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Energy recovery in the water industry using micro-hydropower: an opportunity to improve sustainability

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Abstract

The water industry as a whole consumes a considerable amount of energy in the production, distribution and treatment of water and wastewater. Like all sectors of society today, the industry is focusing efforts on the reduction of its CO_2 emissions and the improvement of the sustainability of its systems and practices. One way of achieving this is through the use of micro-hydropower (MHP) installations in water infrastructure for energy recovery purposes. This paper presents a review of energy use and CO_2 emissions in the water industry as well as highlighting the opportunities and challenges for MHP energy recovery. The results indicate that significant potential exists for energy recovery in the water industry. However, many previous investigations have not considered key complexities such as variations in flows or turbine efficiency. Similarly, accurate costing and return on investment data are often absent or lacking sensitivity analysis. Further research is required to address the risks and long-term reliability of installations and the development of firm policy to direct and incentivise sustainability gains in this area.

Keywords: Collaboration; Energy recovery; Environmental impact; Micro-hydropower; Sustainability; Wastewater; Water supply

1. Introduction

The supply of treated water in the western world is likely to be an unsustainable process in its current form due to the considerable energy consumption and CO_2 emissions inherent in the various treatment and supply processes involved. With the increasing global awareness of the impacts of energy

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consumption and CO_2 emissions on climate change, humankind, finite resources and the environment as a whole, efforts to reduce such impacts are underway in all sectors of society.

The sustainability of the water supply process and its contribution to climate change is a global concern for large urban centres (Jenerette & Larsen, 2006). Recent studies have identified key research questions in the water industry, such as: 'how do we develop and implement low energy water treatment processes?' and 'can we optimise water supply within catchments?' (Brown *et al.*, 2010). Research has also identified the need to focus innovation in wastewater as a resource for potable water, materials and energy (Kwok *et al.*, 2010).

The record global population has resulted in an all-time high in water demand. Transporting and treating water to meet water quality standards are expensive and energy-intensive processes. The ever increasing stringency of water quality legislation across the world has added to these costs (Berndtsson & Jinno, 2008). This, coupled with the rapidly rising costs of energy will adversely affect the extraction and conveyance of water in the future (Zilberman *et al.*, 2008).

Many methods of improving the sustainability of water supply have been investigated. Methods aimed at reducing overall water demand and subsequently its associated energy consumption include: the reuse of grey water; water leakage reduction and pressure management schemes; rainwater harvesting schemes; water metering and hybrid water supply systems (Berndtsson & Jinno, 2008; Rygaard *et al.*, 2011: Ramos *et al.*, 2011). Methods to reduce the energy consumption of individual water/wastewater treatment processes have also been investigated. These include the capture of by-products such as: biogas for use in combined heat and power facilities (Hernandez-Leal *et al.*, 2010); generation of energy from wastewater treatment through anaerobic bioreactors or microbial fuel cells (Kwok *et al.*, 2010); recovery of waste heat; recycling of dried sludge pellets in co-firing combustion systems (Park & Jang, 2010); energy efficient desalinations systems etc.

Using micro-hydropower (MHP) technology in water pipelines and other water infrastructure has also shown potential (Gaius-obaseki, 2010). At points of high excess pressure in water supply networks, energy may be recovered using MHP technology without interfering in the water supply service (McNabola *et al.*, 2011). However, while significant potential is reported in the literature, only limited implementation of this concept has been put in place by the water industry.

This paper presents a review of energy consumption and CO_2 emissions in the water industry. In addition, an assessment of the opportunities and challenges for the recovery of energy using MHP systems is outlined. This review and assessment incorporates the technical, economic, environmental and organisational perspectives which influence the potential of this energy recovery concept.

2. Energy use and CO_2 emissions in the water industry

Globally, 2–3% of energy usage is reported to be associated with the production, distribution and treatment of water (Kwok *et al.*, 2010). In the United States, it is estimated that 5% of national energy consumption is associated with water services. At city level, 30–60% of local government expenditure has been reported to be associated with water services, where the energy consumption requirement thereof is the single largest expense within budgets. Energy prices are rising and their effects on the cost of water supply have been highlighted in literature (Zilberman *et al.*, 2008).

The water industry is the fourth most energy intensive industry in the United Kingdom, responsible for 5 million tonnes of CO_2 emissions annually and consuming 7.9 TWh of energy in 2006/7

(Environment Agency, 2009a, b). In Brazil, 60–80% of water industry costs are reported to be associated with the distribution of water; consuming an estimated 9.6 TWh annually at a cost of approximately US$1 Billion (c. €770 million) or 14% of the annual Brazilian electricity budget (Ramos *et al.*, 2009). In much smaller economies, such as Ireland, the operation of the water industry has been reported as costing over €600 million annually (Zhe *et al.*, 2010). **Q1**

In developed countries, the distribution of water typically accounts for 45% of energy use in the industry (Kwok *et al.*, 2010). Indeed, the pumping of water in California is reported to be the largest single use of electricity in the state (Lofman *et al.*, 2002). Water is heavy and its transport over long distances against large rises in elevation is expensive and energy-intensive. The remaining portion of energy consumption in the water industry is consumed in wastewater management (29%) and water treatment (26%). It has been estimated that 0.8 kWh of energy is required per cubic metre of wastewater treated in Norway, twice the amount of energy required to supply the same volume of drinking water (Venkatesh & Brattebø, 2011).

