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Bachelor's Degree Thesis

# Micro-hydro solutions in Alqueva Multipurpose Project (AMP) towards water-energy-environmental efficiency improvements

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# ABSTRACT

The aim of the current thesis is the evaluation of implementing micro-hydropower (MHP) solutions in water demand scenarios of irrigation systems. For the many advantages that micro production of energy brings to the grid, the use of excess energy of a irrigation water distribution system by the use of MHP, guarantying a water use efficiency and an energy production at the same time is studied.

Firstly a description of the study area, the Alqueva Multipurpose Project (AMP) is presented. With the data collected in EDIA and COTR and simulations using the software EPANET, it was possible to obtain the principal hydraulic parameters of the irrigation network.

The turbo machine theory allows to evaluate, accordingly the obtain results, which hydraulic machine is more suitable to apply in different conveyance water systems. It is presented the main energy converters and is verified the general performance curves of the hydraulic machines.

This study includes an economic analysis to evaluate the energy production viability by the implementation of the micro-hydropower in the Alqueva Multipurpose Project. In the analyses are used some of the principle economic parameters such as Internal Return Rate (IRR) and the Cost/Benefit ratio (C/B) to verify the viability of this project.

Additionally an environmental and social analysis is done, in order to evaluate the impact of this kind of renewable solutions.

This emphasise the promotion of the use of a green energy, with low carbon emissions, in order to assure a sustainable new future development in irrigation systems.

**Keywords:** micro production, water-energy nexus, renewable energy, environmental friendly solutions, Alqueva Multipurpose Project.

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## CONTENTS


1. INTRODUCTION ... 1

1.1. Context and motivation ... 1

1.2. Objectives ... 3

1.3. Thesis structure ... 4

2. CHARACTERIZATION OF THE ALQUEVA MULTIPURPOSE PROJECT ... 7

2.1. General description ... 7

2.2. Approaches to evaluate the water use efficiency and energy production in AMP ... 9

2.2.1. Water use efficiency ... 9

2.2.2. Energy production efficiency ... 15

2.3. Environmental considerations ... 17

2.4. Irrigation network scenarios ... 18

2.4.1. Scenario A - Open irrigation channels ... 18

2.4.2. Scenario B - Pressurized irrigation system ... 19

2.5. Irrigation water consumption ... 20

3. HYDRODYNAMIC EQUIPMENTS ... 24

3.1. Hydropower plants ... 24

3.1.1. Classification of hydropower plants ... 24

3.1.2. Types of hydropower plants ... 24

3.2. Hydraulic machines ... 25

3.2.1. Main characteristics ... 25

3.2.2. Volumetric machines ... 25

3.2.3. Turbo machines ... 26

3.3. Similarity laws and specific speed in turbo machines ... 28

3.4. Hydraulic modeling models ... 29

3.4.1. EPANET ... 29

3.4.2. Model calibration of Scenario B ... 31

4. HYDROPOWER CONVERTERS FOR LOW POWER ... 34

4.1. Introduction ... 34

4.2. Rotary Hydraulic Pressure Machine (RHPM) ... 34

4.3. Pump-as-Turbine (PAT) ........ 41
5. ENERGY, ENVIRONMENTAL AND SOCIAL ANALYSIS ........ 50
5.1. Introduction ........ 50
5.2. Energy production ........ 50
5.2.1. Scenario A - Open irrigation channels ........ 51
5.2.2. Scenario B - Pressurized irrigation system ........ 51
5.3. Environmental benefits ........ 52
5.4. Social impact ........ 53
6. ECONOMIC ANALYSIS ........ 56
6.1. Introduction ........ 56
6.2. Economic analysis ........ 60
6.2.1. Scenario A - Open irrigation channels ........ 62
6.2.2. Scenario B - Pressurized irrigation system ........ 62
7. CONCLUSIONS AND FUTURE WORK ........ 64
7.1. General considerations ........ 64
7.2. Future developments ........ 64
8. REFERENCES ........ 66

## LIST OF FIGURES

Figure 1 - National average per capita $CO_2$ emission and vulnerability index (UNEP, 2008) ................ 1

Figure 2 - Installed power of national electricity generation (2010 vs 2020) (Ramos, 2014) ................. 2

Figure 3 - Mainwork structure ........................................................................................................ 4

Figure 4 - Plan of Alqueva I and II (EDP, 2012)........................................................................... 8

Figure 5 - Freshwater Stress (1995 vs 2025) (UNEP, 2008)........................................................ 10

Figure 6 - Distribution map of the area currently farmed (EDIA, 2015) ........................................ 11

Figure 7 - Water demand by sector (Portugal 2010) (adapted from APA, 2011) ........................ 12

Figure 8 - Average Rainfall in Alqueva ........................................................................................ 13

Figure 9 - Distribution of crops in the Alqueva irrigation zones (EDIA, 2015) .............................. 14

Figure 10 - Water supplied for irrigation (EDIA, 2015).................................................................. 15

Figure 11 - Electricity production from renewable sources (ADENE, 2015) ................................. 16

Figure 12 - Main primary energy sources in Portugal (IEA, 2014)................................................ 16

Figure 13 - Open irrigation channel in Alqueva............................................................................. 19

Figure 14 - Different open channels cross-sections ..................................................................... 19

Figure 15 - Pressurized irrigation system in Alqueva ................................................................... 20

Figure 16 - Topologies of pressurized networks ........................................................................... 20

Figure 17 - Gear pump operation.................................................................................................. 26

Figure 18 - Pump impellers: (a) radial; (b) mixed; (c) axial impellers (adapted from Simão, 2009). .... 27

Figure 19 - Pelton turbine.............................................................................................................. 27

Figure 20 - Francis turbine ............................................................................................................ 28

Figure 21 - Hydraulic and time properties .................................................................................... 31

Figure 22 - Junction and pipe configuration .................................................................................. 32

Figure 23 - EPANET irrigation network ......................................................................................... 32

Figure 24 - RHPM principle........................................................................................................... 36

Figure 25 - Pressure acting on a simple vertical plate ........ 36

Figure 26 - Operation of the RHPM ........ 37

Figure 27 - Reaction force ........ 38

Figure 28 - Head difference ........ 39

Figure 29 - Straight blades RHPM results ........ 39

Figure 30 - Depiction of helical blades RHPM ........ 40

Figure 31 – Helical blades RHPM results ........ 40

Figure 32 - Helical blades RHPM with higher diameter ........ 41

Figure 33 - Scheme operation of a turbine and a pump (adapted from Ramos et al., 2000) ........ 42

Figure 34 - Application range of PATs (Budris, 2011) ........ 43

Figure 35 - Development of PAT performance prediction methods (NAUTIYAL, 2010) ........ 44

Figure 36 - Turbine characteristic curves (KSB, 2005) ........ 45

Figure 37 - Characteristic and efficiency curve for Etanorm 32-160.1 of KSB ........ 46

Figure 38 - Characteristic curves for different rotational speeds ........ 46

Figure 39 - Torque curves ........ 47

Figure 40 - Efficiency curves for different rotational speeds ........ 47

Figure 41 - Etanorm hill diagram ........ 48

Figure 42 - Operating point of a pump in turbine zone (adapted from Ramos et al, 2000b) ........ 49

Figure 43 - Nova Aldeia da Luz ........ 54

Figure 44 - Transference of unitary monetary fluxes by means of the discount rate. ........ 58

