Implementation of Pump-as-Turbines as Energy Recovery Solutions within Water Distribution and Supply Systems

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Abstract

Water distribution systems worldwide are characterized by significant levels of energy consumption and excessive amounts of water losses, which are caused primarily by the inadequate management of water utilities. In fact, the occurrence of ruptures and leakages within water networks is often associated with the poor regulation of water pressures, which significantly hinders the system's efficiency by requiring greater amounts of water and energy to provide the same level of service.

This ineffective management exerts a tremendous pressure on available water and energy resources, whose preservation has become increasingly important to our present-day society and ecosystem. Indeed, the alarming consequences of climate change and the high rates of population growth can only aggravate the serious problem of water scarcity and further complexify the interconnectedness of water and energy in human activities. Therefore, it is of the utmost importance to address the issue of water losses and energy waste in order to attain a sustainable development which does not compromise the quality of life of future generations.

A relatively recent approach to this problem is the implementation of a micro hydro power plant within the water distribution system itself, through the use of pump-as-turbines (PATs). By replacing valves originally intended to control water pressures in the network with PATs, energy could be generated from a clean source while pressure levels are kept within the established limits.

In this dissertation, this alternative has been investigated for the case study of the Funchal water network, which presents optimal conditions for the implementation of this energy recovery method. Several pressure reducing valve (PRV) locations have been selected for the application of PATs, and different hydraulic and electrical configurations have been analyzed with the purpose of evaluating the economic feasibility of this investment.

Key-words

water distribution system (WDS); water losses; water-energy nexus; sustainable development; micro hydro power plant; pressure reducing valve (PRV); pump-as-turbines (PATs).

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1. Introduction

Climate change is one of the greatest challenges of modern society, with serious implications for the environment and human communities worldwide. Although some minorities still refuse to accept it, an overwhelming scientific consensus supports that climate change is a real phenomenon, caused primarily by the human activity. In fact, without serious efforts to mitigate the impacts caused by our activities we could be compromising the quality of life of future generations, not to mention the perfect and invaluable equilibrium of the Earth's ecosystem. It is important to note that the drastic change in weather patterns and rapid increase of average global temperatures are not the only consequences of climate change, with water scarcity being one of the most alarming aspects of this global crisis. Indeed, water has become a scarce commodity in present-day society, with over 844 million people lacking access to clear drinking water and 4.5 billion suffering from inadequate sanitation (WHO, 2017). This is partly responsible for the mortality rates and disease transmission in developing countries, not to mention the ongoing economic and political crisis. Although developed countries do not undergo such hardships, they are the biggest contributors to this global scale environmental threat, with alarmingly high consumption levels required to support their modern industry. As an aggravating factor, energy and water are intricately related as all sources of energy require water in its production methods and energy is fundamental for every stage of water treatment. This implies a deep connection and entails an overall water-energy crisis which can only be tackled considering its strong interdependence.

An important contributor to the problem of water scarcity around the world are the water losses caused by leakages within water distribution systems. In fact, the excessive pressures under which many water distribution networks operate often lead to ruptures in pipes, causing a tremendous waste of freshwater which could be saved with an adequate pressure management. Despite the considerable amount of water that can be saved with leakage control, a lot of energy is still dissipated within the distribution network to maintain satisfactory pressure levels. For that reason, the integration of energy recovery solutions in water supply systems has recently gained increasing relevance, particularly within the context of renewable and sustainable sources of energy, as it enables the generation of power without contributing to climate change.

It should be emphasized that water loss control is always the most important step to save energy within the water distribution network, and evidently implies a tremendous financial impact for water utilities worldwide. However, once that is achieved to an optimal degree, additional measures can be taken to further reduce energy consumption and operational costs in water distribution systems. For this purpose, various studies were carried out to explore and investigate the feasibility of energy recovery solutions within the distribution system, such as the implementation of micro-hydropower plants especially designed for the low and variable flow rates which occur within the pipe system of water distribution networks (Sammartano et al., 2013, Carravetta and Giugni, 2009, Paish, 2002).

