Combining energy recovery and leakage reduction in water distribution networks

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INTRODUCTION

Energy consumption in water supply and distribution networks represents 7% of the world's consumption of energy (Perez-Sanchez *et al* 2017). According to the Key World Energy Statistics published by the International Energy Agency (IEA 2017), the water sector accounted for 820 TWh of global electricity consumption in 2014. This amounts to 70 million tons of oil equivalent (MTOE). These Key World Energy Statistics summarise the average electricity consumption for all processes within the potable water supply chain, from abstraction through treatment to distribution. Incorporating these global averages, and by using average water consumption for South African metros as reported by the Department of Water and Sanitation (DWS 2017) and the Eskom average electricity rate (Eskom 2018), we can approximate the average annual electrical cost for water treatment and distribution of a metropolitan municipality with a population of 3 million to R166 million. According to the GreenCape Market Intelligence Report on Water for 2017 (GreenCape 2017), South African municipalities currently use about 4 500 million m³/year of water, of which 37% is non-revenue water. On this basis, on average, a metropolitan municipality with a population of 3 million loses around 180 million m³ of potable water per year, which amounts to a cost of roughly R60 million per year on the electrical cost for the treatment and distribution of non-revenue water (Figure 1). This R60 million cost could be recovered to some extent through energy recovery using hydro turbines or energy recovery turbines (ERTs). Subsequent savings on water losses and the overall energy cost of the system are also present, but should be quantified on a site-specific level, as these vary according to location and system configuration. The energy recovery benefit figures change with various factors, such as the topography, treatment processes and distribution lengths. The City of Tshwane has a population of roughly 2.9 million, but its energy cost of water would be higher due to the higher pumping cost of water procured through Rand Water and pumped from the lower-lying Vaal Dam.

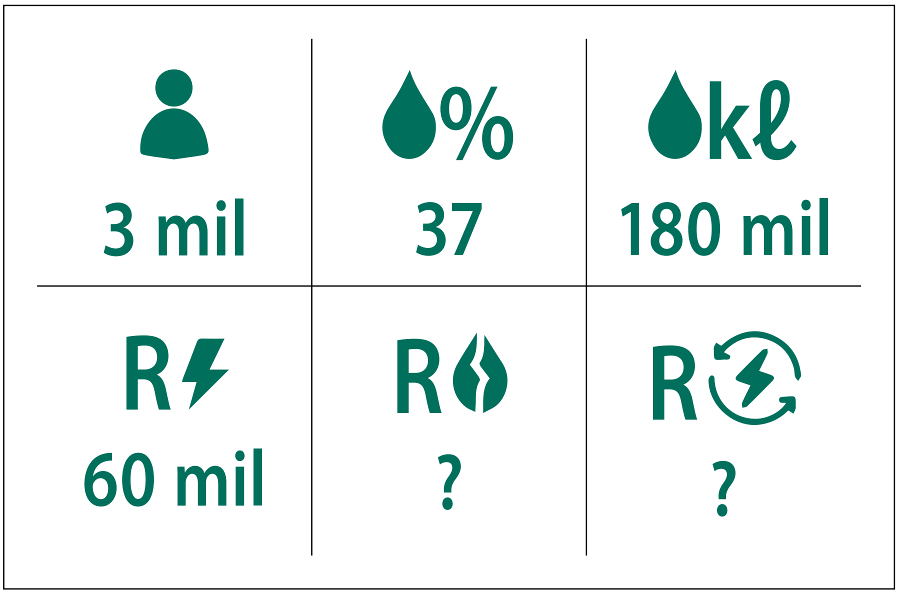

Figure 1 Water losses and energy cost in a South African metro with the size equivalent of the City of Tshwane

POTENTIAL FOR ENERGY RECOVERY

The article titled "Water infrastructure asset management addressing the SDGs through energy recovery" in the June 2018 edition of *Civil Engineering* framed the problems experienced within the South African context since 2008 with regard to electricity supply and drought (Bonthuys *et al* 2018). The article discussed conduit hydropower as a method of recovering energy from a water supply or distribution system where excess pressure energy is recovered by installing a hydro turbine. This also reduces background leakages within the system as pressure is directly proportional to the leakages from a system. Energy recovery, then, addresses both the issues relating to electricity supply and demand, and water scarcity. The potential for energy recovery within municipal water supply and distribution systems exists, and municipal infrastructure asset management systems contain enough water system

Figure 2 In-line turbines, Portland, Oregon – 200 kW

data that could be leveraged to identify the preliminary potential for energy recovery and leakage reduction with regard to both extent and location (Bonthuys *et al* 2018).

