New Challenges in Water Pipe Systems Towards Energy Efficiency

Case Studies of Nampula and Cuamba Water Supply Systems

Nádia da Conceição Ferrete
DECivil, Instituto Superior Técnico, Universidade de Lisboa, Portugal

Abstract: Water Supply Systems (WSSs) must provide water under pressure high enough to satisfy the consumer needs, whilst being low enough to prevent pipe damages. For this purpose, Pressure Reducing Valves (PRVs) are the most used devices to control pipe pressure, through the dissipation of excess energy in the system. In this context, WSSs started to be considered as a potential source for small-hydropower generation, namely with the implementation of Pumps As Turbines (PATs).

This study assesses the potential for energy recovery in two WSSs in the north of Mozambique, through the application of PATs as a replacement or in parallel with the existing PRVs, allowing to reduce the systems costs and environmental impacts while increasing their efficiencies. An economic analysis is carried out to evaluate the economic viability of the projects.

The study demonstrates that if these projects are implemented, additionally to controlling pipe pressure, they can contribute to reductions of real losses and CO_2 emissions. Furthermore, the studied WSSs, which initially only had water supply purposes, will then be able to also generate renewable energy, thus, promoting green and sustainable consciousness. These outcomes can result in total incomes of around 5 000 and 3 000 €/year for each system. However, while Nampula WSS presents favourable economic indexes, with an IRR higher than 39%, Cuamba WSS has low economic indexes, with an IRR around 14%.

Keywords: Pump As Turbine (PAT); Pressure Reducing Valve (PRV); Water Supply System (WSS); energy production; water system efficiency

1. Introduction

Global water demand has been rising by 1% per year since the 1980s and is expected to continue to rise at a similar rate until 2050, with the industrial and domestic sectors being the major contributors for this increase. It is expected that water stress will be more extreme in fast growing economies, particularly in areas of the globe where water resources are already scarce, or water services are deficient [1]–[3]. To overcome these challenges, water utilities need to take action and implement optimisation methodologies to improve water systems efficiencies.

The objective of this study is to evaluate the potential for energy recovery in WSSs by converting the excess pressure, that otherwise would be dissipated, into energy. For this reason, PRVs can be replaced by Pumps As Turbines (PATs), which can, additionally, improve the sustainability and the energetic efficiency while reducing the environmental impacts of the water sector. Hence, PATs are implemented in two case studies which correspond to two bulk water supply systems in the North of Mozambique, wherein the viability of this solution is studied in terms of energy produced and economic feasibility.

2. Loss Control and Pressure Management

The correlation between pressure and water losses has been studied for many years, and it is now widely known that the higher the pressure, the higher the risk of pipe breaks [4], [5]. Water losses, which globally regularly reach values of 30-40%, are a main concern regarding water distribution efficiency and sustainability [6].

While the fundamental objective of pressure management is reducing background leakages, it can also achieve multiple benefits, such as extending infrastructures life through reduction of main breaks and saving water through reduction of consumption by users. Various regulation elements can be used in pressure management: pump control, tank regulation, and pressure reduction by using automatic valves, among others [7].

Some researchers indicate that the best solution to reduce pressure in WSSs must include devices that provoke head losses, particularly Pressure Reducing Valves (PRVs). PRVs are devices with the main purpose of controlling the pressure or head, independently or not of the discharge variation [8]. During this process, these devices cause a dissipation of energy, which could be recovered by substituting the PRV or coupling it with turbines, thus reducing greenhouse gas emissions and improving the systems sustainability [4], [9]. Though, the main challenge regarding the application of PRVs is the optimal location and quantification of these devices [6], [10].

3. Pumps As Turbines (PATs)

Despite PRVs being widely used around the globe, many studies have proven Pumps As Turbines (PATs) to be a long-term cost-effective alternative to PRVs, being capable of recovering up to 40% of the energy dissipated in PRVs and converting it into electricity. PATs are micro-turbines consisting of pumps functioning as turbines, by reversing the flow, while imposing less investment costs than traditional turbines [9]. The reduced cost of PATs in comparison with traditional reaction turbines, can be justified with the fact that turbines must be designed for each site, while standard pumps can be mass produced and are easier to access [11]. The main obstacle of the implementation of PATs is the limited information available regarding PATs costs and performances at very low powers and the lack of studies implementing PAT types other than centrifugal [9].

3.1. Best Efficiency Point (BEP)

Nowadays, PATs are being installed in parallel with PRVs and in pump storage power stations in villages, farms and irrigation systems. To overcome the challenge in the selection of the appropriate PAT for a small hydro-site, the performance of PATs has been studied, through experimental and theoretical methods, based either on the Best Efficiency Point (BEP) or on the specific speed (N_s) [12], [13].

Experimental studies showed that a low-specific-speed centrifugal pump can operate as a turbine in various rotational speeds, heads, and flow rates without any mechanical problem. A pump operating in turbine mode can work in higher head and flow rates than in pump mode, while the efficiencies are similar in both modes [13]. However, a study found that the BEP of a PAT is 8,53% lower than the BEP of pump operating in direct mode [14].

3.2. Operating Conditions

When pumps are working as turbines, specifically for low specific speed, there is a significant risk of hydrotransients, which can affect the pipeline design and the system stability. Therefore, steady and transient state regimes of different pumps were analysed based on Suter parameters, in order to assess the reasonable efficiency of PATs. It was concluded that pumps operating in turbine mode can achieve a maximum relative efficiency up to 80%, with the dynamic behaviour of the machine being comparable to reaction turbines [15].

