New Challenges In Water Pipe Systems Towards Energy Efficiency

Case Studies of Nampula and Cuamba Water Supply Systems

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Civil Engineering

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Declaration

I declare that this document is an original work of my own and that it fulfills all requirements of the Code of Conduct and Best Practices of the University of Lisbon.

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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 in 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

Resumo

Os Sistemas de Abastecimento de Água (SAA) têm a função de fornecer água sob pressão alta o suficiente para satisfazer as necessidades dos consumidores, porém suficientemente baixa para prevenir danos na tubulação. Assim sendo, as Válvulas Redutoras de Pressão (VRPs) são os dispositivos mais usados para o controlo de pressão em condutas, causando a dissipação do excesso de energia no sistema. Neste contexto, os SAA tornaram-se uma potencial fonte para a geração de energia elétrica em pequena escala, nomeadamente através da implementação de bombas a funcionarem como turbinas (PATs).

O presente estudo avalia o potencial de recuperação de energia em dois SAA no norte de Moçambique, considerando a instalação de PATs como substituição ou em paralelo com as VRPs existentes. Permitindo, assim, a redução dos custos e impactos ambientais do sistema e o aumento das eficiências dos mesmos. Realiza-se uma análise económica com a finalidade de avaliar a viabilidade económica dos projetos.

O estudo demonstra que, se estes projetos forem implementados, para além de contribuírem para o controlo de pressão, permitem ainda reduzir as perdas reais e as emissões de CO_2. Os sistemas estudados, que inicialmente tinham como função apenas o abastecimento de água, passarão também a gerar energia renovável, promovendo, assim, a consciência verde e sustentável. Estes efeitos resultam em receitas totais em torno de 5 000 e 3 000 €/ano em cada sistema. Contudo, enquanto o SAA de Nampula apresenta índices económicos favoráveis (TIR > 39%), o SAA de Cuamba apresenta índices económicos baixos (TIR < 14%).

Palavras-chave: Bomba a funcionar como turbina (PAT); Válvula Redutora de Pressão (VRP); Sistema de Abastecimento de Água (SAA); produção de energia; eficiência de sistemas de água

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Abbreviations

APA	Agência Portuguesa do Ambiente
APDA	Associação Portuguesa de Distribuição e Drenagem de Águas
APREN	Associação Portuguesa de Energias Renováveis
B/C	Benefit/Cost ratio
BEP	Best Efficiency Point
CCI	Characteristic Curve of the Installation
CFD	Computational Fluid Dynamic
CNR	Carbon Neutrality Roadmap
CSP	Concentrating Solar Power
CWSS	Conventional Water Supply Systems
ELL	Economic Level of Leakage
ER	Electric Regulation
ERSAR	Entidade Reguladora dos Serviços de Água e Resíduos
EU	European Union
FIPAG	Fundo de Investimento e Património do Abastecimento de Água
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GPV	General Purpose Valve
GVA	Gross Value Added
HR	Hydraulic Regulation
IRR	Internal Rate of Return
NECP	National Energy and Climate Plan
NPV	Net Present Value
PAT	Pump As Turbine
PI	Performance Indicator
PRV	Pressure Reducing Valve
PV	Photovoltaic
PV	Present Value
RES	Renewable Energy Resources
SDG	Sustainable Development Goals

UN	United Nations
VOS	Variable Operating Strategy
VSP	Variable Speed Pumps
WDN	Water Distribution System
WSS	Water Supply System

Symbols

C	Capital costs
E	Energy
H	Head
H_R	Rated head
N	Rotational speed
N_R	Rated wheel speed
N_s	Specific speed
N_{ST}	Rotational speed of the turbine
O	Operation costs
P	Reposition costs
P_h	Hydraulic power
P_m	Mechanical power
P_R	Rated power
P_u	Power
Q	Discharge
R	Revenues
r	Discount rate
Γ	Torque
γ	Specific weight of the fluid
η	Efficiency
Δt	Time interval

1. Introduction

1.1. Scope

In recent years, the middle class has been rapidly growing, especially in developing countries, resulting in populations migrating from rural to urban areas. This rural flight leads to increases in water, food and energy consumption patterns [1].

The growth of the middle class implies progresses in human development. Nonetheless, this development has been unbalanced, with about 1 billion of the world's population not having secure sources of food, clean water, sanitation or constant access to electricity. 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].

Sustainable socio-economic development hinges on, among other factors, the availability and accessibility of freshwater and energy [2]. As access to safe drinking water and sanitation had become a human right, a cross-sectoral management can support the improvement of resource use efficiency especially in multi-use systems, where waste and by-products can become a resource for other products and services, such as wastewater-energy integration, multi-use reservoirs and green agriculture [1].

To overcome these challenges, water utilities need to take action and implement optimisation methodologies to improve water systems efficiencies. Among other measures, the implementation of small-scale hydropower plants to recover excess energy in pipe systems is the focus of the present dissertation.

1.2. Objectives

Many Water Supply Systems (WSSs) contain devices with the purpose of controlling pipe pressure in order to reduce water losses. Usually these devices are Pressure Reducing Valves (PRVs), which cause local head losses through the dissipation of hydraulic energy.

The main 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.

1.3. Structure of the document

This dissertation is organised in 8 chapters. Chapter 1 presents the relevance of the study, as well as its objectives and structure.

Chapter 2 presents the concept of water-energy nexus, how the water sector can affect the energy sector and vice-versa, emphasises the water intensity of the energy sector and the energy intensity of the water sector and how they can be improved. Additionally, this chapter addresses the efficiency of WSSs and possible approaches for its improvement.

Chapter 3 focuses on water losses, its causes, types, and mitigating measures, such as pressure management, which is commonly considered the most effective approach to reduce water leakages. Furthermore, this chapter presents the advantages and limitations of PRVs, its operating conditions and some proposed methods to determine the number and localisation of PRVs to be installed.

Chapter 4 includes the advantages of replacing PRVs with PATs, an explanation of PATs installation scheme and regulation modes. It includes the concept of Best Efficiency Point (BEP) and the existing theoretical and experimental methods to predict this point. This chapter presents the operating conditions of PATs and some basic hydraulic concepts for the design and conception of turbomachines. Additionally, the equations to obtain the energy produced by a turbomachine are presented, as well as the concepts and variables applied in the economic analysis of the case studies.

Chapter 5 presents measures to achieve energy recovery in water supply systems, whilst comparing the advantages/disadvantages of small and large-scale hydropower schemes. It presents an explanation of the existing types of hydraulic turbines, the challenges faced in the implementation of small-scale hydropower plants and a proposed method to select the optimal PAT. This chapter also comprises the results of a study made by *Delloite Consultores, S.A.*, requested by APREN, regarding the evolution of renewable energy sources in Portugal between 2014 and 2018 and predictions until 2030.

Chapter 6 comprises an analysis of data regarding Performance Indicators (PIs) reported to ERSAR by the water entities in Portugal in the years of 2015 and 2017. Among approximately 200 PIs, only those related to water and energy consumption, systems efficiency and systems economic situation were selected to be summarized in tables and pie charts.

Chapter 7 presents the case studies which are two WSSs in the north of Mozambique. It presents the characteristics required for the development of EPANET models, as well as the steps for the implementation of PATs coupled with existing PRVs, whilst assessing the systems potential for energy generation and the economic feasibility of implementation of these micro hydropower schemes.

Chapter 8 refers to the conclusions of the present study and presents some future perspectives and recommendations for future works.

2. Water-Energy Nexus

2.1. Introduction

Water and energy systems have always been studied and managed separately, but with recent effects of climate change, the interconnection and interdependence of water and energy became more evident. Energy is required for extracting, pumping, transporting and treating water and wastewater, while water is essential for energy production, whether in hydropower and fuels production, cooling operations in power plants or as an input for energy crops [1], [2]. When extreme events occur, this interdependence becomes more noticeable, with water supply systems being affected by power cuts and the energy sector being affected by water availability [1], [4].

In developing countries, the middle class has been rapidly growing over the years, leading to an increase in consumption patterns and resource use, especially in urban areas. This growth, despite being positive, means that emissions and demand for natural resources are also increasing, which requires a change in perspective, aiming to achieve sustainability, resource use efficiency and demand management [1].

This led to the consideration of a new paradigm, known as the water-energy nexus, which has the main purpose of achieving a more sustainable and integrated management of these resources, strengthening the resilience of water and energy systems [4]. This paradigm is defined taking into account that water and energy are intertwined, since the production of one requires the other. The nexus approach enables a cross-sectorial management of resources, contributing to increase the systems efficiency and to build synergies, while reducing trade-offs [1]. The water-energy nexus derives mainly from the fact that until now planning and operation in water and energy sectors have been independent, neglecting that their effects are interconnected [4].

Most of the population without access to safe drinking water and electricity live in rural areas and it has also come to light that usually the population who lacks electricity also lacks safe drinking water (Figure 1). This favours an integrated approach to achieve the UN Sustainable Development Goals (SDGs) concerning water and energy [5].

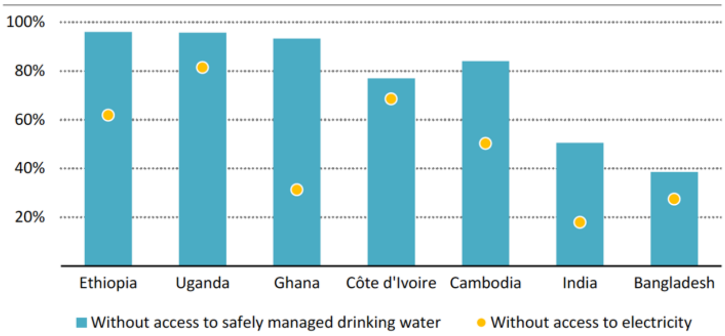


Figure 1 – Share of population without access to electricity or water in rural areas in 2018 [5]

Mini-grids and reverse osmosis systems are energy-based solutions which can contribute to the security of available drinking water in rural areas, where normally the adopted solutions are low energy demanding [5].

Even though off-grid solutions are more cost-effective in rural areas, where the population density is low, they do not account for possible future increases in demand. An integrated water-energy approach can lead to the implementation of more mini-grid solutions, enabling water services to support power generation [5].

Nowadays, a large proportion of the global population still lacks access to safely managed sanitation, both in rural areas, where most people use rudimentary latrines or practice open defecation, and also in urban areas, where wastewater management is still a challenge. Nonetheless, water and wastewater utilities in urban areas represent a big portion of municipal energy bills, sometimes reaching 50% of the total bill. This means that the technologies used when implanting new centralised wastewater facilities, must be more energy efficient. Some of these solutions can be building neutral or energy-positive facilities, which combined with other high efficiency solutions can generate 50% more of the electricity needed and sell the excess. Among other options, some solutions can involve better sludge management, fine bubble aeration and more efficient compressors, and better pipe maintenance. Secondly, in rural areas, where centralised solutions are more difficult to implement, anaerobic digesters can be implemented, producing biogas, thus being able to satisfy numerous domestic energy needs [5].

In addition to decreasing the energy demand, improving the efficiency of wastewater and sanitation services can also reduce GHG emissions. However, most of these techniques are expensive and require high investments [5].

2.2. Water Intensity of the Energy Sector

Even though the energy sector is not one of the main global water users, representing about 10% of global withdrawals and only 3% of consumption, there is potential to reduce its water intensity, through an integrated approach [5].

Increasing the energetic efficiency, implementing PV and wind power generation can decrease the water withdrawals. However, some actions made towards mitigating the effects of climate change, such as carbon capture, nuclear power generation, concentrating solar power (CSP), biofuels production and other decarbonisation techniques, can increase water consumption [4], [5].

The improvement of thermoelectric generation’s efficiency reduces water demand and withdrawals, although increasing consumption, due to more recirculating cooling operations. This effect can be avoided by switching from wet to dry cooling. Furthermore, the produced water in oil and gas extraction, which is normally injected deep underground, could be treated and reused [4].

2.3. Energy Intensity of the Water Sector

Water supply and wastewater treatment comprise the most electricity consuming activities inside the water sector (Figure 2). The water sector consumes 4% of global electricity [5].

The energy consumption in the water sector tends to rise, with desalination and large-scale water transfer projects being the main activities with increasing energy demand. On the other hand, the energy demand for wastewater treatment and water supply and distribution is not increasing exponentially, since there is a large potential to increase the efficiency [5].

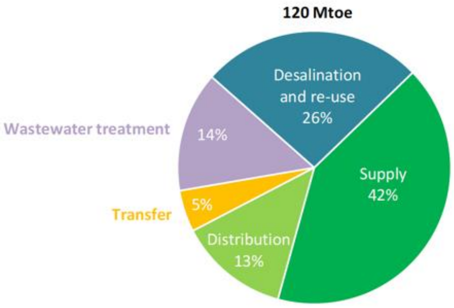


Figure 2 – Global energy use in the water sector in 2016 [5]

Furthermore, the energy intensity also varies depending on source quality, pumping and treatment requirements. Pumping requirements hinge mainly on distance and elevation, whereas treatment is often conditioned by the water source and final use. Groundwater is one of the sources which requires the most energy for pumping, although when it comes to treatment, drinking water and non-conventional water sources, such as reclaimed wastewater and desalinated seawater, are the most energy demanding [1], [2].

2.4. Efficiency of Water Supply Systems (WSSs)

Recently, water transport under pressure is becoming more common, since it presents many advantages, such as layout flexibility, security, quality care, better control, lower environmental impact, and higher efficiency, however, it requires high amounts of energy. In Europe, water transport and distribution represent around 4% of total energy consumption [6].

Some environmental studies have shown that the phases of the urban water cycle which contribute the most to global warming effects are related to water transport, highlighting the necessity to increase water systems efficiency [6].

An analysis of the energy saving potential in EU estimated savings up to 20-30% in the pumping stage, while commercial assessments estimate that 2/3 of all pumps could save up to 60% of energy. This means that when actions related not only to the pumping stage, but to all stages, are implemented, the energy saving potential is much higher [6].

A six-step integrated strategy to improve the systems efficiency has been proposed, consisting of pre-assessing and diagnosing the current state of the system, analysing the energy saving potential, exploring potential actions, prioritizing actions through a cost-benefit analysis and labelling and certification [6], [7].

A water supply system can be defined as a set of structures, facilities and services targeted to produce and distribute water to consumers, meeting quality and quantity needs for domestic consumption, utilities, and other industrial consumption. Water supply systems where the treatment is realized by conventional coagulation, flocculation, settling, and filtration are called Conventional Water Supply Systems (CWSSs) [8].

The energetic and hydraulic efficiencies of WSSs can be improved, with the simultaneous reduction of the electrical energy consumed and of volume of raw water extracted from the source, consisting of an optimisation problem [8].

The use of electricity in CWSSs can be assessed in three dimensions: the project and design dimension, the operational dimension and the physical dimension. Water losses are related to the three dimensions, since the design and operation dimensions are responsible for setting the topographic water levels, the operational limits, and the resulting pressures for the various sector of a network. Moreover, these dimensions and the physical dimension are accountable for the type of material, the pipe layout and the accessories characteristics [8].

Therefore, reducing water losses is essential to increase the efficiency of a WSS since they are the most relevant source of water and energy waste in WSSs. Despite this being widely known, the volumes of water and electricity lost in WSSs around the world are still high, due to two main reasons: the implementation costs associated to the solutions are high from the perspective of system managers and decision makers and the costs related to water and energy losses are passed on to consumers through water bills; the watersheds serving as sources of most of the WSSs still have satisfactory water availability, making the environmental and social importance of water and electricity only gain relevance in water scarcity scenarios [8].

3. Loss Control and Pressure Management

3.1. Water Losses

The recent increase in water demand, particularly in urban areas, along with the fact that most Water Distribution Networks (WDNs) were designed and built more than 80 years ago, led to aging and leaking pipes, which deeply affect the systems energetic efficiency. Therefore, rehabilitation and repair works, as well as optimisation measures, such as pressure management and active leakage control, are required in order to reduce water loss volumes, while increasing the systems energetic efficiency and sustainability [9], [10].

Water losses can be apparent, comprising unauthorized consumption and metering inaccuracies, or real, when related to leakages and overflows in water supply and/or distribution [11]. Moreover, real losses can be classified as background leakages or burst outflows, the former consisting of outflows from small cracks or deteriorated joints and, the latter usually being the natural evolution of background leakages. Bursts are characterised by a sudden pressure drop and are usually quickly reported by the public or detected by flow/pressure monitoring instruments installed in the network, thus having a short repair time. However, background leakages, which are not detectable by monitoring pressure and flow, since the sudden pressure drop does not occur, can go unreported for a long period of time, resulting in high volumes of water loss, hence representing a serious challenge to water distribution networks [12], [13].

As reported by the World Bank, roughly 48 billion m^3 of water is lost annually from water distribution systems, generating a cost of approximately US$14 billion per year to water utilities around the world. Most available tools and methods for water loss management essentially focus on the leakage component of water losses, precisely on leak detection and on transient-based leak detection methods, neglecting the apparent loss component and the management science and sociotechnical aspects of water loss management [14].

When the quantity of water lost is high and keeps increasing, it means that an active leakage control programme should take place [11]. An active leakage control strategy consists of detecting the leakages before they appear on the surface, using various technical equipment. To be effective, it demands high levels of technical and organisational capacities from the water utilities, thus, when only reported leaks are detected, located, and repaired, it is a strategy of passive leakage control [15].

Leakage management consists of four main elements: (1) quantifying water loss; (2) leakage monitoring; (3) leak detection, location and repair; (4) and network pressure and asset management [14]. Common strategies for leakage reduction in WDNs involve pressure reduction, replacing aging mains, establishing suitable sized metered areas, repairing reported leaks and actively finding and fixing hidden leaks [16].

At an early stage in leakage reduction programmes, it is easy to achieve significant leakage reductions, however, as the programme progresses, subsequent reductions can become increasingly difficult and expensive, until reaching a point where it is technically and economically unviable to attempt to reduce the leakage further – the Economic Level of Leakage (ELL) (Figure 3). The ELL can be defined as the point where the financial cost of reducing leakage by 1 m^3 matches the financial value of the 1 m^3 of water saved [16].

In cases where the financial resources are low or it is difficult to keep up with the grow rate of the cities, the ELL can be useful to justify investments and priorities for leakage control strategies. This can be valuable, especially in developing countries, despite the fact that the calculation of the ELL can be very information intensive [15].

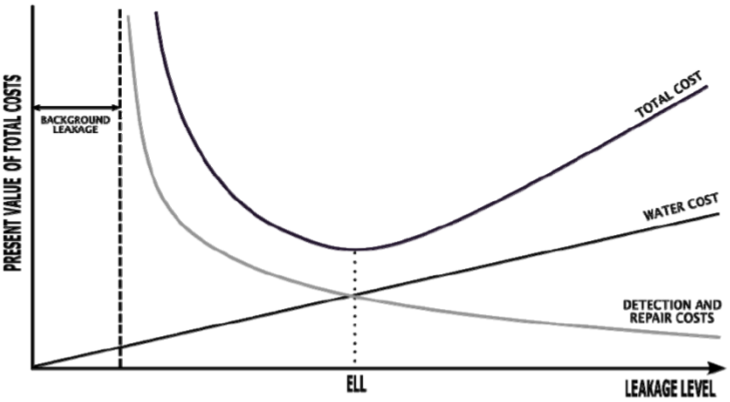


Figure 3 – The Economic Level of Leakage (ELL) [15]

3.2. 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 [9], [15]. Water losses, which globally regularly reach values of 30-40%, are a main concern regarding water distribution efficiency and sustainability [17].

Some authors suggest that pressure management is the most cost-effective approach to reduce leakages in WSSs, while also reducing the incidence of pipe bursts and the associated repair costs as well as avoiding disruptions in road traffic. Fewer pipeline ruptures also improve the performance of the water industry by reducing the disruption in water supply to costumers [8], [15], [18].

Pressure management refers to activities of effective pressure adjustment throughout the day, providing sufficiently high pressure that ensures a constant and adequate service to customers while reducing it to an extent that avoids background leakages or breaks at night [19].

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. Various regulation elements can be used in pressure management: pump control, tank regulation, and pressure reduction by using automatic valves, among others [19].

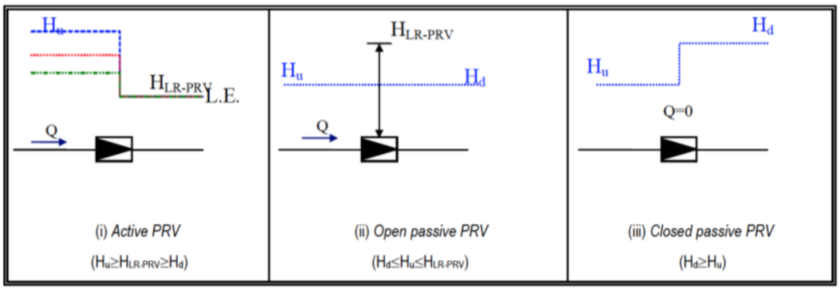
Other researchers indicate that the best solution to reduce pressure in WSSs must include devices that provoke head losses, particularly Pressure Reducing Valves (PRVs). However, the main challenge regarding the application of PRVs is the optimal location and quantification of these devices [8], [17].

3.3. Pressure Reducing Valves (PRVs)

One way to control the pressure, thus reducing water losses, is installing Pressure Reducing Valves (PRVs). PRVs are devices with the main purpose of controlling the pressure or head, independently or not of the discharge variation [20]. 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 [9], [21].

The operation of a PRV consists in acting the lock device whenever the downstream pressure is too high, which increases the local head loss while reducing the downstream pressure until the required value. Or contrarily, the downstream pressure decreases above the load reference value, the valve opens diminishing the local head loss while increasing the downstream pressure to the required value. [22].

Accordingly, PRVs can operate in three states: (1) active state, where the valve provokes a local head loss to reduce the downstream pressure (Figure 4 (i)); (2) passive state, when the upstream pressure is lower than the PRV load reference value, then the valve opens completely maintaining the same pressure upstream and downstream (Figure 4 (ii)); (3) and passive state of the closed valve, when the downstream pressure is higher than the upstream and the valve closes totally, operating as a check valve avoiding the flow inversion (Figure 4 (iii)) [22], [23].



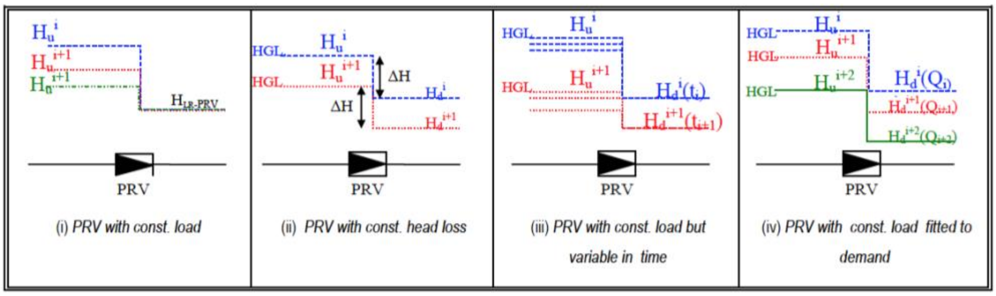
(i) *Active PRV* ($H_u \geq H_{LR-PRV} \geq H_d$)

(ii) *Open passive PRV* ($H_d \leq H_u \leq H_{LR-PRV}$)

(iii) *Closed passive PRV* ($H_d \geq H_u$)

Figure 4 – Typical operation of a conventional type PRV [22]

To obtain a higher hydraulic performance and a better efficient system, the PRVs can be electronically or mechanically controlled, in order to operate for different pressure levels, defined according to consumption variations. Accordingly, there are four different active operation status for PRVs: (1) PRV with constant load – the valve reduces and stabilises the downstream pressure, maintaining the pressure constant and equal to the load reference value for each PRV for any upstream pressure flow in the system (Figure 5 (i)); (2) PRV with constant head loss – the valve reduces the downstream pressure by a constant local head loss independent of the upstream pressure, so the downstream pressure varies with the upstream pressure (Figure 5 (ii)); (3) PRV with constant load but variable in time – analogous to a PRV with constant load however the pressure is maintained constant in predefined intervals varying along the time (Figure 5 (iii)); (4) PRV with constant load fitted to the demand – the valve reduces the downstream pressure as a function of discharge or pressure in critical sections of the network (Figure 5 (iv)) [22].



(i) PRV with const. load

(ii) PRV with const. head loss

(iii) PRV with const. load but variable in time

(iv) PRV with const. load fitted to demand

Figure 5 – Active operation status for different types of PRV [22]

Several studies have proposed methodologies to determine the optimal location and quantity of PRVs through the application of hydraulic simulations and optimisation techniques. A genetic algorithm was proposed, allowing to simultaneously optimise the number and the location of the PRVs, as well as their opening adjustments. This methodology consists of two objective-functions: one for the optimisation of the number and location of valves; and another for the adjustment of valves opening degree in order to optimise the pressure along the system [8], [17].