## LIST OF TABLES


Table 1 - Main characteristic of the AMP ..... 7

Table 2 - Portugal pumped-storage systems (adapted from Ramos, 2014) ..... 8

Table 3 - Main characteristics of Alqueva II hydropower plant (adapted from Ramos, 2014) ..... 9

Table 4 - Average rainfall in the Alqueva region ..... 21

Table 5 - Distribution of the monthly evaporation rate in the AMP ..... 21

Table 6 - Crops needs ..... 22

Table 7 - Main characteristics of the elements of the network ..... 30

Table 8 - Network nodes ..... 33

Table 9 - Network pipes ..... 33

Table 10 - Evolution of small hydropower (adapted from ESHA, 2012) ..... 34

Table 11 - Results of RHPM ..... 40

Table 12 - BEP of Etanorm 160.1-32 ..... 46

Table 13 - PAT working point ..... 49

Table 14 - RHPM working point ..... 51

Table 15 - Energy production RHPM ..... 51

Table 16 - PAT working point and energy production ..... 51

Table 17 - Grams of $CO_2$ equivalent emission per kWh for different energy sources ..... 52

Table 18 - $CO_2$ released ..... 53

Table 19 - Costs of a small hydropower scheme ..... 56

Table 20 - Installed Cost (adapted from Frantzis, 2009) ..... 60

Table 21 - Resume table of the economic analysis of the Scenario A ..... 62

Table 22 - Resume table of the economic analysis of the Scenario B ..... 63

Table 23 - Cutting scheme ..... 70

## NOTATION

| Abbreviation | Meaning |
|---|---|
| **ADENE** | Agência para a Energia |
| **AMP** | Alqueva Multipurpose Project |
| **APA** | Agência Portuguesa do Ambiente |
| **BEP** | Best Efficiency Point |
| **CFD** | Computational Fluid Dynamics |
| **COTR** | Centro Operativo e de Tecnologia de Regadio |
| **EC** | European Commission |
| **EDIA** | Empresa de Desenvolvimento e Infra-Estruturas do Alqueva |
| **EDP** | Energias de Portugal |
| **EPA** | Environmental Protection Agency |
| **FAO** | Food and Agricultural Organization |
| **H-W** | Hazen-Williams |
| **HYLOW** | Hydropower converters for very low head |
| **MDSS** | Market Decision Support Systems |
| **MHERS** | Micro-Hydro Energy Recovery Systems |
| **MHP** | Micro-hydropower |
| **NREAP** | National Renewable Energy Action Plan |
| **PAT** | Pump as Turbine |
| **PNA** | Plano Nacional da Água |
| **PSP** | Pumped-Storage Plants |
| **RHPM** | Rotary Hydraulic Pressure Machine |
| **SHINE** | Smart Hydropower for Improved Network Efficiency |
| **UNEP** | United Nations Environment Programme |
| **UNESCO** | United Nations Educational, Scientific and Cultural Organization |
| **WWF** | World Wildlife Fund |

## LIST OF SYMBOLS

| Symbol | Meaning | Units |
|---|---|---|
| $h_L$ | Head loss | [m] |
| $q$ | Flow rate | [$m^3$/s] |
| $A$ | Resistance coefficient | [-] |
| $B$ | Flow exponent. | [-] |
| $C$ | Hazen-Williams roughness coefficient | [-] |
| $d$ | Pipe diameter | [m] |
| L | Pipe length | [m] |
| $P$ | Pressure | [W] |
| $h$ | Depth of water | [m] |
| $\rho$ | Fluid density | [kg/$m^3$] |
| $g$ | Gravity | [m/$s^2$] |
| D | Diameter | [m] |
| $D_{hub}$ | Diameter of the hub | [m] |
| W | Width | [m] |
| $F_P$ | Force on the blade | [N] |
| $\mathrm{A_b}$ | Area of the blade | [$m^2$] |
| $F_A$ | Counteracting force to acceleration | [N] |
| $P_{out\ ideal}$ | Ideal power output | [W] |
| $F_C$ | Counteracting force | [N] |
| $C_L$ | Loose coefficient | [-] |
| $v_b$ | Velocity of the blade | [m/s] |
| $n_s$ | Specific number of revolutions | [m, kW] |
| $n$ | Nominal rotational speed | [rev/min] |
| $h$ | Head correction factor | [-] |
| $q$ | Flow correction factor | [-] |
| $\mathrm{P_H}$ | Hydraulic power | [W] |
| $\gamma$ | Specific weight fluid | [N/$m^3$] |
| $\mathrm{Q_t}$ | Discharge | [l/s] |
| $\mathrm{H_u}$ | Net head | [m] |
| $\mathrm{P_e}$ | Engine or mechanical power | [W] |
| M | Torque | [W] |
| $\omega$ | Impeller rotational speed | [Hz] |
| $k$ | Free-vortex constant | [-] |
| E | Energy | [W·s] |

| | | |
|---|---|---|
| $P_u$ | Power | [W] |
| $\Delta t$ | Time interval | [s] |
| $P_{annual}$ | Annual installed power | [W] |
| $\eta$ | Efficiency | [%] |
| $Q_{annual}$ | Annual flow | [$m^3$/s] |
| $H$ | Head | [m] |
| $\Delta d_u$ | Head drop | [m] |
| $NPV$ | Net Present Value | [€] |
| $CF_k$ | Cash Flow of year K | [€] |
| $N$ | Number of years of the investment project | [years] |
| $r$ | Discount Rate | [%] |
| $TIC$ | Total Investment Costs | [€] |
| $P$ | Installed power | [kW] |
| $IC$ | Installed Cost | [€/kW] |
| $GB$ | Gross Benefit | [€] |
| $c$ | Unit cost of energy | [€ / kWh] |
| $NB$ | Net Benefit | [€] |
| $GB$ | Gross Benefit | [€] |
| $F$ | Factor update | [-] |
| T | Payback period | [years] |
| IRR | Internal Rate of Return | [%] |

# 1. INTRODUCTION

## 1.1. Context and motivation

Energy production has always been one of the most developed and studied subjects in the history of mankind. The first used energy sources were wind and hydro (Fousa, 2014).

The great economic and social development that the world is facing, makes a lot of regions suffer from energy and water scarcity. It is important that this growth is sustainable, relying on the renewable energies against fossil fuels, since the increasing fossil fuel consumption will significantly increase greenhouse gas emissions, resulting in dangerous levels of global warming (Ramos et al., 2010).

It is important to take climate change policies, as strong negative impacts are predicted in Central America, South America, Arabian Peninsula, Southeast Asia, South Europe and Africa (Samson et al., 2011). Importantly, the regions of greatest vulnerability are generally distant from the high-latitude regions, where the magnitude of climate change will be significant in near future. Furthermore, populations contributing the most to the greenhouse gas emissions on a per capita basis are unlikely to experience the worst impacts of climate change; see Figure 1, making more difficult to take into consideration climate change policies.