For turbines, the operating point is represented through hill diagrams, giving the efficiency values for different values of discharge and net head for a given rotating speed and guide vane position (Figure 1). When it comes to PATs with the generator connected to a large grid, the PATs rotating speed will be constant, and the correlation between head and discharge can be seen through the pump characteristic curve (Figure 2). When pumps/turbines are in isolated operation, the rotating speed is not constant, making the operating conditions more complex. In these cases, the non-used generator power must be dissipated by the electric system, to avoid instabilities along the system [8].

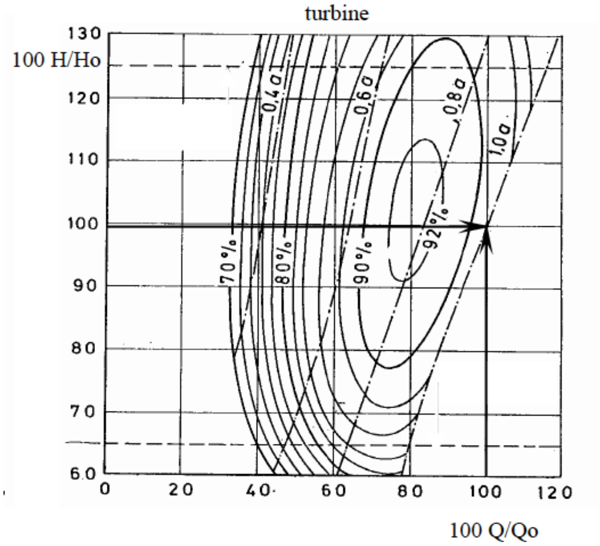


Figure 1 – Operating point in a turbine hill diagram [15]

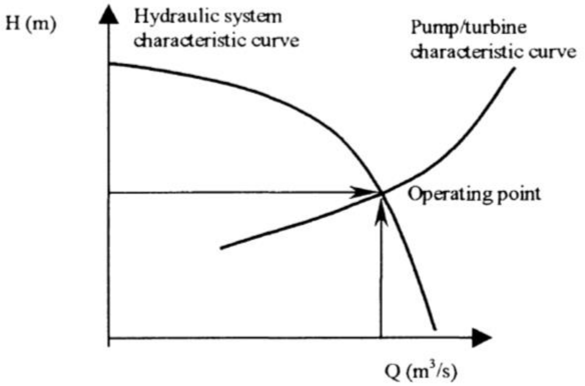


Figure 2 – Operating point in a pump working as turbine[8]

The discharge (*Q*) in pump operation mode is a function of the rotating speed (*N*) and the pumping head (*H*), while the alteration of speed depends on the torque of the motor (*Γ*). The pumps characteristic curves represent the relationships between these parameters and can be presented in dimensionless form using the rated condition (1)) [8], [15]:

$$q = \frac{Q}{Q_R} \qquad h = \frac{H}{H_R} \qquad n = \frac{N}{N_R} \qquad b = \frac{\Gamma_G}{\Gamma_{G\,R}} \tag{1}$$

where $_R$ represents the rated condition, corresponding to the best efficiency point.

The pump runner type is mainly characterized by the specific speed (N_s), which can be obtained through equation (2)[8], [15]:

$$N_s = N_R \frac{\sqrt{P_R}}{{H_R}^{1,25}} \tag{2}$$

where N_R is the rated wheel speed (r.p.m.), H_R is the rated head (m), and P_R is the rated power (kW).

For turbine conditions, the specific speed must be corrected to the normal turbine operating point (equation (3)) [8], [15]:

$$N_{sT} = \frac{N_s}{\sqrt{\frac{Q}{Q_R}}} \tag{3}$$

for $Q=Q_{max}$.

When the speed of a pump operating as turbine increases, the flow fluctuates, which causes changes in pressure. Since the machine does not have control mechanisms, this can cause dangerous operating disturbances, thus, protection devices must be installed.

The PAT efficiency can be obtained through equation (4):

$$\eta = \frac{P_m}{P_h} = \frac{\Gamma N}{\gamma Q H} \tag{4}$$

where P_m and P_h are the mechanical and hydraulic power, respectively. The hydraulic power corresponds to the power transmitted from the flow to the pump, and the mechanical power is the power transmitted by the pump to the generator [8].

The theory of similarity is fundamental for the design and conception of turbomachines, allowing to predict the behaviour of a prototype based on a small-scale model. This theory hinges on the consideration that turbomachines with similar geometries will function in similar conditions as long as they have the same efficiency [16]. Based on this theory, the velocities of homologous points of two turbomachines can be related through the following equations, which are valid at the inlet, outlet and inside the runner (equation (5)) [16]:

$$\frac{V}{V'} = \frac{C}{C'} = \frac{W}{W'} = \left(\frac{H}{H'}\right)^{1/2} \tag{5}$$

For the same machine working in conditions of similarity, the following equations can be verified (equations (6)) [16]:

$$\frac{N}{N'} = \left(\frac{H}{H'}\right)^{1/2} \qquad \frac{Q}{Q'} = \left(\frac{H}{H'}\right)^{1/2} \qquad \frac{P}{P'} = \left(\frac{H}{H'}\right)^{3/2} \tag{6}$$

However, experience shows that due to scale effects, the relation between the net heads of the turbines does not correspond to the square of the relation between the velocities, meaning that homologous specific velocities do not coincide, and the efficiencies are different. Therefore, the prototypes have higher efficiencies than the small-scale models. Nonetheless, the theory of similarity is considered a reliable method for the design of turbomachinery [16].