HYDRO TURBINES

A detailed technical methodology was developed to show how energy can be recovered from excess water pressure through the installation of hydro turbines, governed by Equation 1 (Bonthuys *et al* 2019).

$$P = \rho g Q H \eta \quad (1)$$

Where:
- P = power output (W)
- ρ = density of fluid (kg/m^3)
- g = gravitational acceleration (m/s^2)
- Q = flow rate (m^3/s)
- H = head (m)
- η = turbine system efficiency (%).

The installation of hydro turbines in water supply and distribution networks is a well-known form of energy recovery worldwide. In several instances a pump as turbine (PAT) has been used for energy recovery installations. Lima *et al* (2017) found that, at maximum flow conditions in a system, the energy recovered by a PAT is high and the reduction in leakage comparable to that of conventional pressure reducing valves (PRVs). The advantage of PATs in the South African environment is general availability and aftermarket support. PATs, however, do not have the efficiency that more conventional hydro turbines, such as Pelton wheels, Francis turbines and Crossflow (Banki) turbines have. Figures 2, 3 and 4 show installations of inline turbines, PAT and a cross-flow (Banki) turbine in water distribution systems in the City of Portland (Oregon, USA), Pretoria (South Africa) and Bloemfontein (South Africa) respectively.

Assuming that the leakage within the system is predominantly governed by variable area leaks, the percentage reduction in the current annual real losses (CARL) of a system can be calculated from the percentage reduction in the operating pressure of the system through the variable area term of the FAVAD equation (Equation 2).

$$Q = C_d \sqrt{2g}(A_0 h^{0.5} + m h^{1.5}) \quad (2)$$

Where:
- Q = leakage rate (m^3/s)
- C_d = discharge coefficient
- g = gravitational acceleration (m/s^2)
- A_0 = initial leak opening without any pressure in the pipe (m^2)
- h = pressure head (m)
- m = slope of the pressure area line (m).

Figure 3 PAT, Pretoria, South Africa – 40 kW

GENETIC ALGORITHM FOR OPTIMISATION

The challenges faced with energy recovery in water supply and distribution systems are similar to those faced by pressure management and PRVs, and are related to the determination of the number, location and optimal control setting or size of the installation. Both the location and size of energy recovery installations can be preliminarily identified by leveraging asset management data as previously discussed, but there is an inherent need to optimise these systems in terms of recovered energy and reduced water losses evaluated on an economic basis. Based on the intricate and dynamic nature of water distribution systems, various researchers have employed several different techniques for the operational optimisation of water distribution systems (Mala-Jetmarova *et al* 2017). For the purpose of this study a Genetic Algorithm (GA) was developed to optimise the use of hydro turbines in municipal water distribution systems for energy recovery and leakage reduction.