This genetic algorithm is able to fully satisfy the management of extreme pressures without compromising the efficiency and performance of the system. It was found that the best number and location of valves depends on the typology and characteristics of the system, which are only achievable through a computational sensitivity analysis. The best solution does not correspond to the greater number of valves [17].

Another study proposed an optimisation algorithm to find optimal set points of PRVs and Variable Speed Pumps (VSPs) in WDNs in order to reduce background leakages and pump energy consumption. VSPs are pumps with a variable speed drive that regulates the rotational speed of the pump's electric motor by changing the frequency of the input power. When applied to a real case, it was found that simultaneously using and controlling PRVs and VSPs with the optimisation code, can improve the pressure management process and achieve the highest reduction in leakage and energy consumption, with the reduction of background leakage and power consumption reaching 41,72% and 28,4% respectively, compared to uncontrolled mode [24].

4. Pumps As Turbines (PATs)

4.1. Introduction

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 (Figure 6), while imposing less investment costs than traditional turbines [21]. 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 [25].

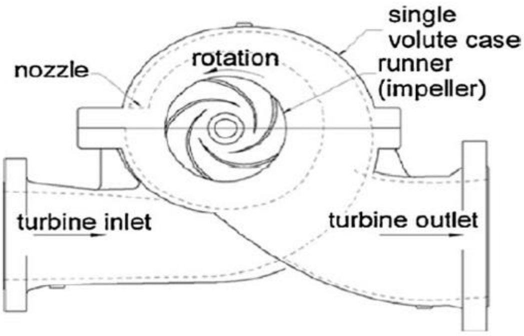


Figure 6 – Direction of flow and rotation in a PAT [26]

The optimal location for a PRV does not coincide with the optimal location for a PAT, considering it only minimises the water losses, not necessarily maximising the energy production, since it depends, not only on the head drop, but also on the flow through the PATs. To maximise the energy production, a different optimisation function should be defined or a multi-objective approach must be considered [25].

A PAT can operate in two regulation modes, namely hydraulic and electrical regulation (Figure 7). The hydraulic regulation (HR) consists of a by-pass conduit and a PRV in series with the turbine, where the series valve (A) dissipates the excess pressure when the available head is higher than the head drop deliverable by the machine. Alternatively, when the discharge is larger, the PAT produces a head drop higher than the available head, thus, the by-pass (B valve) is opened to reduce the discharge flowing in the PAT. Reciprocally, in ER mode the operating speed of the generator is changed to match the load conditions determined by the instant flow discharge and head drop values (Figure 8) [23], [27]–[29].

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 [21].

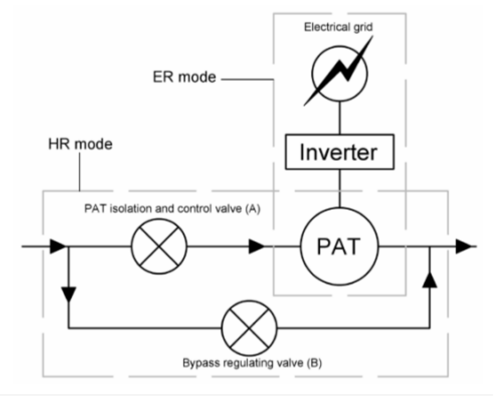


Figure 7 – Installation scheme of a PAT with hydraulic or electrical regulation [27]

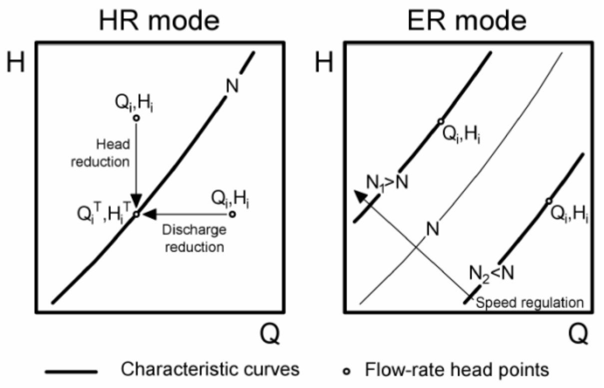


Figure 8 – PAT operating conditions in hydraulic or electrical regulation mode [27]

4.2. 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 micro 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) [26], [30].

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 [30]. However, a study found that the BEP of a PAT is 8,53% lower than the BEP of pump operating in direct mode [31].

A method developed to predict the BEP of a PAT showed that for the same specific speed, the most efficient PAT works in greater head and flow ratios, on the other hand, the bigger impeller implies the highest efficiency. This method is only suited for centrifugal pumps with $N_s < 60$ [30].

Furthermore, a theoretical method was developed to predict the BEP of a PAT based on the geometric and hydraulic characteristics of pump mode. To verify the numerical results, a centrifugal pump was simulated in direct and reverse modes using Computational Fluid Dynamics (CFD). Hence, it showed that the experimental data was in accordance with the CFD results in pump mode. However, in turbine mode, the predicted values were slightly lower than the experimental data, probably related to the effect of geometric simplification in the CFD model [32].

A study using CFD models in low-power hydraulic machines introduces new geometry, involving new hydraulic energy converters, which can be easily manufactured and installed in systems with small flows and/or heads [33].

4.3. 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 [34].

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 9). 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 10). 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 [20].

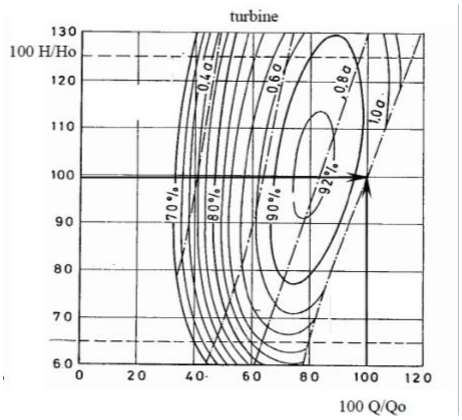


Figure 9 – Operating point in a turbine hill diagram [34]

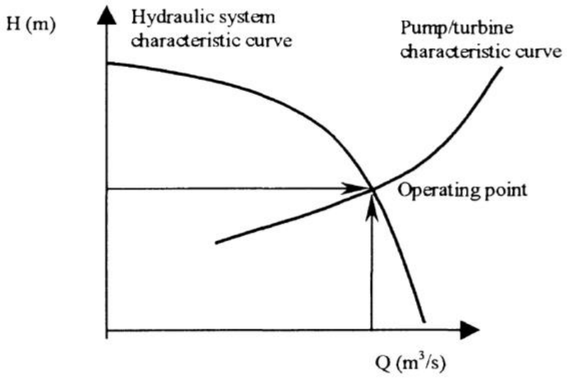


Figure 10 – Operating point of a pump in turbine mode [20]

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)) [20], [34]:

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

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

The signs of q and n define four quadrants, while the signs of h and b define different pump operating zones (Figure 11). In normal pump operating conditions all four parameters are positive, whilst for normal turbine mode, the signs of n and q are negative, and h and b are positive [20], [34].

The pump runner type is mainly characterized by the specific speed (N_s), which can be obtained through equation (2)[20], [34]:

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

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)) [20], [34]:

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

for $Q = Q_{max}$.

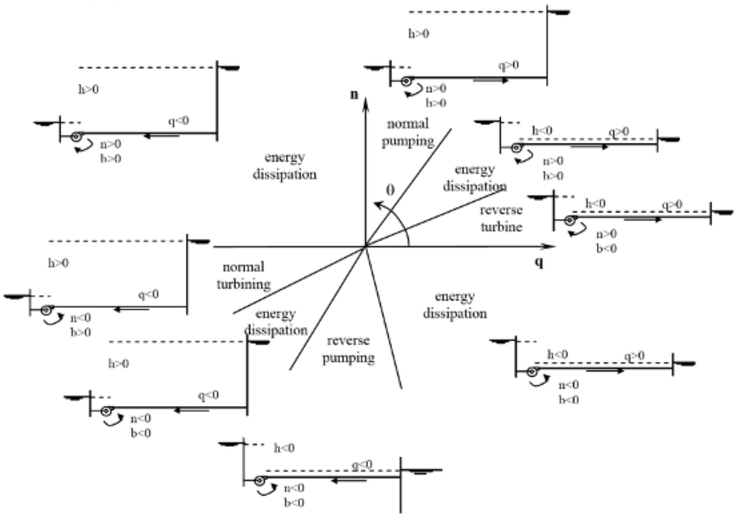


Figure 11 – Operating zones for a pump with the identification of the variability of the typical characteristic parameters [34]

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 [20].

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 [35].

The application of the theory requires the verification of three conditions: (1) the geometric similarity, requiring that the turbine dimension and the flow passage obey one geometrical scale; (2) the kinematic similarity, meaning equivalent velocity triangles at inlet and outlet of the runner; (3) and the dynamic similarity, implying similar action forces [36].

Therefore, the existence of geometric similarity between two turbines implies the equality of the efficiencies of these machines, derived from the equality of the specific speeds at the inlet and outlet of the runner [35].

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)) [35]:

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

For the same machine working in conditions of similarity, the following equations can be verified (equations (6), (7) and (8)) [35]:

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

$$\frac{Q}{Q'} = \left(\frac{H}{H'}\right)^{1/2} \tag{7}$$

$$\frac{P}{P'} = \left(\frac{H}{H'}\right)^{3/2} \tag{8}$$

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 [35].

4.4. Energy Generation

The power, *P*, of a hydraulic turbomachine can be defined as the power in the machine’s shaft. Hence, it corresponds to the power available in the turbine, or it is the power that must be given to the pump. The power of a turbine is less than the power that it receives from the flow and it is given by (equation (9)) [35]:

$$P_u = \eta \gamma Q H \tag{9}$$

The generation of energy in a hydropower scheme depends on the water flowing through the pipeline. In retail water systems the flow depends on the daily demand pattern, whilst in bulk systems the flow does not rely on demand patterns but on whether the tanks are full – the water flow stops – or not – there is constant flow.

The produced energy is obtained by equation (10) [23]:

$$E = \sum_{\Delta t=1}^{n} P_u \Delta t = \sum_{\Delta t=1}^{n} \eta \gamma Q H \Delta t \tag{10}$$

4.5. Economic Feasibility

The fact that a project of a micro hydropower plant is feasible from a technical point of view does not guarantee that it will be advantageous from an economic point of view. Therefore, the final decision on whether the project should be constructed, or the selection of the best design solution is based on an economic analysis, which compares the expected costs and benefits for the useful life of the project [36].

The effectiveness of an economic analysis hinges on the accuracy of the estimates for the project costs and benefits. The costs of a micro hydropower plant include capital costs, corresponding to all expenses necessary to execute the project; annual operation costs, from the exploitation and maintenance of the plant during its useful life; and reposition costs, resulting from the substitution of the equipment with a shorter useful life than the plant [36].

The annual income for this type of project depends on the amount of energy produced during the plant's lifetime and on the conditions of the energy sale contract and the tariffs policy. This income is the only tangible revenue for the investor [36].

The economic analysis will be based on the concept of constant market prices, referred to the first year of exploitation, not considering the inflation, since it will have the same effect in any monetary flux. This concept means that the future costs and benefits are evaluated at present market prices [36].

The discount rate, r, can be used to define the value that a monetary flux had in the past or will have in the future. If n represents a period of n years, from year 1 to year n, one monetary unit of today will be changed in year n by $(1+r)^n$ monetary units. On the other hand, one monetary unit of year n will be changed today by $1/(1+r)^n$ monetary units [23], [36].

The present value (PV) of a single generic monetary flux that will occur in a future year i, C_i can be obtained by equation (11) [23], [36]:

$$PV = \frac{1}{(1+r)^i} C_i \tag{11}$$

To find out whether a project will be economically viable or not, four economic indexes must be evaluated: Net Present Value (NPV), benefit/cost ratio (B/C), internal rate of return (IRR) and payback period (T). However, when comparing various alternatives, the evaluation of this parameters can identify different projects as the most economic [23], [36].

Considering n the number of the project lifetime periods, the present values of capital costs (C), operational costs (O), revenues (R) and reposition costs (P) can be obtained through equations (12), (13), (14) and (15) [23], [36]:

$$C = \sum_{i=1}^{k} \frac{C_i}{(1+r)^i} \tag{12}$$

$$O = \frac{\sum_{j=k+1}^{n} \frac{O_j}{(1+r)^j}}{(1+r)^k} \tag{13}$$

$$R = \frac{\sum_{j=k+1}^{n} \frac{R_j}{(1+r)^j}}{(1+r)^k} \tag{14}$$

$$P = \frac{P_m}{(1+r)^m} \tag{15}$$

where O_j is the operational costs for year j, R_j is revenues in year j, P_m is the reposition cost foreseen for year m $(n/2 < m < n)$.

The Net Present Value, *NPV*, illustrates the cumulative sum of all expected benefits minus the sum of all costs during the lifetime of the project, both expressed in terms of present values (equation (16)). If *NPV* is negative, it is expected that the benefits during the lifetime of the project will not be enough to cover its costs, therefore, the project must be rejected. Furthermore, when comparing alternative design solutions with positive *NPV*, the best ones will be those with greater *NPV* [23], [36].

$$NPV = R - C - O - P \tag{16}$$

The benefit/cost ratio, *B/C*, is the ratio between present values of the net annual benefits and of the capital and reposition costs and can be obtained through equation (17). It gives an immediate perception of the desirability of a project: if it is less than one, the project is undesirable; if it is equal to one, the *NPV* will be equal to zero and the project has a marginal interest; and if it is greater than one, the project is as desirable as *B/C* is higher [23], [36].

$$B/C = \frac{R - O}{C + P} \tag{17}$$

The internal rate of return, *IRR*, is established as the discount rate that makes *NPV* equal to zero (equation (18)). When the discount rate is equal to *IRR*, the *B/C* ratio will be unitary and *NPV* will be null. In a comparative analysis, the best alternative design solution will be the one with higher *IRR* [23], [36].

$$NPV = \frac{\sum_{j=k+1}^{n} \frac{1}{(1+IRR)^j} \left(R_j - O_j\right)}{(1+IRR)^k} - \sum_{i=1}^{k} \frac{1}{(1+IRR)^i} C_i - \frac{P_m}{(1+IRR)^m} = 0 \tag{18}$$

The payback period, *T*, is the number of years it takes before cumulative cash flows equal the initial investment. It corresponds to the year when the cumulative cash flows turn positive [23], [36].

5. Renewable Energy

5.1. Energy Recovery in Water Systems

Gravity water supply systems located in areas with high topographic gradients generally present high pressures, which contributes for the hydropower potential of these systems. Additionally, turbines installed in water systems can replace PRVs, benefitting water loss management. Hydraulic turbines can convert the excess pressures, that otherwise would be dissipated by PRVs, into electricity [8].

Other alternative measures for energy saving in water systems include installing PATs and replacing the pipes before the end of its life cycle, which allows to use the energy loss saving from smoother pipes for hydropower generation [25].

At the end of the 19th century, the use of small hydroelectric plants was on the rise, however, in the 20th century there was a shift towards large-scale hydropower plants. But with sustainability measures and climate change becoming more relevant in the last years, the implementation of small electro-mechanical production devices suitable for small-scale power systems is becoming more appealing. This solution allows the reduction of energy consumption in WDNs, by using its own generation, while offering the possibility to sell the surplus energy to the national grid [26], [27], [37]**.**

Renewable energy sources can be used in water pipe systems to generate clean energy without major environmental impacts, using the guaranteed continuous discharge and potentially generating electricity 24 hours per day, throughout the year, without any constraints for water users [37]**.**

Small and micro-hydropower plants are more eco-friendly than large-scale hydro plants, causing no problems of large water storage and population rehabilitation, furthermore, representing a sustainable method for electricity generation. Moreover, small-scale hydropower plants, when compared to large-scale hydro plants, are a cost-effective alternative for electricity generation in remote areas since these projects can be installed in less time and with low initial costs [26]**.**

Nevertheless, small and micro-hydropower plants have low running cost but high initial capital cost. Using PATs is a cost-effective option, thus reducing the equipment cost and the initial capital cost of the plant [26]**.**

The hydraulic conditions in WDNs are highly variable since the flow discharge and pressure head depend on user demand patterns. The variability of hydraulic conditions, combined with the low available power can increase the unit cost of traditional turbines up to five times more than usual [27]**.**

5.2. Energy Production using Turbines or Pumps as Turbines

Hydraulic turbines are able to convert hydropower energy into rotating mechanical energy. The turbines to be installed in a small-scale hydropower scheme are chosen depending on the systems characteristics, namely: net head, unit's discharge and unit's power. There are two essential types of turbines: impulse turbines, characterised by a free jet at atmosphere pressure; and reaction turbines, characterised by a pressurised flow [36].

The most common model of an impulse turbine is the Pelton turbine, which is composed by a runner with double spoon shaped blades, and one or more nozzles. The jet coming from the nozzle hits the blades of the runner, converting the flow kinetic energy into rotational mechanical energy [36].

Reaction turbines consist of a closed chamber, where the flow transforms part of pressure energy into rotational mechanical energy of the runner. The regulation of the turbine discharge is made by a movable guide vane, while it simultaneously guides the flow around the runner. The most known models of this type of turbines are the Kaplan and Francis turbines [36].

Nonetheless, the application of turbines in pico-hydropower schemes (below 5 kW) is still unusual, since it requires accurate preliminary analysis to ensure the optimal choice of the turbine [25].

Small-scale hydropower plants are in demand in many developing countries, making PATs a more attractive alternative for hydro generation, often with a capital payback period of two years or less for PATs in the range of 5-500 kW [30].

The use of PATs and its induction motor as a generator has been proposed as a way of reducing capital investment in systems with a need to reduce water losses and manage pipe pressure. However, due to discharge and head drop variability, its efficiency can be limited, although a larger flexibility can be achieved through plant modulation [27]**.**

The implementation of small hydro power plants in WDNs faces two main challenges: the lack of available characteristic curves for pumps operating in turbine mode and, the absence of a strategy for turbine selection. A Variable Operating Strategy (VOS) was proposed as an optimisation procedure to select the optimal PAT, maximising the power plant efficiency. Alternatively, the PAT characteristic curve can be experimentally obtained through CFD analysis or analytically calculated through one-dimensional methods [29].

The reliability of PATs hinges on various aspects, such as the manufacturing standards, the operating conditions, the installation, the water typology, etc. Some studies using VOS have found that HR mode is generally more efficient and flexible than ER mode, presenting better system capability, effectiveness and smaller machine diameters, thus affecting the associated costs. Furthermore, VOS can be used in combination with characteristic curves based on CFD, providing accurate design solutions [27]–[29].

5.3. Renewable Energy Sources

Water pumping using wind and solar energy sources has been widely studied. Wind systems and photovoltaic systems are mostly applied for small-scale pumping, essentially for irrigation and water supply in remote areas. Wind power can be used for large-scale pumping whereas photovoltaic systems, due to their high initial cost, are limited to medium scale systems (maximum capacity of 11 kW) [8].

The impact of electricity from Renewable Energy Sources (RES) between 2014 and 2018 was analysed and projected until 2030. This analysis consisted of applying two scenarios: the 2030 National Energy and Climate Plan (NECP), based on the "Peloton" scenario of the 2050 Carbon Neutrality Roadmap (CNR); and another, based on the "Off Track" scenario, also of the CNR, consisting of continuing the currently implemented. It is estimated that by 2030, 80% of the energy mix in Portugal, comes from Renewable Energy Sources [38].

The main estimated impacts of the NECP scenario by 2030 include: creating around 160 thousand jobs by 2030; avoiding CO_2 emissions at a rate of 6,7% per year, allowing to save more than 27 billion euros for avoided imports of fossil fuels. Although the dependence on external energy has reached around 77% in 2018, it is estimated that by 2030, the dependence on imported fossil fuels decreases to 65,8%. In general, the estimated impacts of the "Off Track" scenario are lower than the estimates for NECP (Table 1) [38].

Table 1 – Main impacts summary [38]

	2018	**2020**	**2025**	**2030**	**"Off Track" 2030**
Contribution to GDP	3.306 M€	3.860 M€	8.015 M€	10.959 M€	3.396 M€
Job creation	46.790	55.008	116.796	160.974	47.129
CO_2 emissions avoided	11,3 Mt	12,9 Mt	19,5 Mt	24,6 Mt	11,6 Mt
Imports avoided	1.262 M€	1.243 M€	2.389 M€	3,460 M€	2.087 M€
Energy dependence rate	77,0%	75,7 %	71,1 %	65,8 %	77,0 %

Between 2014 and 2018, the installed capacity in Portugal increased 12%, as a result of investments in new renewable power plants, at the same time the capacity associated with non-renewable sources decreased, representing 36% of the total installed capacity in 2018, comparatively to 41% in 2014 (Figure 12). Among the various RES, about 60% of the total increase in installed capacity comes from hydro, while the evolution of installed capacity from wind energy has stagnated, whilst solar energy increased, although remaining low, in light of the 2030 targets (Figure 13) [38].

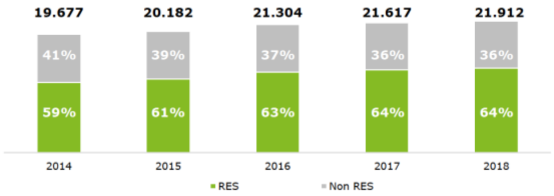


Figure 12 – Evolution of installed capacity in Portugal (MW) [38]

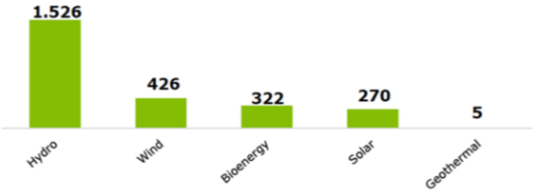


Figure 13 – Increase in RES installed capacity in Portugal, between 2014 and 2018 (MW) [38]

In the period between 2014 and 2018, the electricity produced from RES was accountable for a cumulated value of 15 billion Euros in Portugal GDP, averaging more than 3 billion Euros per year. Wind energy contributed the most (1.9 billion Euros) followed by hydropower (807 million Euros) [38], [39].

In 2018, wind was the RES with the largest impact on Portugal's GDP (58%), followed by hydro (24%). Both sources combined accounted for more than 2,5 billion euros in GVA in that year (Figure 14). However, considering unit contribution, solar is the largest contributor, with the share from hydro sources decreasing since 2010 (Figure 15). According to the NECP 2030 goals, it is estimated that by 2030, the GVA of RES increases to approximately 4,6% of the GDP, representing around 11 billion euros [38].

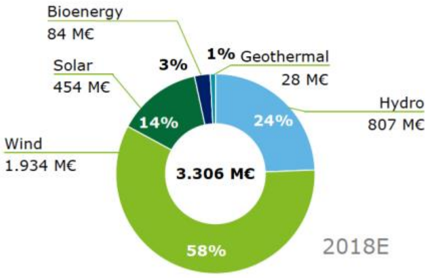


Figure 14 – Distribution of the total contribution towards GDP by RES in 2018E (M€) [38]

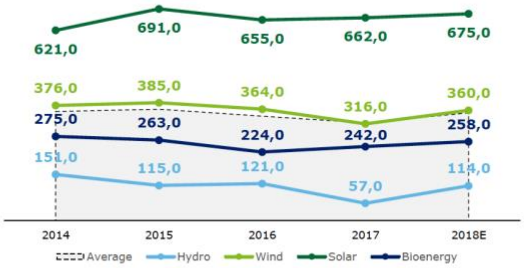


Figure 15 – Evolution of the k€ ration generated for the GDP by installed MW [38]

From 2014 to 2018 the production of renewable energy favoured a reduction of 10 billion Euros and costed 7 570 million Euros, resulting in a net revenue of 2 400 million Euros. This represented a lower electricity market price for consumers, costing 24 Euros less per MW [38], [39].

In the period between 2014-2018, the total gross electricity production in Portugal increased 13%, with the share from RES fluctuating between years, due to variable climate conditions (Figure 16). Hydro generation tends to be the most affected in dry years, although Portugal is one of the countries with the largest share of renewable energy produced in national territory (Figure 17) [38].