4. WSSs Performance Indicators (PIs)

Every year, the management entities in Continental Portugal are required to register and provide data to the sector regulator (ERSAR), which allows to evaluate the entities performances based on reference values. Considering that there are 432 registered entities, providing data related to approximately 200 PIs, it is essential to filter the information that is relevant for the scope of the study. Thus, 39 PIs were selected for 2015 (out of 130), versus 57 PIs for 2017 (out of 197). The analysed PIs were grouped according to the types of PI. Two of these (PIs) are presented below, for the years of 2015 and 2017.

Figure 3 displays the revenue and non-revenue water registered in bulk water systems in 2015 and, also displays how the total water entering the systems is subdivided between these two PIs. Figure 4 displays the same information regarding 2017. ERSAR classifies the quality of service of water systems based on the amount of non-revenue water in three categories: good, average and inadequate. Accordingly, non-revenue water in bulk systems accounted for 5% of all water entering the systems in 2015 and in 2017. Thus, the quality of service can be classified as average [17].

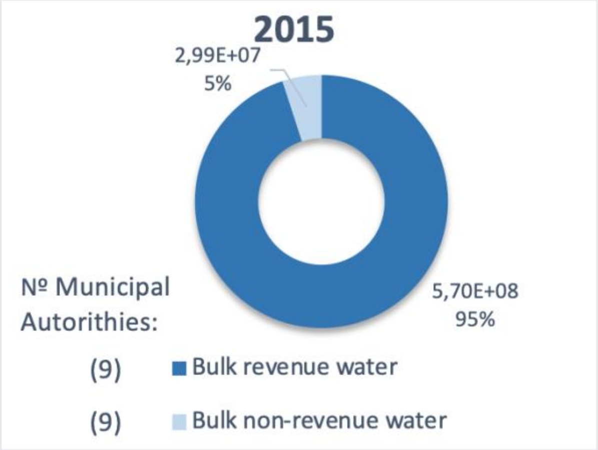


Figure 3 – Bulk revenue and non-revenue water in 2015 (m^3/year)

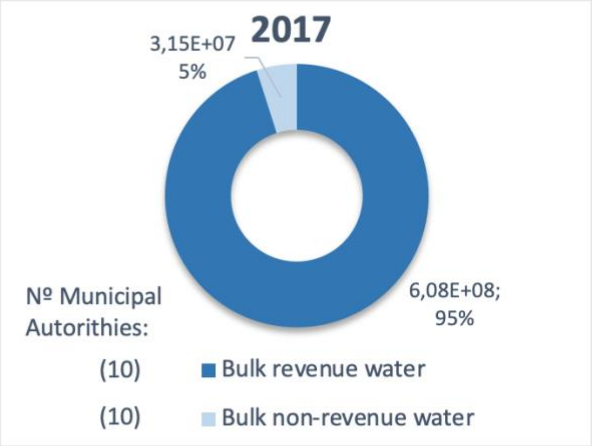


Figure 4 – Bulk revenue and non-revenue water in 2017 (m^3/year)

In accordance with the water-energy nexus, Figure 5 and 6 display, for 2015 and 2017 respectively, how much of the energy consumed in WSSs is produced within the systems and how much comes from the external grid. Most of the consumed energy comes from the external grid, with own energy production corresponding to 28% in 2017. From 2015 to 2017 there was a decrease in energy consumption overall, however, it is desirable that the percentage of own energy production increases, contributing to the sustainability of the systems.

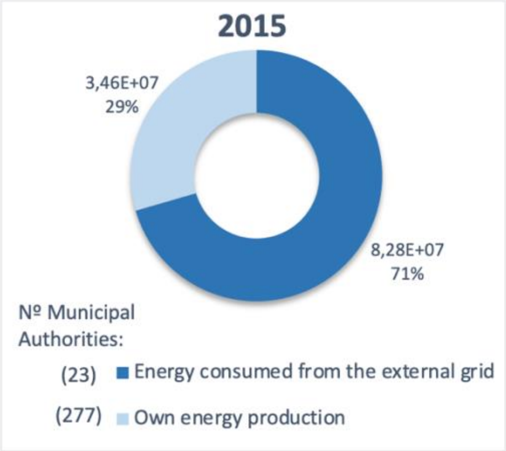


Figure 5 – Energy sources in WSSs in 2015 (kWh/year)

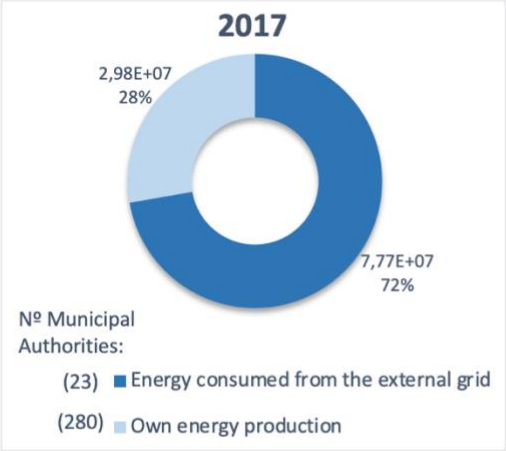


Figure 6 – Energy sources in WSSs in 2017 (kWh/year)

5. Case Studies

5.1. Nampula Water Supply System

5.1.1. Model Development

Nampula water supply system consists of four distribution centres and six pumping stations working with twelve tanks, with a reserve capacity of 23 800 m^3. The study will focus on the section between the pumping stations EB1 and EB2 (Figure 7). Thus, a model was built on *EPANET 2.0*, according to the data provided by *FIPAG*, taking into account that a PRV is installed upstream EB6. A PAT will be installed in parallel with the existing PRV in order to use the surplus to produce energy.