Figure 4 Crossflow (Banki) turbine, Bloemfontein, South Africa – 96 kW

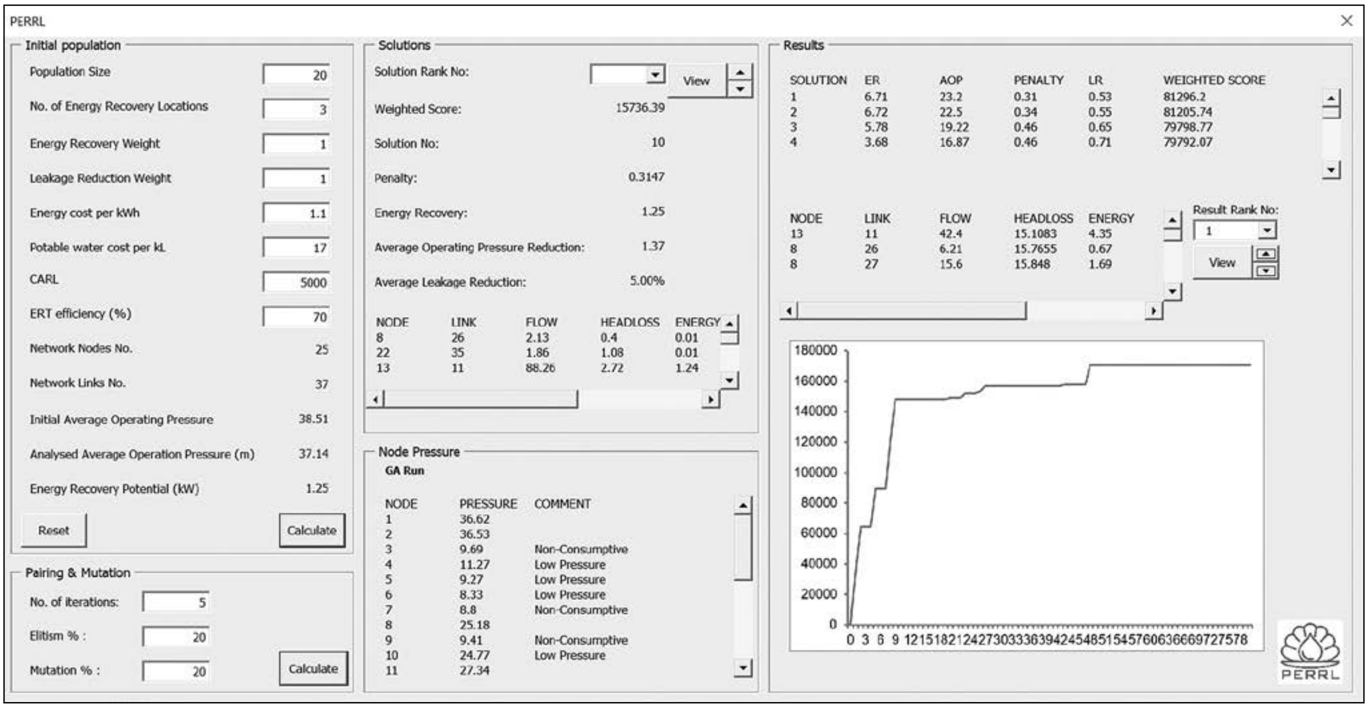

Figure 5 Example of a PERRL user interface

The GA developed was incorporated into an application named the Programme for Energy Recovery and the Reduction of Leakage (PERRL).

PERRL was developed using the Visual Basic programming language and operates from a user-friendly interface (Figure 5). Input required into PERRL is split into user input directly on the interface and a hydraulic model for the system under investigation. Currently, PERRL is compatible only with water networks set up using the US Environment Protection Agency's (EPA) Water Distribution System Modelling Software, EPANET. Both PERRL and the GA have been set up to reject any potential energy recovery location within a network which causes a pressure drop below zero at any node. Penalty functions have also been implemented to penalise heavily any energy recovery solutions that cause pressure drops below the defined minimum operating pressure at consumption nodes. With these constraints in place, EPANET remains a suitable model for energy recovery and leakage reduction and, for this reason, and the fact that EPANET is freeware, other pressure-driven models were not considered.

The direct input required relates to the size of the initial population for the GA, the number of proposed energy recovery locations (budget-based), the weighted importance of energy recovery and leakage reduction, the current annual real losses (CARL) and both the water and electricity cost for the region under investigation. Lastly, the number of GA iterations and the degree of mutation are required.

From the input PERRL randomly compiles an initial population of solutions which is modelled in EPANET and analysed for energy recovery and leakage reduction. These initial solutions serve as input into the GA developed. The GA then pairs different solutions from the initial population utilising elitism and crossover techniques, and mutates a certain degree of solutions to obtain a new set of solutions for modelling in EPANET and analysis. The set of solutions after each iteration of the GA is grouped as a result, and these results are ranked according to a weighted score influenced by the weighted importance of energy recovery and leakage reduction as defined in the user input. The optimisation process is graphically depicted on the interface and is complete once sufficient convergence has been obtained (Figure 5) (PERRL is in a beta testing stage, being tested by water professionals in the industry).

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Currently, PERRL analyses only steady-state problems based on worst-case scenarios, and only utilises fixed-speed energy recovery devices. It is proposed that future research and development of PERRL will include extended period simulation and optimisation based on the time-varied application of energy recovery devices.

