The Technical & Economic Feasibility of Energy Recovery in Water Supply Networks

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Abstract. Water supply is a core service on which civilised society depends. It involves considerable energy consumption and, as a result, CO_2 emissions (in water treatment, pumping and monitoring) and economic costs. Treated water is most commonly supplied from a central storage reservoir by gravity throughout a catchment and this water must be supplied within satisfactory pressure bands. Where the pressure in water flow becomes too high, a Break Pressure Tank (BPT) is commonly installed in the network, whereby the pressure, kinetic and potential energy within the flow is dissipated to the atmosphere. These BPTs present an opportunity to recover energy from water supply networks by means of a hydropower turbine system, thereby improving the sustainability of the network without interfering with the water supply service. This paper presents the results of a preliminary technical and economic feasibility assessment of the energy recoverable from BPTs.

Key words

Energy Recovery, Water Supply, Hydro-power, CO_2 emissions, Sustainability.

1. Introduction

The supply of treated water in the western world is likely to be an unsustainable process in its current form. Considerable amounts of energy consumption and CO_2 emissions are inherent in the various treatment processes and supply processes involved. With the increasing global awareness of the impacts of energy consumption and CO_2 emissions on climate change, humankind, finite resources and the environment as a whole, efforts to reduce consumption and emissions in all sectors of society are underway.

The sustainability of the water supply process and its interaction with climate change has been shown to be of concern on a global scale for large urban centres (Jenerette & Larssen, 2006). Recent research in the water supply industry has identified key research questions in the area, such as: 'how do we develop and implement low energy water treatment processes' and 'can we optimise water supply within catchments' (Browne et al., 2010).

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 schemes; rain-water harvesting schemes; water metering and other water conservation policies (Rygaard et al., 2011).

Methods to reduce the energy consumption of individual water treatment and supply processes have also been investigated. These include the capture of by-products such as biogas for use in combined heat and power facilities, thereby reducing the energy needs of the treatment/supply process (Hernandez Leal et al., 2010). In addition the recycling of dried sludge pellets in co-firing combustion systems to produce energy has received attention in literature (Park and Jang, 2010).

This paper outlines the preliminary investigations of the Hydro-BPT project which is investigating another approach to reducing the energy consumption of the water supply process through the recovery of energy wasted in break pressure tanks (BPTs) on water supply distribution networks.

2. Technical Feasibility

A. Hydro-BPT Concept

Water supply distribution networks are designed under a number of criteria, including pressure. Water pressure within a water supply distribution system is required to fall within an upper and lower design limit. Too little pressure provides and unsatisfactory level of service to consumers and too high pressure increases the risk of burst pipes and water leakage losses. A BPT is installed in a water distribution network where the pressure in the pipelines is too high.

Figure 1 below illustrates a typical water supply scenario where a BPT becomes necessary. A large drop in elevation between the main supply reservoir and majority of the distribution system produces an excessively large static pressure. This can then be reduced by a BPT appropriately located to maintain pressure within the desired upper and lower limits. A BPT is designed to reduce the pressure in the pipeline by dissipating the pressure and kinetic energy contained in flow at any point. This is done by creating a break in the pipeline where water is spilled into an open (unpressurised) chamber. From this chamber the water flows on to the rest of the distribution network where only the potential energy of the flow is left due to the break in the system. Figure 2 illustrates the typical layout of a BPT. Once water flows past the break pressure point the pressure and kinetic energy it contained is dissipated in the well below.

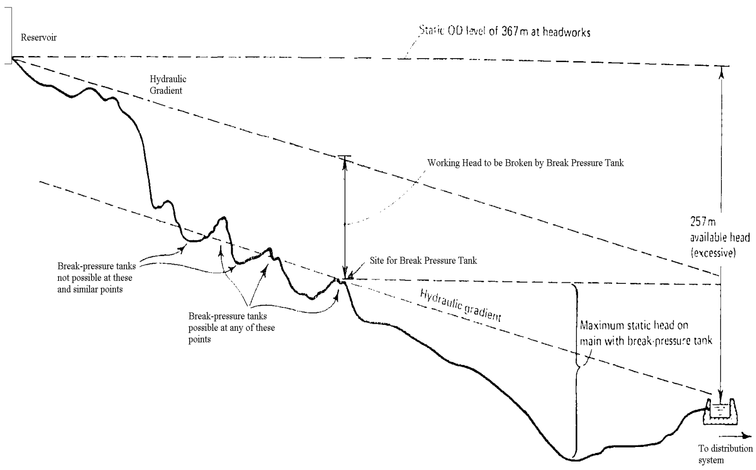

Fig.1 Typical scenario where break pressure tank becomes necessary (Gray, 2010)

Many BPTs are in existence in water distribution systems around the world today but as previously outlined the increasing need to improve the sustainability of water supply highlights the potential benefit of BPTs as an outlet for energy recovery in supply systems. Through the incorporation of a hydropower turbine at, or slightly upstream of, the break pressure point illustrated in Figure 2, significant potential for energy recovery exists.