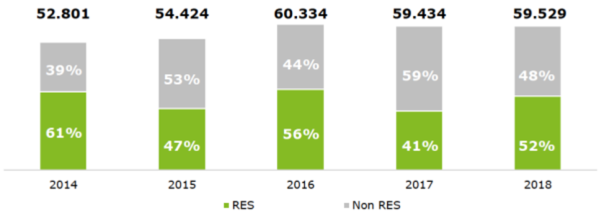


Figure 16 – Evolution of gross production of electricity in Portugal (GWh) [38]

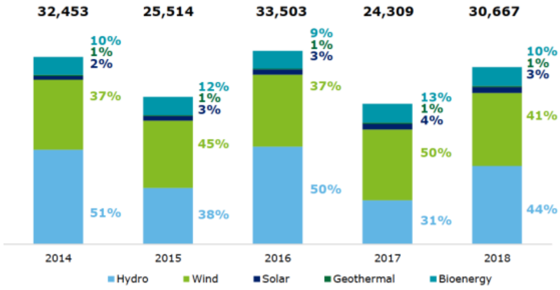


Figure 17 – Evolution of electricity production in Portugal by RES (GWh) [38]

The total installed capacity in Portugal is expected to grow around 63% from 2015 to 2030, with RES representing 86% of the installed capacity mix in 2030, according to the proposed goals by NECP (Figure 18). Solar generation is estimated to become the largest contributor among RES, representing 34% of the RES installed capacity, followed by wind (32%) and hydro (31%) generation, with the total installed capacity from RES reaching 28 300 MW in 2030 (Figure 19) [38].

In the period from 2015 to 2030, the NECP predicts a decrease of 61% in non-renewable electricity production. Although, for the same period, the electricity production is expected to grow more than 40%. Regarding the renewable production mix, it is estimated that the wind sector will have the largest share (35%), followed by solar (33%) and hydro (26%) sectors. The NECP estimates that the required investment to achieve the 2030 goals, will be from 22 000 million euros to 23 600 million euros [38].

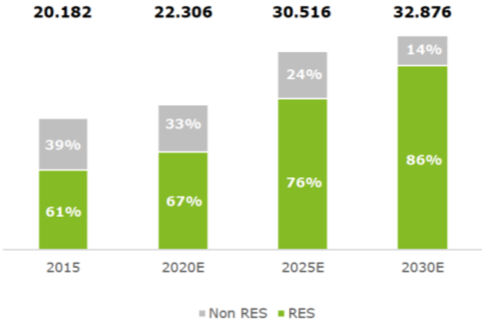


Figure 18 – Estimate of evolution of installed capacity in Portugal (MW) [38]

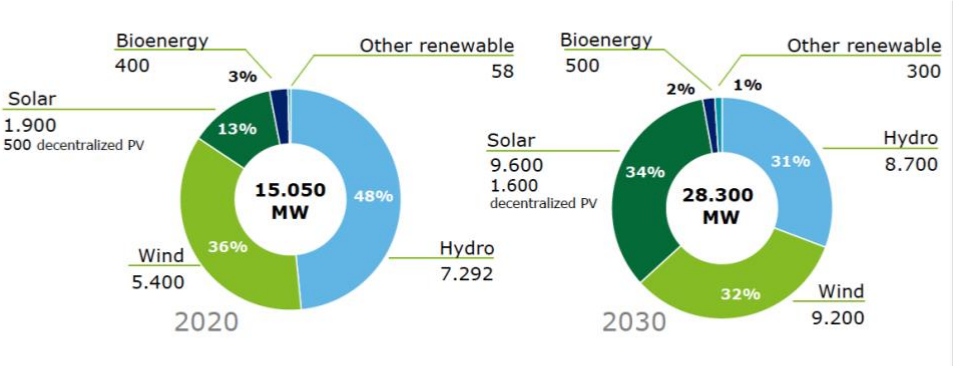


Figure 19 – Distribution of installed capacity by RES in 2020 and 2030 (MW) [38]

6. Analysis of Water Sector Performance Indicators (PIs)

6.1. Introduction

In Portugal, the water sector consists of various entities which play the roles of legislation, regulation, and management. The Portuguese Government is responsible for the legislation and regulation of the sector, while the Portuguese Regulatory Entity for Water and Waste Services (*Entidade Reguladora dos Serviços de Água e Resíduos* – ERSAR) is only accountable for the sector regulation. The sector management, which can be direct, delegated or concession is responsibility of various entities that can be state-owned or municipal or intermunicipal (Figure 20).

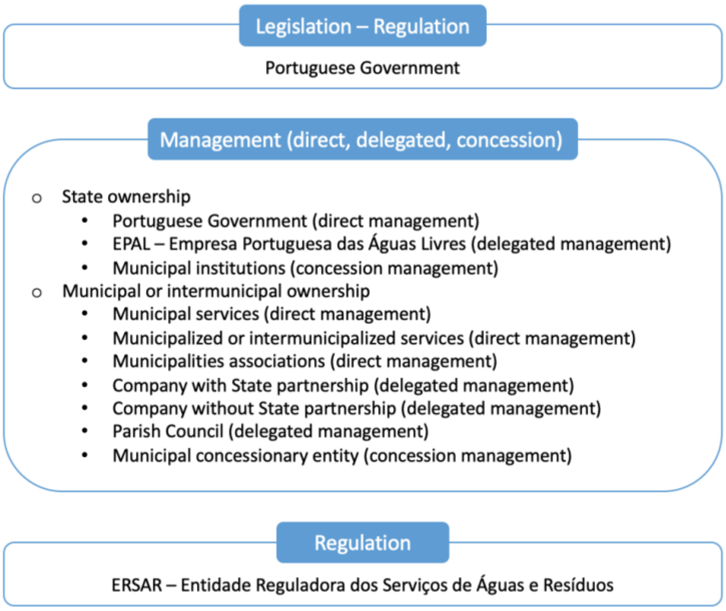


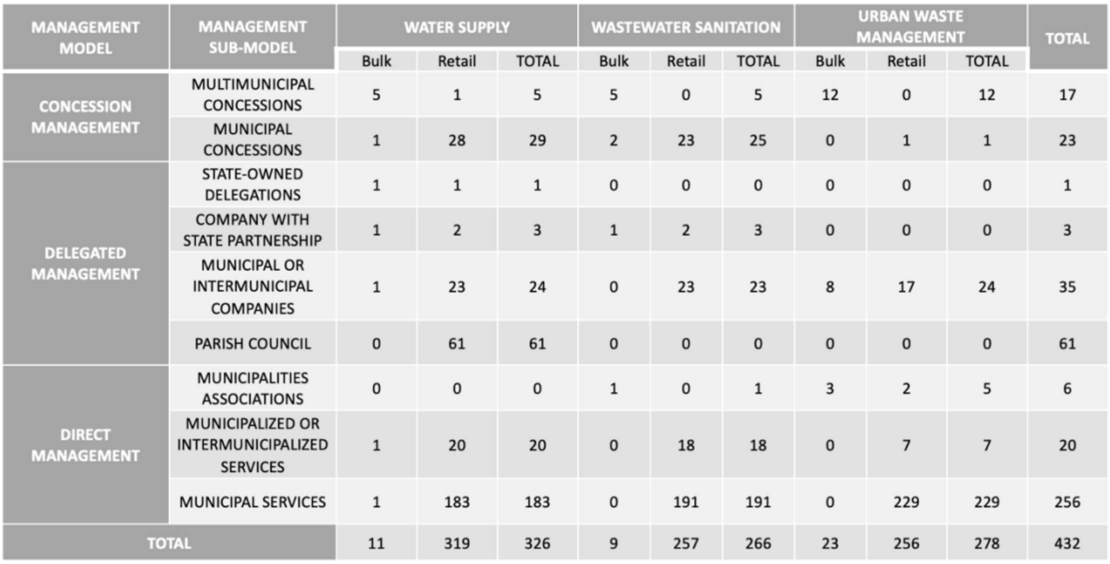
Figure 20 – Water sector entities in Portugal

The distribution of management models in Portugal are presented in Table 2, according to the branches of activity within the water sector – water supply, wastewater sanitation and urban waste management. There is a total of 432 entities in the water sector in Portugal.

Every year, the management entities in Continental Portugal are required to register and provide data to the sector regulator (*Entidade Reguladora dos Serviços de Água e Resíduos* – ERSAR), which allows to evaluate the entities performances based on reference values. This chapter comprises an analysis of this data, namely performance indicators (PIs), considering the years of 2015 and 2017.

The information registered and provided by ERSAR is organised in a spreadsheet, where each line contains the name of the entity, the PI, its value and units, the type of systems (bulk/retail) and the branch of activity of the entity. Considering that there are 432 registered entities, providing data related to approximately 200 PIs, it was essential to filter the information that is relevant for the scope of this study.

Table 2 – Distribution of models of management in Portugal



MANAGEMENT MODEL	MANAGEMENT SUB-MODEL	WATER SUPPLY			WASTEWATER SANITATION			URBAN WASTE MANAGEMENT			TOTAL
		Bulk	Retail	TOTAL	Bulk	Retail	TOTAL	Bulk	Retail	TOTAL	
CONCESSION MANAGEMENT	MULTIMUNICIPAL CONCESSIONS	5	1	5	5	0	5	12	0	12	17
	MUNICIPAL CONCESSIONS	1	28	29	2	23	25	0	1	1	23
DELEGATED MANAGEMENT	STATE-OWNED DELEGATIONS	1	1	1	0	0	0	0	0	0	1
	COMPANY WITH STATE PARTNERSHIP	1	2	3	1	2	3	0	0	0	3
	MUNICIPAL OR INTERMUNICIPAL COMPANIES	1	23	24	0	23	23	8	17	24	35
	PARISH COUNCIL	0	61	61	0	0	0	0	0	0	61
DIRECT MANAGEMENT	MUNICIPALITIES ASSOCIATIONS	0	0	0	1	0	1	3	2	5	6
	MUNICIPALIZED OR INTERMUNICIPALIZED SERVICES	1	20	20	0	18	18	0	7	7	20
	MUNICIPAL SERVICES	1	183	183	0	191	191	0	229	229	256
TOTAL		11	319	326	9	257	266	23	256	278	432

For a better perception of the analysed information, Table 3 displays the number of management entities per subsector in 2015 and 2017, which provided data do ERSAR. Therefore, it is possible to know the percentage of entities providing data to ERSAR. Although, it should also be taken into account that the presented information exclusively corresponds to data that is registered by management entities and provided to ERSAR, not necessarily corresponding to reality, since there is always some information that is not registered.

Table 3 – Number of management entities which provided data in 2015 and 2017

Subsector	2015	2017
Water supply	263	264
Wastewater	266	269
Urban waste	281	277

For 2015, the registered information was related to less PIs than for 2017, which led to the selection of 39 PIs to be presented for 2015 (out of 130), versus 57 PIs for 2017 (out of 197). The analysed PIs were grouped according to the types of PI as stated by the Portuguese Water Distribution and Wastewater Sanitation Association APDA (*Associação Portuguesa de Distribuição e Drenagem de Águas*) [40]. Therefore, the analysed PIs were divided in five categories: (1) water volumes, (2) infrastructures, (3) energy consumption, (4) systems operation and maintenance, and (4) economic and financial.

6.2. Water Volumes

A water supply system input volume consists of revenue and non-revenue water, wherein the first comprises revenue authorized consumption, and the latter concerns non-revenue authorized consumption and water losses, which can be apparent or real losses, as stated in previous chapters. In this regard, it is important to assess the amount of non-revenue water, as it affects the systems efficiency.

Non-revenue water corresponds to the water that is abstracted, treated, transported, stored and distributed, but is not charged to the users, due to leakages along the systems or because it is donated to associations or services, such as the fire department [41].

Table 4 displays the revenue and non-revenue water values in bulk water systems in 2015 and 2017, as well as Figure 21 displays how the total water entering the systems, for the same years, is subdivided between these two PIs. 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 [41].

Table 4 – Bulk revenue vs. non-revenue water in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Bulk revenue water	5,70E+08	m^3/year	9
	Bulk non-revenue water	2,99E+07	m^3/year	9
2017	Bulk revenue water	6,08E+08	m^3/year	10
	Bulk non-revenue water	3,15E+07	m^3/year	10

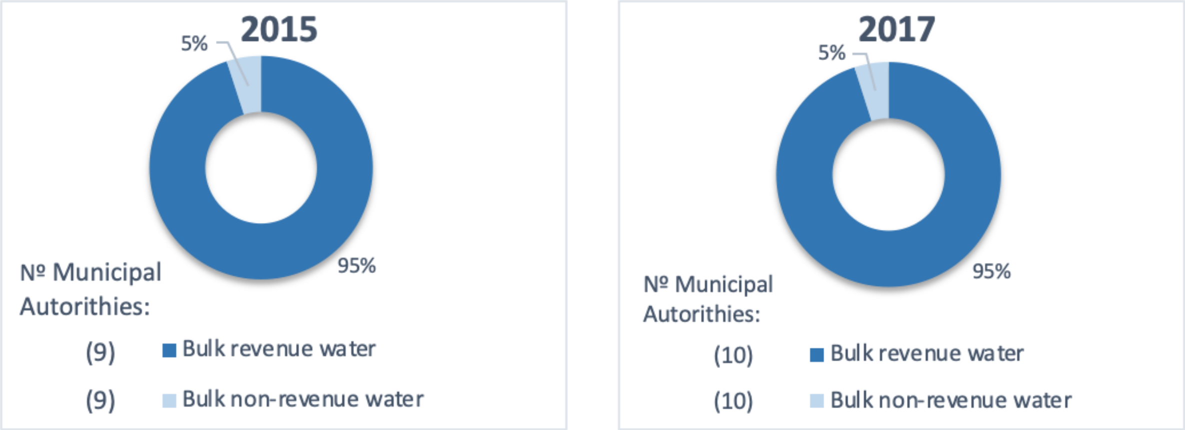


Figure 21 – Bulk revenue vs. non-revenue water in 2015 and 2017

The values of revenue and non-revenue water for retail systems in 2015 and 2017 can be seen in Table 5. Moreover, Figure 22 shows that 30% of water volume entering the systems was non-revenue, hence, based on the reference values defined by ERSAR, the quality of service can be classified as average [41].

The amount of non-revenue water in Portugal is classified as average in bulk, as well as in retail water systems and, as displayed in Figure 21 and 22, between 2015 and 2017 there has not been an improvement in terms of percentage of non-revenue water. Hence, reducing water losses and improving billing procedures can help to improve these PIs.

Table 5 – Retail revenue vs. non-revenue water in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Retail revenue water	5,80E+08	m^3/year	263
	Retail non-revenue water	2,45E+08	m^3/year	263
2017	Retail revenue water	5,98E+08	m^3/year	264
	Retail non-revenue water	2,57E+08	m^3/year	264

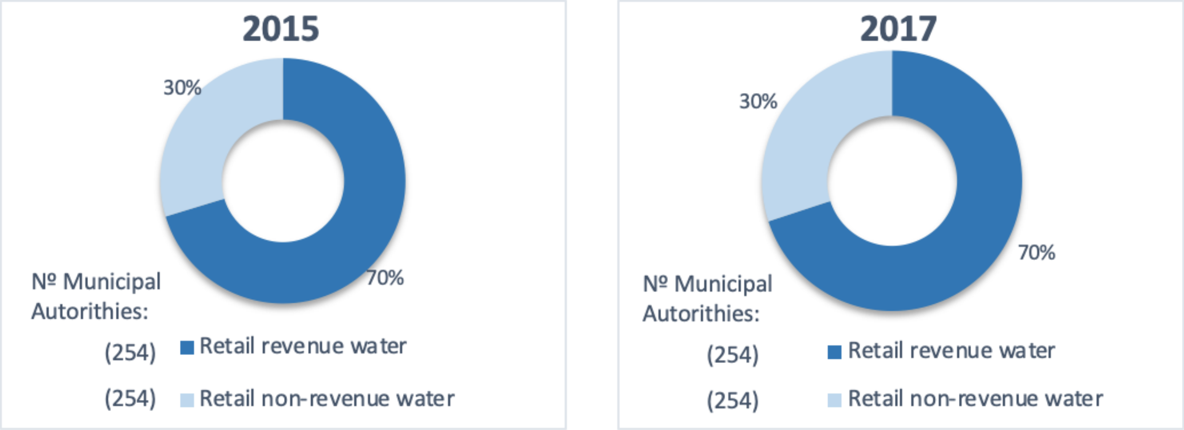


Figure 22 – Retail revenue vs. non-revenue water in 2015 and 2017

Part of the system input volume is treated and exported from one entity to another. As displayed in Figure 23, there was an increase in the exported treated water. However, the value of this PI for 2015 may not be accurate, as it was provided by only 3% of the water supply entities, when on the other hand, in 2017 100% of the entities provided this information, making it more accurate (Table 6).

Water can be abstracted from two types of sources, namely groundwater, which consists in taking freshwater from underground sources, such as aquifers, and surface water, being the one where water is directly taken from natural or artificial waterways containing freshwater, such as rivers and lakes [42].

On the one hand, surface water abstractions guarantee large and regular volumes of water, but the water provided usually requires complex and expensive treatment processes [42]. On the other hand, groundwater abstractions, despite providing lower volumes of water, offer much better quality conditions, hence not requiring complex treatment processes. Therefore, surface water is mainly used for water supply in large urban areas, while groundwater normally serves small communities [43].

Table 6 – Exported treated water in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	System input volume (remained)	8,44E+08	m^3/year	263
	Exported treated water	5,69E+08	m^3/year	9
2017	System input volume (remained)	8,38E+08	m^3/year	264
	Exported treated water	6,51E+08	m^3/year	264

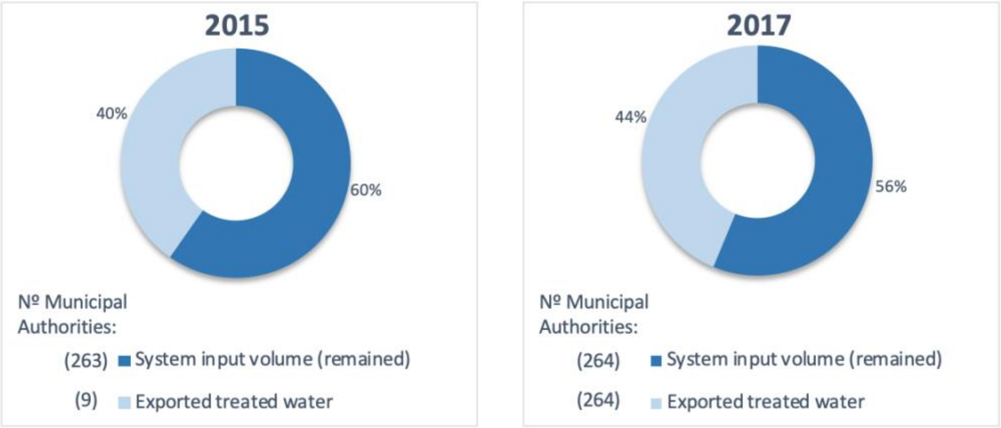


Figure 23 – Exported treated water in 2015 and 2017

As displayed in Table 7, there was a decrease in the total number of abstractions. Essentially because there is a tendency to prefer less abstractions in number, but larger in size, over more abstractions which are smaller. This tendency is related to the growing number of multi-municipal bulk water supply systems [41]. According to Figure 24, 95% of the water abstractions in Portugal are from groundwater sources. However, according to ERSAR, in 2016 around 68% of the water that entered the system for supply, was obtained from surface water abstractions [41]. This shows that in some cases, surface water abstractions are preferable, since they are more reliable, providing regular volumes of water over time.

Table 7 – Groundwater vs. surface water abstraction in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Groundwater abstractions	6016	N.º	263
	Surface water abstractions	267	N.º	263
	Total abstractions	6283	N.º	263
2017	Groundwater abstractions	5842	N.º	264
	Surface water abstractions	289	N.º	264
	Total abstractions	6131	N.º	264

Figure 24 – Groundwater vs. surface water collection in 2015 and 2017

The abstraction of water resources of public domain requires licenses or concessions emitted by the Portuguese Environment Agency APA (*Agência Portuguesa do Ambiente*).

Table 8 displays data regarding abstracted water for the years of 2015 and 2017, where it is possible to notice that, even though the percentage of entities providing data did not change, the values of the parameters did change between the years. However, according to Figure 25, the percentage of collected water in licensed areas only increased by 1%.

Table 8 – Abstracted water vs. abstracted water in licensed areas in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Abstracted water (remained)	2,03E+08	m^3/year	263
	Abstracted water in licensed areas	5,91E+08	m^3/year	263
2017	Abstracted water (remained)	2,08E+08	m^3/year	264
	Abstracted water in licensed areas	6,28E+08	m^3/year	264

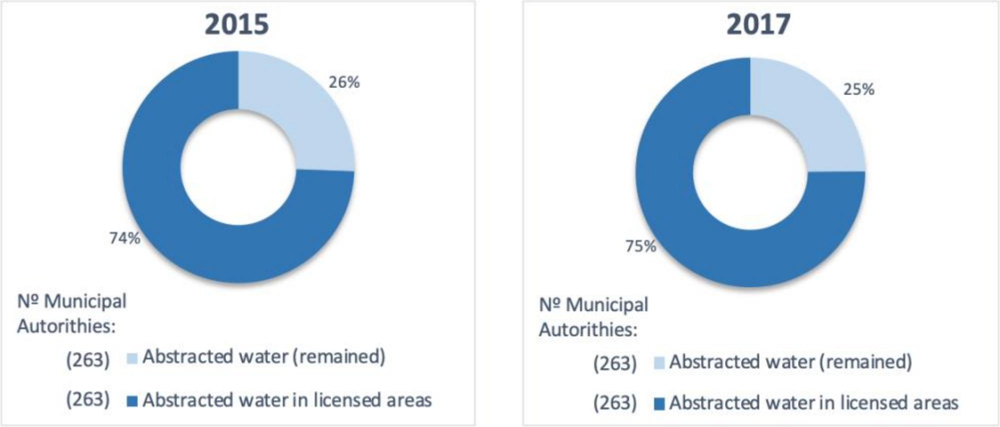


Figure 25 – Abstracted water vs. abstracted water in licensed areas in 2015 and 2017

It is very important to analyse the losses that occur in a water supply system, since water is a scarce resource, hence needing rational management. Furthermore, as mentioned in previous chapters, losses can significantly affect the systems efficiency significantly.

In Portugal, real losses are mainly connected to the lack of rehabilitation works in the systems [41]. Thus, as displayed in Table 9, from 2015 to 2017, both authorized consumption and real losses increased. However, when it comes to the total volume of water entering the system, according to Figure 26, the percentage of authorized consumption increased, which is positive for the water sector.

Regarding wastewater, it is relevant to consider the percentage of non-revenue wastewater, for the same reason as it is for non-revenue water. Table 10 displays the values of revenue and collected wastewater, which, according to Figure 27, remained approximately the same between 2015 and 2017. However, although 15% of collected non-revenue wastewater is below the limit of 30%, it still affects the systems losses significantly, consequently affecting the systems efficiency.

Table 9 – Consumption vs. losses in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Authorized consumption	6,13E+08	m^3/year	256
	Real losses	1,85E+08	m^3/year	263
2017	Authorized consumption	1,25E+09	m^3/year	264
	Real losses	2,06E+08	m^3/year	264
	Water losses by metering inaccuracies	3,35E+07	m^3/year	264

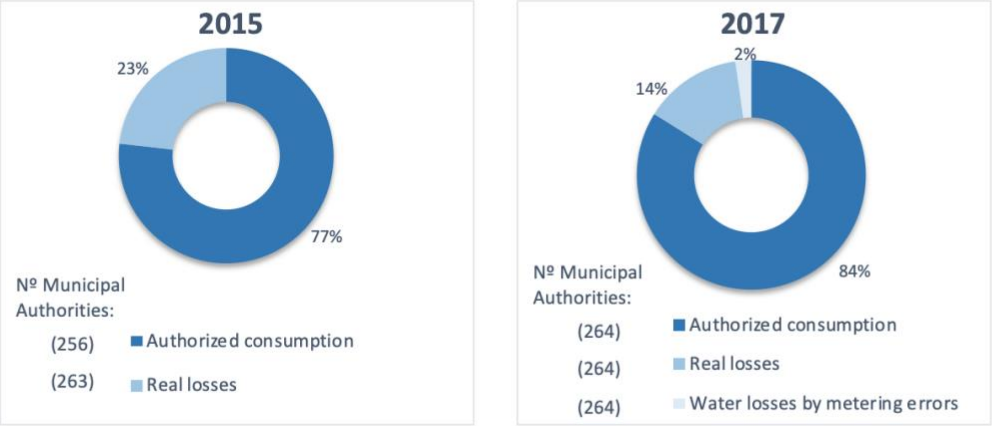


Figure 26 – Consumption vs. losses in 2015 and 2017

Table 10 – Revenue vs. collected wastewater in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Revenue wastewater	9,05E+08	m^3/year	266
	Collected wastewater (remained)	1,71E+08	m^3/year	266
2017	Revenue wastewater	9,24E+08	m^3/year	269
	Collected wastewater (remained)	1,69E+08	m^3/year	269

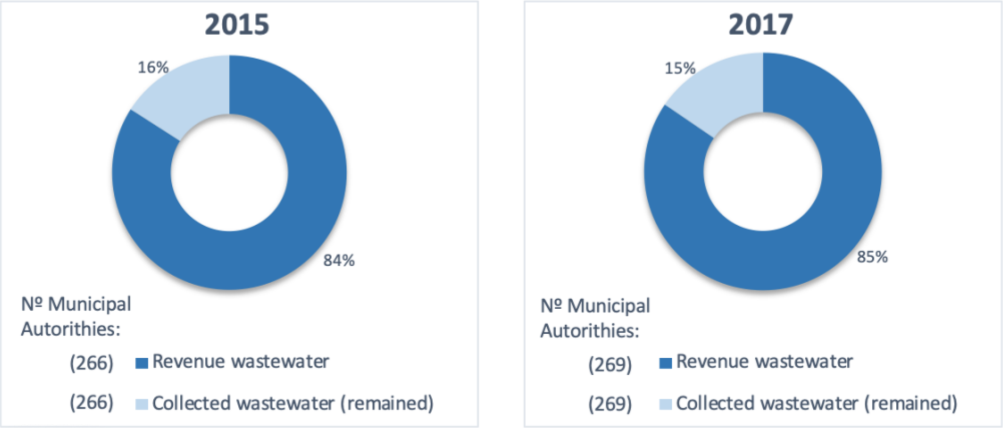


Figure 27 – Revenue vs. collected wastewater in 2015 and 2017

The amount of wastewater treated in treatment plants, comparing to the amount of collected wastewater is displayed in Table 11. According to Figure 28, the amount of wastewater treated in treatment plants represents 58% of the wastewater collected in the system. This means that, probably, the remaining percentage is discharged directly to the environment without treatment, or is treated by other means. The possibility of 42% of collected wastewater being discharged to the environment without treatment is very alarming, since it means that almost half of collected wastewater in Portugal is contributing to environmental degradation when sustainability and environmental protection are part of humanity's main concerns nowadays.