Small-scale hydropower presents innumerous advantages over many other sources of renewable energy, mainly the fact that it imposes virtually no risks for the ecosystem. For instance, while conventional hydroelectrical plants may present a significant threat to biological and physical habitats, micro or mini power plants can be implemented within water distribution networks without any kind of interference with the outside environment. In these small-scale systems, the energy is generated by the flow of water running through the installed turbines where there is sufficient pressure head and flow rate to produce energy. Since a well-managed and properly designed distribution network usually contains a significant amount of pressure reducing valves (PRVs) which serve the purpose of dissipating the energy contained in the flow of water, there are presumably adequate conditions for energy recovery wherever those valves are placed. With this in mind, several researches were carried out to investigate the possibility of replacing the PRVs by micro turbines (Paish, 2002, Sammartano et al., 2013), thus allowing the conversion of hydraulic energy into electric power while ensuring an optimal pressure management (Ramos et al., 2010).

Although this solution might be appealing at first, one should not forget that conventional turbines and its required electric equipment are usually unreasonably expensive investments for water utilities. For this reason, a different and compelling alternative has been considered to generate hydro power and recover energy in distribution systems – using pumps in reverse mode, as hydraulic turbines (Chapallaz et al., 1992; Ramos et al., 1999). Indeed, the use of pumps presents significantly advantageous perspectives, since they are considerably cheaper than conventional turbines, easier to install, and readily accessible in most countries. Therefore, several studies were conducted to explore the possibility of using pumps as an alternative renewable energy solution, creating the concept of pump-as-turbine (PAT).

2. Case Study

The purpose of this thesis is to analyze the energy recovery potential of the water distribution system of Funchal (Portugal) through the replacement of PRVs by PATs, ensuring both an adequate pressure management and valuable energy savings. Only a section of the Funchal water distribution system was studied – the pilot zone selected for the study of leakage reduction carried out by the Hydraulic Engineering company RSS – which comprises of roughly 40% of the entire municipality of Funchal and corresponds to the area of influence of the reservoirs of Terça, S. Martinho, Penteada, Ribeira Grande and Nazaré.

Currently, almost 70% of the total water entering the pilot zone of the water network of Funchal is lost within the system, mostly as a result of inadequate pressure regulation. This poses a serious threat to the environment and presents a significant economic impact for the water utility of Funchal. However, RSS estimated that a minimum of 15% can be achieved by 2033 if the correct measures are taken, particularly the definition of new areas of influence in the water distribution network and the implementation of new PRVs.

After these modifications, the installation of micro hydro power plants within the system through the use of PATs can further improve the efficiency of the system. Indeed, the recovered energy which would otherwise be dissipated in PRVs to control the pressure, could then be converted into electricity and stored in three different ways: the energy output can be connected to the grid; the energy can be stored in batteries; or it can directly supply electrical equipment/devices. Different PAT configurations were analyzed for each of these variants with the purpose of identifying the one which minimized the payback period for every PAT location in the distribution system.

These alternatives were tested using the flow conditions provided by the digital software EPANET, which models pressurized water networks and allows the simulation of hydraulic behavior and pressure distribution. The EPANET models utilized to perform these simulations were based on the models RSS had previously developed to analyze and control the level of water losses, and the time period used in the analysis was the same RSS adopted - from 2018 to 2033.

2.1. PAT Implementation

The first required step to evaluate the possibility of recovering energy within the network was to investigate the best possible locations for the implementation of PATs, in order to make sure these would provide the optimal conditions for energy production. Since RSS proposed the implementation of 50 different PRVs, there are 50 available locations. Despite the considerable number of possible locations, only 10 of these PRVs were selected for the implementation of PATs since that would provide sufficient data to conclude about the network's potential for energy recovery. This required a selection process which consisted of a basic pre-assessment of each PRV's potential for the implementation of a PAT, wherein the head drop defined for the PRV was multiplied by the flow rate, and the 10 PRVs which provided the highest values (Q×H) were selected for further analysis. The 10 selected PRVs are displayed in **Table 1** (values correspond to peak discharge conditions).

Table 1 – PRVs selected for PAT implementation.