The head and flow values throughout the entire system remain almost constant along the day, because the present water system is a bulk system, which means that the flow does not depend on consumption patterns (Figure 8 and 9). Hence, this can be an advantage for energy generation purposes, as the system can be used to generate energy for a long period.

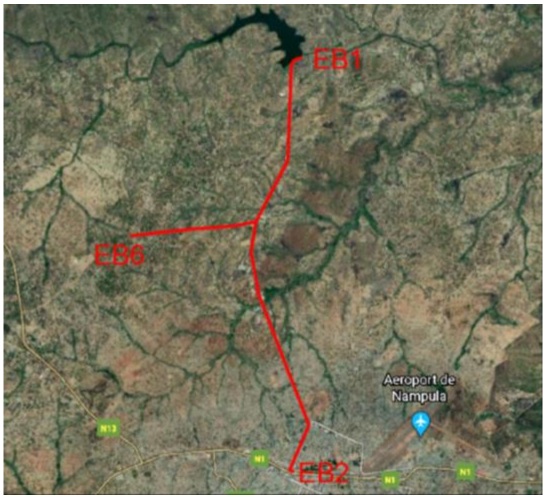


Figure 7 – Satellite view of implantation area

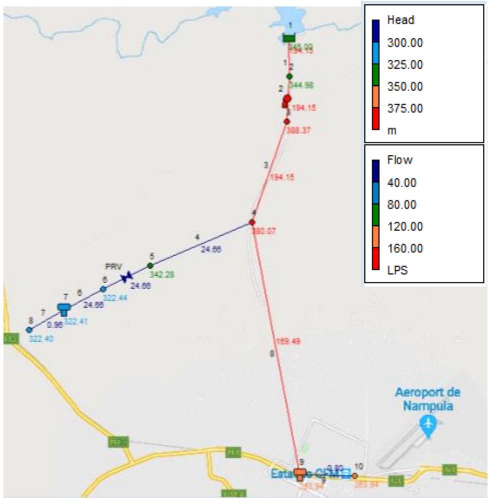


Figure 8 – Current situation values of head and flow at 3:00 AM

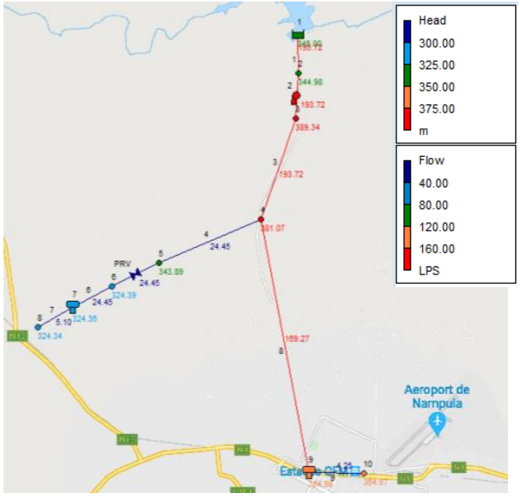


Figure 9 – Current situation values of head and flow at 11:00 AM

5.1.2. Implementation of PATs

According to the available head and flow in the system, the chosen turbomachine for this case was the *Etanorm 80-250 Turbine* with a diameter of 269 mm. To simulate the use of the selected PAT in *EPANET*, the PRV was replaced by a General Purpose Valve (GPV), associated with the related characteristic curve, as provided by the manufacturer. Based on that curve, characteristic curves for different rotation speeds were defined using the theory of similarity [16].

The characteristic curve of the installation (CCI) was obtained based on the results from *EPANET*, considering the head losses along the system. The interception of the CCI with the characteristic curves of the PATs corresponds to the operating point of the system (Figure 10). The system can operate in different operating points, although to avoid instability problems, the operating point must match the point of the characteristic curve with the maximum power [18]. To define the operating point, an economic comparative analysis will take place.

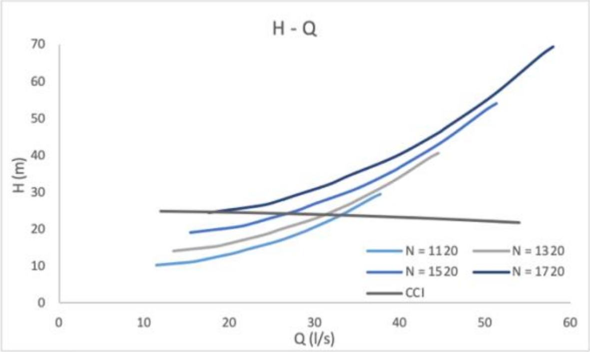


Figure 10 – Characteristic curves of the PAT and CCI

5.1.3. Economic Feasibility and Energy Generation

To simulate the use of the selected PAT in *EPANET*, the PRV was replaced by a General Purpose Valve (GPV). Thus, the PATs characteristic curves were applied to the *EPANET* model, in order to estimate the curve which leads to higher generation. Since the flow values are almost constant throughout the day, the considered turbined flow is assumed to be the minimum round value that is available for most of the day, i.e., if the flow varies between 20,00 and 21,00 L/s, the considered flow is 20,00 L/s.