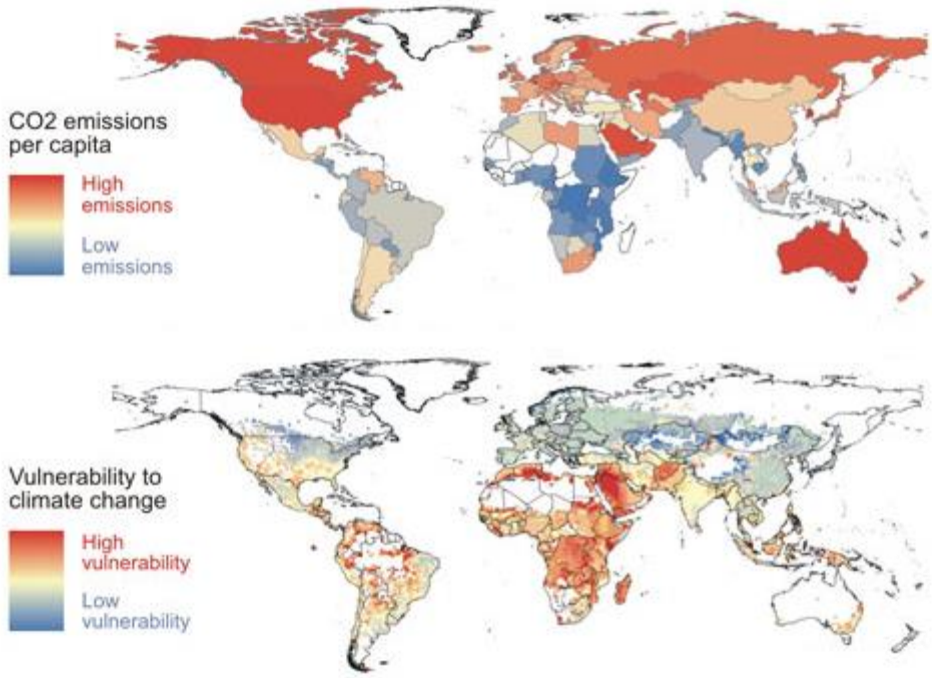



**Figure 1 - National average per capita $CO_2$ emission and vulnerability index (UNEP, 2008)**

The main alternative to reduce the pollution derived from fossil fuels is to replace such fuels by means of renewable energy sources, such as wind, sun, water and geothermal heat. These are unlimited energy sources that produce low environmental impact, which makes them have several advantages over the use of fossil fuels (Ramos et al., 2014).

The European Community has been working intensively to improve energy efficiency in all sectors while at the same time increasing the use of renewable energies. This can be a key issue for solving environmental, self-sufficiency, cost problems, and adequately providing for increasing energy demand without major surprises. In Portugal there are many renewable sources, see Figure 2. This kind of energy is growing in the total electricity generation, and it is expected to represent a bigger percentage in the future.

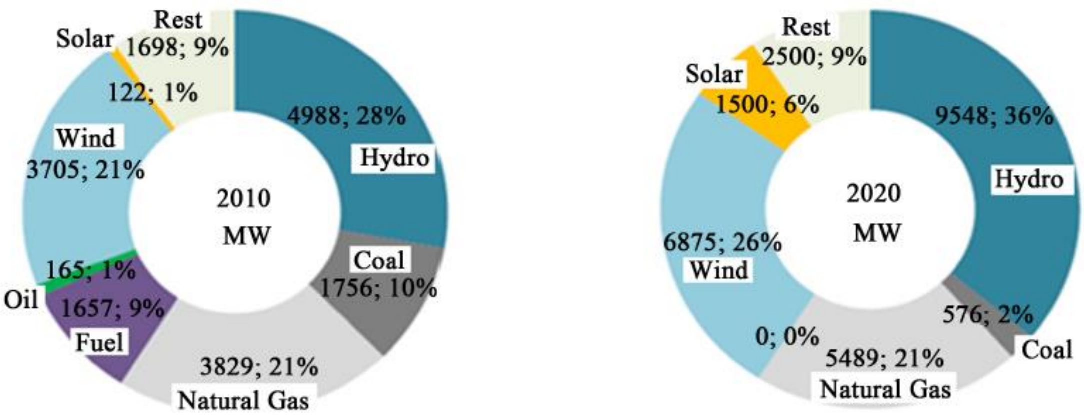



**Figure 2 - Installed power of national electricity generation (2010 vs 2020) (Ramos, 2014)**

During the past two centuries, the great rise of fossil fuels has set unprecedented challenges for agriculture. On one hand, agriculture has become dependent on fossil fuels for fertilizers, pesticides, work activities and transportation. For another, the release of greenhouse gases from the burning of fossil fuels is creating climate changes which are often unfavorable to agriculture. Agriculture needs to find new solutions to use compatible environmental solutions. Moving away from fossil fuels means to integrate the modern forms of renewable energy in the agricultural production.

Electricity production from hydropower has been, and still is today, the first renewable source used to generate electricity (ESHA, 2004). A water turbine is a rotary engine that takes energy from moving water, which were first developed in the 19$^{th}$ century and were widely used for industrial power prior to electrical grids (Fousa et al., 2014). During the $19^{th}$ and $20^{th}$ centuries the technological and industrial revolution, together with some scientific discoveries allowed the development of novel more efficient turbines that use artificially created hydraulic heads by dams. Now they are mostly used for electric power generation from water kinetic and/or potential energy.

The Alentejo region occupies almost a third of the mainland of Portugal. This area has low demographic density, accounting for only 5 percent of the population. The scarcity of water in the region has been one of the main restraints to social development and agricultural modernization, and the sustainability of public water supply services (EDIA, 2015). The Alqueva Multipurpose Project (AMP) is a regional development project aimed at meeting the needs of the Alentejo region in southern Portugal (Radomes, 2013). Efficient use of water through a better water management is important, since without adequate water use, the Alentejo region in Portugal faces desertification. Damming the Guadiana River enabled the AMP to tackle the problem. This project is of utmost importance because provides stable water supply to the region even with fluctuating demands.

## 1.2. Objectives

The main objective of this thesis is to develop and test a multipurpose water distribution system to obtain an integrated management of water and energy production, water-energy nexus taking into account factors associated to technological developments, the economy, the social-demography, the climate, and government policies. This methodology will provide useful information to promote a more efficient use of water resources as well as to ensure the sustainability of water irrigation systems at same time the energy is recovered.

This research presents a better perception of how to generate green electricity by an optimal use of the water resource in an existing irrigation infrastructure using the micro-hydropower (MHP). With the objective of promoting MHP in the unused market segments to increase the renewable electricity generation, identify and develop further solutions for this purpose, which have to be cost-effective, reliable, and can be easily integrated to the existing water systems.

It is important to analyze which are the potentials in the water distribution system to obtain energy and how can this energy be recovered by a MHP solution.

To achieve the proposed goal, the research has the following specific objectives:

1. Selection of energy recovery solutions economically viable at small capacity sites (2-20 kW), being resilient to the long-term viability challenges presented by climate change, socio-demographic adaptation and policy factors.
2. Development and implementation a methodology for water-energy-environmental efficiency for drink systems, industrial and agricultural system.
3. Analyses of market decision support system (MDSS) to facilitate the optimal design, implementation and operation of micro-hydro energy recovery systems (MHERS) in the Alqueva Multipurpose Project (AMP). The MDSS will enable:
    i) Best practice feasibility and business case assessments
    ii) Optimization of the implementation of MHERS

iii) Optimization of the carbon footprint and environmental performance of MHERS using life cycle assessment and eco-design.

### 1.3. Thesis structure

This study develops a multi-criteria optimization process to ensure the cost-effectiveness of the system, taking into account technical, social and environmental criteria. To achieve its goals, a brief description of the system studied is firstly provided. Then the method used to conduct the optimization is explained, followed by the results obtained and their analysis. The conclusion finally allows selecting the best configurations of parameters to achieve the cost-effectiveness of the system.