Valve	Q	Upstream Pressure	Downstream Pressure	Head Drop
(-)	(l/s)	(m)	(m)	(m)
MP-03.5A-1	32,20	44,75	23,71	21,04
MP-02.5A-1	20,66	52,27	22,35	29,92
SM04.5A-1	25,68	40,1	17,80	22,3
SM04.5B	43,12	53,36	29,80	23,56
RP04.5A	24,65	55,66	31,10	24,56
TR08B	152,41	44,26	25,55	18,71
TR07.5C	24,12	49,7	25,25	24,45
TR06.5B	22,47	48,6	24,30	24,3
TR05.5G	26,89	47,37	24,28	23,09
TR07.5F	82,28	44,15	21,60	22,55

Considering the predictable reduction of water losses which results from the leakage control program, the PRV head drop values display a tendency to increase and the flow rate values tend to decrease throughout the years. For this reason, to be able to perform an energy recovery analysis till 2033, the software EPANET was required to calculate these values for each PRV and each year. This implied the creation of a specific EPANET model for each year, which was accomplished using the Funchal water network model provided by RSS as a starting point. This provided model corresponded to the 2018 situation and included every water loss control measure previously defined, such as the implementation of newly installed PRVs and the establishment of new DMAs. After concluding the PRV selection process and the calculation of hydraulic models, specific PATs had to be selected for each PRV. Having in consideration the vast number of pumps and manufacturers to choose from, it was established that only pumps from the manufacturer KSB would be analyzed in the present work. However, since KSB does not provide the data for most pumps operating as turbines, only 28 KSB pumps from the Etanorm series were analyzed. By associating the PAT curves to the selected PRVs in the EPANET model, the energy production could be calculated for every year from 2018 to 2033 by running the model and extracting the variables included in the equation (1).

$P = \eta \rho Q g h$, where: (1)

- $P = available\ power\ (W)$
- $\eta = efficiency\ of\ the\ turbine$
- $\rho = density\ of\ water\ (1000\ kg/m^3)$
- $Q = water\ flow\ (m^3/s)$
- $g = \ gravity\ acceleration\ (9{,}81\ m/s^2)$
- $h = height\ (m)$

2.2. Modes of Operation

There are several different PAT configurations which can be applied to generate power, namely: Hydraulic Regulation (HR); Electric Regulation (ER); Hydraulic and Electric Regulation (HER); No Regulation (NR). All these configurations can provide interesting energetic results depending on the water distribution network conditions, presenting a great economic benefit for water utilities if implemented correctly. However, in the case study of the Funchal water network, only the NR and ER operating modes were tested and analyzed, while the other configurations were disregarded. In these alternatives, the PAT backpressure and flow rate values are not regulated, and the PAT operational conditions are totally dependent on factors which influence the network's pressure and discharge levels, i.e. the consumer demand patterns. While the NR mode operates with the nominal rotational speed of the PAT, the ER mode enables the selection of the rotational speed which maximizes the energy production, with the aid of a variable speed drive (VSD) which controls the frequency and voltage of the motor connected to the PAT. It is important to emphasize that two distinct variants of the ER mode were considered: fixed ER mode and variable ER mode. While the variable ER mode (also known as simply ER mode) continuously adjusts the PAT rotational speed according to the input flow rate, in the fixed ER mode the rotational speed remains constant throughout the years and does not adjust itself to flow rate levels to optimize its energy production.

Although no valves were installed to optimize the PAT operating conditions (as in the HR and HER modes), some measures were taken to ensure these energy production methods would not interfere with the network stipulated pressure levels. Firstly, despite the fact that the NR and ER modes do not usually include a bypass line, a flow control valve (FCV) was placed in parallel with the PAT. Indeed, the flow rate entering the PAT had to be limited to prevent an excessive head drop, since high flow rates might lead to head drop values above the value defined for the PRV, which is particularly important to avoid water supply issues caused by insufficient pressure levels. Secondly, also unlike the standard modes, the existing PRV was kept to ensure pressure levels did not exceed the stipulated limit in case the flow rates were too low to induce a higher head drop in the PAT. Additionally, the PRV was a critical element in case the PAT did not operate correctly. The NR and ER configurations are displayed in **Figure 1**.