The increasing political efforts to improve water quality across the globe have seen water service companies invest in high-tech, energy-intensive treatment facilities. Indeed, the ever increasing stringency of, for example, the EU water quality directives has served to increase the energy consumption of the water industry over the past decade (Zakkour *et al.*, 2002a). These rising monetary and energy costs in the water industry require intensified research efforts to improve the sustainability of the process overall.

As outlined earlier, the water industry is increasingly exploring the use of MHP as a means of energy recovery. The best available estimate of the hydropower potential in the UK water industry for example is 17 MW (Zakkour *et al.*, 2002b), with a capacity of 9 MW installed at present (Howe, 2009). The following subsections outline reported research findings of energy recovery using MHP.

3. Energy recovery in the water industry

3.1. MHP systems

MHP systems comprise a means of converting the energy of flowing fluid into mechanical and subsequently electrical energy on a small scale (<100–300 kW). These systems may be suitable for providing energy for a typical house or small community depending on the magnitude of the fluid resources available. As such, MHP could be considered as a form of decentralised hydroelectric energy conversion. The energy available from a particular MHP installation is a function of the fluid flow rate and available head at that particular site. It is also a function of the efficiency at which the available energy resource may be converted to electrical energy, commonly in the range of 50% to 75% depending on turbine type and flow/head conditions. The costs of MHP installation are reported to be in the region of €3,000–6,000 per kW (Gaius-obaseki, 2010).

These systems have been installed in numerous locations across the globe and have been particularly popular in developing countries; with tens of thousands of such installations in countries like China, Nepal, Sri Lanka and other East Asian and African countries (Khennas & Barnett, 2000). In recent years, MHP installations in western countries have also become more widespread. Sites in which it is technically and economically viable to produce hydropower on a large scale have become increasingly scarce. In addition, the reduced environmental impact of MHP and the lower associated costs (which made it popular in developing countries) have increased its attractiveness (Da Silva *et al.*, 2011). Furthermore, the international focus on energy sustainability and climate change has been a driver in this activity.

3.2. Origins of MHP energy recovery in the water industry

Some of the earliest published records of research in this area were carried out by Williams (1996), who identified the scope for MHP use as a form of energy recovery in water pipelines. It was identified that there are many instances in water supply networks where control valves are in place to manage downstream pressure. Here the installation of a MHP turbine could achieve the same reduction in pressure required while simultaneously recovering some of the available energy (Williams *et al.*, 1998). Thus energy could be generated for use by the water service provider without reducing the level of service to consumers and reducing the cost of water production and supply.

This hypothesis was tested at a control valve, acting as a pressure management control in a water supply system in the UK. The control valve was located in the vicinity of an isolated new chemical dosing plant which required 4 kW of power for operation. The available resource of 50 l/s and 36 m of head was sufficient to recover an estimated 17 kW of power. As this exceeded the local energy demand, an energy recovery MHP scheme was constructed whereby only a proportion of the flow was diverted through the turbine, sufficient to generate the 4 kW required by the chemical dosing plant. With the total investment in this energy recovery infrastructure costing €44,000 and also saving the expense of a connection to the grid (estimated at €62,000), the scheme was an obvious success.

Other similar installations are known to pre-date this example, with energy recovery installations in Germany (Mikus, 1984) and Scotland (Williams, 1996). In Vartry reservoir, Ireland, a MHP system was put in place in 1947 to recover energy from flow between an upper storage reservoir and the treatment plant below. The MHP plant was later decommissioned and the belt driven Pelton turbine was recently upgraded in with a 90 kW plant, generating sufficient energy to operate the works and sell the excess to the grid (Figure 1). Such cases are commonplace at older water storage and treatment facilities, whereby older MHP turbine technology was sufficient to meet the power demands of treatment facilities in the earlier parts of the 20th century. However as water treatment regulations became more stringent and hence more energy intensive, many of these hydropower installations were no longer fit for purpose and fell into disrepair. With later advances in turbine technology and overall plant efficiencies, as well as the introduction of renewable energy Feed-in Tariff (FIT) schemes to incentivise MHP production, many schemes have since been refurbished.

Clearly, a precedent for the recovery of energy in water supply systems using MHP has existed long before international pressures on renewable energy, sustainability and climate change arose. However, in response to these, renewed focus on this concept is emerging in the literature. Furthermore, of those hydropower installations in the water industry today, the vast majority could be described as the ‘low hanging fruit’ of the total pool of potential resources available. It is likely that many suitable sites for energy recovery exist within the water infrastructure but that their potential remains untapped.