The work structure presented in Figure 3 was followed in order to achieve the proposed goal.

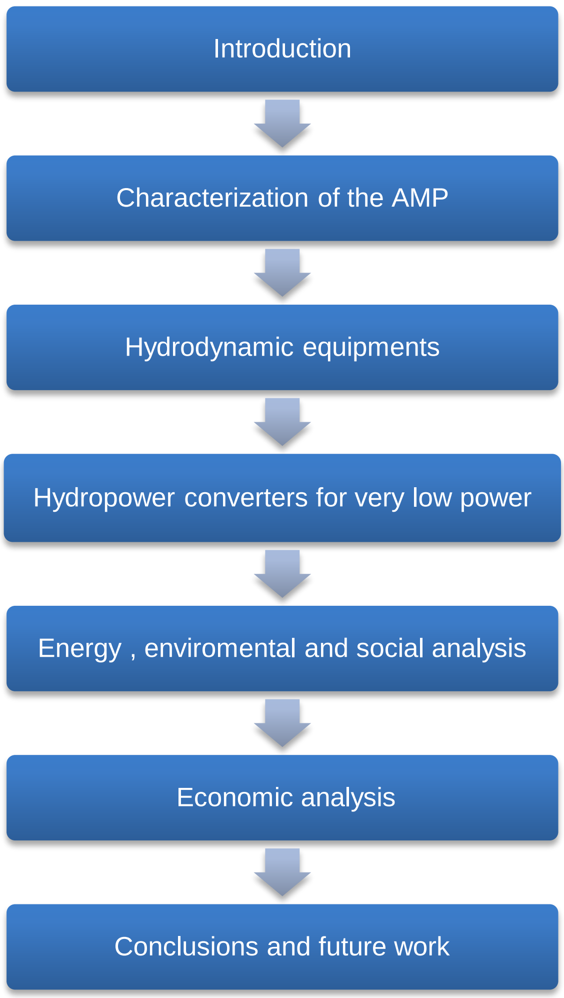



**Figure 3 - Mainwork structure**

This study comprises seven chapters briefly described as follows:

- **Chapter 1**: The current chapter introduces the topic of the thesis, the case problem to be studied, describing the goals and the structure of the proposed work.
- **Chapter 2**: Describes the system of Alqueva Multipurpose Project (AMP) and defines the two scenarios of study.
- **Chapter 3**: Defines the different types of hydropower plants and hydraulic machines and the main hydraulic parameters to be implemented in EPANET model.
- **Chapter 4**: Analysis of micro-hydropower solutions, such as Rotary Hydraulic Pressure Machine (RHPM) and pump operating as turbines (PAT) are developed.
- **Chapter 5**: Focuses in the energy production for irrigation networks. It also includes an environmental and social impact analysis.
- **Chapter 6**: Describe the procedure used in the economic analysis, all the results and data obtained for each scenario.
- **Chapter 7**: Summarizes the final conclusions of the developed study and includes suggestions for future studies.

# 2. CHARACTERIZATION OF THE ALQUEVA MULTIPURPOSE PROJECT

## 2.1. General description

Choulot (2010) defined the multipurpose systems as those in which electricity generation is not their primary priority, but the second. This implies the integration of the power plant in the existing infrastructure while guaranteeing its primary function. For example, for a drinking water network, the primary priority is to supply in quantity and quality the needed water; whilst for a desalination plant, it is to generate drinking water from seawater.

*"Alqueva is today the brand image of a dynamic and modern Portugal,*
*focused on sustainable development."*
(*Minister for Agriculture, Sea, Environment and Spatial Planning – News conference, 2015* )

The Alqueva Multipurpose Project (AMP), located in the lower Alentejo, is an infrastructure system fueled by the resources of the basin of the Guadiana river to capture, storage and distribution of water for irrigation and public supply, as well as for the production of electricity. The AMP is operated by EDIA (Enterprise Development and Infrastructures of Alqueva), which is responsible for construction, maintenance and operation of infrastructure and the collection and distribution of water from these. The hydroelectric exploitation is held by Energias de Portugal (EDP), through an agreement. The company began operations in 2002 with the completion of construction of the Alqueva dam which created the largest reservoir of Portugal.

The AMP is primarily an agricultural project, that its Global Irrigation System is centered on the Alqueva dam, the largest strategic water reserve in Europe, with a catchment area of approximately 10,000 km$^2$, divided between the districts of Beja, Évora, Portalegre and Setúbal, and covering a total of 20 municipalities. Apart from the main dam it also has 47 pumping stations, 6 mini hydroelectric stations and one photovoltaic power station (EDIA, 2015). In Table 1 it is shown the characteristics of the AMP.

**Table 1 - Main characteristic of the AMP**

| ALQUEVA MULTIPURPOSE PROJECT (AMP) | |
|---|---|
| Area irrigated | 68000 ha |
| Dams, reservoirs and weirs | 69 |
| Pumping stations | 47 |
| Mini hydroelectric stations | 6 |
| Primary network | 382 km |
| Secondary network | 1620 km |

The hydropower station of Alqueva I is located at the Guadiana river, in the Alqueva dam, and started operating in 2004, with the objectives of electricity supply, public water supply, irrigation of agricultural land and implementation of leisure and tourism infrastructures (Ramos, 2014). Two Francis turbines compose it, each one with a capacity of 128 MW (EDP, 2012).

The Alqueva project has developed and added other renewable energies, namely wind energy. Due to the intermittency that this kind of energies present, it was decided to upgrade the project, see Figure 4, to have a pumped-storage system (Ramos et al., 2014).

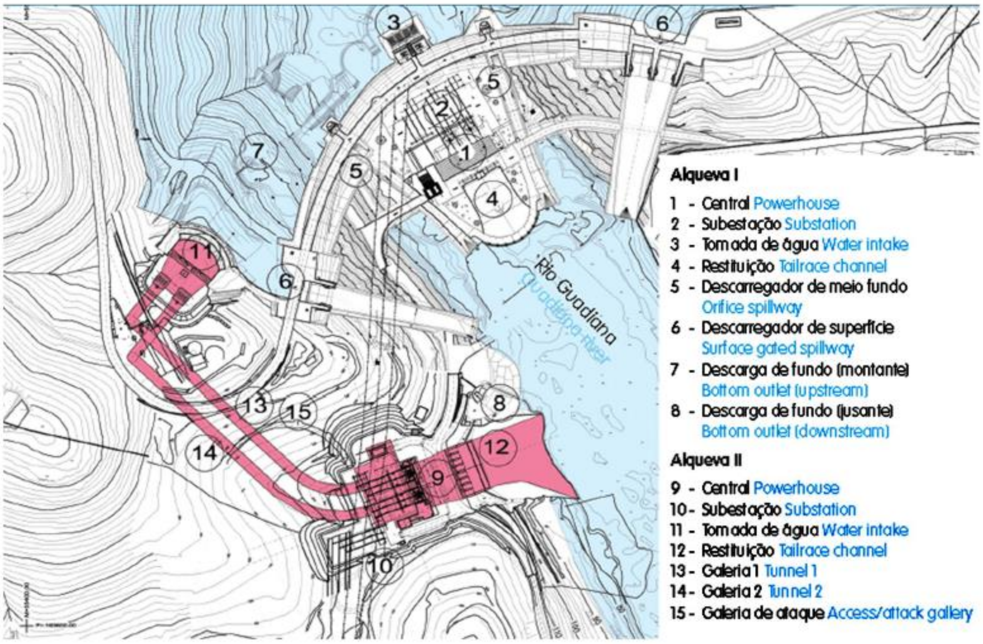



**Figure 4 - Plan of Alqueva I and II (EDP, 2012)**

Pumped-storage hydropower plants seem a solution to cover these fluctuations. In Table 2 it is shown the influence of these kinds of installations in Portugal.