Table 11 – Wastewater treated in treatment plants vs. collected wastewater in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Collected wastewater (remained)	4,53E+08	m^3/year	266
	Wastewater treated in treatment plants	6,24E+08	m^3/year	266
2017	Collected wastewater (remained)	4,63E+08	m^3/year	269
	Wastewater treated in treatment plants	6,30E+08	m^3/year	269

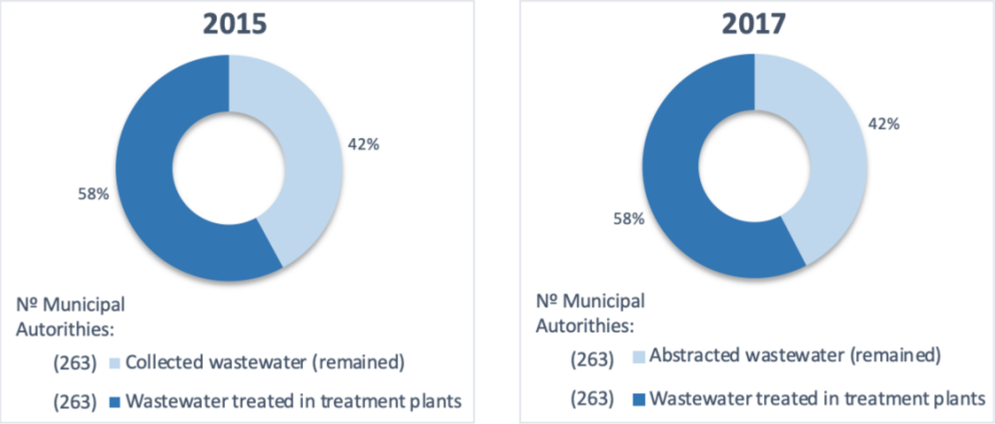


Figure 28 – Wastewater treated in treatment plants vs. collected wastewater in 2015 and 2017

For the year of 2017, it was found that the entities provided data regarding more PIs than in 2015. Thus, the following PIs will not be compared to values from 2015. Furthermore, this means that in this period there was an improvement in the collected and registered data from water entities.

Raw water corresponds to water found in the environment, which has not been treated, for instance, rainwater, groundwater and water from lakes, rivers, etc. It can be divided in exported raw water, when it is transferred to another entity, and imported raw water, which is the opposite. Therefore, according to Table 12, the amount of exported raw water is much higher than imported raw water, as Figure 29 illustrates that it matches 66% of total transferred raw water.

Additionally, Table 12 and Figure 30 display the same parameters regarding exported treated water, wherein it can be found that half of transferred treated water is exported, while the other half is imported.

Table 12 – Exported vs. imported raw and treated water in 2017

Year	Parameter	Value	Units	Nº entities
2017	Exported raw water	1,24E+06	m^3/year	264
	Imported raw water	6,50E+05	m^3/year	264
	Exported treated water	6,51E+08	m^3/year	264
	Imported treated water	6,47E+08	m^3/year	264

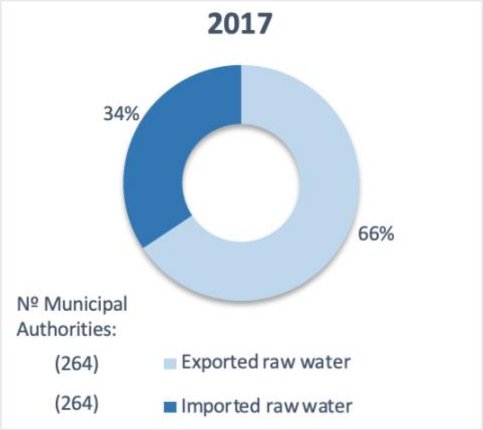


Figure 29 – Exported vs. imported raw water in 2017

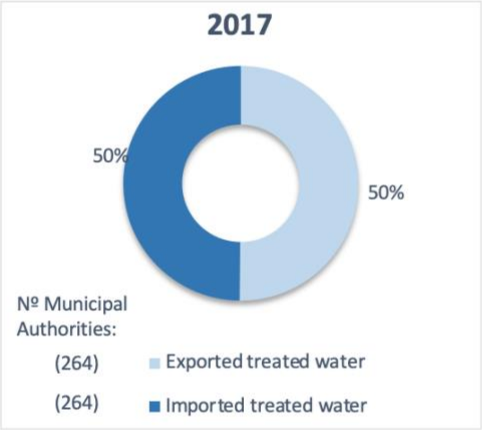


Figure 30 – Exported vs. imported treated water in 2017

Similar to raw water, raw wastewater corresponds to collected wastewater which has not been treated. Table 13 displays the amount of exported and imported raw wastewater in 2017. Where the concepts of exported and imported resemble those explained above. According to Figure 31, 79% of raw wastewater is exported.

The values regarding exported and imported treated wastewater can also be found in Table 13. Accordingly, Figure 32 shows that only 3% of transferred treated wastewater is imported.

Thereby, it is possible to notice that, either regarding water or wastewater, the amount exported is always much higher than the imported, except in the case of treated water, where the two parcels are approximately the same.

Table 13 – Exported vs. imported raw and treated wastewater in 2017

Year	Parameter	Value	Units	Nº entities
2017	Exported raw wastewater	4,12E+08	m^3/year	269
	Imported raw wastewater	1,07E+08	m^3/year	269
	Exported treated wastewater	1,16E+06	m^3/year	269
	Imported treated wastewater	3,20E+04	m^3/year	269

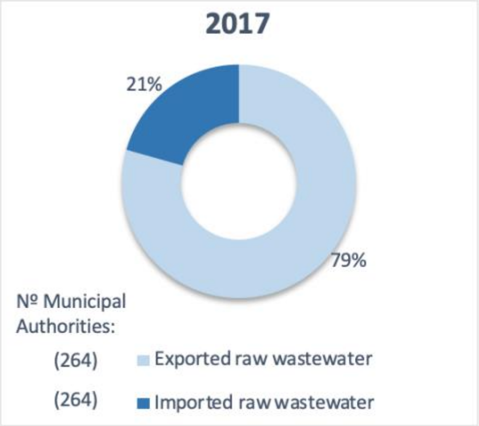


Figure 31 – Exported vs. imported raw wastewater 2017

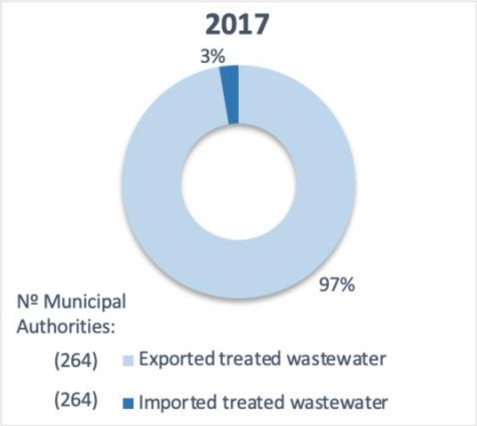


Figure 32 – Domestic vs. non-domestic revenue water in 2017

In agreement with ERSAR's recommendation regarding practiced tariffs (IRAR n.º 01/2009), there should be a difference between domestic and non-domestic consumers, where the latter must have a higher tariff, since their activities are supposed to be profitable. Domestic consumption exclusively concerns habitational consumption, with individual contracts, whilst non-domestic includes commercial and industrial activities [44]. Table 14 displays the amount of domestic and non-domestic revenue water registered in 2017 and, according to Figure 33, 65% of revenue water comes from domestic use, which means that the majority of clients are domestic.

Table 14 – Domestic vs. non-domestic revenue water in 2017

Year	Parameter	Value	Units	Nº entities
2017	Domestic revenue water	3,86E+08	m^3/year	256
	Non-domestic revenue water	2,12E+08	m^3/year	256

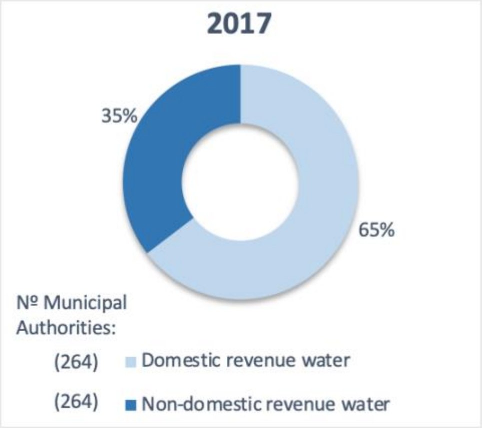


Figure 33 – Domestic vs. non-domestic revenue water in 2017

Measured revenue water represents the total authorized revenue consumption which is measured including exported water. It can be obtained from the client's meter readings. Meanwhile, non-measured revenue consumption represents the total authorized revenue consumption which is not measured including exported water. Normally, it is estimated using surveys [40].

The table below (Table 15) presents the values registered for these two parameters, while Figure 34 illustrates that only 2% of revenue consumption is not measured. The fact that this percentage is very low is positive, because it means that the amount of non-measured revenue consumption does not weigh too much on revenue consumption, since almost all revenue consumption is measured.

Additionally, applying the same reasoning to non-revenue consumption, Table 15 displays the value of measured and non-measured non-revenue consumption and shows that 64% of non-revenue consumption is not measured. Therefore, it would be beneficial if there was an increase in measured non-revenue consumption, since it would allow a better insight over authorized consumption.

Table 15 – Measured vs. non-measured revenue and non-revenue consumption in 2017

Year	Parameter	Value	Units	Nº entities
2017	Measured revenue consumption	1,19E+09	m^3/year	264
	Non-measured revenue consumption	1,90E+07	m^3/year	264
	Measured non-revenue consumption	1,40E+07	m^3/year	264
	Non-measured non-revenue consumption	2,51E+07	m^3/year	264

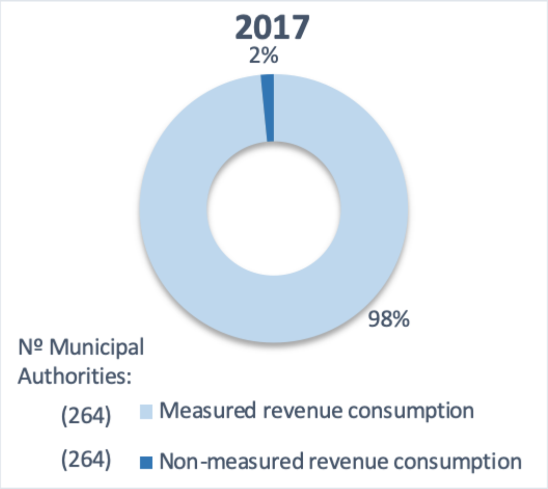


Figure 34 – Measured vs. non-measured revenue consumption in 2017

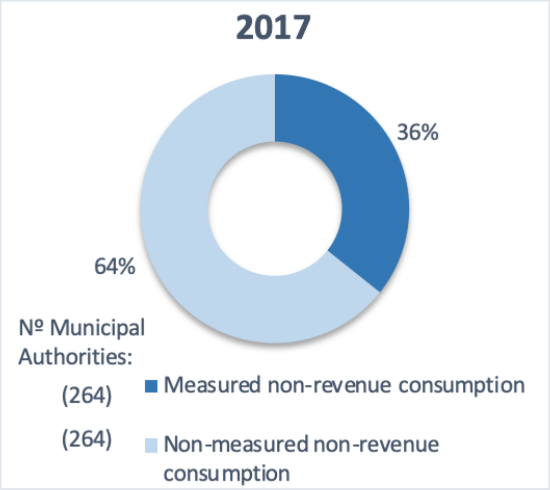


Figure 35 – Measured vs. non-measured non-revenue consumption in 2017

6.3. Infrastructures

The PIs regarding infrastructures represent the existing facilities related to water supply and wastewater sanitation, such as treatment plants and pumping stations. With the increase in the number of infrastructures there is room for improvement in systems efficiency as well. As displayed in Table 16 and in Figure 36 and 37, there was an increase in water and wastewater infrastructures from 2015 to 2017, although the number of sea outfalls remained the same. For most of the parameters, 100% of the entities provided information, with the exception of wastewater pumping stations, where only 5 to 6% of the entities provided information. However, the registered amount of wastewater pumping stations represents almost half of all the infrastructures.

Table 16 – Water and wastewater infrastructures in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Water treatment plants	261	N.º	263
	Water pumping stations	2313	N.º	263
	Wastewater treatment plants	2673	N.º	266
	Wastewater pumping stations	5375	N.º	14
	Septic tanks	1585	N.º	266
	Sea outfalls	24	N.º	266
2017	Water treatment plants	267	N.º	264
	Water pumping stations	2362	N.º	264
	Wastewater treatment plants	2751	N.º	269
	Wastewater pumping stations	5773	N.º	16
	Septic tanks	1610	N.º	269
	Sea outfalls	24	N.º	269

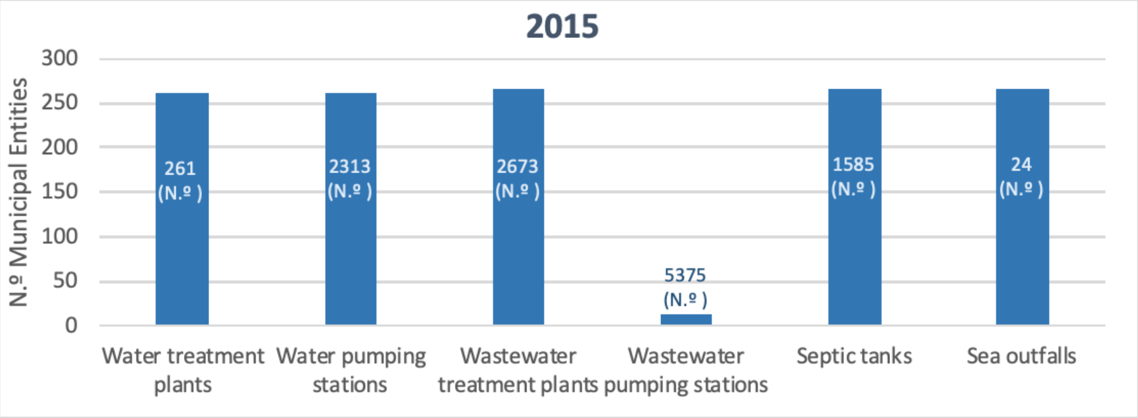


Figure 36 – Water and wastewater infrastructures in 2015

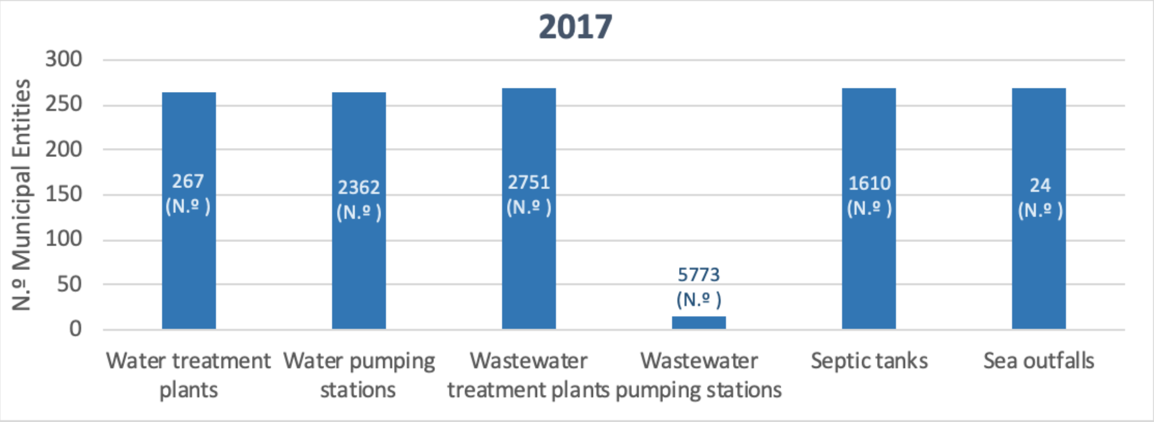


Figure 37 – Water and wastewater infrastructures in 2017

In Portugal, wastewater treatment is done mainly through two different solutions, which are septic tanks or wastewater treatment plants (WWTP) [41]. According to Figure 38, septic tanks represent 37% of the solutions. This percentage remained the same from 2015 to 2017, even though there was an increase in both septic tanks and WWTP, as displayed previously in Table 16.

The distribution between the two solutions mentioned above is due to many factors, such as the distribution of population density throughout the country, which is very unbalanced, the fact that the north of Portugal has a much more rough terrain than the south, and due to the rainfall conditions which can cause seasonal peak flows [41].

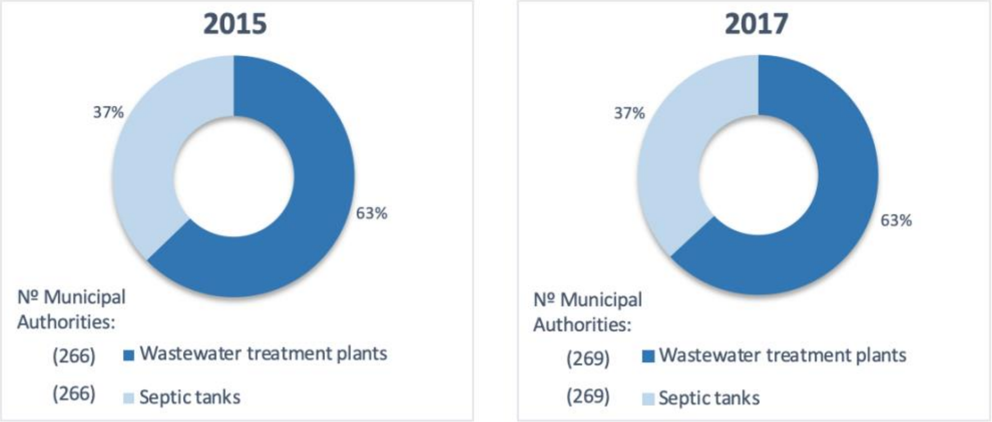


Figure 38 – Wastewater treatment plants vs. septic tanks in 2015 and 2017

Water reserve capacity in water supply and distribution systems can be defined as the total volume of the reservoirs within water supply and distribution, excluding building reservoirs, since they are the responsibility of the consumers [40]. Between 2015 and 2017, the data registered by ERSAR was very similar, with the all of the entities providing this information. There was an increase of only 2% in the indicator's value, reaching $5{,}17\times10^{6}$ m^{3} in 2017.

There is a PI which evaluates the level of sustainability of the entities, in environmental terms, regarding the usage of energy resources, since they are scarce, therefore needing to be controlled and used properly. This PI corresponds to energy efficiency of pumping stations and can be defined as the normalized average energy consumption of pumping installations [40].

According to ERSAR, although there was an increase of 3 entities in the sub-sector of water supply, and all of them provided this information, the PI value decreased 21%. This means that the energy consumption in pumping stations decreased significantly from 2015 to 2017, implying a huge improvement regarding the systems efficiency and sustainability, reaching the value of 202,28 kWh/m^{3} at a pump head height of 100 m in 2017. However, the efficiency of pumping stations in Continental Portugal is still considered average, hence, there is room for improvement if operational and monitorisation methodologies are implemented [41].

6.4. Energy Consumption

In accordance with water-energy nexus, Table 17 displays the sources of the energy consumed by water systems, taking into account that part of this consumption comes from own energy production within the systems and the other part comes from the external grid. In this regard, as displayed in Figure 39, 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.

Table 17 – Energy sources in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Energy consumed from the external grid	8,28E+07	kWh/year	23
	Own energy production	3,46E+07	kWh/year	277
2017	Energy consumed from the external grid	7,77E+07	kWh/year	23
	Own energy production	2,98E+07	kWh/year	280

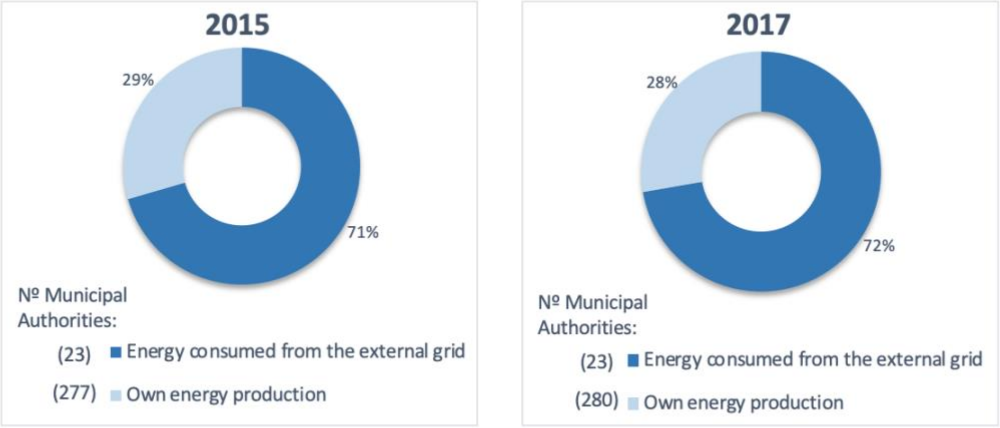


Figure 39 – Energy sources in 2015 and 2017

Usually, most of the energy consumption in water systems is due to water pumping, as displayed in the figure below (Figure 40). Accordingly, Table 18 shows that there was a decrease in energy consumption for water pumping, from 2015 to 2017, even though the total energy consumption increased.

Table 18 – Energy consumption in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Energy consumption (remained)	3,72E+08	kWh/year	277
	Energy consumption for water pumping	6,45E+08	kWh/year	277
2017	Energy consumption (remained)	4,60E+08	kWh/year	280
	Energy consumption for water pumping	6,41E+08	kWh/year	280

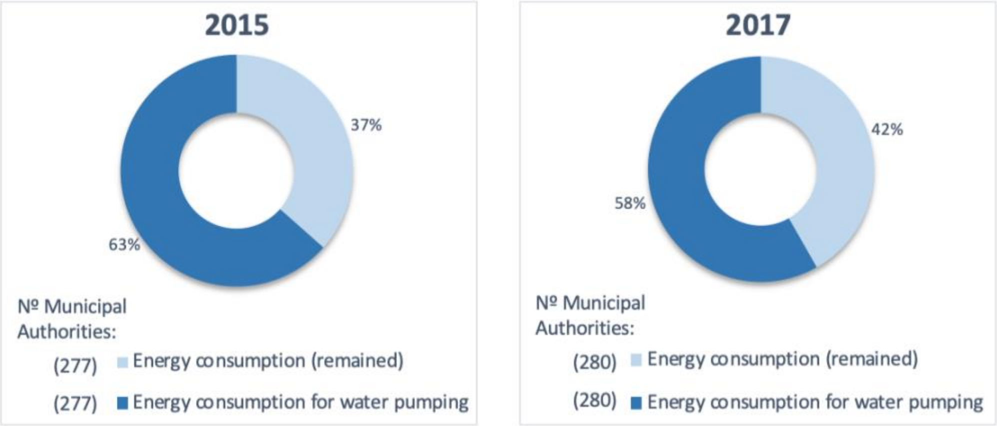


Figure 40 – Energy consumption in 2015 and 2017

6.5. Systems Operation and Maintenance

Regarding the operation and maintenance of the systems, it is important to evaluate the total number of water supply failures. These failures must include failures due to systematic intermittent supply and unexpected supply failures, with duration greater than 12 h, caused by ruptures or failures in the water supply system. Accordingly, from 2015 to 2017, there was a decrease of 35% in the registered number of water supply failures, which means that there was an improvement regarding the quality of the service.