The energy production is only possible for 20 h per day since during the remaining 4 h the tanks are full and, there is no water flow along the system. Therefore, hourly results were extracted from *EPANET* and, turbined flows, installed powers, efficiencies and produced energy depending on the rotational speed are displayed in Table 1. It is perceptible that a rotational speed of 1120 r.p.m. leads to higher energy production, thus, it will be the chosen solution. In this case it is possible to see that, the lower the rotational speed, the lower the unit head loss will be and the higher the turbined flow, efficiency and produced energy.

The cost of the PAT can be assessed considering a cost curve which displays the cost of the PAT per kW [19]. According to this curve, the greater the value of produced energy, the lower the unit cost. For an installed power of 3,13 kW, the PAT will cost 1300 €. The construction of the bypass and the interconnection to the national grid cost 500 € each.

Table 1 – Produced energy

N (r.p.m.)	Q (L/s)	H (m)	η (-)	P_u (kW)	Δt (h)	E (kWh)	E (MWh/year)
1520	23,00	22,30	0,53	2,66	20,00	53,28	19,45
1320	24,00	18,80	0,68	3,01	20,00	60,14	21,95
1120	25,00	16,40	0,78	3,13	20,00	62,68	22,88

For the economic analysis a period of 40 years was considered, including the replacement of the PAT at the year 20. The maintenance costs are based on the investment costs and are 1,0% of the investment for the civil construction works and 2,5% for the equipment. The discount rates applied in the analysis were 6, 8 and 10%. Two scenarios will be compared varying the energy selling price, which will be 0,095 €/kWh in the first scenario and 0,110 €/kWh in the second.

The main results of the economic analysis are presented in Table 2. Both scenarios present positive NPVs and B/*C* ratios higher than 1 independently of the analysed discount rates. Nonetheless, for the first scenario, the payback period is 4 years and the IRR is 39,2%. For the second scenario, with the increase in the selling price, the economic attractiveness of the project also increases, with the IRR reaching 45,7% and the payback period falling off to 3 years.

Table 2 – Results of the economic analysis

Energy Selling Price (€/kW]	Discount Rate	NPV (€)	B/C (-)	Payback period (years)
0,095	6,0%	25 185	5,262	4
	8,0%	18 932	4,315	4
	10,0%	14 632	3,624	4
0,11	6,0%	30 349	6,136	3
	8,0%	23 024	5,031	3
	10,0%	17 988	4,225	3

Figure 11 and 12 present the flow and head values along the system after applying the PAT at 3:00 AM and 11:00 AM, respectively. The implementation of the selected PAT in the present system results in lower unit head losses in the section where the PAT is located and, higher values of flow and velocities, without exceeding the velocity limits.

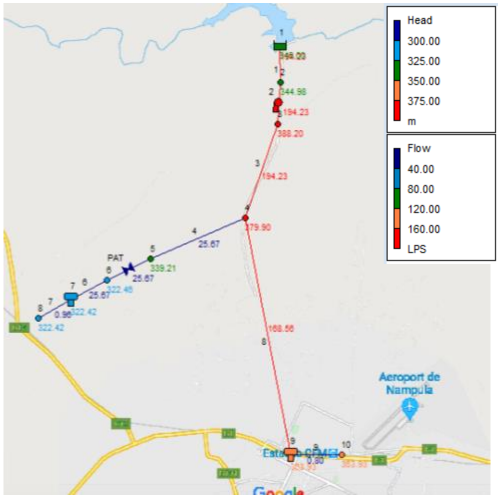


Figure 11 – Results at 3:00 AM after applying the PAT to the model

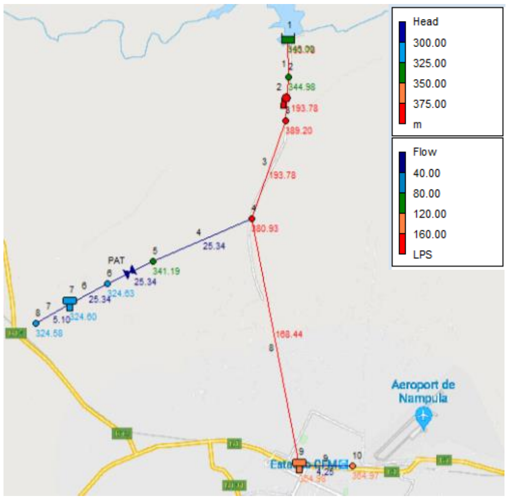


Figure 12 – Results at 11:00 AM after applying the PAT to the model

5.2. Cuamba Water Supply System

5.2.1. Model Development

This system is constituted by one branch, destined to water distribution for domestic use and it has two installed PRVs. The installation of one of the PRVs can be seen in Figure 14. Considering the flow direction, the first PRV will be referred to as PRV1 and the second one as PRV2.

Similar to the previous case, the objective is to install PATs in parallel with the existing PRVs, in order to control pressure values while producing energy. According to the model built on *EPANET*, also similar to the previous case study, the values of head and flow are almost constant throughout the day, which is positive for energy production purposes. The current head and flow values at 4:00 AM and 12:00 AM are displayed in Figure 15 and 16, where it is possible to see that PRV1 and PRV2 provoke equal head losses. Thus, the PATs to be installed will also be equal.