**Table 2 - Portugal pumped-storage systems (adapted from Ramos, 2014)**

| Portugal | | | |
|---|---|---|---|
| Inhabitants | 10,707,000 | Area [$km^2$] | 92,345 |
| Number of pumped-storage plants (PSP) | 4 | Capacity [MW] | 1089 |
| Number of storage power plants | 36 | Capacity [MW] | 4526 |
| Share of PSP of renewable energies [%] | 14.2 | Share of PSP of total electricity gen. [%] | 4.6 |

The construction of the Alqueva II has add two reversible Francis turbines (see Table 3), with the same capacity of the turbines of Alqueva I, that will pump water in hours of low demand, when the energy is at low cost, and will work as turbine when the energy is needed, at the highest price. Normally the periods of highest consumption of energy and water occurs approximately at the same time (Ramos et al., 2010). The idea of pumped-storage plants is that the volume of pumped and turbine water is the same.

**Table 3 - Main characteristics of Alqueva II hydropower plant (adapted from Ramos, 2014)**

| Main indicators | |
|---|---|
| Construction works (started) | 2008 |
| Commissioning year (estimated) | 2012 |
| Number of units | 2 (reversible) |
| Power | 256 MW |
| Annual average capacity | 381 GWh |
| Reduction in CO2 equivalent per year | 235 kt |
| Estimated investment (ref. 2009) | 171 M€ |
| National contribution | 80% to 85% |

## 2.2. Approaches to evaluate the water use efficiency and energy production in AMP

### 2.2.1. Water use efficiency

The current growth in urbanized area raises serious issues regarding water management (Huchet et al., 2014). Water stress and scarcity is becoming a big problem in many countries of the world and it is expected to get worse in the future (see Figure 5), due to the unprecedented economic and social development (Ramos, 2010). This is creating awareness and concern around the world, initiatives and studies are being carried out for a more efficient and reasonable use of the water.

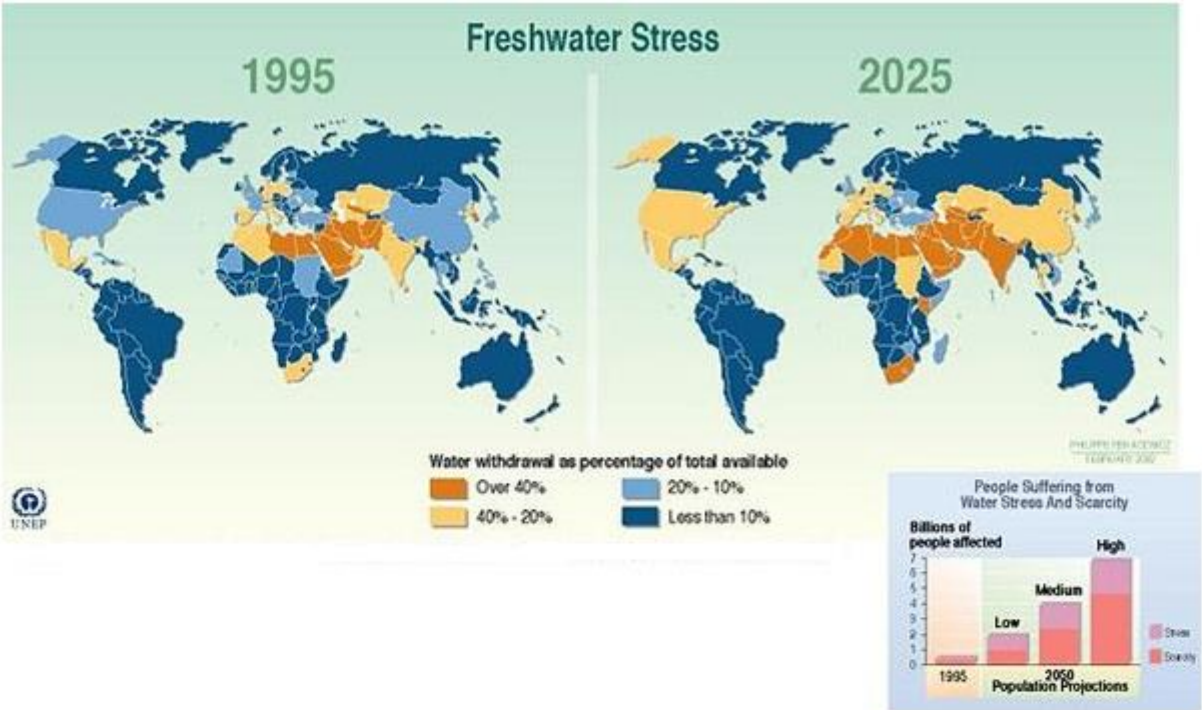



**Figure 5 - Freshwater Stress (1995 vs 2025) (UNEP, 2008)**

Hoekstra (2003) introduced the concept of water footprint as a measure of humanity's appropriation of fresh water in volumes of water consumed and/or polluted to produce each of the goods and services we use. It provides a framework to analyze the link between human consumption and the appropriation of the globe's freshwater. We can divide this concept of water footprints into three different (Mekonnen et al., 2010):

Green water footprint is water from precipitation that is stored in the root zone of soil and evaporated, transpired or incorporated by plants. It is particularly relevant for agricultural, horticultural and forestry products.

Blue water footprint is water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time. Irrigated agriculture, industry and domestic water use can each have a blue water footprint.

Grey water footprint is the amount of fresh water required to assimilate pollutants to meet specific water quality standards. The grey water footprint considers point-source pollution discharged to a freshwater resource directly through a pipe or indirectly through runoff or leaching from the soil, impervious surfaces, or other diffuse sources.