Another relevant parameter related to this matter, is pipe failures, as it evaluates the sustainability of the entities in operational terms, regarding the existence of a small number of failures in the systems water pipes. It consists of the number of failures in water pipes per length unit. From 2015 to 2017 there was an increase of 7% of registered failures, meaning that there was a deterioration regarding this parameter.

6.6. Economic and Financial

Water supply is one of the basic needs for human life in society and wastewater treatment is essential for the sustainability of the water sector. Hence, one of the United Nations Sustainable Development Goals for 2030 is to ensure availability and sustainable management of water and sanitation for all [45]. Therefore, the priority of the water sector is not to be profitable, but to make clean water available for everyone. However, since water supply and wastewater treatment have associated costs, it is essential to make the sectors activities profitable enough to cover these costs.

Table 19 and Figure 41 display the total costs and revenues in 2015 and 2017, where both parameters decreased.

Table 19 – Total costs vs. Revenue in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Total costs	2,81E+09	€/year	372
	Revenue	2,76E+09	€/year	372
2017	Total costs	1,94E+09	€/year	374
	Revenue	1,88E+09	€/year	374

Also important for the systems efficiency, are the associated charges, being the main goal to decrease the charges as the efficiency increases. According to Table 20 and Figure 42, these PIs and the relation between them did not change significantly from 2015 to 2017. The average charges with water supply services represent the majority of the water and sanitation sector, essentially because this sub-sector requires more energy, since it involves more energy consumption and more expensive technology than the other sub-sectors.

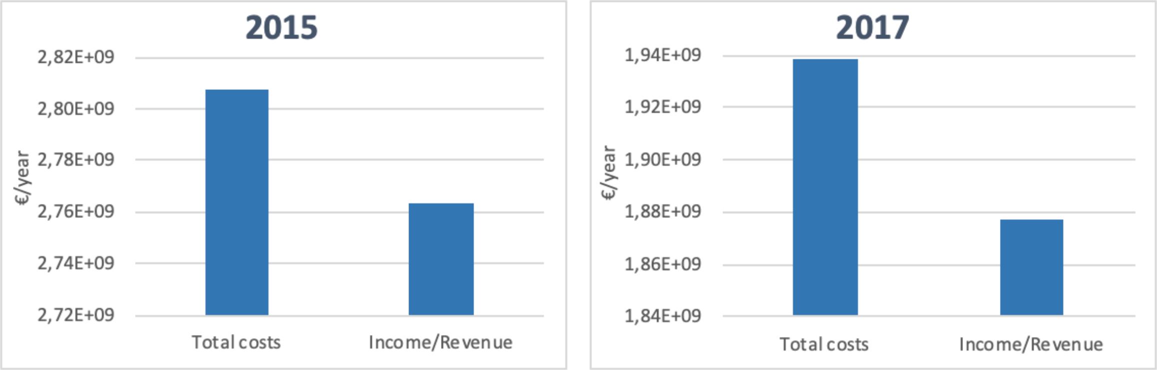


Figure 41 – Total costs vs. Revenue in 2015 and 2017

Table 20 – Average charges in 2015 and 2017

Year	Parameter	Value	Units	Nº entities
2015	Average charges with water supply services	2,90E+04	€/year	263
	Average charges with wastewater treatment services	1,90E+04	€/year	266
	Average charges with urban waste management services	1,32E+04	€/year	280
2017	Average charges with water supply services	2,96E+04	€/year	264
	Average charges with wastewater treatment services	2,02E+04	€/year	269
	Average charges with urban waste management services	1,28E+04	€/year	255

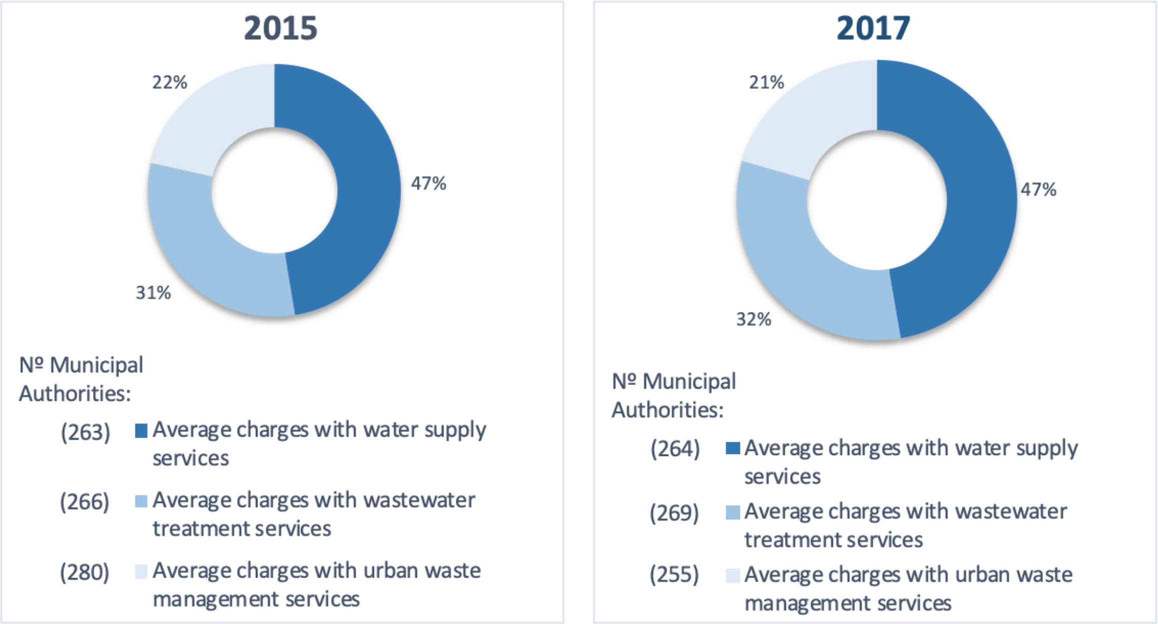


Figure 42 – Average charges in 2015 and 2017

According to the figure below (Figure 43), which displays the approved tariffs for water supply in 2017, 10 of the bulk water supply entities provided data, where the tariffs vary between 0,410 €/m^3 in Águas de Santo André and 0,881 €/m^3 in Águas Públicas do Alentejo, Regarding wastewater, as displayed in Figure 44, the approved tariffs vary between 1,130 €/m^3 in Águas da Serra and 0,170 €/m^3 in Associação de Municípios de Terras de Santa Maria.

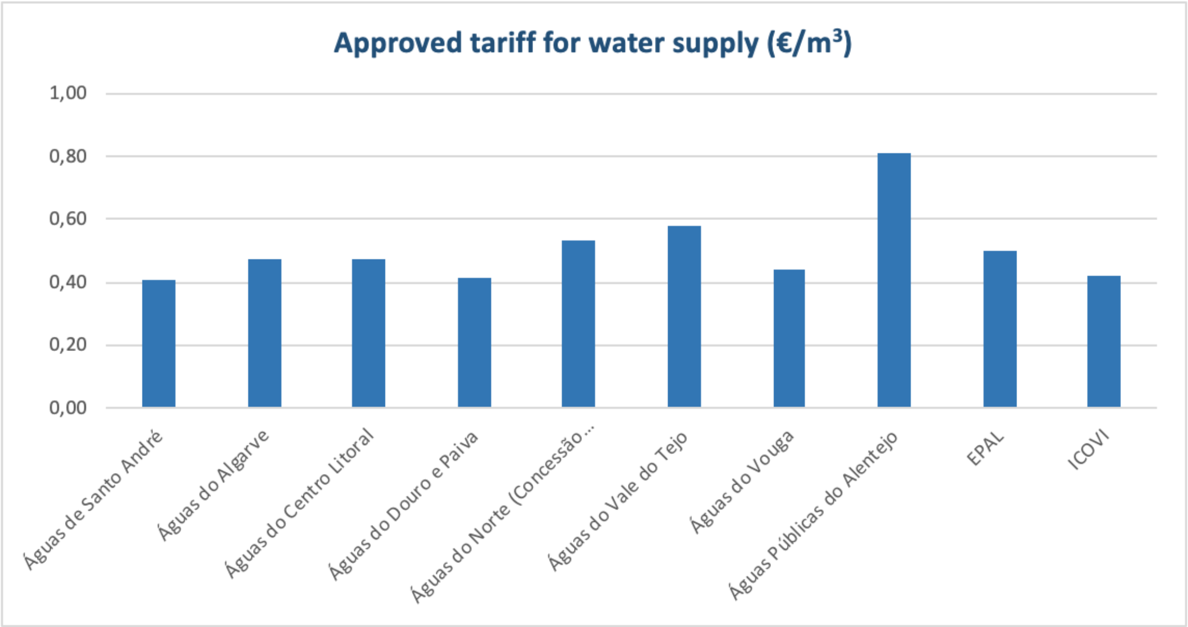


Figure 43 – Approved tariffs for water supply in 2017

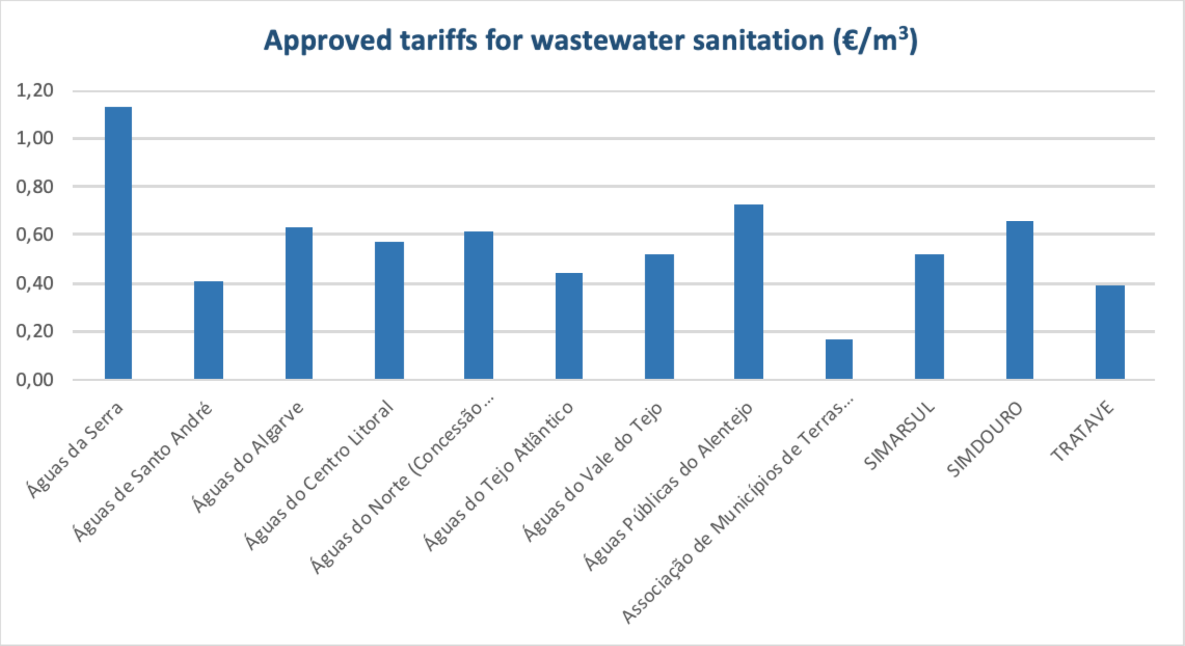
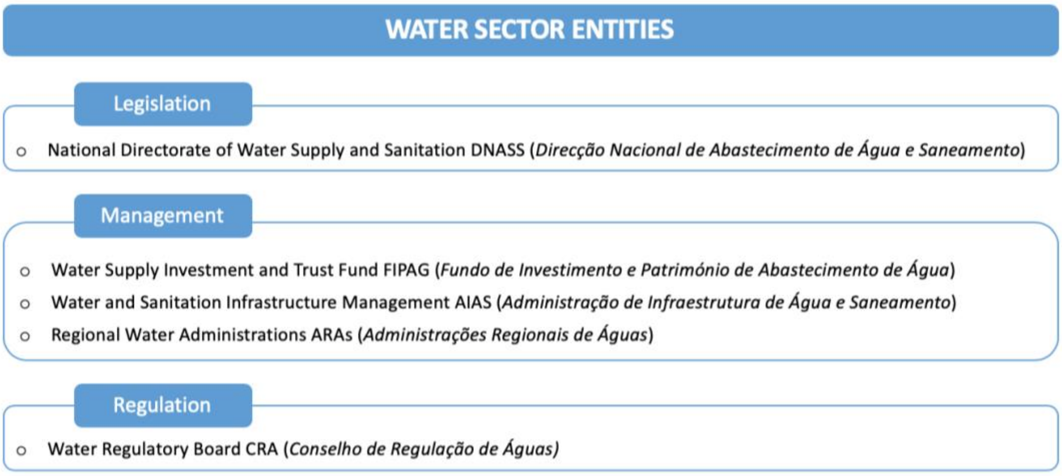


Figure 44 – Approved tariffs for wastewater sanitation in 2017

7. Case Studies

7.1. Background

In Mozambique, the water supply sector is divided in two levels, namely central and local (Figure 45). The National Directorate of Water Supply and Sanitation DNASS (*Direcção Nacional de Abastecimento de Água e Saneamento*) performs on every level and is responsible for the strategic management of the water supply and sanitation sector in Mozambique. While, in turn, the Water Supply Investment and Trust Fund FIPAG (*Fundo de Investimento e Património de Abastecimento de Água)*, the private companies, local governments and disperse sources managed by the communities are responsible for water supply at operational level. The Water Regulatory Board CRA (*Conselho de Regulação de Águas*) is the entity responsible for the regulation of the sector.



WATER SECTOR ENTITIES

Legislation

- National Directorate of Water Supply and Sanitation DNASS (*Direcção Nacional de Abastecimento de Água e Saneamento*)

Management

- Water Supply Investment and Trust Fund FIPAG (*Fundo de Investimento e Património de Abastecimento de Água*)
- Water and Sanitation Infrastructure Management AIAS (*Administração de Infraestrutura de Água e Saneamento*)
- Regional Water Administrations ARAs (*Administrações Regionais de Águas*)

Regulation

- Water Regulatory Board CRA (*Conselho de Regulação de Águas)*

Figure 45 – Water sector entities in Mozambique

Two cases are going to be studied to assess the potential of energy recovery in water supply systems with high pressures and/or losses. In collaboration with FIPAG the case studies are two water supply systems located in the north of Mozambique, wherein the abstraction occurs in mountainous areas and the distribution stations are in areas with much lower elevations.

7.2. Nampula Water Supply System

7.2.1. Model Development

Nampula water supply system provides water to the city of Nampula in northern Mozambique, with more than 610 000 inhabitants. The water is abstracted from a reservoir in Monapo Dam, located 10 km from Nampula City. The abstraction capacity goes up to 20 000 m^3/day and the Water Treatment Plant (WTP) is located next to the abstraction, with a treatment capacity of 40 000 m^3/day. The 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 45) (Appendix A).

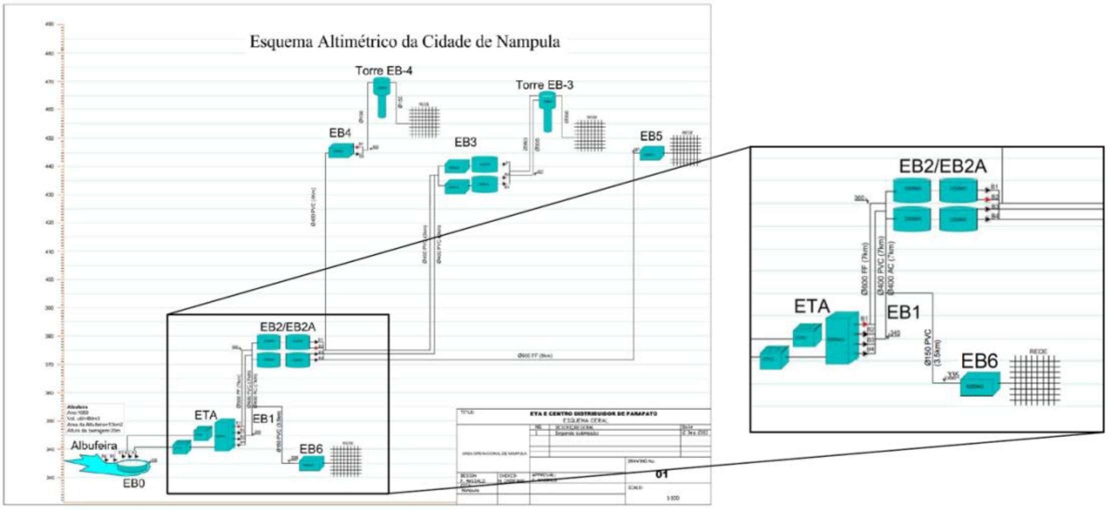
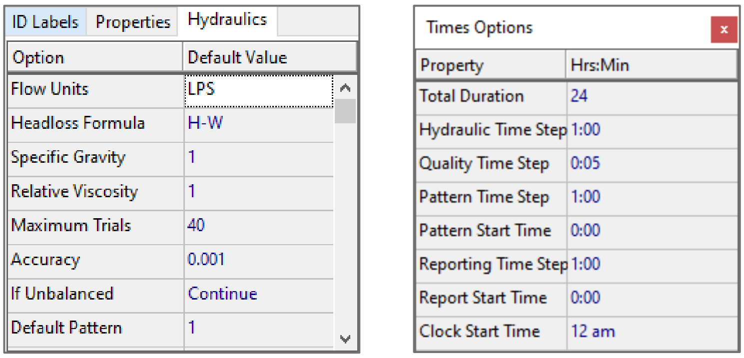


Figure 46 – Nampula water supply system – altimetric scheme

The objective of the study is to control the pressure in the system while reducing leakages and assess the potential for energy recovery. Thus, a model was built on *EPANET 2.0*, according to the data provided by FIPAG.

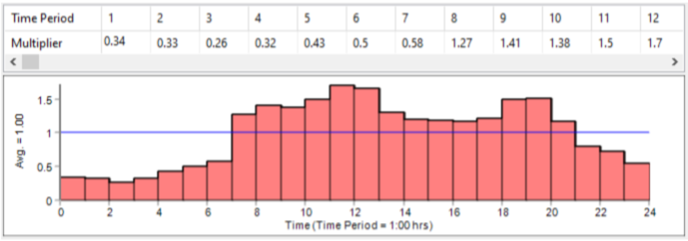
The hydraulics and times options in *EPANET* were defined as shown in Figure 47, considering a simulation with a total duration of 24:00 h and a time step of 1:00 h. The simulation was based on the demand pattern for an average day (Figure 48), allowing to obtain the pressure variation along the system.



Option	Default Value
Flow Units	LPS
Headloss Formula	H-W
Specific Gravity	1
Relative Viscosity	1
Maximum Trials	40
Accuracy	0.001
If Unbalanced	Continue
Default Pattern	1

Property	Hrs:Min
Total Duration	24
Hydraulic Time Step	1:00
Quality Time Step	0:05
Pattern Time Step	1:00
Pattern Start Time	0:00
Reporting Time Step	1:00
Report Start Time	0:00
Clock Start Time	12 am

Figure 47 – Hydraulics and times options



Time Period	1	2	3	4	5	6	7	8	9	10	11	12
Multiplier	0.34	0.33	0.26	0.32	0.43	0.5	0.58	1.27	1.41	1.38	1.5	1.7

Figure 48 – Demand pattern

The area of implantation of the system pipes to be studied can be seen in Figure 49, where EB2 is the pumping station designed for water distribution for consumption, while EB6 is a pumping station designed for water distribution for irrigation purposes. The model was built taking into account that a

PRV is installed upstream EB6 (Figure 50). A PAT will be installed in parallel with the existing PRV in order to use the surplus to produce energy.

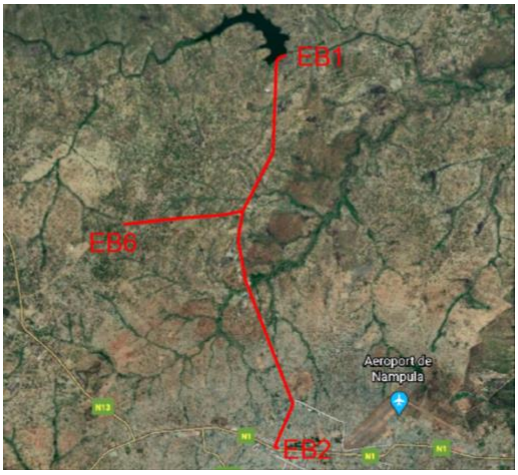


Figure 49 – Satellite view of implantation area

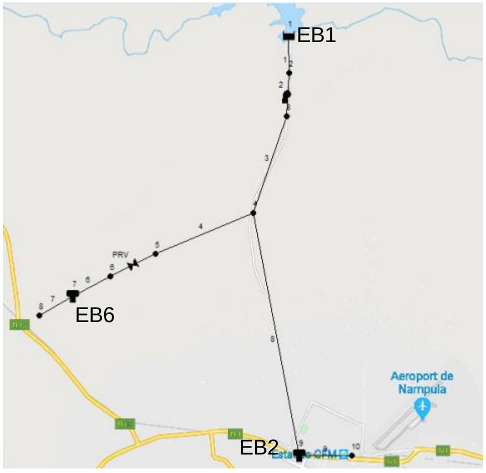


Figure 50 – Model on EPANET

The values of flow, velocity and unit head losses caused by the PRV were obtained from the EPANET model and are presented in Table 21.

Table 21 – Flows, velocities and unit head losses at the PRV section

Time (h)	**Flow (L/s)**	**Velocity (m/s)**	**Unit Headloss (m/km)**
00:00	24,26	1,37	19,20
01:00	24,39	1,38	19,41
02:00	24,53	1,39	19,63
03:00	24,66	1,40	19,85
04:00	24,80	1,40	20,06
05:00	24,80	1,40	20,06
06:00	24,74	1,40	19,96
07:00	24,68	1,40	19,86
08:00	24,62	1,39	19,77
09:00	24,56	1,39	19,68
10:00	24,51	1,39	19,59
11:00	24,45	1,38	19,50
12:00	24,39	1,38	19,41
13:00	24,34	1,38	19,32
14:00	24,31	1,38	19,29
15:00	24,31	1,38	19,29
16:00	24,31	1,38	19,29
17:00	24,31	1,38	19,29
18:00	24,31	1,38	19,29
19:00	24,31	1,38	19,29
20:00	24,31	1,38	19,29
21:00	24,31	1,38	19,29
22:00	24,31	1,38	19,29
23:00	24,31	1,38	19,29
24:00	24,31	1,38	19,29

As expected, the 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 51 and 52). Hence, this can be an advantage for energy generation purposes, as the system can be used to generate energy for a long period.

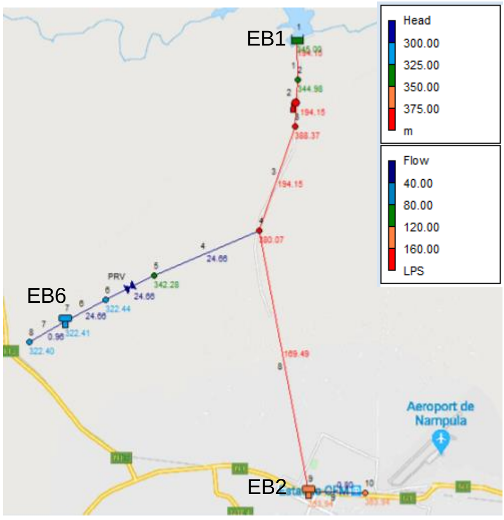


Figure 51 – Current situation values of head and flow at 3:00 AM

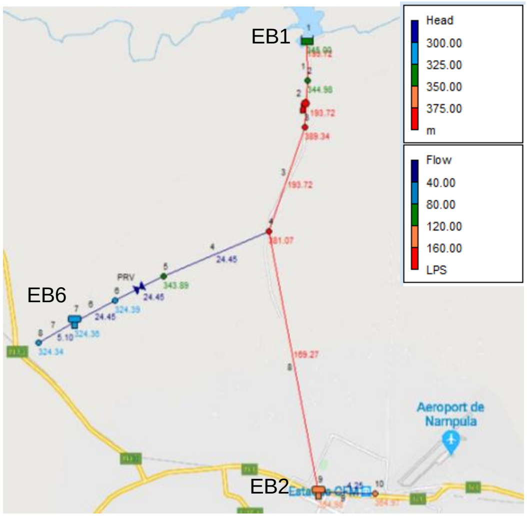


Figure 52 – Current situation values of head and flow at 11:00 AM

7.2.2. 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 (Figure 53) (Appendix B).