For ease of terminology, the addition of a hydropower turbine and a break pressure tank for energy recovery purposes shall be termed a Hydro-BPT.

B. Energy Potential

The size of a BPT and the energy recoverable from it depend greatly on the flow and pressure in the water distribution system at any given point. The power output from a hydropower turbine can be estimated from equation 1:

$$P = Q\rho g H e_o \qquad (1)$$

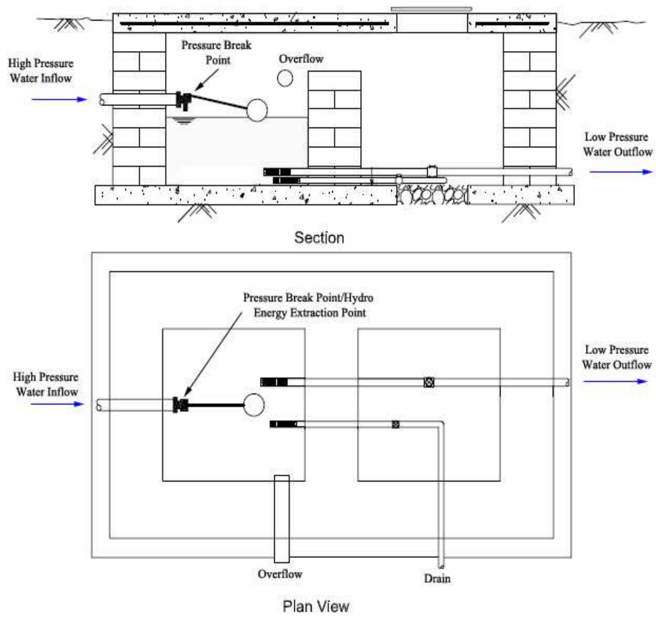

Fig.2 Typical Break Pressure Tank

Where P is the power output, Q is the flow rate through the turbine, ρ is the density of the fluid (water), g is acceleration due to gravity, H is the head available at the turbine and e_o is the efficiency of the overall power generation plant. The plant efficiency accounts for losses in energy during conversion from kinetic energy to mechanical energy to electrical energy and can be conservatively estimated at approximately 65% (including turbine losses, energy transformation & distribution losses). The density of water and acceleration due to gravity are known constants.

The flow (Q) and head (H) at any existing BPTs around the world are therefore the key variables in determining the usefulness or otherwise of the energy recoverable at a particular site. For the purposes of conservative estimation we could assume that pressure in the incoming flow at a BPT is equal to the typical maximum allowable design value for water supply of 6 bar which is equivalent to 61.2m of water or 600kPa. 6 bar is typically taken as the upper limit of pressure within a water distribution system to avoid water leakage and/or bursting water mains.

Therefore for a hypothetical Hydro-BPT with an incoming pressure at the maximum allowable design value the power output equates to 390,241.8 times the flow rate. If we assume that BPTs could reasonably have flow rates in the range of 0.01 m^3/s up to 1 m^3/s then the power output from a Hydro-BPT could be in the range of 3.9 kW to 390 kW.

Clearly if flows in a BPT were lower than 0.1 m^3/s and head was also less than 6 bar then the Hydro-BPT would generate less than 3.9 kW but also if flows and head in a

BPT were higher than the assumed values, power greater than 390 kW could be generated.

C. Case Study

Flow and pressure data were collected from a selection of 7 BPTs located around county Kildare in Ireland. Kildare is a relatively small county with a population of over 180,000 (CSO, 2006), hence its demand for water and the resultant flows in its water distribution systems could be expected to be relatively small compared to those of larger population centres. Table 1 below shows the flow, head and resulting power output estimation for the 7 BPTs investigated.

It can be seen that the energy obtainable from the 7 Kildare BPTs is quite modest with a range of 27 to 2kW estimated. By way of comparison a typical domestic household in Ireland consumes 3000 – 5000 kWh per year and taking the BPT with the highest potential, Old Kilcullen, a 27kW Hydro-BPT at this location could produce approximately 236,520 kWh per year or enough energy to meet the demand of 47-78 homes. The least productive BPT at Ardscull would produce enough energy to power just 3-5 homes.

Name	Pressure (kPa)	Flow (m^3/day)	Power (kW)
Old Kilcullen	200	17,910	27
Castlewarden	190	8,968	13
Allen	600	4,250	19
Ardscull	280	714	2
Ballycagan	600	1,172	5
Ballygoran	200	9,041	14
Redhills	180	2,880	4

Table 1, Flow, Head and Power Estimate for 7 BPTs in Kildare, Ireland.