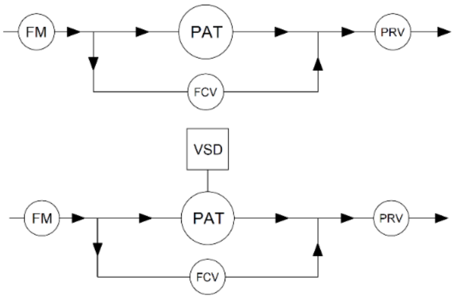

Figure 1 – NR (above) and ER (below) configuration schemes. FM (flow meter); PRV (pressure reducing valve); PAT (pump-as-turbine); FCV (flow control valve); VSD (variable speed drive).

In order to calculate the alternative rotational speed characteristic and efficiency curves for each PAT for both ER modes, the affinity law of turbomachines was applied to the respective nominal rotational speed curve. Indeed, through the ratio between the desired speed and the nominal rotational speed, the new PAT curves can be obtained with the equations (2).

$$\frac{Q'}{Q} = \frac{n'}{n} \qquad \frac{H'}{H} = \frac{n'^2}{n^2} \qquad \frac{P'}{P} = \frac{n'^3}{n^3} \tag{2}$$

, where n is the rotational speed and ' is relative to the new conditions.

2.3. Digital Algorithm

After defining the configuration for both modes of operation, the most appropriate PATs had to be selected for each PRV location. However, having in consideration that there were 5 selected PAT models to choose from and apply to the 10 PRV locations, not to mention they could operate at different rotational speeds, an automatic procedure was required to perform a complete analysis of these energy recovery methods. This was accomplished with a digital algorithm capable of providing the energy results for every possible scenario throughout the years, enabling the development of a fast and detailed testing analysis. In fact, with the aid of this program, all five previously analyzed PATs could be tested for every PRV location and every rotational speed, not to mention the different modes of operation. The range of rotational speeds analyzed by the digital algorithm correspond to the minimum and maximum rotational speed limits at which the considered PATs could operate, as referred in the KSB Etanorm catalog - 770 rpm to 3500 rpm (KSB, 2015).

Summed up briefly, the program utilizes the nominal speed curves of each PAT and creates alternative rotational speed curves through dimensional analysis, treating them as distinct PATs. Then, for the fixed ER mode, the data relative to the flow rate and head drop values of every PRV and every year is combined with each characteristic curve, taking into consideration the head drop limit defined for each PRV. The ER variable speed mode follows the same principle but changes the rotational speed which maximizes the amount of energy generated for each hour of the day, instead of testing each rotational speed for each PAT. Finally, the program displays the energy production results relative to each possible scenario for every year along with the total accumulated energy from 2018 to 2033.

2.4. Fixed ER mode energy results

The optimal fixed ER energy results for each PRV location, along with the respective optimal PAT selection and rotational speed, are displayed in **Table 2** and **Figure 2**. Note that the NR mode does not correspond to the optimal scenario of energy recovery for any PAT, since the nominal rotational speed (1500 rpm) was not selected.

Table 2 – Fixed ER mode optimal energy results. Emax corresponds to the total accumulated energy.

PRV	PAT	Speed (rpm)	Emax (MWh)
TR08B	100-200	1310	1005
TR07.5F	80-200	1470	686,7
SM04.5B	65-250	1370	328,6
TR05.5G	65-250	1170	149,9
SM04.5A-1	65-250	1170	142,1
MP03.5A-1	65-250	1120	125,7
TR07.5C	65-250	1070	111,7
TR06.5B	65-250	1020	87,9
RP04.5A	65-250	1020	87,4
MP02.5A-1	65-250	770	34,3

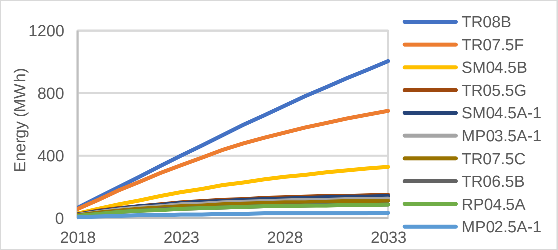

Figure 2 – Evolution of energy production throughout the period under analysis for the fixed ER mode.