3.3. Energy recovery in water supply and wastewater infrastructure

Investigations examining the recovery of energy in water supply and wastewater systems have included studies on pressure reducing valves (PRV), control valves, break pressure tanks (BPTs),

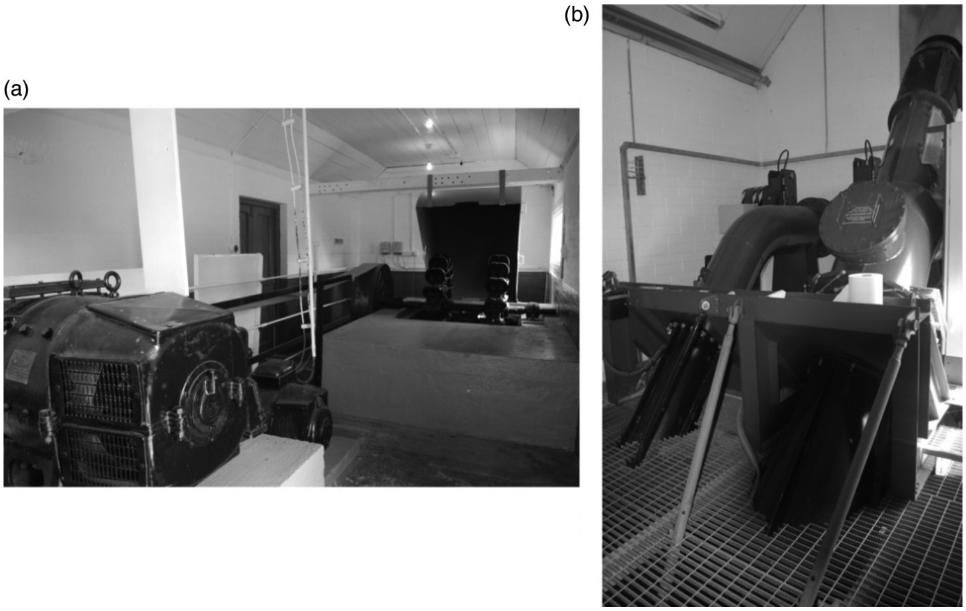

Fig. 1. (a) 90 kW MHP energy recovery system (1947) Vartry Reservoir, Ireland; (b) 90 kW MHP energy recovery system upgrade, Vartry Reservoir, Ireland.

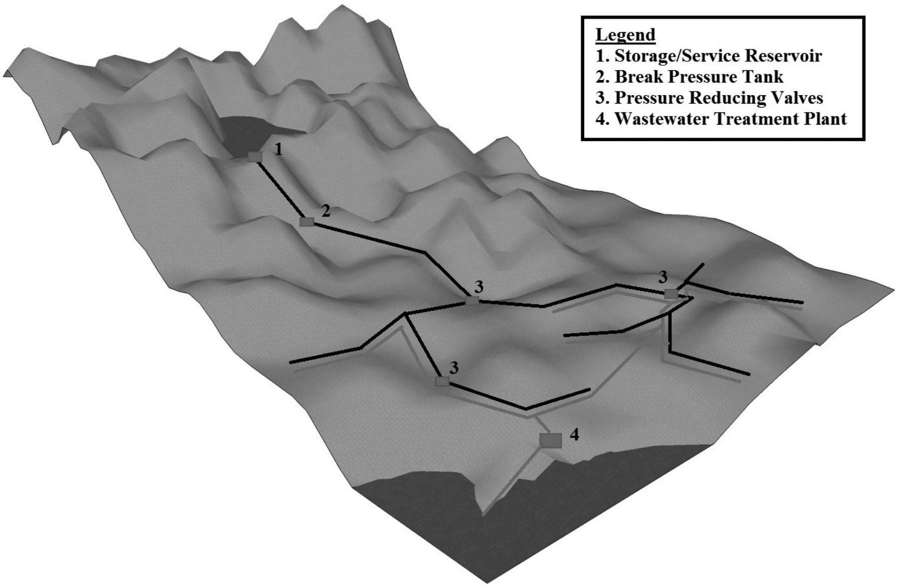

Fig. 2. Locations with energy recovery potential in the water and wastewater infrastructure.

storage/service reservoirs and wastewater treatment plants (Gaius-obaseki, 2010). These locations for energy recovery can be seen in Figure 2 and information regarding these locations are discussed in the subsequent subsections with information regarding case studies summarised in Table 1.

Table 1. Research findings from literature dealing with energy recovery in water and wastewater infrastructure.