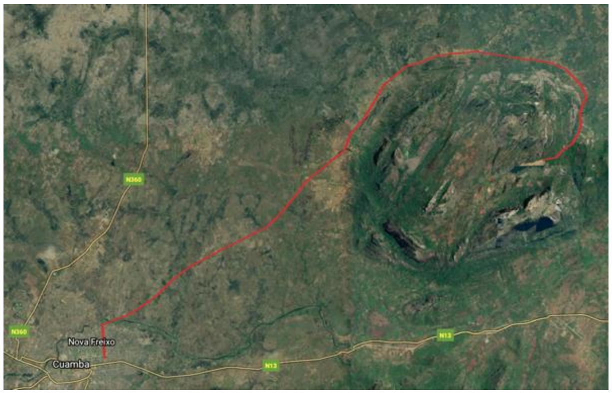


Figure 13 – Satellite view of implantation area

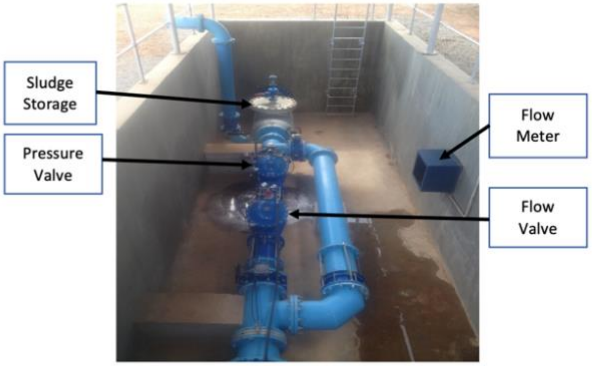


Figure 14 – Installed PRV

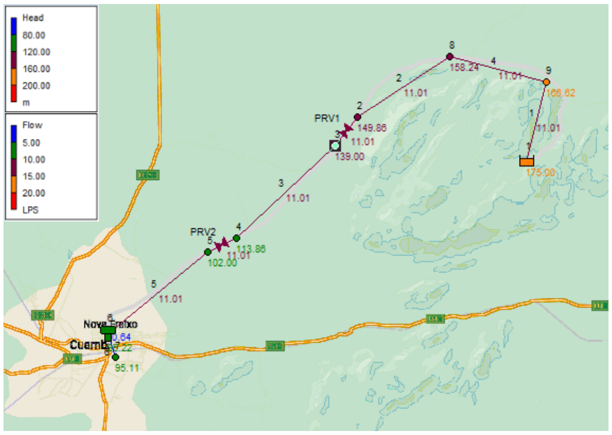


Figure 15 – Values of head and flow at 4:00 AM

Figure 16 – Values of head and flow at 12:00 AM

5.2.2. Implementation of PATs

The chosen PAT for this case was the *Etanorm 50-125 Turbine* with a diameter of 142 mm. The characteristic curve of the PAT was provided by the manufacturer. As stated in the previous section, both PATs will be equal and, will be referred to as PAT1 and PAT2, in accordance with the respective PRV.

Based on the characteristic curve of the PAT and on the theory of similarity [16], characteristic curves for different rotation speeds were defined. Since this system has two PRVs, two CCIs will be defined: the first corresponding to the stretch from the abstraction until PRV/PAT1 (Figure 17); and the second corresponding to the stretch from PRV/PAT1, passing through PRV/PAT2, until the distribution tower (Figure 18). Accordingly, the PRVs in the *EPANET* model were substituted by GPVs to simulate the PATs, and the related characteristic curves were added to the model.

5.2.3. Economic Feasibility and Energy Generation

An economic analysis will take place in order to define the operating point which maximises the energy production while providing greater profit. Since the flow in the system is almost constant, for this analysis the considered turbined flow depending on the rotational speed will be defined as explained in the previous case study. Assuming that the flow stops when the tanks are full, the system is able to generate energy for 20 h a day.

For the analysed rotational speeds, the corresponding turbined flows, installed powers and values of produced energy for one PAT are presented in Table 3. Differently from the first case study, in this case lower rotational speed does not result in higher flow and installed power. Thus, the rotational speeds that leads to higher generation is 1520 r.p.m.

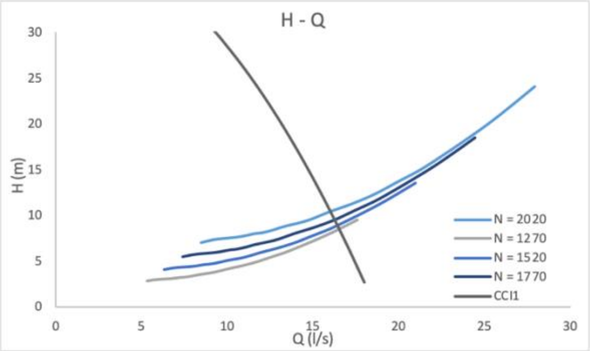


Figure 17 – Characteristic curves of the PAT and CCI1

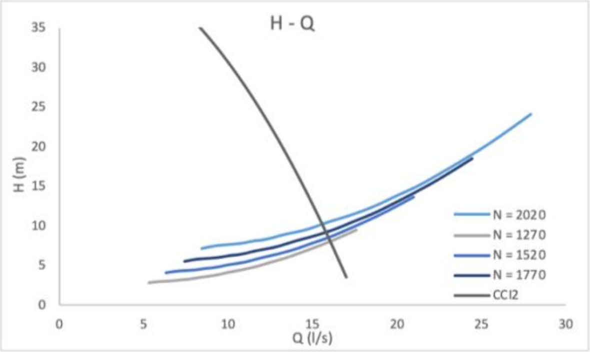


Figure 18 – Characteristic curves of the PAT and CCI2

Table 3 – Produced energy

N (r.p.m.)	Q (L/s)	H (m)	η (-)	P_u (kW)	Δt (h)	E (kWh)	E (MWh/year)
1520	12,00	6,00	0,72	0,51	20,00	10,16	3,71
1270	12,00	5,00	0,78	0,46	21,00	9,63	3,35
1770	11,00	6,40	0,50	0,34	22,00	7,59	2,52
2020	11,00	7,90	0,35	0,30	23,00	6,86	2,18

For a turbined flow of 12,00 L/s at a rotational speed of 1520 r.p.m., the installed power for each PAT is 0,51 kW, allowing to produce 3,71 MWh/year individually. Based on the installed power, according to the curve in the cost of each PAT is 3600 €/kW.

