contribution analysis

The results of the LCA are presented in Table 4 as the total environmental burdens per kWh of electricity generated over the 30-year lifespan by the three MHP turbines. The table also shows the carbon payback time in relation to offset grid electricity generation.

The total GWP impact associated with the three MHP installations over the lifespan of the project ranged from 2.14 to 4.36 g CO_2 eq./kWh. These results are comparable to previous results from LCA studies of hydropower projects: 5.6 g CO_2 eq./kWh for a 116 MW project (Rule et al., 2009), a conservative 15 g CO_2 eq./kWh by Gagnon and van de Vate (1997), and a range from 0.3 to 13 g CO_2 eq./kWh for 11 run-of-river hydro projects (Raadal et al., 2011).

Fig. 2 displays the contribution of major components towards the environmental burdens per kWh of electricity generated for each of the turbines. The figure displays the core components (turbine/generator and pipework) and variable components (ancillary metals, concrete and other) as block and hatched sections, respectively.

The turbine/generator and pipework (solid blocks) are considered as the only two core components across each of the three projects. Turbine housing and ancillaries varied significantly between the projects. Examining all five impact categories in Fig. 2 shows an incremental pattern for the turbine/generator, as a

Table 4
Total environmental impacts of MHP projects for different impact categories and carbon payback time (expressed per kWh generated over project 30-year lifespan).

Case study	Impact categories[a]					Carbon payback (years)
	GWP (g CO_2)	ARDP (g Sb)	AP (g SO_2)	HTP (g 1,4DCBe)	FRDP (MJ)	
15 kW	2.14	1.4E-04	4.0E-02	10.05	2.7E-02	0.16
90 kW	4.36	1.1E-04	4.3E-02	9.17	1.1E-01	0.31
140 kW	2.78	9.4E-05	3.3E-02	8.91	6.1E-02	0.21

[a] GWP, global warming potential; ARDP, abiotic resource depletion potential; AP, acidification potential; HTP, human toxicity potential; FRDP, fossil resource depletion potential.