	Research studies			
Location	No. of sites	Location	Potential kW energy recovery (mean, range)	Other information
Water supply infrastructure				
Storage/service reservoirs	1	Portugal	260, –	120 m^3/day mean flow, €113,800 per annum (Ramos *et al.*, 2009)
	3	Ireland	67, 12–115	Potentially generating €144,000 annually from electricity (McNabola *et al.*, 2011)
Break pressure tanks (BPTs)	7	Ireland	12, 2–27	Economic feasibility omitted long-term uncertainties of flow and energy output (McNabola *et al.*, 2011)
Pressure reducing valves (PRVs)	6	US	83, –	Produced 5–15 kW of predicted 35 kW (Rentricity, 2007)
	23	Brazil	10, 2.6–40	50–110 mm pipes, efficiency of 90% over-estimation, flow and pressure variations omitted (Da Silva *et al*, 2011)
	1	Italy	9.5, –	Low installation costs and no long-term sensitivity analysis (Giugni *et al.*, 2009)
	–	Canada	–	Feasibility study identified uncertainties: long-term growth, diurnal and seasonal demand variations, pipe frictions and future costs. Probabilistic framework suggested (Colombo & Kleiner, 2011)
	30	Ireland	8.5, 0.1–47	Annual average flow used overestimates potential (Corcoran *et al.*, 2012)
Wastewater infrastructure				
Wastewater treatment plants	1	Switzerland	210, –	Demonstration project using PAT from sewage outfall (Williams *et al.*, 1998)
	1	India	190, –	Economically viable turbine installation at sewerage storage plant on University campus (Saket, 2008)
	1	Australia	1,370, –	330 Ml/day and 60 m head to deep sea outfall and annually generates 12 GWh of electricity and offsets 80,000 tCO$_2$e (EcoGeneration, 2008)
	1	UK	180, –	Two parallel Archimedes screw turbines, saving €160,000 in annual electricity costs (Engineering & Technology, 2010)
	1	UK	177, –	3.3 km sea outfall and 40 m head, 149–193 kW range due to turbine efficiency and tidal flows. €560, 000 cost, €11,000 in annual generation, reliable system bypass necessary (Griffin, 2000)
	1	Ireland	133, –	One feasible site at largest treatment works in Ireland (Power *et al.*, 2012)

3.3.1. Pressure reducing valves. PRVs aim to reduce the pressure of flow passing through them to a preset level. Their use in the water industry has become widespread in response to drives to reduce leakage losses in the system through pressure management. The installation of PRVs also prevent exceedances in downstream hydraulic grades (Fontana *et al.*, 2012). PRVs are a more versatile solution to pressure control than their predecessor, the BPT. Owing to their size, likely higher costs and increased risks of water contamination, the BPT has become a less popular design solution. In addition, PRVs offer the additional functionality of reducing pressure to a range of values as opposed to a single value in the case of a BPT.

Replacing a PRV with a MHP turbine has been shown in the literature to be a feasible mechanism of both reducing pressure and recovering useful energy in certain circumstances. Placing a MHP turbine in parallel with a PRV and bypassing the valves allows system operators to recover energy while maintaining the integrity of the water supply system should the turbine break down (Wallace, 1996). In the US, a commercial assessment of 6 PRV sites reported an estimated energy recovery potential of 500 kW. A demonstration plant was subsequently constructed at one of the sites, however the completed MHP installation produced just 5–15 kW, lower than initial estimations of 35 kW (Rentricity, 2007).

An investigation of the energy recovery potential of 23 PRVs in Brazil found a mean energy recovery capacity across the valves of 10 kW with a range of 2.6–40 kW (Da Silva *et al.*, 2011). The majority of these PRVs were in place on 50 mm internal diameter (ID) pipelines where the mean energy recovery capacity was typically 8 kW. One PRV in the dataset was in place on a larger 110 mm ID pipeline which was estimated could produce over 40 kW of electricity. However, the 90% system efficiency used in this investigation could be considered an optimistic value if it is to take account of all system losses. Furthermore, this investigation and many others of this nature failed to account for the variation in flows and pressure which are likely to occur across a typical day, week and seasonally. Thus, such estimates of energy potential do not present the full picture and may overestimate the scale of the resource.

An investigation of a PRV in a section of the water supply network in Napoli, Italy estimated an energy recovery potential of 9.5 kW (Giugni *et al.*, 2009). However, the estimates of cost were considerably lower than those adopted by the majority of investigations in this field. Furthermore, no consideration was given to the long-term uncertainty in any of the influencing variables of the Hydro-PRV system, such as flow, pressure, energy prices, etc.

A Canadian study examined the feasibility of MHP within the water distribution network from a probabilistic perspective in order to address the issue of demand variation (Colombo & Kleiner, 2011). A number of other potential uncertainties were flagged, including, long-term demand growth, diurnal and seasonal demand variations, pipe friction coefficients and future cost fluctuations. They concluded that because demand is uncertain, a probabilistic framework should be used in calculations when deciding on the viability of a micro-turbine installation.