Flow and pressure data at much larger BPTs in Dublin, Ireland were also collected. Dublin is the capital city of Ireland with a population over 1.6 million (CSO, 2006), hence the demand for water and resultant flows and water infrastructure are much larger than those in Table 1. Table 2 shows the flow, pressure and estimated power output for 3 BPTs in the Dublin area.

Name	Pressure (kPa)	Flow (m^3/day)	Power (kW)
Stillorgan	60	26,400	12
Cookstown	150	64,728	73
Saggart	100	152,760	115

Table 2, Flow, Head and Power Estimate for 3 BPTs in Dublin, Ireland.

The largest BPT shown at Saggart, with an estimated power output potential of 115kW, would have the potential to power 200 to 330 homes. This collection of data demonstrates that some but not all existing BPTs have the potential to produce significant amounts of electricity which could contribute to local energy needs.

D. Retrofitting and New Design challenges

The data in the previous subsection clearly demonstrates that in certain cases the conversion of a BPT to a Hydro-BPT is a viable option producing significant gains in sustainability. However the design of such a system, whether it is a new BPT or retrofitting or an existing tank, must overcome a number of key design challenges:

- System by-pass: the Hydro-BPT system must include a back-up bypass system such that in case of turbine failure the water supply service is not cut-off for consumers.
- Water demand profile: the daily flow of water in water supply systems is known to follow a diurnal pattern i.e. the flow and pressure are not constant and therefore neither would the power generated be constant. Hence a design for a Hydro-BPT must overcome this challenge.

Further research is required to investigate and overcome both of these concerns through modelling and demonstration projects. Once a working design for Hydro-BPTs is complete, this will enable a new approach to be taken to the design of new water supply systems. In the past, BPTs in water distribution networks were to be avoided where possible as they would add an additional structure to the network and hence increase capital and operating costs. However, Hydro-BPTs could be incorporated into the design of new water supply distribution systems and would not impede on the service provided to the water consumer. The additional capital cost of a Hydro-BPT could be offset against the future revenue the system would create through the generation of electricity which can subsequently be sold back to electricity providers.

E. Environmental Impact

Taking the estimated energy obtainable from the 10 BPTs examined in this study, Table 3 shows the CO_2 equivalent emissions savings for each of these quantities of energy on an annual basis. CO_2 emissions equivalents were calculated using UK Carbon Trust conversion factors from kWh to kg CO_2 equivalents from grid electricity (UK Carbon Trust, 2009).

Name	Annual Power (MWh/yr)	CO_2 emissions saving (Tonnes CO_2 equivalent)
Old Kilcullen	236	128
Castlewarden	112	61
Allen	168	91
Ardscull	13	7
Ballycagan	46	25
Ballygoran	119	65
Redhills	34	19
Stillorgan	104	57
Cookstown	640	348
Saggart	1007	548

Table 3, Power and CO_2 emissions saving estimates for 10 BPTs in Ireland.

By taking the 10 BPTs examined, the total annual reduction in energy consumption of the water supply would be 290 kW, which equates to a total annual CO_2 emissions saving of 1350 tonnes. These 10, local examples give an indication of the energy and environmental potential of this concept. Extrapolating these values nationally and internationally could evidently yield significant energy savings and reduced CO_2 emissions.

3. Economic Feasibility

A. Business Model

The economic feasibility of the Hydro-BPT concept requires the development of a business model. Five key elements define such a model: the revenue model; the gross margin model; the operating model; the working capital model; and, the investment model (Mullins & Komisar, 2009). Together, these elements create value for customers, shareholders and others:

The *revenue model* specifies the expectations of how revenue may arise. The *gross margin model* specifies the gross margin or the sum remaining after the expenses directly related to producing or delivering power are subtracted from the revenue. There are two key components in these costs of power sold: cost of materials and labour. The gross margin remaining defines how much money is available to cover operating costs and to contribute to profit and cash flow. The *operating model* is based upon the operating costs incurred in addition to the cost of goods sold. These operating costs or expenses may be fixed or variable. The *working capital model* specifies the cash which an enterprise needs to pay employees and suppliers among others. Expressed differently, working capital is the difference between current assets and current liabilities. Central to the working capital model is the timing of cash flows and the amounts of cash that must be tied up in current assets before any energy is sold. Finally, the *investment model* specifies the investment in facilities and equipment and also in market development activities.