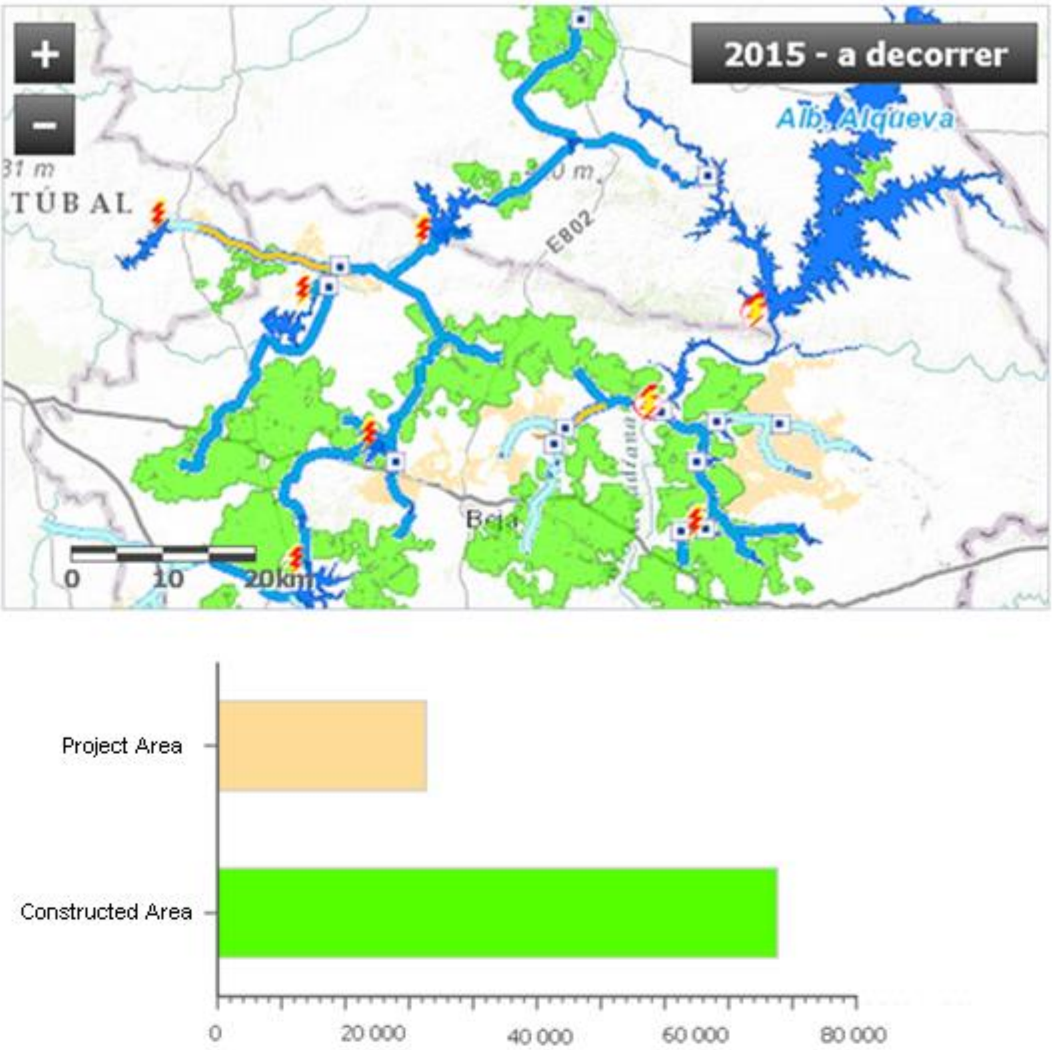



**Figure 6 - Distribution map of the area currently farmed (EDIA, 2015)**

The Alqueva Multi Purpose Development is primarily an agricultural project, that its Global Irrigation System is centered on the Alqueva dam, the largest strategic water reserve in Europe, with a catchment area of approximately 10.000 km$^2$ (EDP, 2012). About 68.000 ha of irrigated land are being farmed in the current irrigation year: see Figure 6, out of a total of 120.000 ha of the Alqueva Multipurpose Development (EDIA, 2015).

Water is indispensable for farming. Farming in turn uses the vast majority of all water withdrawn for human use, approximately 81% of freshwater consumption, and food production needs to increase in the coming decades to support a growing world population (UNESCO et al., 2010). This is creating many political conflicts over water by the increasing scarcity of freshwater resources. It seems clear that if human needs are to be met, while at the same time conserving biodiversity and maintaining vital ecosystem services, a new approach is required that makes the best use of the limited water that is available (WWF et al., 2003).

In the Figure 7 it is illustrated the percentage of water consumed by each sector in Portugal, 2010. The difference between agriculture and the rest it is clear. Due to that major consume it is important to optimize and reduce the inefficiency in water consumption for irrigation (Hoekstra et al., 2011) .

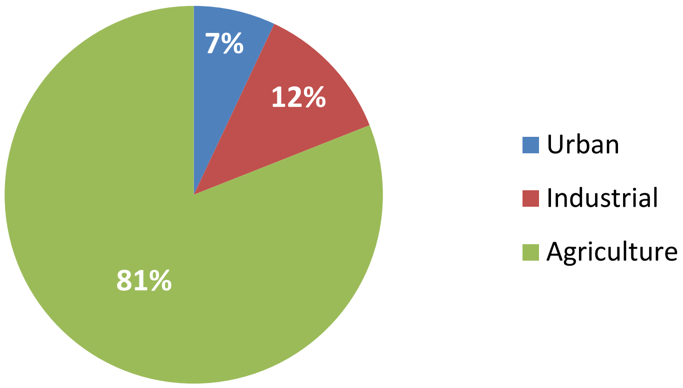



**Figure 7 - Water demand by sector (Portugal 2010) (adapted from APA, 2011)**

So this is why it is important to know the crop water need, or in other words the amount of water needed by a certain crop to grow optimally. This consumption mainly depends on the climate, the crop type, the growth stage of it and the evaporation (FAO et al., 1986):

- **The climate**: Influences directly in the water spent for irrigation. For example in a sunny and hot climate crops need more water per day than in a clouded and cool climate. In the case of Alqueva, it can be seen in Figure 8 that the precipitation amongst the year it is not constant. This would determinate the quantity of extra water needed to harvest.

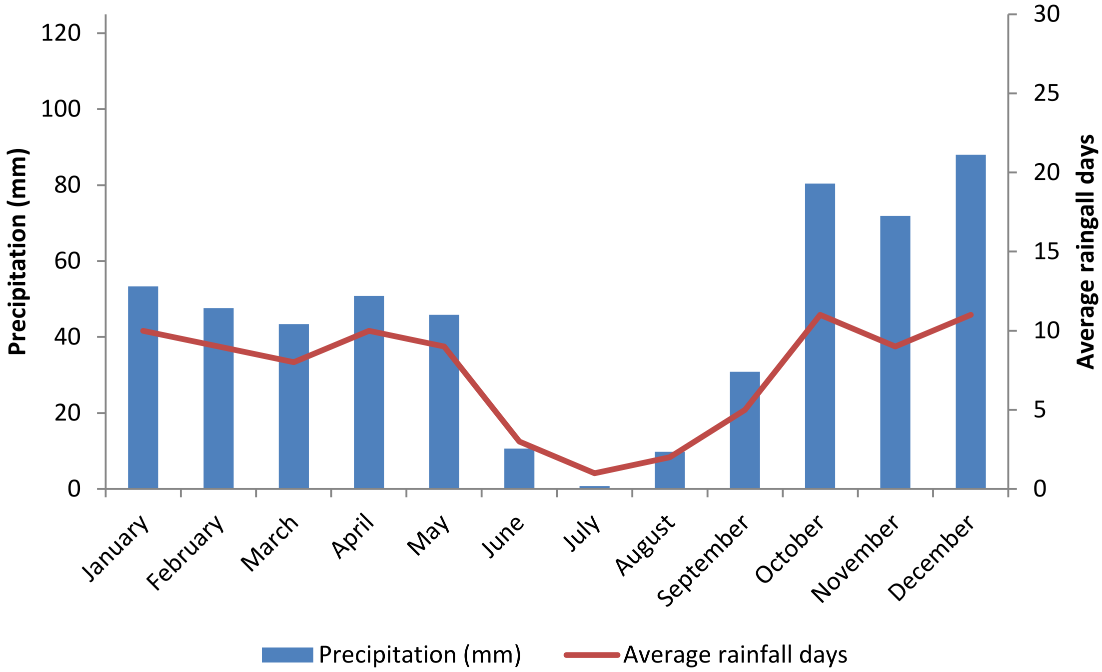



**Figure 8 - Average Rainfall in Alqueva**

- **The crop type**: Is really important in terms of water consumption. Each crop has a special needs and that means that the quantity of water will change depends on the crop. That's why it will be crucial to determine and know which crops are in the area (see Figure 9).