In Ireland, Corcoran *et al.* (2012) examined the potential of 30 PRVs and control valves for energy recovery purposes. The existing PRVs were found to have a mean potential for energy recovery of 8.5 kW based on average flow and head conditions, while results varied from 0.1–47 kW. Examination of the potential of the existing control valves showed higher energy potential with a mean of 94 kW. However, it was also highlighted by the authors that the likely energy recovery potential at such water infrastructure based on yearly average flow and head data may be misleading. It was noted that flow, head and turbine efficiency vary considerably as would the subsequent power production.

3.3.2. Break pressure tanks. BPTs offer a similar functionality to a PRV. However the BPT reduces pressure in a pipeline by creating a break in the system where the flow is open to the atmosphere. When this occurs all the pressure that had built up in the pipeline is dispelled to the atmosphere and the continuation flow is driven by its potential energy from the break point onwards. For energy recovery purposes, a MHP turbine may be installed prior to the break point to recover energy without interfering with the level of pressure in the system downstream of the BPT.

An investigation in Ireland examined the energy recovery potential of seven existing BPTs (McNabola *et al.*, 2013). It was reported that the mean energy recovery potential was 12 kW (range 2–27 kW). Several of the BPTs examined were found to be financially viable as hydro energy recovery installations, however, again these estimates failed to address the long-term uncertainty in flow or energy related system variables.

In addition to the earlier observations on flow variation, many investigations have also omitted the variation in turbine and system efficiency with flow rate and pressure resulting in further inaccuracies in estimations. Furthermore studies of this nature have also failed to address the long-term reliability of such energy recovery systems. MHP installation in a water supply network may be at risk of significant changes in flow and pressure conditions from the original design values. Should a new water demand arise upstream of a PRV or BPT, then flow and pressure may be significantly altered, rendering the MHP installation no longer viable.

3.3.3. Storage/service reservoirs. Storage or service reservoirs in this context comprise water storage infrastructure. Service reservoirs are typically used in a water supply system to balance the diurnal demands in a section of the distribution network while storage reservoirs are used to feed a large portion of the entire network by gravity. Service reservoirs are commonly fed by gravity but many storage reservoirs are fed via pumped mains and would be unsuitable for energy recovery in this context.

A study in Portugal of an interconnector main flowing by gravity between two reservoirs found that for a mean flow of 120 m^3/day over a drop in head of 22.5 m, the annual energy production would amount to 2.28 GWh (i.e. a 260 kW plant). The value of this energy recovery was estimated at €0.05/kWh, equating to €113,800 per annum (Ramos *et al.*, 2009). A similar investigation in Ireland, which considered a number of service reservoirs, estimated the recoverable energy at 12–115 kW depending on the particular tank in question. The reservoir with the highest energy capacity was estimated to have the potential to generate over €144,000 annually in electricity (McNabola *et al.*, 2011).

Of the available estimates in the literature, service reservoirs have shown the highest energy recovery potential in many cases, followed by BPTs and PRVs. However, in many cases the return on investment estimation has not accounted for FIT incentivisation, available in many countries, or the savings costs of electricity to the water industry (including all taxes and charges) as opposed to the unit price.

3.3.4. Wastewater treatment plants. The flow of sewage effluent can also be directed through a penstock under pressure, through a MHP turbine to recover energy in wastewater treatment infrastructure (Gaius-obaseki, 2010). This can be carried out at treatment works outfalls or inflows; and the inlet to pumping station wet wells or in sewer mains where sufficient flow and pressure is available.

Investigators have reported on the feasibility of sewage-treatment outfalls for energy recovery using pumps as turbines (PATs). For example, a demonstration project built in 1993 in Switzerland used a PAT to produce up to 210 kW of electrical power from a sewage outfall (Williams *et al.*, 1998). In **Q2** India a demonstration energy recovery plant has been constructed on a sewage storage tank located on a University campus. Although the plant capacity was reported as just 190 W, the project was still deemed economically viable (Saket, 2008).

However, more notable and successful examples of energy recovery at treatment works outfalls can be seen in Sydney, Australia. Here wastewater flow of 330 Ml/day (dry weather flow) over a 60 m drop in head at a deep sea outfall has been used to recover energy, generating approximately 12 GWh annually. It is estimated that the plant will offset 80,000 tonnes of CO_2 emissions annually as a result of this energy recovery (EcoGeneration, 2008).

In the UK, an Archimedes screw turbine has been installed to recover energy from the outfall pipe of a wastewater treatment plant. Two turbines in series are reported to produce a total of 180 kW, saving the water service provider €160,000 in annual electricity costs (Engineering & Technology, 2010).

Similarly an energy recovery feasibility study was carried out at another wastewater treatment plant in the UK, which included a 3.3 km long sea outfall pipe with a 40 m drop in head (Griffin, 2000). **Q3** The mean energy potential at the site was estimated to be 177 kW, within the range 149–193 kW. Energy production estimates varied with the diurnal variations in dry weather outflow from the treatment works. The effects of variations in turbine efficiency and tide levels were also included in the analysis as was the design of the plant and a suitably reliable bypass system. The investigation estimated a capital cost of €560,000 but an income from electricity generation of approximately €11,000 per annum.