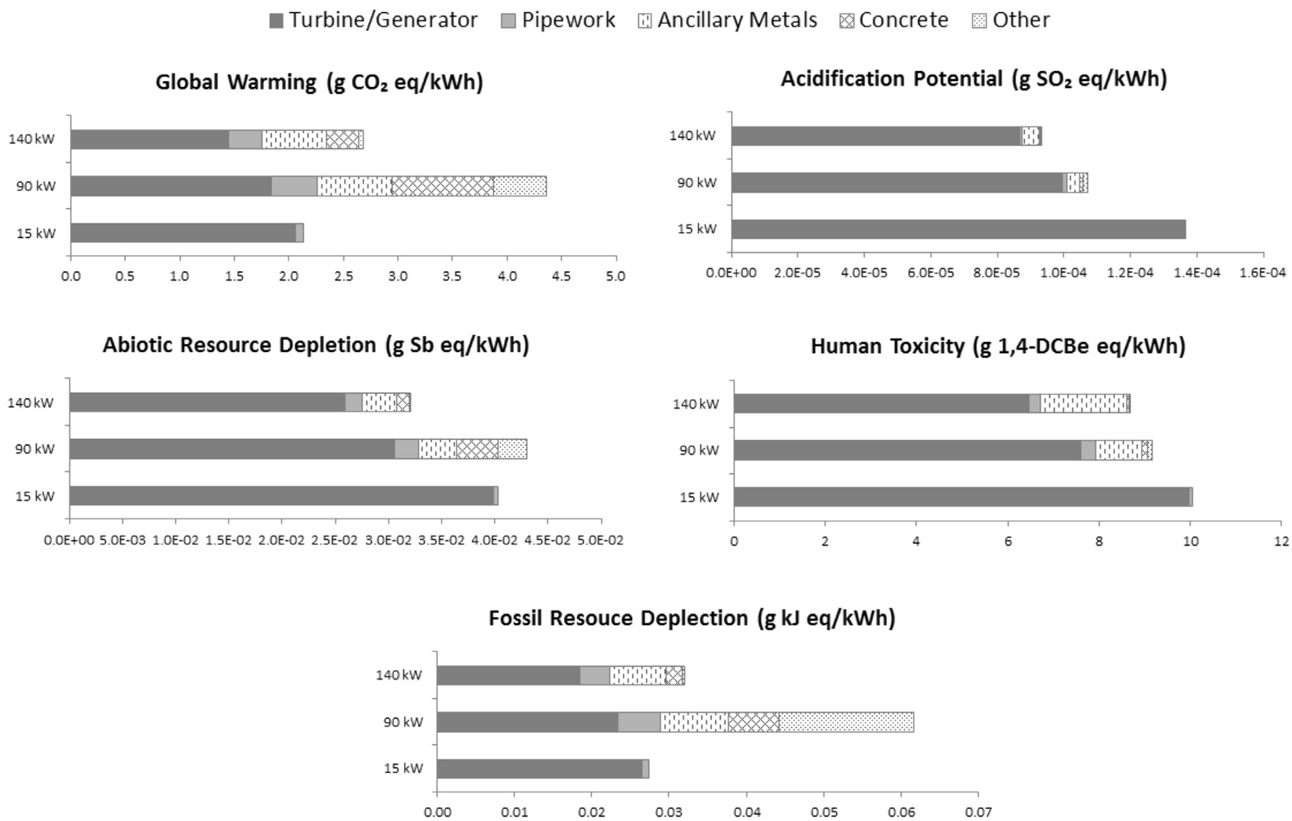


Fig. 2. Breakdown of environmental impacts of MHP case studies expressed per kWh generated over project 30-year lifespan (solid blocks represents core components and hatched blocks represent variable components).

reduction in the capacity of the turbine related to an increase in the environmental impact of each category.

The 90 kW MHP project demonstrated the highest contribution to GWP as the building constructed for housing the turbine/generator used more materials than the larger MHP installation. Variances in the contributions to the different impact categories between the two larger MHP projects were primarily due to the use of different types and quantities of construction materials for housing. A prefabricated kiosk was used for the 140 kW installation in preference to a concrete structure for the 90 kW project. Despite accounting for the longer lifespan of the 90 kW turbine building, the quantity of materials used in its construction outweighed the structure selected for the larger installation over the nominal 30-year lifespan.

LCA has recently been adopted to quantify the environmental impacts of water systems (Lim et al., 2008), but it can also be considered as a tool for directing sustainable product design and manufacturing (Basbagill et al., 2013; Sala et al., 2012). As there was significant variability in construction practices and materials used by the three case studies examined, we could therefore consider an environmental and sustainable design approach for MHP projects.

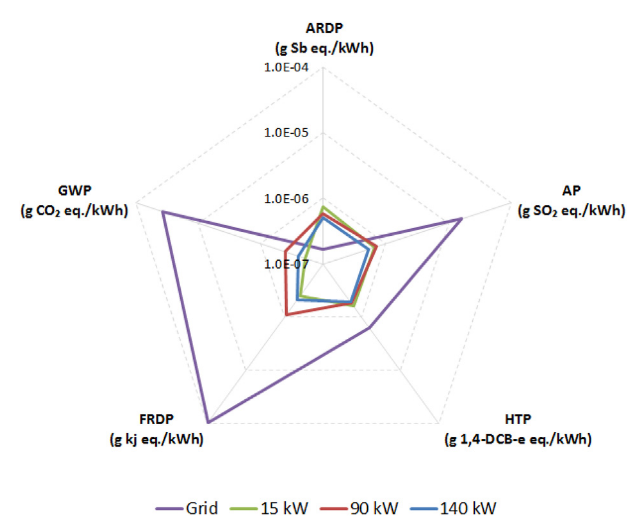


Fig. 3. Normalised impact category contributions for each of the MHP installations compared with marginal grid electricity generation by NG-CCT reference system (compared per kWh generated over a 30-year project lifespan).

3.2. Comparison with grid electricity

Fig. 3 illustrates the comparative results between the three MHP installations and a 300 MW natural gas combined cycle power plant (CCPP) reference system, assumed to be a typical scale of NG-CCT marginal electricity (DECC, 2012).

Compared with the reference system, normalised life cycle environmental burdens for MHP electricity were reduced by: > 99% for GWP; >98% for FRDP; >93% for AP; 50–62% for HTP. However, ARDP burdens were 251–353% higher for MHP than marginal grid-electricity, reflecting the comparatively large quantities of raw materials embodied in the infrastructure required to generate each kWh of MHP electricity.

Based on offsetting GHG emissions from marginal grid electricity generation, the carbon payback time calculated ranged from 0.16 to 0.31 years for the MHP projects. The payback periods for the MHP installations were significantly lower than the economic

Table 5
LCA sensitivity analysis of manufacturing and transportation for MHP installations assuming ±50% margin of error in estimating environmental burdens of project components.