The observation of **Table 2** reveals an apparent link between the amount of generated power and the PAT rotational speed. This connection is likely a result of the greater flow rates usually occurring in PRVs with higher energy outputs, whose PATs require higher rotational speeds to operate at their optimal energy recovery potential. The only exception present is PAT 100-200 in PRV TR08B, which generates three times as much power as PAT 65-250 in PRV SM04.5B with an inferior rotational speed. This is related to the fact that PAT 100-200 has a much wider characteristic curve than PAT 65-250 at the nominal speed, which has an impact on its optimal rotational speed.

Another important aspect to consider is the connection between the maximum amount of energy generated and the optimal PAT choice for each case. While PAT 100-200 is the optimal selection in PRV TR08B, the PRV MP02.5A-1 generates the greatest amount of power with PAT 65-200. Indeed, a greater energy production is often associated with higher discharge rates and head drop values, which usually demands larger turbomachines to achieve the maximum potential for energy recovery.

For a better understanding of the energy production with the fixed ER mode, the PRV TR08B was analyzed in greater detail. The **Figure 2** displays the PRV TR08B total accumulated energy production for every analyzed PAT as a function of its rotational speed and **Figure 3** illustrates its annual production throughout the years for the respective optimal rotational speed. The **Table 3** includes the total accumulated energy production for every analyzed PAT and its optimal rotational speed.

Table 3 – Total accumulated energy production for every analyzed PAT and its optimal rotational speed.

TR08B			
PAT	rpm	v/vnom (%)	Emax (MWh)
100-200	1310	86,75	1005,0
80-200	1270	83,55	719,3
65-200	1225	80,33	440,7
65-250	1070	70,39	367,2
150-200	970	63,82	310,0

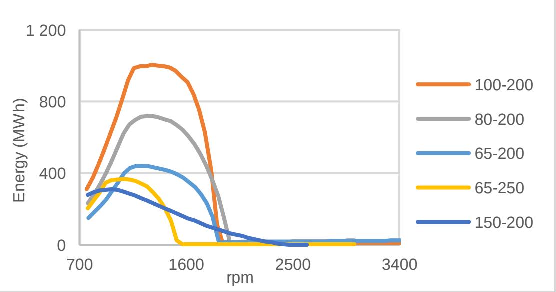

Figure 3 – Total accumulated energy production for every analyzed PAT as a function of its rotational speed;

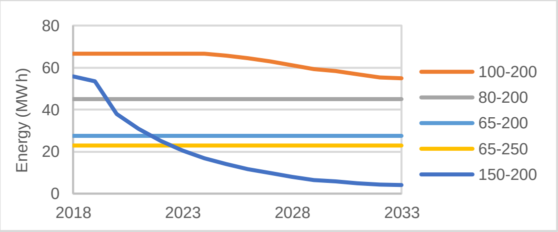

Figure 4 – Annual production throughout the years for the optimal rotational speed.

As displayed in **Table 3,** the optimal rotational speed for any PAT is below the nominal rotational speed, which can be explained by the decreasing flow rate levels in the distribution system throughout the years. Indeed, higher speeds are usually more suitable to higher flow rates, while the opposite remains applicable as well - while PAT 100-200 generates the highest amount of energy at 1310 rpm (86.75% of its nominal speed) with a total energy production of 1005 MWh, PAT 150-200 displays a maximum of accumulated energy at 970 rpm (63.82% of its nominal speed), recovering only 310 MWh from the system over the entire period.

Regarding the evolution of generated power throughout the years, another relevant conclusion can be drawn as well. As illustrated, larger PATs display a tendency to decrease their energy production at a faster rate than smaller PATs over the years, eventually reaching a point where they produce less energy than smaller ones, which occurs with PAT 150-200 in **Figure 4**. This is due to the fact that the flow rate decreases over the years and larger PATs become increasingly less adequate to the new hydraulic conditions.

2.5. Variable ER mode energy results

Contrarily to what might be expected, only a very slight increase in generated power was obtained with the variable ER mode when compared to the fixed speed ER. This is displayed in **Table 4** and **Figure 5**, which contain the total accumulated energy in every PRV and its evolution over time, respectively, exhibiting a strong similarity with **Table 2** and **Figure 2.**

Table 4 – Variable ER mode optimal energy results. Emax corresponds to the total accumulated energy.