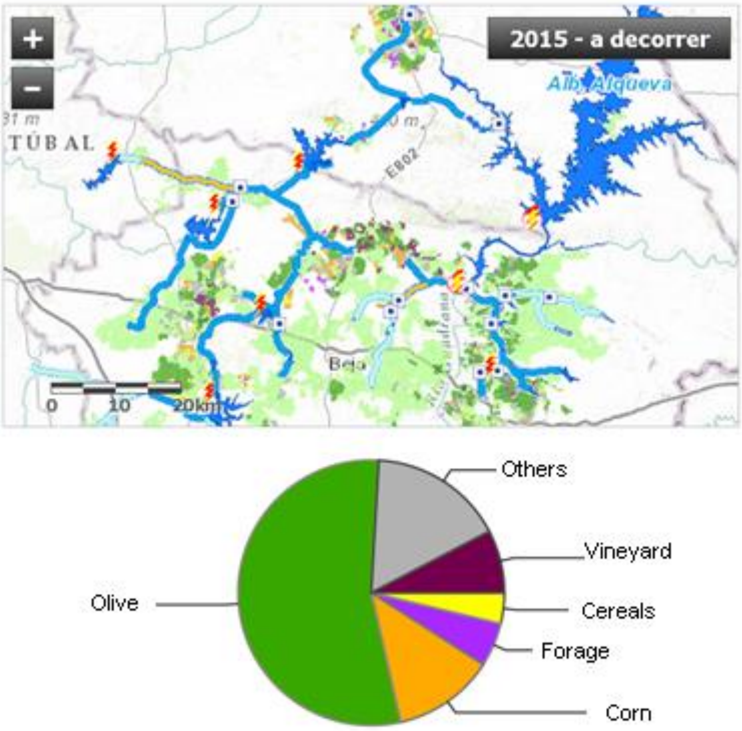



**Figure 9 - Distribution of crops in the Alqueva irrigation zones (EDIA, 2015)**

- **The growth stage of the crop**: Determines the water supplied for irrigation. All crops have different growing periods, during these processes; the demand of water varies (FAO et al., 1986). For example a fully-grown crops need more water than crops that have just been planted. So knowing the different stages of the crops and when to harvest them will enable a more respectful and efficient use of the water.
- **The evaporation**: It is important to take into account the evaporation because a percentage of the water that is putted on the soil escapes as vapor to the atmosphere and cannot be used to water the crops.

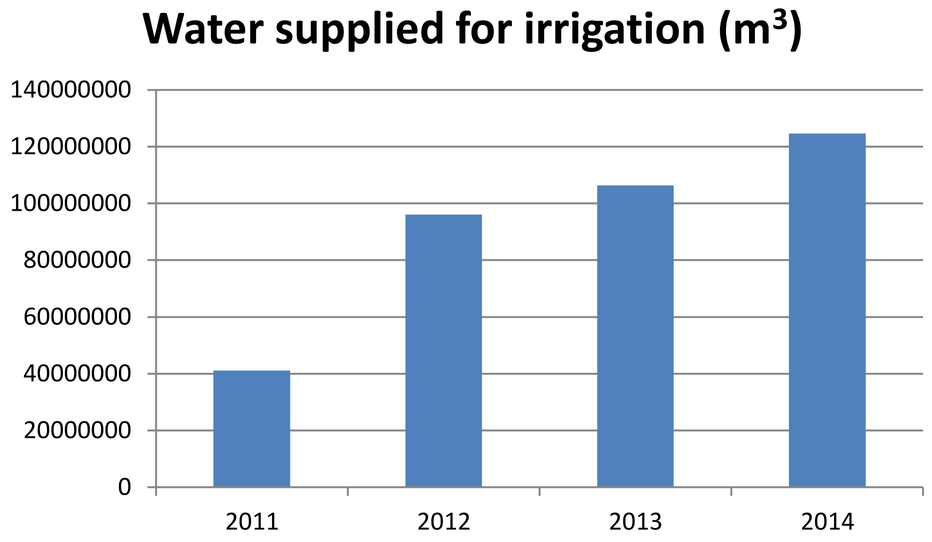



**Figure 10 - Water supplied for irrigation (EDIA, 2015)**

The increase in the irrigated area of the Alqueva region has made it possible to progressively change the farming model of Alentejo, traditionally based on dry farming but now, with the guarantee of water from Alqueva, new opportunities are generated in irrigated crops and this opens the doors to agro-industry (EDIA et al., 2015), this directly means an increase in the water supplied for irrigation in the area of the Alqueva Multipurpose Project (see Figure 10). So it becomes more important to guarantee and eco-friendly use of the water and try to optimize this use being more efficiency.

### 2.2.2. Energy production efficiency

Regarding energy, the unprecedented economic and social development is also creating energy scarcity (Ramos et al., 2010). This growth has to be sustainable, so it is important to bet for the renewable energies, because increasing fossil fuel consumption will significantly increase greenhouse gas emissions, which result in creating dangerous levels of global warming.

In the last years the production of energy from renewable sources and the implementation of energy efficiency measures in Portugal has grown. In the Figure 11 it is illustrated the evolution of electricity production by renewable energies.

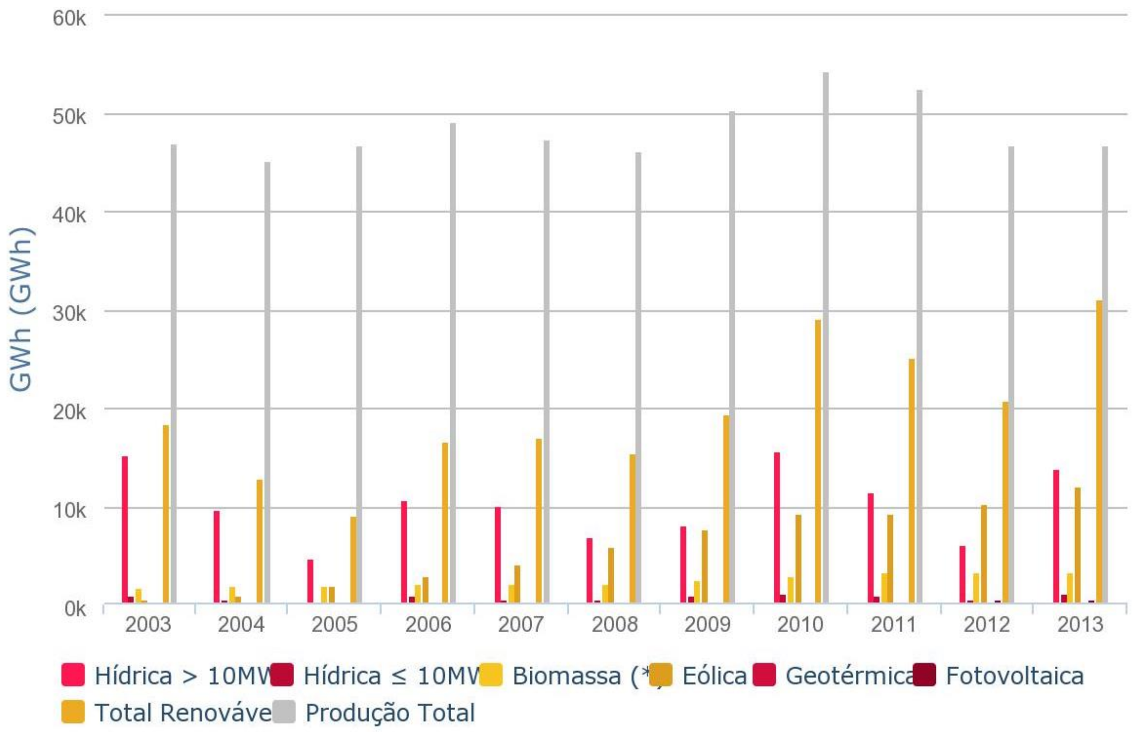



**Figure 11 - Electricity production from renewable sources (ADENE, 2015)**

Despite the effort of including new energy, Figure 12, such as wind and solar, energy dependency of Portugal is still very high, about 66.28% in 2013 (ADENE, 2015). In order to reduce this energy dependency have emerged strategic programs in the various sectors in terms of sustainability.