Scenario	MHP installation	Impact categories[a] (±%)				
		GWP	ARDP	AP	HTP	FRDP
S1 – Manufacturing of turbine/generator	15 kW	21.1%	1.9%	7.5%	5.0%	21.3%
	90 kW	9.3%	1.8%	5.4%	4.2%	4.7%
	140 kW	11.8%	1.8%	6.1%	3.8%	6.7%
S2 – Manufacturing of pipework	15 kW	0.8%	0.0%	0.3%	0.1%	0.8%
	90 kW	2.2%	0.3%	1.4%	0.7%	1.1%
	140 kW	2.6%	0.3%	1.3%	0.5%	1.5%
S3 – Manufacturing and construction of housing	15 kW	–	–	–	–	–
	90 kW	9.5%	1.0%	0.6%	5.3%	1.1%
	140 kW	6.3%	0.7%	0.9%	6.2%	1.8%
S4 – Transportation of materials	15 kW	0.1%	0.0%	0.0%	0.0%	0.2%
	90 kW	6.0%	0.7%	3.0%	0.4%	3.5%
	140 kW	0.7%	0.1%	0.3%	0.0%	0.4%

[a] GWP, global warming potential; ARDP, abiotic resource depletion potential; AP, acidification potential; HTP, human toxicity potential; FRDP, fossil resource depletion potential.

payback for the projects, which ranged from 2.8 to 8.3 years (Dublin City Council, 2013; Dŵr Cymru Welsh Water, 2013; Zeropex, 2013). These figures provide lower carbon payback times than the range of 1.1–3.1 years for different renewable and non-renewable energy sources outlined by Guezuraga et al. (2012). The lower carbon payback may be due to the continuous power generation from MHP installations in water infrastructure in comparison to the irregular generation of electricity from other renewables.

3.3. Sensitivity analysis

The sensitivity analysis accounted for uncertainties within the LCA process for manufacturing processes and transportation of materials to site. The results from this sensitivity analysis are presented in Table 5 as the percentage change in the total environmental burden from electricity generated by each MHP installation.

Variations in manufacturing burdens for the turbine/generator had the most notable impact upon final results, in part reflecting the shorter (30-year) lifespans for turbines compared with other project components (see Table A1 in Appendices). The 15 kW installation results were particularly sensitive to turbine manufacturing burdens compared with the other two projects (e.g. ±21% versus ±9–12% for GWP) due to the low proportion of site preparations during installation. Results were insensitive to uncertainty in the amount of additional pipework required (maximum difference of ±2.6%), especially for the 15 kW project where infrastructure modifications were minimal.

Overall, the default environmental burden results presented in Figs. 2 and 3 appear to be robust to the key uncertainties identified during the LCA study. The combined uncertainties from the manufacturing and transport scenarios equate to a potential increase in the carbon payback time of between 21 and 27%, equivalent to 0.19–0.40 years. The results for the carbon payback remain significantly lower than the economic payback for the three MHP installations and those of alternative forms of renewable energy available to the water industry, previously mentioned.

Table 6
Mitigation forecasting for total GHG emissions offset by MHP installations between 2015 and 2050 (displacements of CO_2 emissions associated with gas power plant).

MHP installation	Cumulative GHG emissions offset (t CO_2 eq.)					
	Decline of marginal grid electricity					No change
	2014[a]	2015	2025	2045[b]	2050	2050
15 kW	−7	36	450	1206	1379	1873
90 kW	−86	173	2658	7191	8233	11195
140 kW	−80	300	3944	10592	12121	16465

[a] Assuming MHP installations constructed by the end of 2014.
[b] Signifies GHG emissions produced over the 30-year lifespan.

3.4. Mitigation forecasting for MHP

The three projects examined in this study have been constructed, yet there is the potential for a large number of additional MHP installations in the water infrastructure. The power generated from the MHP installations can reduce GHG emissions from electricity and offset the carbon footprint of the water industry, but this carbon offset potential will decline over time as the carbon intensity of marginal grid electricity declines, as projected by (DECC, 2012). Table 6 summarises the evolution of cumulative GHG mitigation for the three case studies up to 2050, making the assumption that the MHP projects are all constructed in 2014 and GHG emissions are offset from 2015. The calculations account for a reduction in the GHG emissions through offsetting electricity generated from a gas power plant.

Over the 35 year period to 2050, the case study MHP projects are forecast to avoid between 1379 and 12,121 t CO_2 eq., based on displacement of marginal grid electricity throughout the period. However, if grid average electricity is displaced, and assuming the carbon footprint of grid average electricity declines at the same rate as forecast for marginal grid electricity (DECC, 2012), then the cumulative GHG avoidance would increase by 36% for each MHP system. If MHP electricity displaces coal electricity generation over the same period, GHG avoidance would amount to three times higher than the projected savings. These results highlight the magnitude of lifetime GHG mitigation achieved by small scale MHP projects, and the sensitivity of long-term GHG mitigation forecasts to assumption about the carbon intensity of grid electricity.