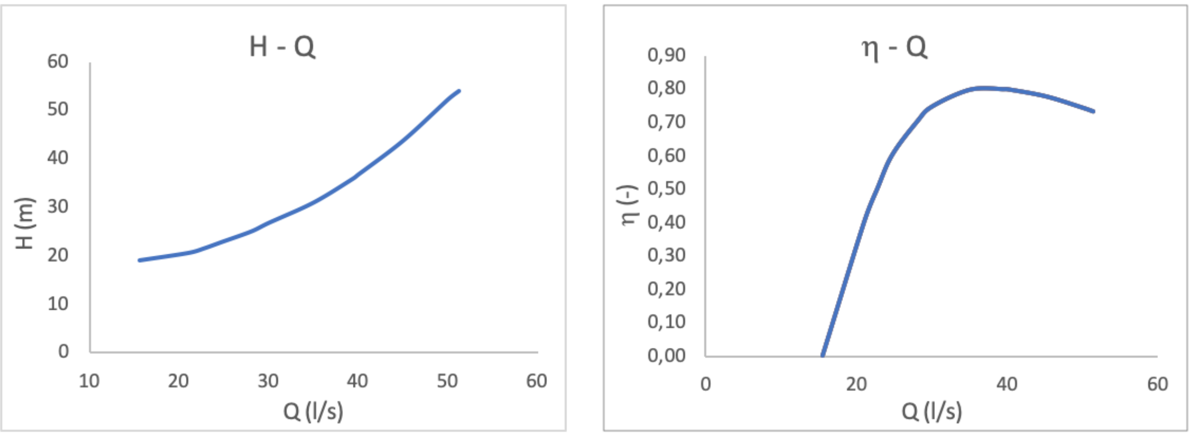


Figure 53 – Characteristic curve of the PAT

Based on the curve provided by the manufacturer, characteristic curves for different rotation speeds were defined using the theory of similarity (Figure 54), as explained in Chapter 4.

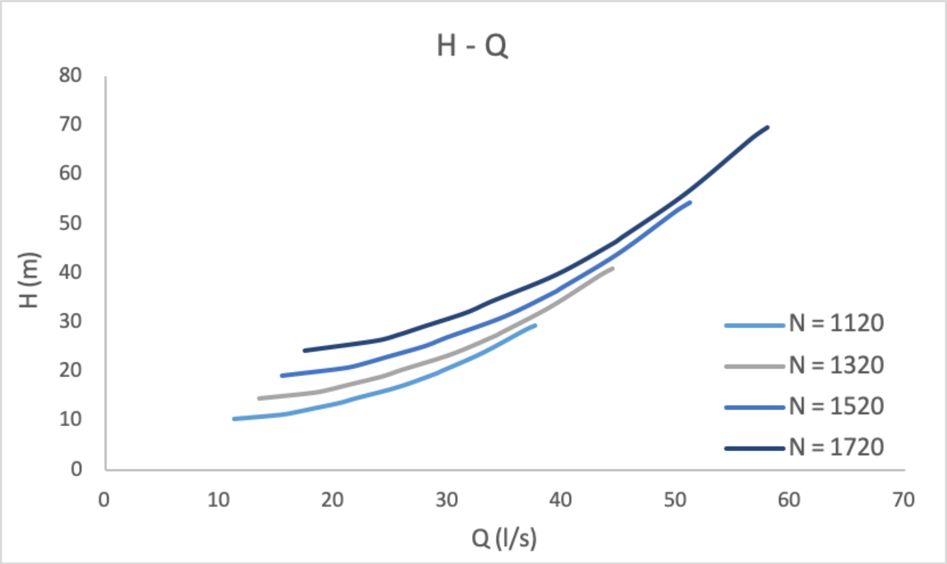


Figure 54 – Characteristic curves of the PAT for different rotational speeds

The characteristic curve of the installation (CCI) shows the relation between the turbine flow and the corresponding available head. This curve 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 55). 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 [46]. To define the operating point, an economic comparative analysis will take place.

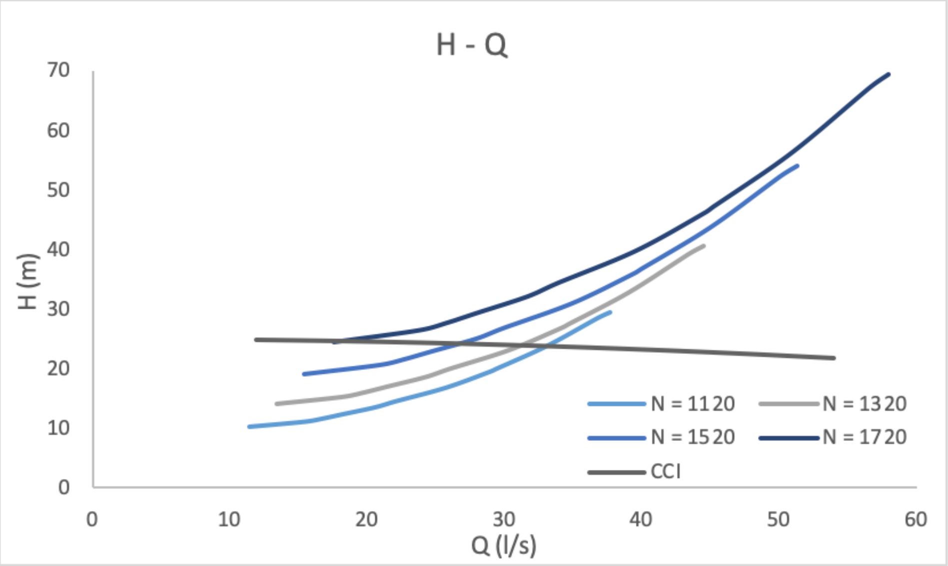


Figure 55 – Characteristic curves of the PAT for different rotation speeds and characteristic curve of the installation

7.2.3. Economic Feasibility and Energy Generation

After the definition of the PATs characteristic curves, the production of energy in the water system can be assessed. Thus, the 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 turbined flow is 20,00 L/s.

Moreover, 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* (Appendix C) and, turbined flows, installed powers, efficiencies and produced energy depending on the rotational speed are displayed in Table 22. It is perceptible that a rotational speed of 1120 r.p.m. leads to higher energy production, thus, it will be the chosen solution.

Table 22 – 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

The cost of the PAT can be assessed considering the red curve in Figure 56 which displays the cost of the PAT per kW. 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.

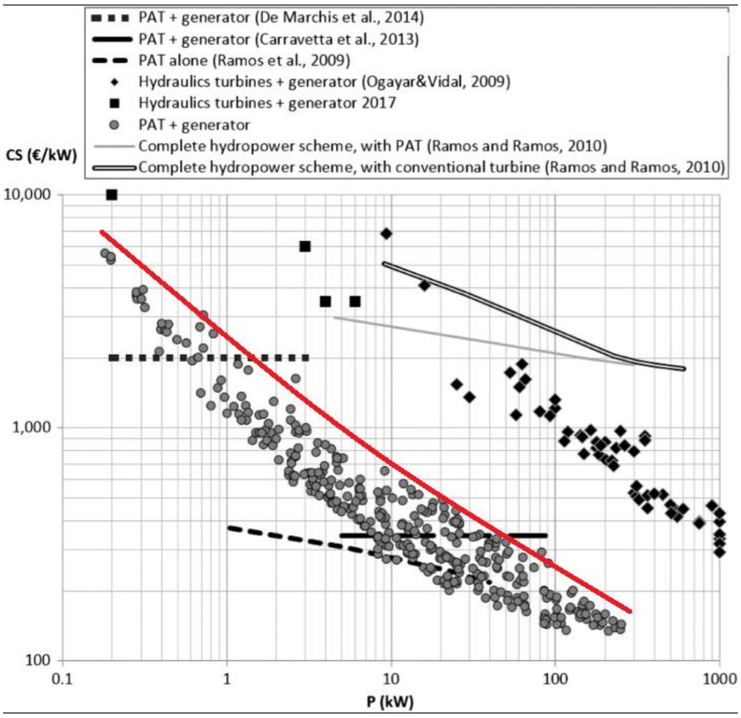


Figure 56 – PAT cost per kW [47]

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, considering the context of the energy market in Mozambique.

The main results of the economic analysis are presented in Table 23 (Appendix D). 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 23 – Main results of the economic analysis

Energy Selling Price (€/kWh]	0,095			0,110		
Discount Rate	6,0%	8,0%	10,0%	6,0%	8,0%	10,0%
NPV (€)	25 185	18 932	14 632	30 349	23 024	17 988
B/C (-)	5,262	4,315	3,624	6,136	5,031	4,225
Payback period (years)	4	4	4	3	3	3

Overall, the results obtained are positive, highlighting that the project can be highly profitable regardless of the chosen scenario.

Figure 57 and 58 present the flow and head values along the system after applying the PAT at 3:00 AM and 11:00 AM, respectively.

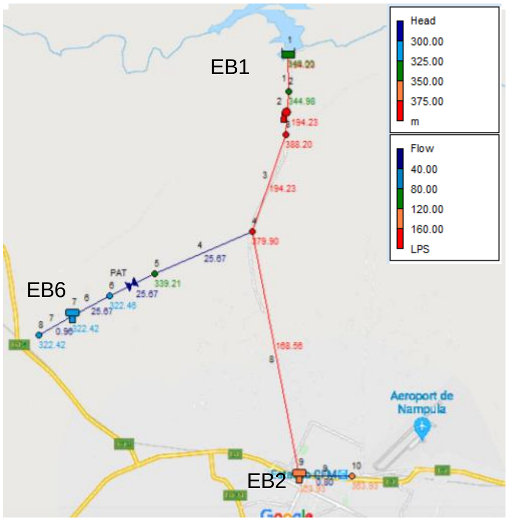


Figure 57 – Results at 3:00 AM after applying the PAT to the model

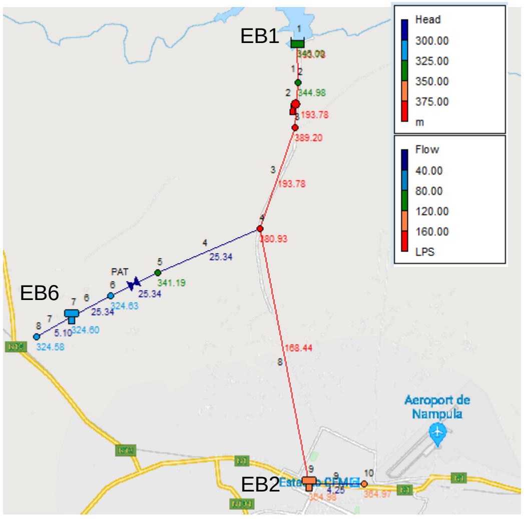


Figure 58 – Results at 11:00 AM after applying the PAT to the model

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 (Table 24).

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.

Table 24 – Flows, velocities and unit head losses at the PAT section

Time (h)	Flow (L/s)	Velocity (m/s)	Unit Head Loss (m/km)
00:00	25,17	1,42	16,45
01:00	25,34	1,43	16,55
02:00	25,50	1,44	16,65
03:00	25,67	1,45	16,75
04:00	25,83	1,46	16,86
05:00	25,83	1,46	16,86
06:00	25,74	1,46	16,80
07:00	25,66	1,45	16,75
08:00	25,58	1,45	16,70
09:00	25,50	1,44	16,65
10:00	25,42	1,44	16,60
11:00	25,34	1,43	16,55
12:00	25,27	1,43	16,51
13:00	25,24	1,43	16,49
14:00	25,24	1,43	16,49
15:00	25,24	1,43	16,49
16:00	25,24	1,43	16,49
17:00	25,24	1,43	16,49
18:00	25,24	1,43	16,49
19:00	25,24	1,43	16,49
20:00	25,24	1,43	16,49
21:00	25,24	1,43	16,49
22:00	25,24	1,43	16,49
23:00	25,24	1,43	16,49
24:00	25,24	1,43	16,49

7.3. Cuamba Water Supply System

7.3.1. Model Development

Cuamba water supply system supplies water to the city of Cuamba in Niassa Province in Mozambique, with more than 140 000 inhabitants. The main water source of the system is the reservoir in Mpopole Dam located 30 km from the city, with a reserve capacity of 3 000 000 m^3 and an abstraction capacity of 60 m^3/h. The bulk 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 60.

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. Therefore, the model was built on *EPANET*, considering the same conditions as in the previous case study, and values of flow, velocities and unit head losses caused by PRV1 are presented in Table 25. 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 61 and 62, where it is possible to see that PRV1 and PRV2 provoke equal head losses. Thus, the PATs to be installed will also be equal.

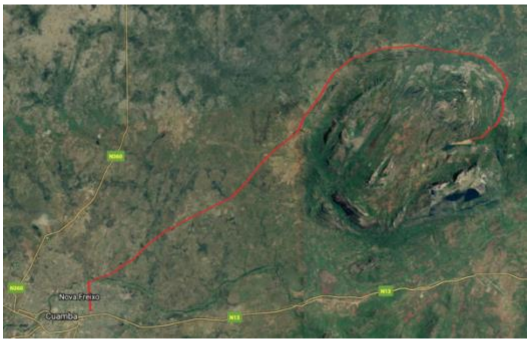


Figure 59 – Satellite view of implantation area

Figure 60 – Installed PRV

Table 25 – Flows, velocities and unit head losses at the section of PRV1

Time (h)	Flow (L/s)	Velocity (m/s)	Unit Head Loss (m/km)
00:00	11,20	0,56	10,05
01:00	11,20	0,56	10,05
02:00	11,10	0,55	10,46
03:00	11,06	0,55	10,66
04:00	11,01	0,55	10,86
05:00	10,96	0,55	11,06
06:00	10,92	0,54	11,25
07:00	10,87	0,54	11,44
08:00	10,83	0,54	11,61
09:00	10,79	0,54	11,77
10:00	10,75	0,53	11,94
11:00	10,75	0,53	11,94
12:00	10,71	0,53	12,10
13:00	10,68	0,53	12,25
14:00	10,60	0,53	12,57
15:00	10,60	0,53	12,57
16:00	10,52	0,52	12,90
17:00	10,48	0,52	13,07
18:00	10,44	0,52	13,23
19:00	10,44	0,52	13,23
20:00	10,36	0,52	13,54
21:00	10,32	0,51	13,70
22:00	10,28	0,51	13,87
23:00	10,23	0,51	14,05
24:00	10,19	0,51	14,22

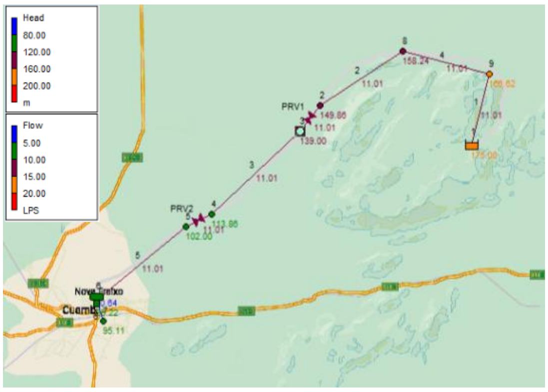


Figure 61 – Values of head and flow at 4:00 AM

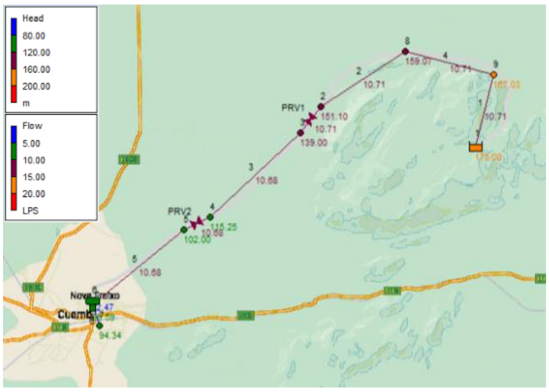


Figure 62 – Values of head and flow at 12:00 AM

7.3.2. 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 and is presented in Figure 63 (Appendix E). 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, characteristic curves for different rotation speeds were defined. To choose the operating point which maximises the energy production, the CCI must be 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 64); and the second corresponding to the stretch from PRV/PAT1, passing through PRV/PAT2, until the distribution tower (Figure 65). 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.

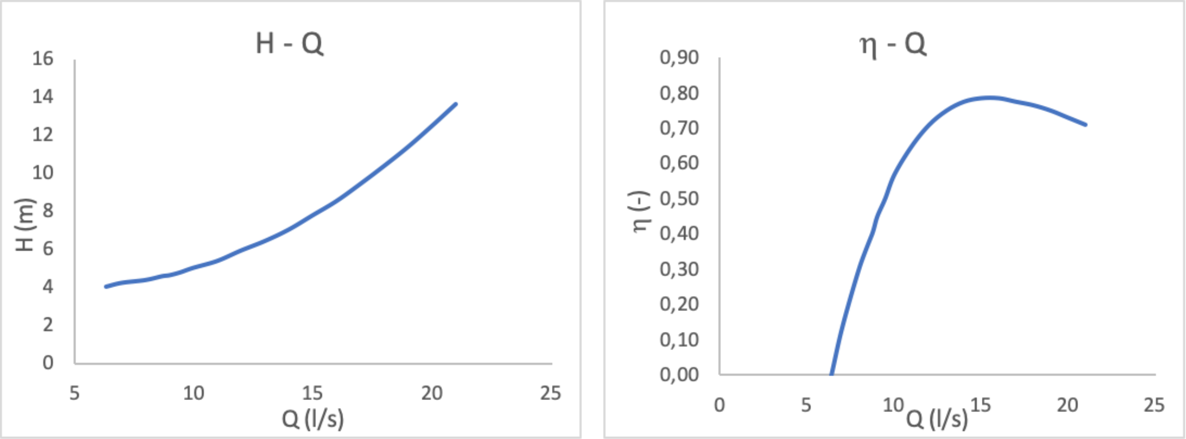


Figure 63 – Characteristic curve of the PAT

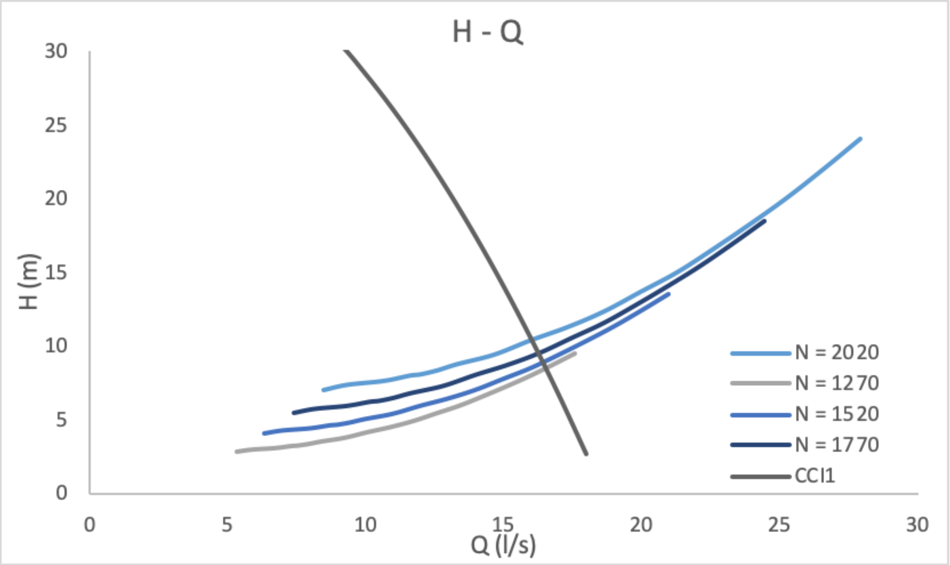


Figure 64 – Characteristic curves of the PAT and CCI1

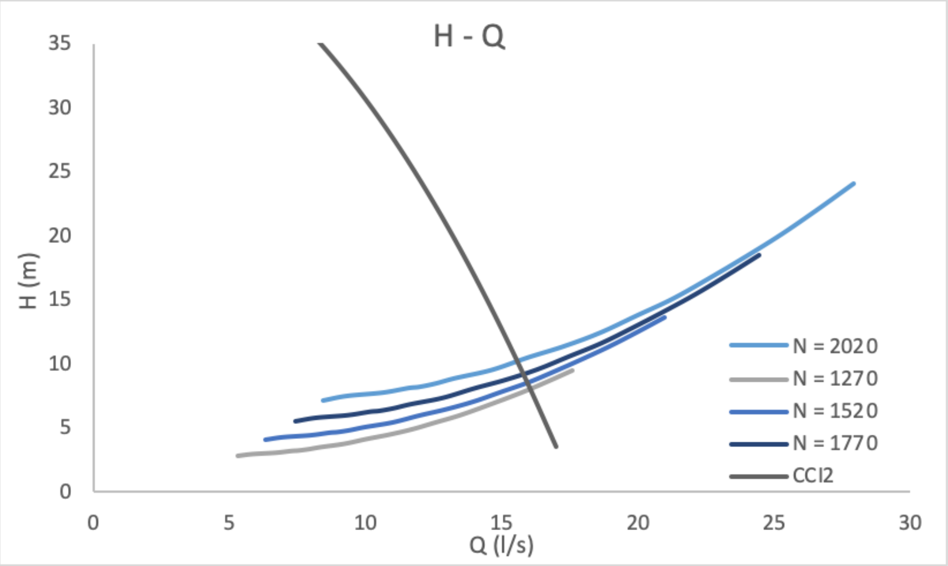


Figure 65 – Characteristic curves of the PAT and CCI2

7.3.3. 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 (Appendix F). 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 26. 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.

Table 26 – 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	0,720	0,51	20,00	10,16	3,71
1270	12,00	5,00	0,780	0,46	21,00	9,63	3,35
1770	11,00	6,40	0,500	0,34	22,00	7,59	2,52
2020	11,00	7,90	0,350	0,30	23,00	6,86	2,18

For a turbined flow of 12,00 L/s and 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 Figure 56 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 (Appendix G).

The obtained results are presented in Table 27. 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.

Table 27 – Main results of the economic analysis

Energy Selling Price (€/kWh]	0,095			0,110		
Discount Rate	6,0%	8,0%	10,0%	6,0%	8,0%	10,0%
NPV (€)	15721	11511	8616	5397	3329	1906
B/C (-)	3,896	3,193	2,680	1,994	1,634	1,372
Payback period (years)	4	5	5	4	5	5

The values of flow, velocity and unit head loss at the section of PAT1 are presented in Table 28 and, the flow and head values along the system at 4:00 AM and 12:00 AM can be seen in Figure 66 and 67.

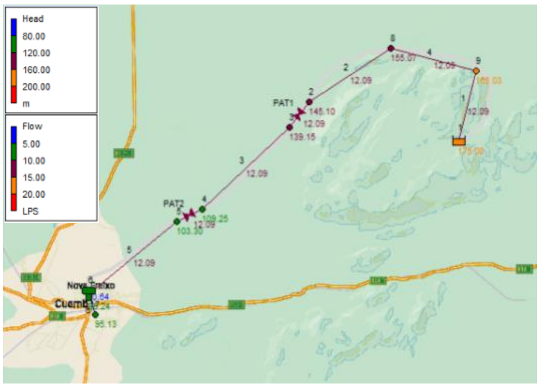


Figure 66 – Results at 4:00 AM after applying the PAT to the model

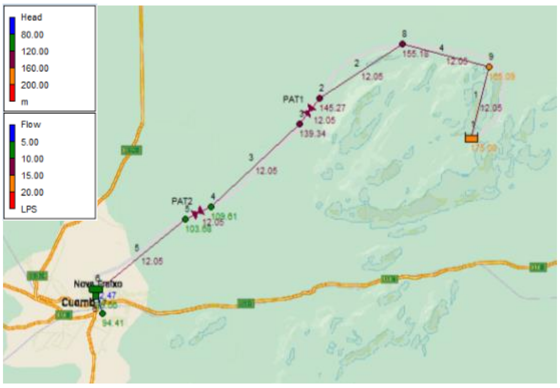


Figure 67 – Results at 12:00 PM after applying the PAT to the model

Table 28 – Flows, velocities and unit head losses at the section of PAT1

Time (h)	**Flow (L/s)**	**Velocity (m/s)**	**Unit Head Loss (m/km)**
00:00	12,11	0,60	5,96
01:00	12,11	0,60	5,95
02:00	12,10	0,60	5,95
03:00	12,10	0,60	5,95
04:00	12,09	0,60	5,95
05:00	12,09	0,60	5,94
13:00	12,05	0,60	5,92
14:00	12,04	0,60	5,92
15:00	12,04	0,60	5,92
16:00	12,03	0,60	5,92
17:00	12,03	0,60	5,92
18:00	12,03	0,60	5,91

Table 28 (Cont.) – Flows, velocities and unit head losses at the section of PAT1

Time (h)	Flow (L/s)	Velocity (m/s)	Unit Head Loss (m/km)
06:00	12,08	0,60	5,94
07:00	12,07	0,60	5,94
08:00	12,07	0,60	5,94
09:00	12,07	0,60	5,93
10:00	12,06	0,60	5,93
11:00	12,06	0,60	5,93
12:00	12,05	0,60	5,93
19:00	12,02	0,60	5,91
20:00	12,02	0,60	5,91
21:00	12,01	0,60	5,91
22:00	12,01	0,60	5,90
23:00	12,00	0,60	5,90
24:00	12,00	0,60	5,90

7.4. Discussion of Results

7.4.1. 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 193,18 €/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 29.