TESTING OF PERRL

PERRL was used to analyse the very small example network (Figure 6) used by Jowitt and Xu (1990). The consequence of installing three hydro turbines within the water network was analysed. One hundred iterations were run, and the result was the installation of three hydro turbines with sizes 2.62 kW, 400 W and 412 W respectively at locations A, B and C in Figure 6(b). The installation of these hydro turbines reduced the average operating pressure of the system by 20%, resulting in a total potential leakage reduction of 24% and

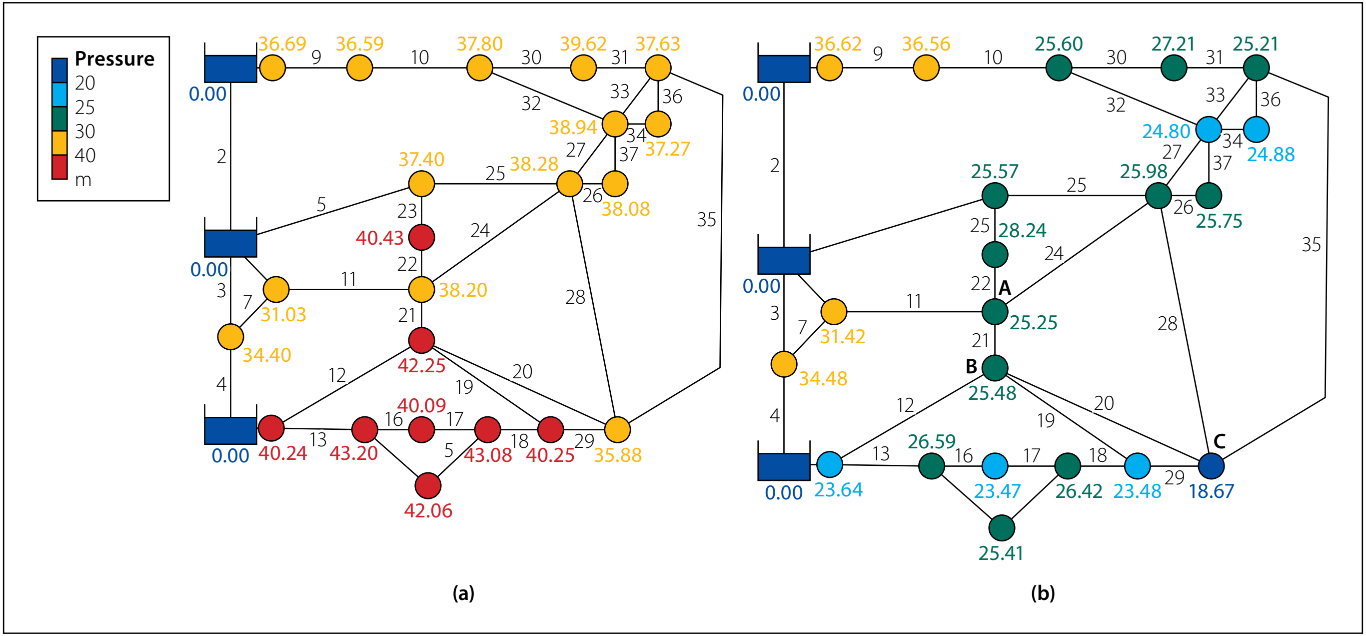

Figure 6 (a) Pressure distribution with no ERT, (b) pressure distribution with ERTs installed at locations A, B and C

potential energy recovery of 3.44 kW. It is important to note that these results were obtained in the benchmark test of PERRL against the example network used by Jowitt and Xu (1990) for the optimisation of pressure-reducing valve locations and is not an ideal network for energy recovery. Subsequent "real" networks analysed show significantly more energy recovery potential. The results of PERRL analyses on the example network compare well with the different optimisation techniques employed on the same network by several other researchers (Nicolini & Zovatto 2009; Saldarriaga & Salcedo 2015; Gupta *et al* 2017). The leakage reduction calculation in the model assumed that water losses are predominantly from background leakages and used an emitter exponent of 1.18. The average leakage reduction values obtained in the previous studies ranged from 15% to 24%. In summary, the subsequent benefits of the installation of hydro turbines within a water distribution network, as shown in the example network, are as follows:

- Reduced operating pressure resulting in potentially fewer pipe bursts
- Reduced operating pressure resulting in a potential reduction in leakages and water losses
- Energy recovery (converting excess pressure through turbine) generating an augmented income or energy cost saving
- Reduction in the system water demand, i.e. saving in purification and distribution costs. □

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