In Ireland, the feasibility of MHP energy recovery at a number of wastewater treatment plant outlets was also examined. Low heads were reported for the majority of plants investigated resulting in only those with significant daily flow demonstrating useful potential (Power *et al.*, 2012). The largest energy recovery potential was reported as 133 kW at the country's largest wastewater treatment facility.

No studies were found which examined the feasibility of energy recovery using MHP at the inlets to pumping station wet wells or in large sewage collector mains. Further research in this area is required to gauge the feasibility of such operations.

3.4. Variability of energy recovery potential

As previously noted, the potential of energy recovery in the water infrastructure is dependent on a number of factors; in particular the flow and pressure characteristics evident at each site (McNabola *et al.*, 2013). As population growth has led to increased demands of the water industry, the infrastructure, that is, the locations and number of water and wastewater treatment facilities, and the continuous evolution of the distribution networks provide a significant challenge to quantify the potential energy recoverable. An example of this is the replacement of BPTs with PRVs, or BPTs becoming surplus to requirements with the optimisation of water flow and pressure characteristics in the water infrastructure.

In addition, it should also be noted that the service life of the water infrastructure has also recently been highlighted as a challenge (Scholten *et al.*, 2013), as it could affect the potential for MHP energy recovery. Water properties also vary depending on source and treatment type. Such properties (e.g., low pH, or high pressure pipe networks (Engelhardt *et al.*, 2000)) could affect turbines installed within some networks and hence affect energy recovery potential. However, particular issues such as 'aggressive water' are likely to reduce as: (i) older iron-based pipe networks are or have been replaced, and this reduces corrosive particles in the networks; and (ii) most MHP sites are within the treated water distribution networks, and the latest WHO (2008) *Guidelines for Drinking-water Quality* report ensures that the water is of a defined quality to minimise particles.

3.5. Hybrid systems

Some of the strategies that have been investigated and proven to achieve energy savings in the water infrastructure include: water network optimisation models (Vieira & Ramos, 2009a, b), renewable energy systems used in pumped storage systems (Ramos & Ramos, 2010) and energy recovery using turbines connected to the water infrastructure (Ramos & Ramos, 2009; Carravetta *et al.*, 2012). These strategies have also been considered as a collective or hybrid set of improvements to improve the sustainability of water distribution networks (Gonçalves *et al.*, 2011; Ramos *et al.*, 2011), and have been investigated and **Q4** implemented by Gonçalves & Ramos (2012) and Gonçalves *et al.* (2011) using a neural network model. **Q5** The conclusions from these studies found that a hybrid approach to achieving sustainability in the water industry has more impact than any individual energy optimisation or recovery strategy.

3.6. Economic viability

The economic viability of MHP energy recovery systems in the water industry is the key question which remains to be comprehensively addressed in literature. Numerous research investigations, as listed above, highlight the existing or theoretical energy potential of various water infrastructure sites, but fail to examine the potential variation of such average energy potential estimates (Da Silva *et al.*, 2011). Water flow and pressure are known to vary significantly throughout a typical day, from day to day, weekday to weekend, by season and over the longer term. Water flow and pressure are also subject to significant changes due to the addition of new industries, new demands, water charging or water saving schemes, etc. Such changes in flow and pressure would have a significant influence on the efficiency of a turbine converting the excess energy to electricity.

Turbines are typically designed for a particular design flow and variations as either increases or decreases in flow and head will reduce power production. The extent of the reduction will depend on the magnitude of the change in flow conditions and the type of turbine in question. For example, a 50% increase or decrease in the design flow for a PAT would result in a reduction in energy conversion efficiency from typically 80% to less than 30%. PATs have been cited in several investigations as a suitable turbine for energy recovery in water pipelines (Williams, 1996; Williams *et al.*, 1998; Giugni, *et al.*, 2009). Changes in the average flow in a water pipeline of 50% or more is a common occurrence in water supply networks.

Aside from the aforementioned technical limitations in existing feasibility studies, sufficient scrutiny of the economic viability, in terms of revenue generation, is also lacking in many studies. Many investigations determine the annual return from a MHP installation using the unit price of electricity or using the local FIT rate of hydropower generation (Ramos *et al.*, 2011). However the economic viability of such installations is influenced to a very significant degree by the end use of the electricity generated. Plants which use the electricity on-site will make a saving on electricity purchases at market rates while plants which sell the electricity to the grid will do so using the local FIT rate. The savings electricity purchases includes not only the unit price but also any taxes or duties applied to the supply of electricity such as sales tax, value added tax and carbon tax. Many studies fail to account for the actual cost to the water industry of electricity savings including all taxes and charges. Furthermore, studies also fail to determine the effect on plant feasibility of future changes in energy prices. Electricity prices vary significantly across Europe, for example from as little as €0.08/kWh in Bulgaria to as much as €0.29/kWh in Denmark.