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 29).

Table 29 – 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 29 can be evaluated in terms of quality of service considering the reference values defined by ERSAR (Chapter 6). Accordingly, the volume of real losses in Nampula WSS before the installation of 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 significant improvement in terms of energy recovery and reduction of CO_2 emissions. It should be considered that, before 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 29 with those presented in Chapter 6, regarding the related indicators, 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%.

7.4.2. 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 implementation of PATs in WSSs for energy recovering while controlling pressures and reducing losses can have various positive social and environmental impacts. The presented case studies can 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.

8. Conclusions and Future Perspectives

8.1. 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.

Energy recovery in WSSs is a way of producing renewable energy without compromising water consumption needs. Small-scale hydropower plants are eco-friendlier and more cost-effective than large-scale hydropower plants.

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.

8.2. Future Perspectives

The present dissertation conducted an analysis of the economic and technical viability of the implementation of PATs in two WSSs in Mozambique, whilst evaluating the possibility to reduce the systems costs and environmental impacts. The presented methodology can be complemented with the following suggestions:

- Studying the systems behaviour in hydrotransient conditions;
- Assessing the systems effectiveness;
- Analysing the possibility of installing only one PAT in the case study of Cuamba.

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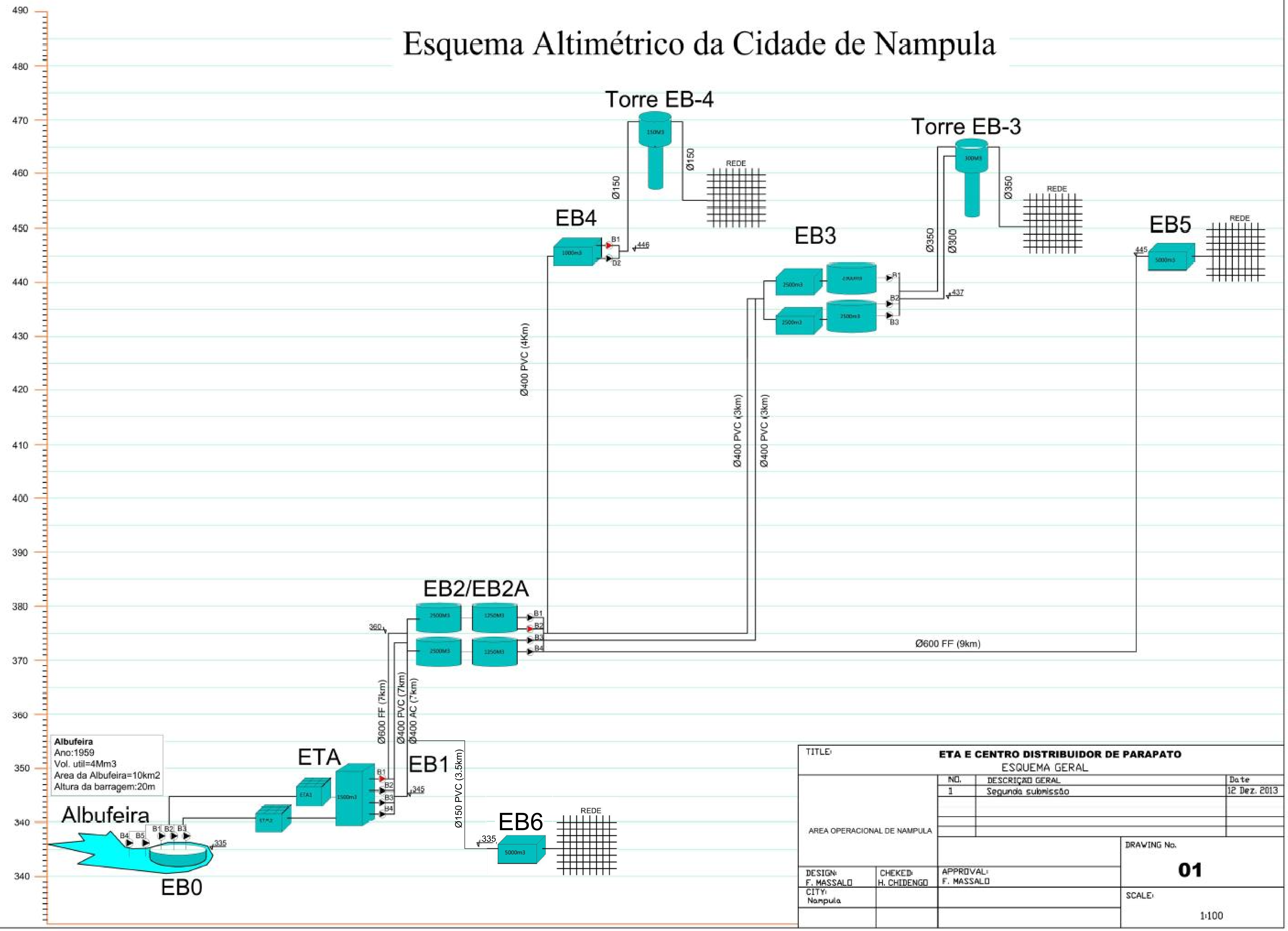
Appendix

Appendix A - Nampula Water Supply System (Altimetric Scheme)

Esquema Altimétrico da Cidade de Nampula



TITLE:
ETA E CENTRO DISTRIBUIDOR DE PARAPATO
ESQUEMA GERAL

AREA OPERACIONAL DE NAMPULA

NO.	DESCRIÇÃO GERAL	Date
1	Segunda submissão	12 Dez. 2013

DRAWING No.
01

DESIGN:
F. MASSALO

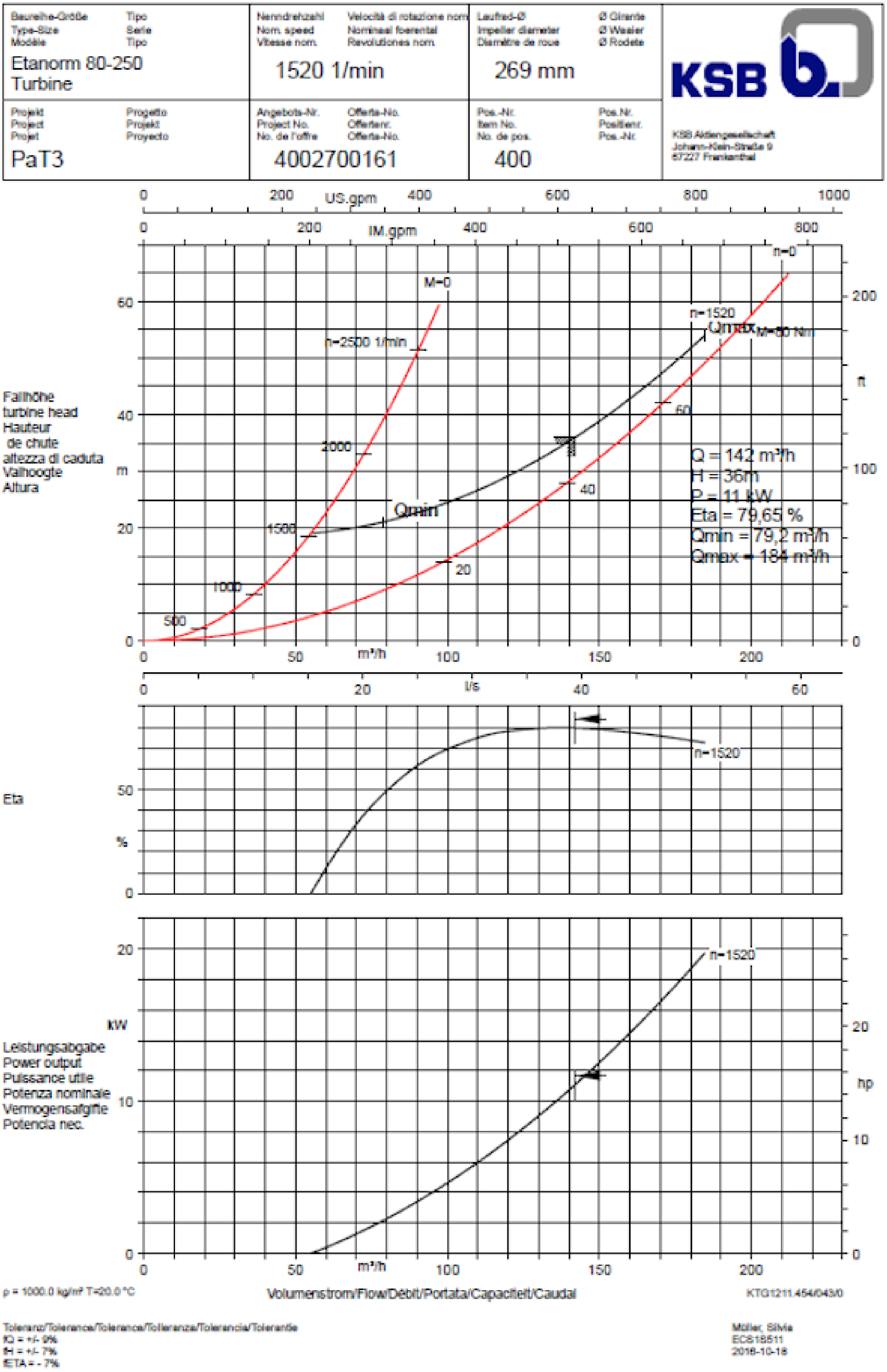
CHEKED:
H. CHIDENGO

APPROVAL:
F. MASSALO

CITY:
Nampula

SCALE:
1:100

Appendix B - Etanorm 80-250 Characteristic Curve



Baureihe-Größe Type-Size Modèle	Tipo Serie Tipo	Nenndrehzahl Nom. speed Vitesse nom.	Velocità di rotazione nom. Nominaal toerental Revoluciones nom.
Etanorm 80-250 Turbine		1520 1/min	
Projekt Project Projet	Progetto Projekt Proyecto	Angebots-Nr. Project No. No. de l'offre	Offerta-No. Offertenr. Offerta-No.
PaT3		4002700161	

Laufrad-Ø Impeller diameter Diamètre de roue	Ø Girante Ø Waaier Ø Rodete
269 mm	
Pos.-Nr. Item No. No. de pos.	Pos.Nr. Positienr. Pos.-Nr.
400	

KSB Aktiengesellschaft
Johann-Klein-Straße 9
67227 Frankenthal

ρ = 1000.0 kg/m³ T=20.0 °C

Volumenstrom/Flow/Débit/Portata/Capaciteit/Caudal

KTG1211.454/043/0

Toleranz/Tolerance/Tolerance/Tolleranza/Tolerancia/Tolerantie
fQ = +/- 9%
fH = +/- 7%
fETA = - 7%

Möller, Silvia
ECS18511
2016-10-18

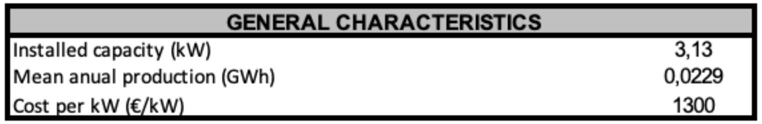
Appendix C - EPANET Results for Nampula WSS

PAT N = 1520			
Time	**Flow**	**Velocity**	**Unit Headloss**
Hours	LPS	m/s	m/km
00:00	23,33	1,32	21,89
01:00	23,51	1,33	22,01
02:00	23,69	1,34	22,13
03:00	23,86	1,35	22,24
04:00	24,04	1,36	22,36
05:00	24,03	1,36	22,35
06:00	23,94	1,35	22,30
07:00	23,86	1,35	22,24
08:00	23,78	1,35	22,19
09:00	23,70	1,34	22,13
10:00	23,62	1,34	22,08
11:00	23,54	1,33	22,03
12:00	23,46	1,33	21,98
13:00	23,41	1,32	21,94
14:00	23,41	1,32	21,94
15:00	23,41	1,32	21,94
16:00	23,41	1,32	21,94
17:00	23,41	1,32	21,94
18:00	23,41	1,32	21,94
19:00	23,41	1,32	21,94
20:00	23,41	1,32	21,94
21:00	23,41	1,32	21,94
22:00	23,41	1,32	21,94
23:00	23,41	1,32	21,94
24:00	23,41	1,32	21,94

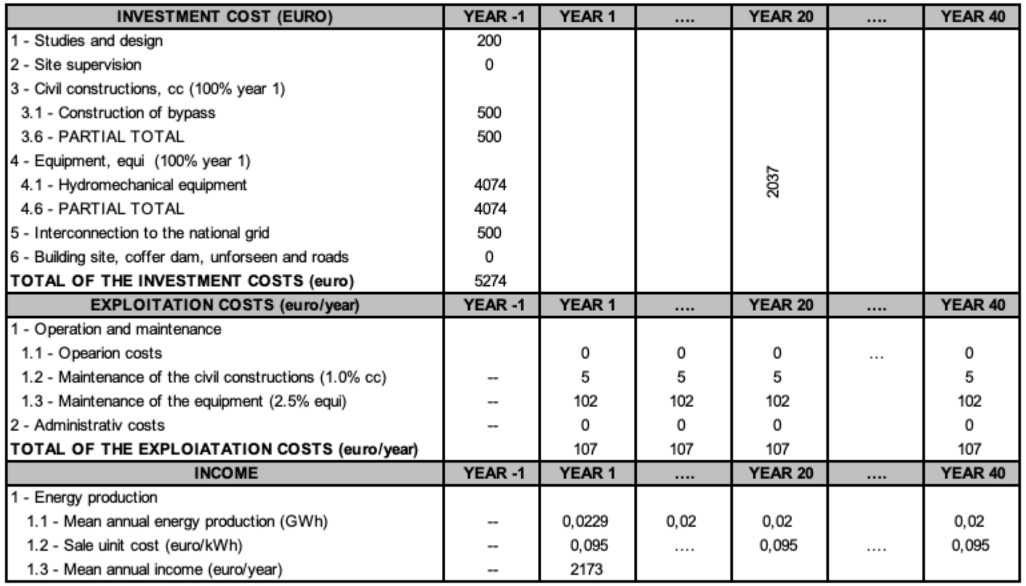
PAT N = 1320			
Time	**Flow**	**Velocity**	**Unit Headloss**
Hours	LPS	m/s	m/km
00:00	24,36	1,38	18,90
01:00	24,50	1,39	19,10
02:00	24,64	1,39	19,29
03:00	24,78	1,40	19,48
04:00	24,92	1,41	19,67
05:00	24,92	1,41	19,67
06:00	24,85	1,41	19,57
07:00	24,78	1,40	19,48
08:00	24,71	1,40	19,39
09:00	24,65	1,39	19,30
10:00	24,58	1,39	19,21
11:00	24,52	1,39	19,12
12:00	24,46	1,38	19,04
13:00	24,42	1,38	18,98
14:00	24,42	1,38	18,98
15:00	24,42	1,38	18,98
16:00	24,42	1,38	18,98
17:00	24,42	1,38	18,98
18:00	24,42	1,38	18,98
19:00	24,42	1,38	18,98
20:00	24,42	1,38	18,98
21:00	24,42	1,38	18,98
22:00	24,42	1,38	18,98
23:00	24,42	1,38	18,98
24:00	24,42	1,38	18,98

Appendix D - Economic Analysis for Nampula Case Study

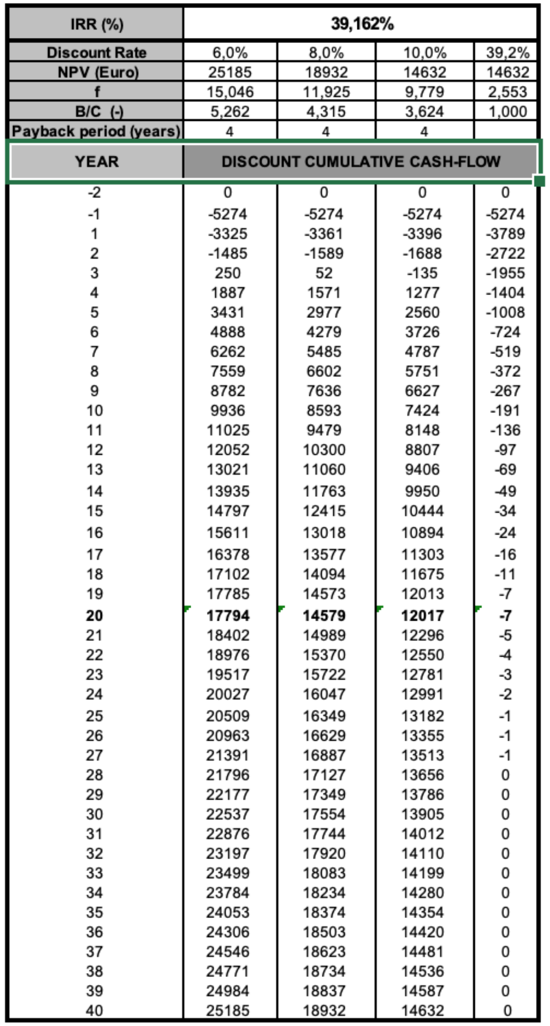
- Scenario 1



GENERAL CHARACTERISTICS	
Installed capacity (kW)	3,13
Mean anual production (GWh)	0,0229
Cost per kW (€/kW)	1300

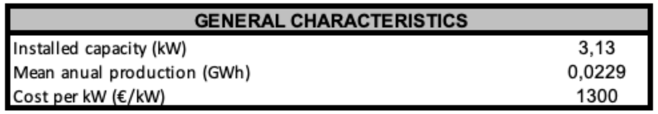


INVESTMENT COST (EURO)	YEAR -1	YEAR 1	....	YEAR 20	....	YEAR 40
1 - Studies and design	200					
2 - Site supervision	0					
3 - Civil constructions, cc (100% year 1)						
3.1 - Construction of bypass	500					
3.6 - PARTIAL TOTAL	500					
4 - Equipment, equi (100% year 1)						
4.1 - Hydromechanical equipment	4074			2037		
4.6 - PARTIAL TOTAL	4074					
5 - Interconnection to the national grid	500					
6 - Building site, coffer dam, unforseen and roads	0					
TOTAL OF THE INVESTMENT COSTS (euro)	5274					
EXPLOITATION COSTS (euro/year)	**YEAR -1**	**YEAR 1**	**....**	**YEAR 20**	**....**	**YEAR 40**
1 - Operation and maintenance						
1.1 - Opearion costs		0	0	0	...	0
1.2 - Maintenance of the civil constructions (1.0% cc)	--	5	5	5		5
1.3 - Maintenance of the equipment (2.5% equi)	--	102	102	102		102
2 - Administrativ costs	--	0	0	0		0
TOTAL OF THE EXPLOIATATION COSTS (euro/year)		107	107	107		107
INCOME	**YEAR -1**	**YEAR 1**	**....**	**YEAR 20**	**....**	**YEAR 40**
1 - Energy production						
1.1 - Mean annual energy production (GWh)	--	0,0229	0,02	0,02		0,02
1.2 - Sale uinit cost (euro/kWh)	--	0,095	....	0,095	....	0,095
1.3 - Mean annual income (euro/year)	--	2173				

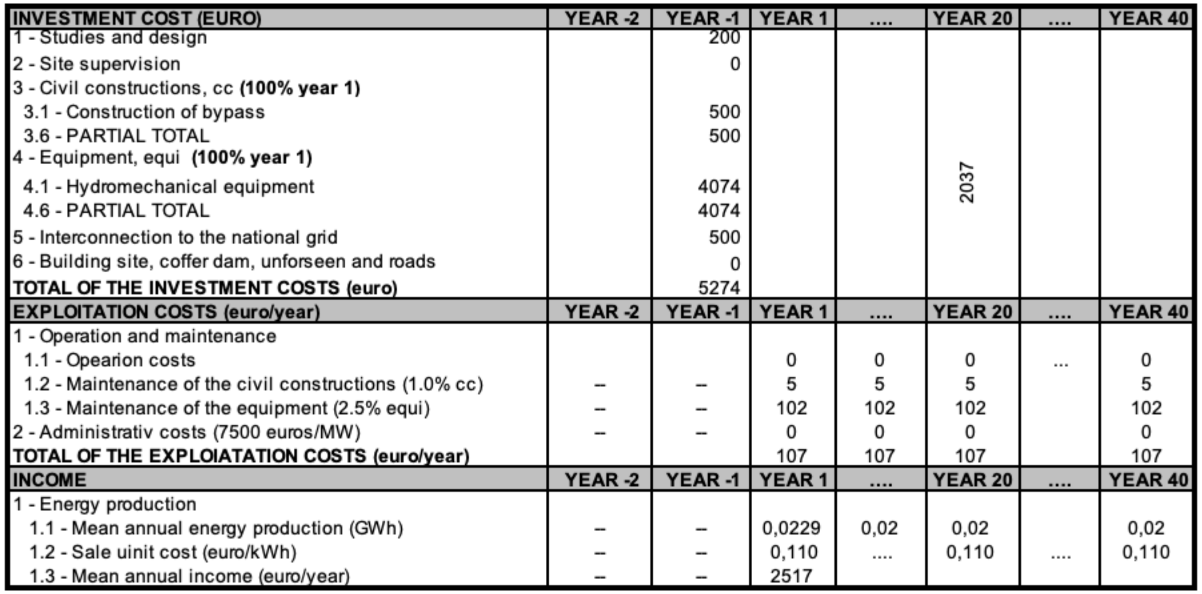


IRR (%)	39,162%			
Discount Rate	6,0%	8,0%	10,0%	39,2%
NPV (Euro)	25185	18932	14632	14632
f	15,046	11,925	9,779	2,553
B/C (-)	5,262	4,315	3,624	1,000
Payback period (years)	4	4	4	
YEAR	**DISCOUNT CUMULATIVE CASH-FLOW**			
-2	0	0	0	0
-1	-5274	-5274	-5274	-5274
1	-3325	-3361	-3396	-3789
2	-1485	-1589	-1688	-2722
3	250	52	-135	-1955
4	1887	1571	1277	-1404
5	3431	2977	2560	-1008
6	4888	4279	3726	-724
7	6262	5485	4787	-519
8	7559	6602	5751	-372
9	8782	7636	6627	-267
10	9936	8593	7424	-191
11	11025	9479	8148	-136
12	12052	10300	8807	-97
13	13021	11060	9406	-69
14	13935	11763	9950	-49
15	14797	12415	10444	-34
16	15611	13018	10894	-24
17	16378	13577	11303	-16
18	17102	14094	11675	-11
19	17785	14573	12013	-7
20	**17794**	**14579**	**12017**	**-7**
21	18402	14989	12296	-5
22	18976	15370	12550	-4
23	19517	15722	12781	-3
24	20027	16047	12991	-2
25	20509	16349	13182	-1
26	20963	16629	13355	-1
27	21391	16887	13513	-1
28	21796	17127	13656	0
29	22177	17349	13786	0
30	22537	17554	13905	0
31	22876	17744	14012	0
32	23197	17920	14110	0
33	23499	18083	14199	0
34	23784	18234	14280	0
35	24053	18374	14354	0
36	24306	18503	14420	0
37	24546	18623	14481	0
38	24771	18734	14536	0
39	24984	18837	14587	0
40	25185	18932	14632	0

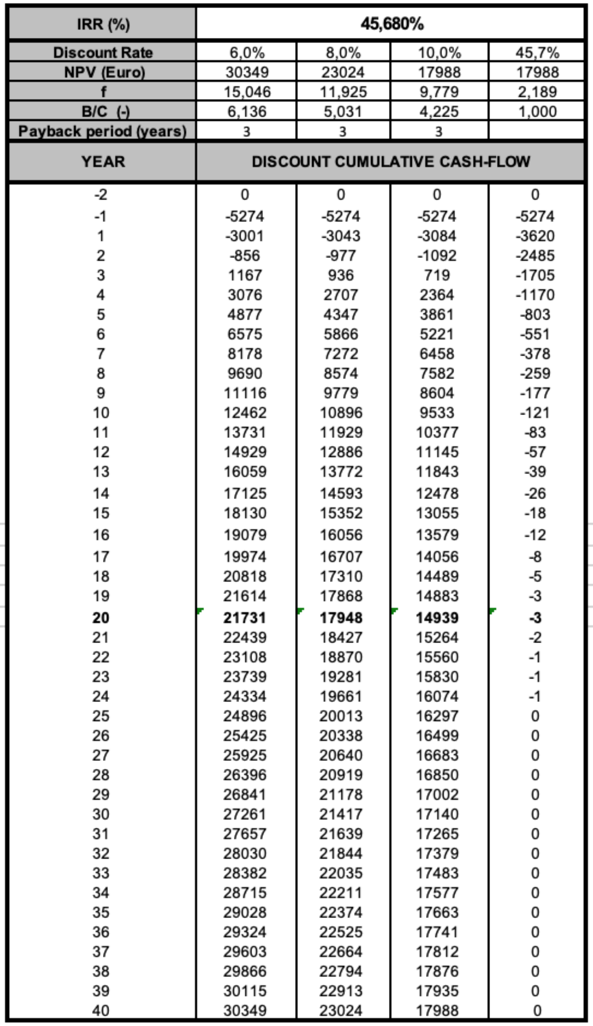
- Scenario 2



GENERAL CHARACTERISTICS	
Installed capacity (kW)	3,13
Mean anual production (GWh)	0,0229
Cost per kW (€/kW)	1300