PRV	PAT	Emax (MWh)
TR08B	100-200	1013,7
TR07.5F	80-200	702,4
SM04.5B	65-200	347,4
TR05.5G	65-250	162,1
SM04.5A-1	65-250	153,6
MP03.5A-1	65-250	136,6
TR07.5C	65-250	125,1
RP04.5A	65-250	99,1
TR06.5B	65-250	99,0
MP02.5A-1	65-250	37,2

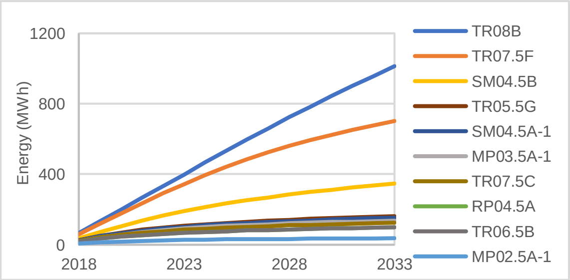

Figure 5 – Evolution of energy production throughout the period under analysis for the variable ER mode.

As demonstrated, it is clear that the total amount of energy produced does not vary substantially between each mode of operation, nor does the optimal PAT choice for each PRV. In fact, although the variable ER mode invariably provides the greatest amount of generated power for any given situation, the energy increase is rarely significant since the selected fixed rotational speeds in the fixed ER mode are already sufficiently well-adjusted to most discharge and head drop levels over the years.

With the purpose of deepening the understanding of the variable ER mode, the **Figure 6** displays the rotational speed variation throughout the day over the years for PAT 100-200 and 150-200 in PRV TR08B. Note that the PAT 100-200 corresponds to the optimal PAT selection while the PAT 150-200 is the lowest energy producing PAT.

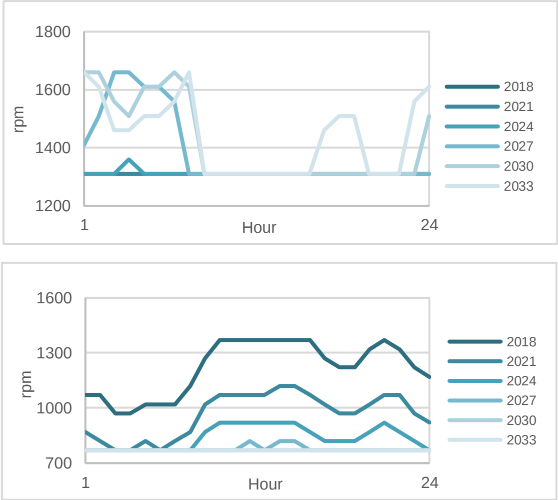

Figure 6 – Rotational speed variation throughout the day over the years for PAT 100-200 (above) and 150-200 (below) in PRV TR08B.

As illustrated, the PAT 100-200 reveals a tendency to maintain a constant rotational speed for a significant fraction of the day, while the PAT 150-200 displays a nearly constant speed fluctuation throughout the day, particularly in the first years of operation. This means that the least adequately selected PATs are forced to change their operating conditions with greater frequency.

2.6. Energy recovery in the water supply system

A specific analysis was carried out to evaluate the plausibility of recovering energy within the water supply system of Funchal, using the data relative to an existing mini hydro power plant located upstream the Alegria reservoir. Considering the information regarding the currently utilized turbomachinery wasn't available, the energy production was calculated assuming an efficiency of 70%.

It should be noted that there are certain restraints which limit the adopted operating flow rate, such as the minimum and maximum water velocities allowed, and the maximum reservoir peak discharge, which must be guaranteed to avoid water supply problems. Additionally, the supply hydro power plant cannot operate 24 hours per day for any flow rate. Indeed, flow rates above the maximum required to fill the reservoir's daily volume in 2018 require a reduced period of operation to prevent excessive amounts of water from entering the distribution system. This impacts the generated power, as illustrated in **Figure 7**, whose energy production curve displays a negative gradient as the power plant starts to operate for fewer hours. The **Figure 8** displays the energy production throughout the years for the optimal flow rate and the respective operating hours. The system's characteristics are: D = 400 mm; L = 783 m; ΔZ = 179 m; c = 0,54.