The economic analysis considers the same parameters as the previous case study, hence, two energy selling prices will be analysed, allowing to perceive how the selling price affects the profitability of the project. The obtained results are presented in Table 4. Despite both scenarios having positive NPV and B/C ratios higher than 1 regardless of the discount rates, they present IRR of 11,9% for the first scenario and 14,4% for the second.

Although the results are not totally undesirable, this project does not have great attractiveness in terms of economic profitability. The flow and head values along the system at 4:00 AM and 12:00 AM can be seen in Figure 19 and 20.

Table 4 – Results of the economic analysis

Energy Selling Price (€/kW]	Discount Rate	NPV (€)	B/C (-)	Payback period (years)
0,095	6,0%	15 721	3,896	4
	8,0%	11 511	3,193	5
	10,0%	8 616	2,68	5
0,11	6,0%	5 397	1,994	4
	8,0%	3 329	1,634	5
	10,0%	1 906	1,372	5

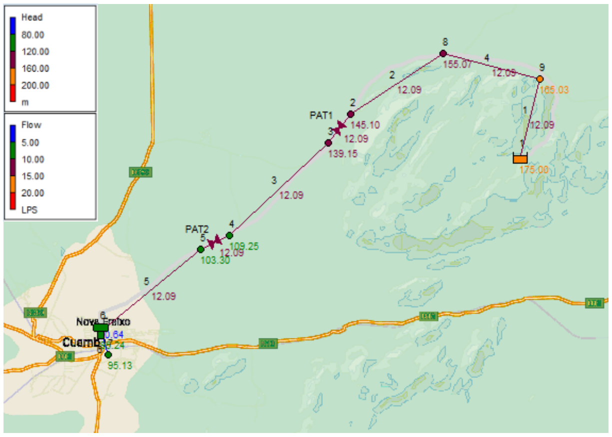


Figure 19 – Results at 4:00 AM after applying the PAT to the model

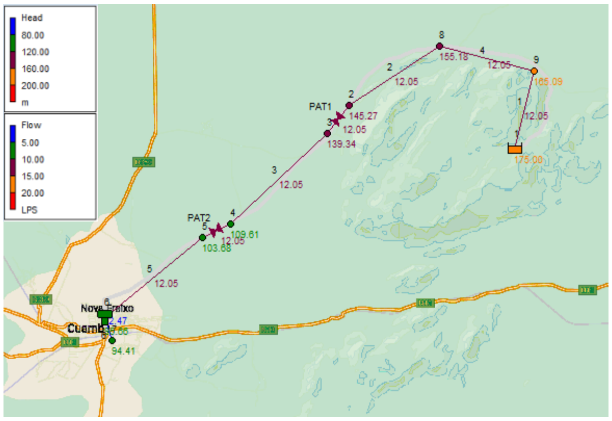


Figure 20 – Results at 12:00 PM after applying the PAT to the model

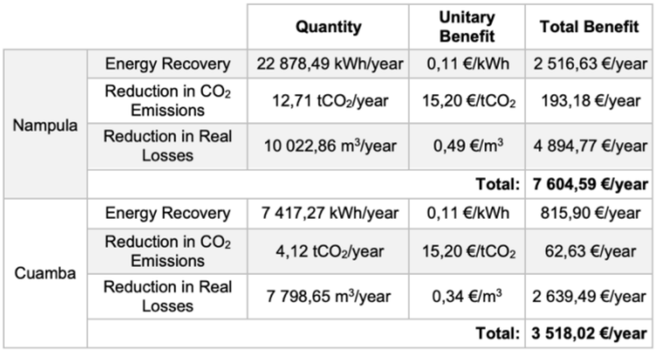
5.3. Discussion of Results

5.3.1. Income of the Projects

To assess the income of the projects, the energy selling price of 0,11 €/kWh was considered, taking into account the average selling price among the energy sector in Mozambique. Hence, the PAT to be installed in Nampula WSS can produce 22 878 kWh/year that will be directly used for the system operation, resulting in a benefit of approximately 2 500 €/year. In terms of CO_2 emissions, the plant will avoid the emission of 12,71 tCO_2 generating an income of 7 604,59 €/year. The selected PAT will contribute for water losses reduction, which is one of the biggest challenges in WSS in Mozambique. This project will favour a real losses reduction of 10 022,86 m^3/year. Moreover, this volume of water can then be supplied to the consumers, resulting in an income of 4 894,77 €/year. The total economic benefits of the project are presented in Table 5.

Regarding Cuamba WSS, annually, the installation of the micro hydropower plant results in an energy recovery of 7 417 kWh, a reduction in CO_2 emissions of 4,14 tCO_2 and a reduction in real water losses of 7 798,65 m^3, hence, generating a total income of 3 518,02 €/year (Table 5).