For plants which have no use for electricity generated on site, selling to the grid will provide a longer return on investment as FIT rates are often lower than consumer price of electricity including all taxes and charges, but higher than the market rates. Again FIT rates vary significantly across different countries and previous investigations have failed to examine the sensitivity of proposed energy recovery sites to the value of the FIT rate.

4. Environmental impact

Primary environmental concerns in relation to the water industry relate to the depletion of freshwater resources and pollution arising from wastewater treatment. The availability of freshwater resources vary widely, for example within the EU, it ranges from less than 1,000 m^3 per capita in the Czech Republic and Cyprus, to over 20,000 m^3 per capita in Finland and Sweden (Eurostat, 2012). It is projected that climate change will reduce the availability of freshwater in lower mid-latitude regions such as the Mediterranean and increase the frequency of severe droughts (Gössling *et al.*, 2011). According to the UNEP **Q6** (2002), one-third of the world's population currently live in countries suffering from moderate or high water stress (where water consumption is more than 10% of renewable freshwater resources), and this is projected to increase to two-thirds of the world's population by 2030. An important environmental impact from the water industry is the consumption of energy, usually entailing the depletion of non-renewable resources (fossil fuels), and associated greenhouse gas (GHG) emissions (Rothausen & Conway, 2011).

A carbon footprint is a measure of the total amount of GHG emissions, expressed as CO_2 equivalents (CO_2e) according to their global warming potential, that result from an activity or series of activities involved in the life cycle of a product or process (Shrestha *et al.*, 2012). Most of the energy used by the water sector is in the form of electricity, with an associated carbon footprint of between less than 0.1 kg CO_2e/kWh for nuclear and renewable generated electricity to over 0.9 kg CO_2e/kWh for coal generated electricity. Average emission factors are 0.38 and 0.57 kg CO_2e/kWh, respectively, for the EU27 and US (DEFRA, 2011). The water industry in the United States is responsible for 5% of total US carbon emissions annually (Griffiths-Sattenspiel, & Wilson, 2009). In the UK, emissions associated with water supply and treatment are estimated to average 0.34 and 0.7 kg CO_2e/m^3, respectively, totalling 5.01 Mt CO_2e/year in 2010/11 (Water UK, 2012); equivalent to approximately 1% of UK GHG emissions. In Italy, investigations have estimated that the carbon footprint of public water supply is 0.9 kg CO_2e/m^3 (Botto *et al.*, 2011). Energy consumption and GHG emissions from the water industry are related to local freshwater availability. In regions where demand exceeds availability from freshwater resources, freshwater is pumped long distances from regions of water surplus, or produced from desalination, incurring considerable energy consumption and GHG emissions. The carbon emissions associated with the water industry worldwide are likely to grow if current trends are not reversed due to: rising water demand; limited and remote locations of fresh water; more stringent and energy intensive water treatment regulations and technology.

Investigations have highlighted the effects of numerous water management and water supply scenarios on the carbon footprint of specific systems. An investigation in the US compared five water management scenarios to the baseline scenario and found that the carbon footprint of existing water services in Las Vegas was 0.84 million tonnes CO_2e per annum. It was also found that increases in demand for water could increase this figure by over 12% by 2020, and that increasing renewable energy input could reduce emissions by over 20% (Rothausen & Conway, 2011). In Florida, US, a similar investigation examined the effect of twenty water infrastructure expansion alternatives on the carbon footprint of the service (Qi & Chang, 2012). The investigation examined the expansion of the Manatee County water supply system in the period 2011 to 2030 using options such as exploiting further ground water, surface water, transferring regional water and others. Transferring raw water from regional sources was estimated to result in the highest carbon footprint of 2.26 million tonnes CO_2e over the assessment period. However, no investigations have been found during this review which examined the effects of widespread implementation of MHP energy recovery on carbon footprints in the water industry. Further research is required to investigate the potential impact of this on the water industry.

Within the UK, the water industry does contribute to national GHG emission reductions through renewable energy generation. In 2010/11, 877 GWh were generated by the UK water industry (Water UK, 2012), equivalent to a saving of approximately 0.521 Mt CO_2e. Over 90% of this energy is sourced from anaerobic digestion in wastewater treatment plants, suggesting that renewable energy generation (or at least energy capture) from the supply network may be underexploited. Capturing energy from the supply system could help the UK water industry meet its proposed target for 20% of energy to be sourced from renewable sources, which would exceed the advised 15% target set out by the government for 2020 (Environment Agency, 2009a, b). Investigations have also highlighted the equivalent CO_2 emissions savings of a number of potential sites or demonstration projects. In Ireland, an investigation of seven BPTs and three service reservoirs estimated a potential CO_2 emissions saving of 1,350 tonnes annually (McNabola *et al.*, 2011).