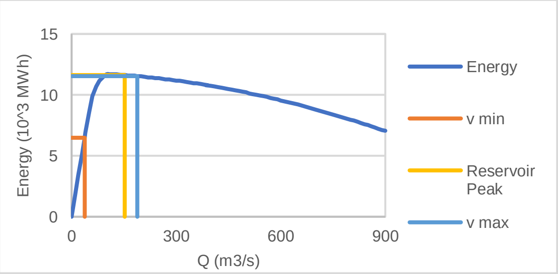

Figure 7 – Total accumulated energy production with respective restrictions.

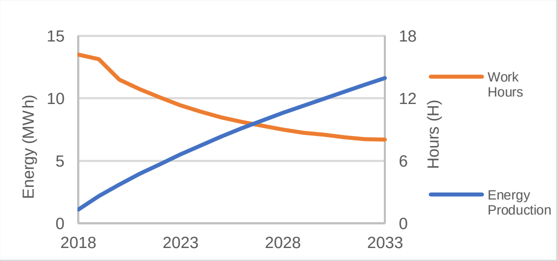

Figure 8 – Energy production over the years for the optimal flow rate and the respective operating hours.

2.7. Economic analysis

To study the feasibility of the energy recovery solutions proposed in the WDS of Funchal, an economic analysis was performed for each PAT application separately, considering each mode of operation and storage method. This was essential to accurately determine the most advantageous investment and exclude unprofitable PAT applications which could undermine the economic potential of the project. The adopted electricity selling prices are 0.057 €/kWh for grid connections and 0.098 €/kWh for local and battery alternatives, and the discount rate considered for every solution is 7.5%. The **Figure 5** and **Figure 6** display the optimal investment for the water distribution and supply system energy recovery solutions, respectively. Note that the fixed ER mode was not included since it generates less power than the variable ER mode while the equipment costs are identical. Regarding the battery alternatives, they were disregarded as well, since they are incomparably more expensive than grid and local connections. It is important to mention that the required investment for each solution includes every hydraulic and electric equipment, along with installation costs.

Table 5 – Water distribution system optimal investment

Mode of Operation	ER Variable Rotational Speed	
Storage Method	Grid	Local
PRVs	TR08B + TR07.5F	TR08B + TR07.5F + SM04.5B
Total Investment (€)	24 648	38 851
Total Energy Produced (MWh)	1716	2063
IRR (%)	23%	34%
NPV (€)	24 855	69 203
B/C (-)	2,0	2,8
T (years)	5	4

Table 6 – Water supply system optimal investment

Storage Method	Grid	Local
Total Investment (€)	200 000	
Total Energy Produced (MWh)	11623	
IRR (%)	19%	47%
NPV (€)	134 741	499 395
B/C (-)	1,7	3,5
T (years)	6	3

2.8. Conclusions

Reverse operation pumps (PATs) have appeared as an alternative to conventional turbines, since they are less expensive and easily accessible, while displaying reasonable efficiency levels. In order to analyze the feasibility of this technology, the water distribution system of Funchal (Portugal) was utilized to study the implementation of several PATs in conjunction with PRVs along the water network in locations with high potential for energy recovery. These are some of the most relevant conclusions:

- Variable rotational speed ER is preferable to fixed rotational speed ER since it generates slightly more power while their equipment cost is identical.
- Although the NR mode hasn't been economically analyzed, it is certainly not a worthy investment since its lack of versatility does not enable an adequate adaptation to constant fluctuating conditions, which is reflected on its limited energy output.
- Battery storage alternatives are not a viable option since they are incomparably more expensive than grid and local connections.
- Of all 50 new PRVs implemented in the WDS of Funchal, only PRVs TR08B, TR07.5F and SM04.5B represent profitable investments for the implementation of PATs considering a local connection. Together they produce a total of 2063 MWh and their collective investment has an NPV of 38.851 €. Since these PRVs are supplied almost directly by major reservoirs, unlike most PRVs within the water network, the implementation of PATs is economically viable only under very particular circumstances, where discharge and head drop values are exceptionally high.
- The supply hydro power plant of Alegria generates a total of 11.623 MWh and has an NPV of 499.395 € adopting a local connection, which makes it more profitable than the water distribution system optimal investment by a large margin. Therefore, it reveals promising energetic and economic results, which entail a positive environmental impact by promoting the sustainability of water distribution.

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