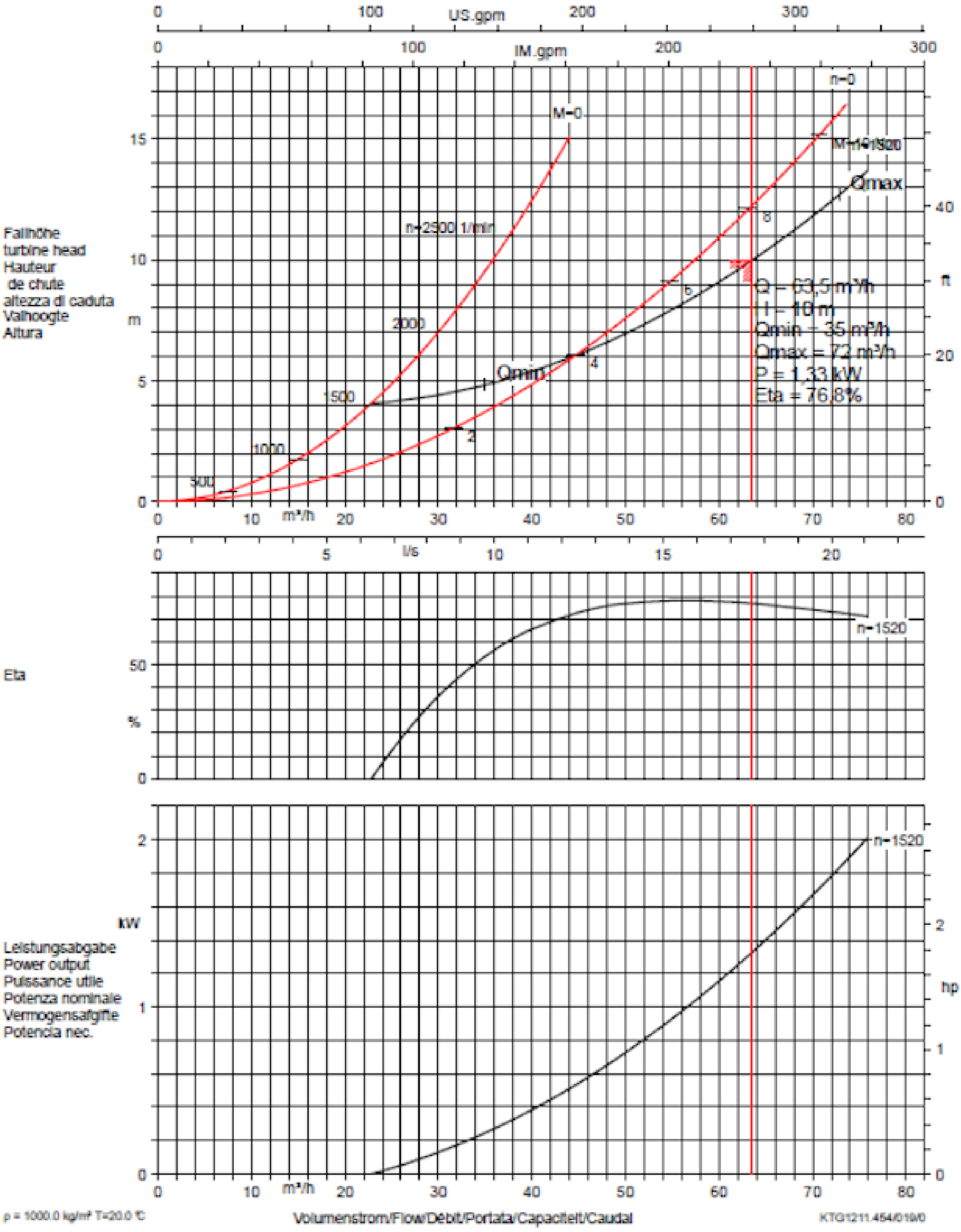
INVESTMENT COST (EURO)	**YEAR -2**	**YEAR -1**	**YEAR 1**	**....**	**YEAR 20**	**....**	**YEAR 40**
1 - Studies and design		200			2037		
2 - Site supervision		0					
3 - Civil constructions, cc **(100% year 1)**							
3.1 - Construction of bypass		500					
3.6 - PARTIAL TOTAL		500					
4 - Equipment, equi **(100% year 1)**							
4.1 - Hydromechanical equipment		4074					
4.6 - PARTIAL TOTAL		4074					
5 - Interconnection to the national grid		500					
6 - Building site, coffer dam, unforseen and roads		0					
TOTAL OF THE INVESTMENT COSTS (euro)		5274					
EXPLOITATION COSTS (euro/year)	**YEAR -2**	**YEAR -1**	**YEAR 1**	**....**	**YEAR 20**	**....**	**YEAR 40**
1 - Operation and maintenance							
1.1 - Opearion costs			0	0	0	...	0
1.2 - Maintenance of the civil constructions (1.0% cc)	–	–	5	5	5		5
1.3 - Maintenance of the equipment (2.5% equi)	–	–	102	102	102		102
2 - Administrativ costs (7500 euros/MW)	–	–	0	0	0		0
TOTAL OF THE EXPLOIATATION COSTS (euro/year)			107	107	107		107
INCOME	**YEAR -2**	**YEAR -1**	**YEAR 1**	**....**	**YEAR 20**	**....**	**YEAR 40**
1 - Energy production							
1.1 - Mean annual energy production (GWh)	–	–	0,0229	0,02	0,02		0,02
1.2 - Sale uinit cost (euro/kWh)	–	–	0,110	....	0,110	....	0,110
1.3 - Mean annual income (euro/year)	–	–	2517				



IRR (%)	**45,680%**			
Discount Rate	6,0%	8,0%	10,0%	45,7%
NPV (Euro)	30349	23024	17988	17988
f	15,046	11,925	9,779	2,189
B/C (-)	6,136	5,031	4,225	1,000
Payback period (years)	3	3	3	
YEAR	**DISCOUNT CUMULATIVE CASH-FLOW**			
-2	0	0	0	0
-1	-5274	-5274	-5274	-5274
1	-3001	-3043	-3084	-3620
2	-856	-977	-1092	-2485
3	1167	936	719	-1705
4	3076	2707	2364	-1170
5	4877	4347	3861	-803
6	6575	5866	5221	-551
7	8178	7272	6458	-378
8	9690	8574	7582	-259
9	11116	9779	8604	-177
10	12462	10896	9533	-121
11	13731	11929	10377	-83
12	14929	12886	11145	-57
13	16059	13772	11843	-39
14	17125	14593	12478	-26
15	18130	15352	13055	-18
16	19079	16056	13579	-12
17	19974	16707	14056	-8
18	20818	17310	14489	-5
19	21614	17868	14883	-3
20	**21731**	**17948**	**14939**	**-3**
21	22439	18427	15264	-2
22	23108	18870	15560	-1
23	23739	19281	15830	-1
24	24334	19661	16074	-1
25	24896	20013	16297	0
26	25425	20338	16499	0
27	25925	20640	16683	0
28	26396	20919	16850	0
29	26841	21178	17002	0
30	27261	21417	17140	0
31	27657	21639	17265	0
32	28030	21844	17379	0
33	28382	22035	17483	0
34	28715	22211	17577	0
35	29028	22374	17663	0
36	29324	22525	17741	0
37	29603	22664	17812	0
38	29866	22794	17876	0
39	30115	22913	17935	0
40	30349	23024	17988	0

Appendix E - Etanorm 50-125 Characteristic Curve

Baureihe-Größe Type-Size Modèle	Tipo Serie Tipo	Nenndrehzahl Nom. speed Vitesse nom.	Velocità di rotazione nom Nominaal toerental Revoluciones nom.	Laufrad-Ø Impeller diameter Diamètre de roue	Ø Girante Ø Waaier Ø Rodete	KSB
Etanorm 50-125 Turbine		1520 1/min		142 mm		
Projekt Project Projet	Progetto Projekt Proyecto	Angebots-Nr. Project No. No. de l'offre	Offerta-No. Offertenr. Oferta-No.	Pos.-Nr. Item No. No. de pos.	Pos.Nr. Positienr. Pos.-Nr.	KSB Aktiengesellschaft Johann-Klein-Straße 9 67227 Frankenthal



Q = 63,5 m³/h
H = 10 m
Qmin = 35 m³/h
Qmax = 72 m³/h
P = 1,33 kW
Eta = 76,8%

ρ = 1000.0 kg/m³ T=20.0 °C

KTG1211.454/019/0

Toleranz/Tolerance/Tolerance/Tolleranza/Tolerancia/Tolerantie
fQ = +/- 9%
fH = +/- 7%
fETA = - 7%

Jerger, Sabine
8-EA1132
2015-11-27

Appendix F - EPANET Results for Cuamba WSS

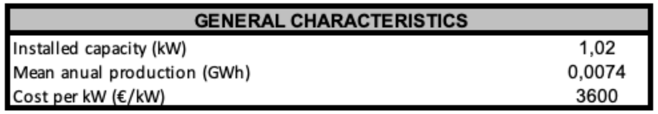
PAT N = 1270			
Time	**Flow**	**Velocity**	**Unit Headloss**
Hours	LPS	m/s	m/km
00:00	12,25	0,61	5,23
01:00	12,24	0,61	5,23
02:00	12,24	0,61	5,23
03:00	12,23	0,61	5,22
04:00	12,23	0,61	5,22
05:00	12,22	0,61	5,22
06:00	12,22	0,61	5,21
07:00	12,21	0,61	5,21
08:00	12,21	0,61	5,21
09:00	12,20	0,61	5,21
10:00	12,20	0,61	5,20
11:00	12,20	0,61	5,20
12:00	12,19	0,61	5,20
13:00	12,19	0,61	5,20
14:00	12,18	0,61	5,19
15:00	12,18	0,61	5,19
16:00	12,17	0,61	5,19
17:00	12,17	0,61	5,18
18:00	12,17	0,61	5,18
19:00	12,16	0,60	5,18
20:00	12,16	0,60	5,18
21:00	12,15	0,60	5,17
22:00	12,15	0,60	5,17
23:00	12,14	0,60	5,17
24:00	12,14	0,60	5,16

PAT N = 1770			
Time	**Flow**	**Velocity**	**Unit Headloss**
Hours	LPS	m/s	m/km
00:00	11,93	0,59	6,89
01:00	11,93	0,59	6,89
02:00	11,92	0,59	6,88
03:00	11,91	0,59	6,88
04:00	11,91	0,59	6,88
05:00	11,90	0,59	6,88
06:00	11,90	0,59	6,88
07:00	11,89	0,59	6,87
08:00	11,89	0,59	6,87
09:00	11,88	0,59	6,87
10:00	11,88	0,59	6,87
11:00	11,88	0,59	6,87
12:00	11,87	0,59	6,87
13:00	11,87	0,59	6,86
14:00	11,86	0,59	6,86
15:00	11,86	0,59	6,86
16:00	11,85	0,59	6,86
17:00	11,85	0,59	6,86
18:00	11,84	0,59	6,85
19:00	11,84	0,59	6,85
20:00	11,84	0,59	6,85
21:00	11,83	0,59	6,85
22:00	11,83	0,59	6,85
23:00	11,82	0,59	6,84
24:00	11,82	0,59	6,84

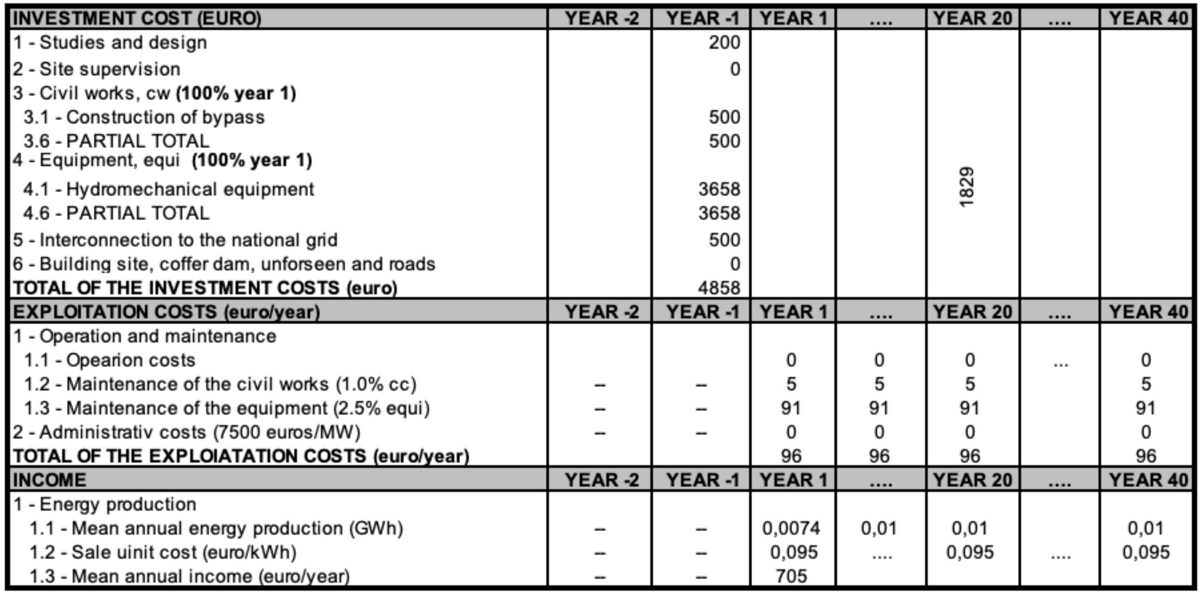
PAT N = 2020			
Time	**Flow**	**Velocity**	**Unit Headloss**
Hours	LPS	m/s	m/km
00:00	11,70	0,58	8,07
01:00	11,69	0,58	8,07
02:00	11,69	0,58	8,07
03:00	11,68	0,58	8,06
04:00	11,68	0,58	8,06
05:00	11,67	0,58	8,06
06:00	11,67	0,58	8,06
07:00	11,66	0,58	8,06
08:00	11,66	0,58	8,06
09:00	11,65	0,58	8,06
10:00	11,65	0,58	8,06
11:00	11,64	0,58	8,06
12:00	11,64	0,58	8,06
13:00	11,63	0,58	8,05
14:00	11,63	0,58	8,05
15:00	11,62	0,58	8,05
16:00	11,62	0,58	8,05
17:00	11,61	0,58	8,05
18:00	11,61	0,58	8,05
19:00	11,61	0,58	8,05
20:00	11,60	0,58	8,05
21:00	11,60	0,58	8,05
22:00	11,59	0,58	8,05
23:00	11,59	0,58	8,05
24:00	11,58	0,58	8,04

Appendix G -Economic Analysis for Cuamba Case Study

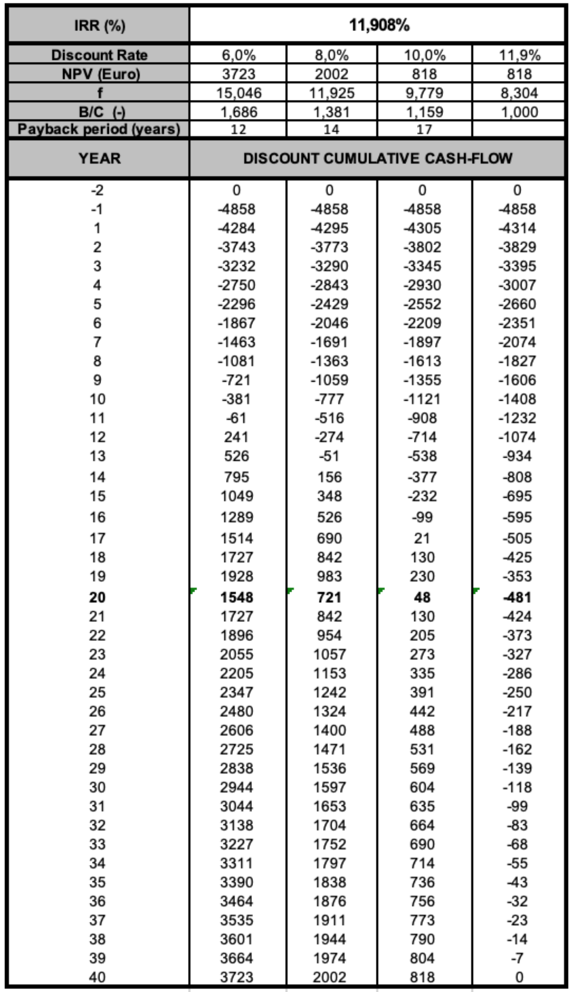
- Scenario 1



GENERAL CHARACTERISTICS	
Installed capacity (kW)	1,02
Mean anual production (GWh)	0,0074
Cost per kW (€/kW)	3600



INVESTMENT COST (EURO)	**YEAR -2**	**YEAR -1**	**YEAR 1**	**....**	**YEAR 20**	**....**	**YEAR 40**
1 - Studies and design		200			1829		
2 - Site supervision		0					
3 - Civil works, cw **(100% year 1)**							
3.1 - Construction of bypass		500					
3.6 - PARTIAL TOTAL		500					
4 - Equipment, equi **(100% year 1)**							
4.1 - Hydromechanical equipment		3658					
4.6 - PARTIAL TOTAL		3658					
5 - Interconnection to the national grid		500					
6 - Building site, coffer dam, unforseen and roads		0					
TOTAL OF THE INVESTMENT COSTS (euro)		4858					
EXPLOITATION COSTS (euro/year)	**YEAR -2**	**YEAR -1**	**YEAR 1**	**....**	**YEAR 20**	**....**	**YEAR 40**
1 - Operation and maintenance							
1.1 - Opearion costs			0	0	0	...	0
1.2 - Maintenance of the civil works (1.0% cc)	–	–	5	5	5		5
1.3 - Maintenance of the equipment (2.5% equi)	–	–	91	91	91		91
2 - Administrativ costs (7500 euros/MW)	–	–	0	0	0		0
TOTAL OF THE EXPLOIATATION COSTS (euro/year)			96	96	96		96
INCOME	**YEAR -2**	**YEAR -1**	**YEAR 1**	**....**	**YEAR 20**	**....**	**YEAR 40**
1 - Energy production							
1.1 - Mean annual energy production (GWh)	–	–	0,0074	0,01	0,01		0,01
1.2 - Sale uinit cost (euro/kWh)	–	–	0,095	....	0,095	....	0,095
1.3 - Mean annual income (euro/year)	–	–	705				



IRR (%)	**11,908%**			
Discount Rate	6,0%	8,0%	10,0%	11,9%
NPV (Euro)	3723	2002	818	818
f	15,046	11,925	9,779	8,304
B/C (-)	1,686	1,381	1,159	1,000
Payback period (years)	12	14	17	
YEAR	**DISCOUNT CUMULATIVE CASH-FLOW**			
-2	0	0	0	0
-1	-4858	-4858	-4858	-4858
1	-4284	-4295	-4305	-4314
2	-3743	-3773	-3802	-3829
3	-3232	-3290	-3345	-3395
4	-2750	-2843	-2930	-3007
5	-2296	-2429	-2552	-2660
6	-1867	-2046	-2209	-2351
7	-1463	-1691	-1897	-2074
8	-1081	-1363	-1613	-1827
9	-721	-1059	-1355	-1606
10	-381	-777	-1121	-1408
11	-61	-516	-908	-1232
12	241	-274	-714	-1074
13	526	-51	-538	-934
14	795	156	-377	-808
15	1049	348	-232	-695
16	1289	526	-99	-595
17	1514	690	21	-505
18	1727	842	130	-425
19	1928	983	230	-353
20	**1548**	**721**	**48**	**-481**
21	1727	842	130	-424
22	1896	954	205	-373
23	2055	1057	273	-327
24	2205	1153	335	-286
25	2347	1242	391	-250
26	2480	1324	442	-217
27	2606	1400	488	-188
28	2725	1471	531	-162
29	2838	1536	569	-139
30	2944	1597	604	-118
31	3044	1653	635	-99
32	3138	1704	664	-83
33	3227	1752	690	-68
34	3311	1797	714	-55
35	3390	1838	736	-43
36	3464	1876	756	-32
37	3535	1911	773	-23
38	3601	1944	790	-14
39	3664	1974	804	-7
40	3723	2002	818	0

- Scenario 2

GENERAL CHARACTERISTICS	
Installed capacity (kW)	1,02
Mean anual production (GWh)	0,0074
Cost per kW (€/kW)	3600

INVESTMENT COST (EURO)	**YEAR -2**	**YEAR -1**	**YEAR 1**	**....**	**YEAR 20**	**....**	**YEAR 40**
1 - Studies and design		200					
2 - Site supervision		0					
3 - Civil works, cw **(100% year 1)**							
3.1 - Construction of bypass		500					
3.6 - PARTIAL TOTAL		500					
4 - Equipment, equi **(100% year 1)**							
4.1 - Hydromechanical equipment		3658			1829		
4.6 - PARTIAL TOTAL		3658					
5 - Interconnection to the national grid		500					
6 - Building site, coffer dam, unforseen and roads		0					
TOTAL OF THE INVESTMENT COSTS (euro)		4858					
EXPLOITATION COSTS (euro/year)	**YEAR -2**	**YEAR -1**	**YEAR 1**	**....**	**YEAR 20**	**....**	**YEAR 40**
1 - Operation and maintenance							
1.1 - Opearion costs			0	0	0	...	0
1.2 - Maintenance of the civil works (1.0% cc)	–	–	5	5	5		5
1.3 - Maintenance of the equipment (2.5% equi)	–	–	91	91	91		91
2 - Administrativ costs (7500 euros/MW)	–	–	0	0	0		0
TOTAL OF THE EXPLOIATATION COSTS (euro/year)			96	96	96		96
INCOME	**YEAR -2**	**YEAR -1**	**YEAR 1**	**....**	**YEAR 20**	**....**	**YEAR 40**
1 - Energy production							
1.1 - Mean annual energy production (GWh)	–	–	0,0074	0,01	0,01		0,01
1.2 - Sale uinit cost (euro/kWh)	–	–	0,110	....	0,110	....	0,110
1.3 - Mean annual income (euro/year)	–	–	816				

IRR (%)	**14,373%**			
Discount Rate	6,0%	8,0%	10,0%	14,4%
NPV (Euro)	5397	3329	1906	1906
f	15,046	11,925	9,779	6,925
B/C (-)	1,994	1,634	1,372	1,000
Payback period (years)	9	11	12	
YEAR	**DISCOUNT CUMULATIVE CASH-FLOW**			
-2	0	0	0	0
-1	-4858	-4858	-4858	-4858
1	-4179	-4192	-4204	-4229
2	-3539	-3575	-3609	-3679
3	-2935	-3004	-3069	-3198
4	-2365	-2475	-2577	-2777
5	-1827	-1985	-2131	-2410
6	-1320	-1532	-1724	-2088
7	-842	-1112	-1355	-1807
8	-390	-723	-1020	-1562
9	36	-363	-714	-1347
10	437	-30	-437	-1159
11	816	278	-185	-995
12	1174	564	44	-851
13	1511	829	253	-726
14	1829	1074	442	-616
15	2130	1300	614	-520
16	2413	1510	771	-436
17	2680	1705	913	-363
18	2932	1885	1043	-298
19	3170	2052	1160	-242
20	**2824**	**1813**	**995**	**-318**
21	3036	1956	1093	-275
22	3235	2089	1181	-238
23	3424	2211	1261	-205
24	3601	2325	1334	-176
25	3769	2430	1401	-151
26	3927	2527	1461	-129
27	4076	2617	1516	-110
28	4217	2701	1566	-93
29	4350	2778	1611	-79
30	4475	2849	1653	-66
31	4593	2915	1690	-55
32	4705	2977	1724	-45
33	4810	3033	1755	-36
34	4909	3086	1783	-29
35	5003	3135	1809	-22
36	5091	3180	1832	-17
37	5174	3221	1853	-12
38	5253	3260	1873	-7
39	5327	3296	1890	-3
40	5397	3329	1906	0