5. Organisational challenges

For an energy recovery project to be implemented within the water industry, it is necessary for a number of stakeholders to come together, such as local government, water utilities, electricity suppliers and regulators, turbine manufacturers, etc. Effective collaboration between this network of organisations will ensure the successful, cost- and time-effective implementation of such schemes. The development of a strong collaboration network from an early stage could also increase and encourage future collaborative projects to be implemented. In a recent paper by Gausdal & Hildrum (2012), a process-based framework for the development of inter-firm networks in the water technology industry was established. It outlined how the researchers facilitated group meetings, encouraged dialogue and promoted action from dialogue with a focus on trust building among the network. **Q7**

To encourage collaboration between different organisations in the water and energy industries it is necessary to first investigate and understand these organisations, including both their structure and characteristics and previous collaborative history. Over 90% of the approximately 250,000 water service systems worldwide are municipally owned water and wastewater utilities, while only 8% are privately operated and/or owned (Kwok *et al.*, 2010). The water industry comprises asset owners, operators, engineering specialists (design and constructions), and suppliers of equipment. On the supply side the industry includes the following technologies: water filtration membranes, UV radiation, biological water-cleansing processes and energy efficient recycling of sludge and industrial wastewater. On the demand side, the customer base includes waterworks, sewer plants and construction firms. There is a significant growth potential in this industry as the global demand for clean water and the need for energy-efficient water purification increases.

Within the boundaries of the industry, the networks of firms may collaborate on joint research and development (R&D) projects and enhanced water-cleansing technologies. However, there may not be a history of trust to enable firms to engage in progressively more complex and risky collaboration activities. The challenges of the need for development and innovation translate into the need for collaboration among firms in the industry and, even, the establishment of new firms to exploit the new technologies. This collaboration requires trust and can take time to emerge (Coughlan & Coghlan, 2011).

The evolution of networks of firms, with contractual bases for their relationships, brings to mind the twin concerns of competition and collaboration (Coughlan & Coghlan, 2011). Competition comes easily to firms whose focus is on the market. Further, collaboration comes (relatively) easily to firms who have an interest in a relationship. Where it becomes difficult is where the improvement imperative requires both collaboration and competition. Then market-based relationships need to be re-visited in an environment of potential reconciliation, a search for sustainability and a reduction of risk. Here, working to achieve sustainable strategic improvement and a corresponding transition from a strategic to a learning and transformational network is a problem, the resolution of which requires time and thoughtful application of resources.

Further research in this field is required to develop a model of organisational collaboration between the water and energy industries. This may then facilitate the more widespread implementation of energy recovery technology in water infrastructure.

6. Discussion and conclusions

It can be seen from the available literature that energy recovery using MHP in the water industry is a growing area of research and industrial activity. Many successful demonstration projects are in existence and many promising feasibility studies have been carried out. However, to date the examples in existence have been implemented on an ad hoc basis and little market penetration of this concept has occurred (Zakkour *et al.*, 2002b).

From the review, it is clear that further research is required in a number of key areas. Future research should aim to address the uncertainties which exist due to the variation in water demands daily, weekly, seasonally and in the longer term. These should also address the sensitivity of projects to changes in electricity prices and/or FIT rates. Such uncertainty creates an unacceptable risk to investment in MHP infrastructure if design conditions are open to significant change during its lifetime. These uncertainties may be part of the reason why, given the vast number of suitable sites identified in the literature, only a small number of MHP installation are in existence in the industry.

In addition, more detailed information on the investment costs are required to facilitate the growth of this sector. Many studies to date have used cost estimates for MHP construction, however the expenses associated with consulting, planning, connection to the grid, maintenance, etc., are often neglected. In essence, a more transparent and reliable model of energy recovery potential and return on investment is required for MHP energy recovery to prosper.

The environmental impact of the water industry, its carbon footprint and energy consumption have all been shown to be globally significant. Studies have set out to examine means of limiting or reducing the carbon footprint of the water industry, but none have included the option of the widespread implementation of MHP energy recovery systems. Quantification of the carbon footprint of MHP energy recovery in the water industry in comparison to other methods of energy saving or generation is an important missing element in the development of this concept. It has been noted that the water industry has a range of options through which it may choose to reduce its energy demand such as wind or solar power and biogas combustion. The selection of such investment options should be informed by both the economic viability of a potential scheme and the environmental benefits of the various alternatives.

It has also been shown that the need exists for the development of collaboration models between the water and energy industries to facilitate a more widespread implementation of MHP energy recovery in water infrastructure. The governance, regulation and organisation of the water industry across jurisdictions is diverse and complex. The structure of these organisations influences the ability of the water industry to deliver on sustainable strategic improvements such as MHP energy recovery. Collaboration models shedding light on the operation of these large sets of organisations may enable the development of more effective policy to promote the implementation of MHP energy recovery in future. This together with more dissemination of research findings to industry and policymakers may act as a catalyst for the improvement of the sustainability of the water industry.

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