DECC (2012) predicts a 15–17% increase in electricity costs by 2025, suggesting that these MHP projects can contribute to mitigating energy costs, as well as helping to meet GHG emission reduction targets in the UK. The installation of energy recovery sites in water infrastructure is likely to proceed for some time after 2014, therefore the downward trend of GHG emissions associated with marginal electricity generation will increase the carbon payback period for each MHP installation by approximately 1% annually; equating to a maximum increase of 0.02 years by 2025 for a typical MHP installation. The energy forecasting for these MHP projects demonstrates significant savings in GHG emissions, and continuing short carbon payback periods into the future. As electricity prices continue to increase, MHP may become an increasingly attractive low-carbon renewable energy source into the future.

These results conclusively demonstrate the overwhelmingly positive overall environmental balance of MHP electricity generation. Only the ARDP burden is higher compared with replaced marginal grid electricity, especially where housing is constructed for the MHP turbines. However, there are various options available to reduce ARDP burdens. The variable project components (e.g. powerhouse) presents an opportunity to control materials selection such as precast concrete sections/structures, or substituting materials with more environmentally friendly alternatives could reduce ARDP burdens. Notwithstanding uncertainty over the number of material recycling loops, that will dictated by future resource prices, and allocation methodology, recycling of materials used in the MHP projects could reduce ARDP burdens by 15% (e.g. wind turbine installation (D'Souza et al., 2011)). The results presented in this study prefers to omit the recycling of MHP project components, as significant uncertainties exist for accurately quantifying the reuse of raw materials in future products.

Findings from within this project indicate that approximately 18 GWh of electricity can be generated through the implementation of MHP technology by water companies in Ireland and Wales (Gallagher et al., unpublished work). Whilst implementing these systems would initially add approximately 1700 t CO_2 eq. to the footprint of the industry, the carbon payback period for these installations would be short (0.2–0.4 years), and they have the potential to offset approximately 5750 t CO_2 eq. per year and provide a 2% reduction (20 g CO_2 eq. per m^3 of water) in the GHG emissions associated with water supply and treatment (Defra, 2012). The positive environmental balance of MHP technology presents an opportunity for the long-term sustainability of the water industry.

4. Conclusions

Micro-hydropower is a growing area of interest to water companies as potential energy recovery sites can capture excess energy within water infrastructure and can generate between 5 and 300 kW. This paper quantifies the environmental impacts of electricity generation from three MHP case studies in the water industry, using a life cycle assessment approach.

Sites may present different technical challenges to other MHP sites. Environmental burdens were therefore 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.

Acknowledgements

The Hydro-BPT project is part funded by the European Regional Development Fund (ERDF) through the Ireland–Wales Programme (INTERREG 4A). The authors would also like to thank the organisations who supplied data for these case studies: Dublin City Council, Dŵr Cymru Welsh Water and Zeropex.

Appendix A1

Table A1
Contribution of component to MHP installation (GHG emissions of component, expressed as kg CO_2 eq., as a fraction of the total kW generated over project lifespan).

Item	MHP installation			Component lifespan (years)
	15 kW	90 kW	140 kW	
Turbine & Generator	4.5E-03	4.0E-03	3.1E-03	30
Pipework	1.6E-04	9.1E-04	6.6E-04	100
Concrete	–	1.5E-03	6.4E-04	100
Roof/Purlins/Ridge plate	–	5.6E-04		100
Reinforcing Steel	–	5.6E-04	6.9E-04	100
Concrete Block	–	5.1E-04		100
Galvanised Steel	–		2.5E-04	100
Ductile Iron	–		1.0E-04	100
Bitumen	–	4.0E-04		30
Formwork/Shoring	–	2.8E-04	7.0E-05	–
Crane	–	9.0E-05		–
Fencing Panels	–	2.9E-04		30
Mineral Wool	–	6.2E-05	<u>8.6E-06</u>	100
Acoustic Vent	–	1.0E-04	1.5E-04	30
Power Cable	–	<u>3.8E-05</u>		100
Strip/Excavate/Backfill	–	<u>2.5E-05</u>	<u>1.8E-05</u>	–
Hardcore/Blinding	–	2.3E-05	<u>9.7E-07</u>	30
Finishing	–	1.4E-04		100
Painting	–	<u>3.3E-05</u>	4.7E-05	10
2.2 × 2 m Double Door + Frame	–	<u>9.9E-06</u>	<u>7.8E-06</u>	30
Contraction/Expansion joint	–	<u>4.2E-06</u>	<u>2.8E-06</u>	100
Waterbar	–	<u>1.8E-06</u>		100
Fascia/soffit etc	–		4.7E-05	60
PVC Pipework	–		2.2E-05	60
Rubber Seals	–		<u>7.8E-07</u>	60
Acoustic Board	–		<u>6.0E-07</u>	60

Note: The underlined values signify the materials that fall below the 0.5% cut-off threshold in quantifying the environmental burdens of the MHP installations.

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