A key part of future work planned will be the development of a business model for the Hydro-BPT concept in these terms. For illustrative purposes, standard electricity rates vary across the globe but, taking Ireland as an example, the typical rate is €0.143 per kWh. The Hydro-BPT concept is closely aligned with that of a micro-hydropower plant where the typical source of renewable energy is a small stream or river and the typical power outputs are less than 200kW. The Hydro-BPT replaces the small stream with piped water but the order of energy output can be seen to be similar. The typical capital costs of a 100kW micro-hydropower plant is in the range of €100,000 to €140,000 and the cost per kilowatt of micro-hydro power, over its expected life (25-50 years), is known to be the lowest of any available source, typically of the order of €0.02 per kWh (BHA, 2005). The capital cost and cost per kilowatt of Hydro-BPTs could be expected to be similar although significantly less civil works would be required in the case of existing BPTs, therefore the capital cost of a Hydro-BPT conversion could be expected to be €65,000 to €85,000. Therefore, if a 100kW Hydro-BPT conversion costing €85,000 to construct produced 876,000 kWh per annum, revenue would equate to over €125,000. Roughly, this conversion would yield an illustrative payback on investment of less than one year.

Based upon the above estimates, Table 4 shows the estimated annual revenue generated by the 10 BPTs examined in this study along with their illustrative payback periods, assuming an €85,000 construction cost in each case. Considering some of the energy potential estimates, it is clear that not all BPTs would be economically viable as Hydro-BPTs. However, Saggart BPT in Dublin demonstrated the highest potential for revenue generation and the shortest payback period. Furthermore, 6 of the 10 BPTs examined had payback periods of less than 5 years and could be considered viable ventures for a water supply authority/company in light of the additional benefits of CO_2 emissions savings and reduction in energy usage. In addition, smaller Hydro-BPTs in terms of kW produced may cost less to construct than a 100kW plant and hence the cost estimate of €85,000 maybe be overly conservative in some of the cases presented in Table 4.

Name	Energy (kW)	Annual Revenue (€)	Payback period (years)
Old Kilcullen	27	33,757	3
Castlewarden	13	16,057	5
Allen	19	24,031	4
Ardscull	2	1884	45
Ballycagan	5	6627	13
Ballygoran	14	17,040	5
Redhills	4	4885	17
Stillorgan	12	14,937	6
Cookstown	73	91,557	<1
Saggart	115	144,052	<1

Table 4, Revenue and payback period estimates for 10 BPTs in Ireland.

B. Collaboration Model

Realisation of the potential of Hydro-BPTs requires the exploitation of new forms of collaboration among the key stakeholders: local authorities, hydropower specialists and engineering researchers. As a group, they need to be able to, not just work together, but also co-develop this new technology as they learn from their shared operating experience. As such they need to transition from a strategic network to a learning and transformational network of collaborators to develop and implement this new technology. This transition requires that they develop a mode of collaboration with the active involvement of key stakeholders, capable of reflecting on its effectiveness in practice and of implementation in response to similar further opportunities.

4. Conclusion

In conclusion, the Hydro-BPT concept can be seen to be a worthwhile venture in terms of reduction in energy consumption, reduction in CO_2 emissions, revenue generation and return on investment. In examples observed in Ireland, BPTs with the potential to generate as little as 13kW were shown to be financially viable.

The implementation of Hydro-BPTs in the water supply network has significant potential to improve the sustainability of the industry. Further research is required to explore the intricacies and practicalities of Hydro-BPT design, construction and optimisation as well as in the development of a business and collaboration model for its widespread deployment in the industry.

Incorporating Hydro-BPTs into the design of new water supply distribution networks also offers the capability of a sustainable design approach by optimising the available pressures to maximise the use of Hydro-BPTs, thus reducing energy consumption and CO_2 emissions.

5. Future Work

Future work in the Hydro-BPT project comprises a number objectives which will be executed to complete a holistic assessment of the Hydro-BPT concept, including:

- Determining the technical/economic feasibility of applying Hydro-BPTs to water infrastructure: continuing from this preliminary work and using experimental and numerical models, the energy recoverable from BPTs will be assessed in greater detail and demonstrated through a laboratory-scale model. Solutions to the design challenges highlighted above will also be included.

- Determining the environmental impact of this new technology: detailed assessments will be made in terms of the potential CO_2 emissions savings and environmental impacts should Hydro-BPT technology be adopted by the water supply industry. This will consider the energy inputs and outputs in a holistic life cycle analysis (“cradle to grave”) approach.

- A practical feasibility study for the application of Hydro-BPTs in existing BPTs: information on the existing BPTs in Ireland and Wales will be gathered in a GIS database which will be used to demonstrate the untapped energy potential in water supply networks in two contrasting regions as an initial case study.

- Development of the five elements of a business model for Hydro-BPTs of differing sizes and energy recovery potential.

- An exploration of the potential for collaboration among the key stakeholders in the development and exploitation of the business model: this section of the project will develop guidelines for the implementation of this technology by industry

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