Table 5 – Estimated incomes for Nampula and Cuamba projects



		Quantity	Unitary Benefit	Total Benefit
Nampula	Energy Recovery	22 878,49 kWh/year	0,11 €/kWh	2 516,63 €/year
	Reduction in CO_2 Emissions	12,71 tCO_2/year	15,20 €/tCO_2	193,18 €/year
	Reduction in Real Losses	10 022,86 m^3/year	0,49 €/m^3	4 894,77 €/year
			Total:	**7 604,59 €/year**
Cuamba	Energy Recovery	7 417,27 kWh/year	0,11 €/kWh	815,90 €/year
	Reduction in CO_2 Emissions	4,12 tCO_2/year	15,20 €/tCO_2	62,63 €/year
	Reduction in Real Losses	7 798,65 m^3/year	0,34 €/m^3	2 639,49 €/year
			Total:	**3 518,02 €/year**

The values presented in Table 5 can be evaluated in terms of quality of service considering the reference values defined by ERSAR [17]. Accordingly, the volume of real losses in Nampula WSS before the installation the hydropower scheme is 720 911 m^3/year, corresponding to 15% of the total volume of water that enters the system. Thus, since it is above 7,5%, the system has an inadequate quality of service for this indicator. With the application of a PAT, this percentage will decrease to approximately 13%, however, the service quality will still be inadequate. In Cuamba WSS, the real losses without the installation of PATs account for 18% of the water entering the system. Hence, it also has an inadequate quality of service. After the PATs installation, this value will decrease by 4%, reaching approximately 187 000 m^3/year of real losses.

Although service quality regarding real losses remains inadequate after the application of PATs in both systems, the proposed solutions still represent a significative improvement in terms of energy recovery and reduction of CO_2 emissions. It should be considered that, without the implementation of micro hydro plants, these systems did not produce energy, hence, requiring all energy needs to be satisfied by the national grid and, consequently, contributing for the carbon footprint of the water sector.

Comparing the values presented in Table 5 with the corresponding ones regarding WSSs in Portugal (Chapter 4), it is possible to conclude that the effects of the proposed solutions do not resemble the current conditions of the WSSs in Portugal. Given that the own energy production represents around 30% of the energy consumption in most WSSs in Portugal and, the energy produced in the studied systems will only account for as much as 3 to 4%.

5.3.2. Economic Viability and Social and Environmental Impacts

The economic analysis demonstrated that Nampula WSS can be a profitable investment, with an IRR of 39,2 or 45,7%, depending on the energy selling price. However, Cuamba WSS did not offer attractive economic indexes, although the obtained indexes indicate that it can be profitable, with NPVs above zero and B/C ratios higher than 1 for the considered discount rates, while the IRR can be 11,9 or 14,4%. The low IRR values for Cuamba WSS can be explained by the fact that this solution implies the application of two equal PATs with low turbined flows and heads, resulting in higher investment costs and lower installed power. Nevertheless, the presented case studies can both avoid the emission of almost 16 tCO_2, which, additionally to generating economic benefits to the managing entities, contribute to reduce the carbon footprint of the water sector in Mozambique, thus reducing its environmental impacts.

In terms of social impacts, these studies propose the production of renewable energy, contributing to better air quality and promoting the idea of eco-friendlier and more sustainable life in the communities. These projects can motivate other communities to install similar solutions, reducing fuel consumptions and, making the systems more self-sufficient. The installation of PATs can generate job positions, namely for the construction works and promotion of the initiative. During the operation and maintenance of the plants, the employees will remain the same who are already are responsible for these functions.

6. Conclusions

One of the most cost-effective measures to reduce leakages in WSSs is pressure management. In addition to reducing leakages, this measure also expands the infrastructures life and increases water savings. PRVs are the most commonly used devices to control pipe pressures. Despite being widely used and efficient in pressure control, these devices dissipate hydraulic energy. Therefore, the possibility of replacing and coupling PRVs with pumps operating as turbines is studied. PATs can improve the systems sustainability and are more cost-effective than common reaction turbines. The energy produced by the implementation of PATs can be used within the system, reducing its associated costs or, it can be sold to the national grid.

Nampula water supply system has a promising potential for energy recovery if PATs are installed in parallel with the existing PRV, or as a replacement of this device. The proposed micro hydropower plant has a capacity to generate 22,88 MWh/year, which can help reducing the system costs. The economic analysis indicated that the project can be profitable, with an IRR between 39 and 45% depending on the energy selling price. This project can avoid the emission of more than 12 tCO_2 to the atmosphere and, it can help reduce the system's real losses by more than 10 000 m^3/year. Consequently, it can create an economic benefit of 7 604 €/year.

The micro hydropower plant of Cuamba water supply system has a potential to generate 7,42 MWh/year and requires the implementation of two PATs. The economic analysis indicated that this project, despite having positive NPVs and B/C ratios higher than 1, may not be as promising as the Nampula project, presenting IRR values between 11 and 14%. However, if implemented it will allow an annually reduction of 7 798 m^3 in real losses. Furthermore, it reduces the emissions of CO_2 by 4,12 tCO_2/year. Overall it would generate 3 518 €/year.

Despite the fact that both case studies are very similar and profitable, with the water flowing by gravity through the sections where the PATs will be installed, they both have different outcomes. The proposal for Nampula WSS is more profitable, resulting in an economic benefit two times higher than the benefit obtained in Cuamba WSS. This system is much longer than the system of Nampula, culminating in lower pipe pressures, which reduces the potential for energy recovery. Also, the system of Cuamba has two installed PRVs, implying the installation of two PATs. Thus, the investment costs increase while achieving a recovery of approximately 7 MWh/year, compared to the recovery of more than 22 MWh/year with just one PAT in Nampula.

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