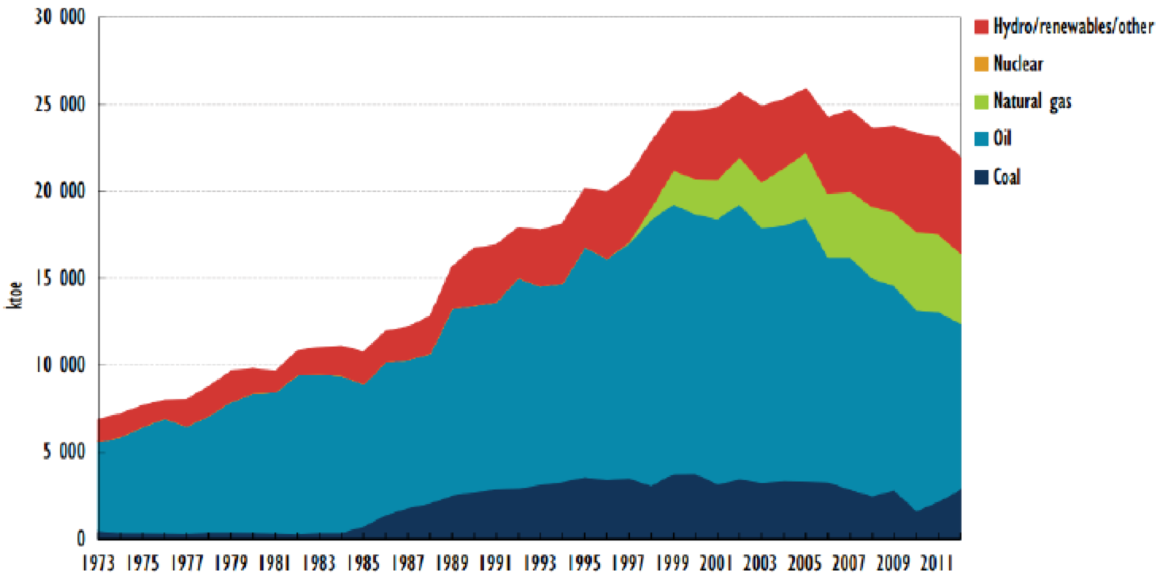



**Figure 12 - Main primary energy sources in Portugal (IEA, 2014)**

Electricity production from hydropower has been, and still is today, the first renewable source used to generate electricity (ESHA, 2004). Significant potential exists within various differing elements of water network infrastructure to recover energy, reduce costs, reduce climate change impacts and improve environmental performance (EC, 2015). So it is important to search for new solutions regarding the energy production of available low power in water systems (Simão et al., 2009).

Major concerns in the management of water supply networks are water and energy savings (Carravetta, 2012). The hydropower equipment known as micro-hydro represents an advantageous economic alternative in terms of hydroelectric exploitation in water systems, when compared with dissipative structures. A new branch of research is turning to the integrated management of water and energy networks (Huchet et al., 2014). The idea is to obtain the potential energy of a mass of water into electrical energy (ESHA et al., 2004).

The AMP represents a big opportunity to implement this kind of technology, occupying an area of 68.000 ha for irrigation, it has a huge potential to introduce the micro-hydro in the water irrigation network to produce electricity from renewable sources. Some studies have been carried out, namely EC (2015), that their aim is to demonstrate the long term viability of improved micro-hydropower (MHP) technology for the recovery of energy and reduction of $CO_2$ emissions in water networks.

## 2.3. Environmental considerations

Air gas emissions in energy generating process with fossil fuels and the future problem that nuclear wastes are going to create, increases a world concern about the sustainability, which is emphasizing the advantages of energy production trough renewable sources (Ramos et al., 2000).

Hydropower plants represent an important environmental benefit because there is no release of carbon dioxide and other global warming emissions, which cause ozone depletion that induces to trapping heat, steadily drive up the planet’s temperature, and create significant and harmful impacts on our health, our environment, and our climate (Shuman et al., 2006). Although hydropower has no air quality impacts, construction and operation of hydropower dams can significantly affect natural river systems as well as fish and wildlife populations.

Moreover, solid or water wastes are not produced. This contributes in having a sustainable development. Other benefits may include water supply during dry summer months and flood control, which are growing in importance with regards to climate change effects (ESHA et al., 2012). However, there are also a lot of impacts related with hydropower plants, created by retaining water, inducing sediment to settle down, obstructing the fish passage and upsetting the wildlife habitats.

The land occupied by a hydropower plant can vary widely; it depends basically on the size of the hydroelectric generators and the topography of the region, so in flat areas much more land normally is required than those in hilly areas or canyons where deeper reservoirs can hold more volume of water in a smaller space. Flooding land for a hydroelectric reservoir has an extreme environmental impact; it destroys forest, wildlife habitat, agricultural land, and scenic lands (Shuman et al., 2006).

Regarding small hydropower, they do not require high dams because the majority of them are run-of-river schemes, meaning simply that the turbine only generates when there is available water

(Ramos et al., 2000). A minimum daily storage and flow regulation is typically guaranteed in order to have more control in the energy production. Nevertheless, when the river dries up the generation ceases. The small hydropower plants can still occupy a relevant contribution around the world, existing a huge potential in existing structures or natural rivers for energy production (EC et al., 2015). According to the National Renewable Energy Action Plan (NREAP), small hydropower should contribute 1,511 GWh in 2020, corresponding to a total installed capacity of 750 MW (Liu et al., 2013).

In order to avoid serious damages to aquatic biota between the intake and the tailrace, the abstraction of water from a watercourse must be controlled. In fact, between the diversion dam and the power plant a variable residual flow should remain along the year (Ramos et al., 2000). This residual flow, also known by reserved flow, compensation or ecological flow, must be environmentally acceptable. In particular, in seasons of low flow the residual flow is very important in order to keep a steady regime to warrant the aquatic natural development and the water quality. Hence, it is important to ensure that the maximum energy is produced with maintenance of the equilibrium of the aquatic system (Ramos et al., 2000).

## 2.4. Irrigation network scenarios

### 2.4.1. Scenario A - Open irrigation channels

For the Scenario A, it will be considered that open irrigation channels only compose our irrigation network. An open channel is an open waterway whose purpose is to carry water from one place to another (Figure 13), they use gravity forces to convey water from water sources to agricultural areas.

Open channels were the first means of transport of big amount of water for irrigation. Although, it exists other ways to transport the water, the open channels are still widely use because they require a low capital investment and are easily to modify and expand. However, open channels have the problem of leakage and evaporation losses and the risk of pollution carrying water of poor quality. Also they represent a loss of land.

The open channels are characterized by three factors:

1. **The freeboard**: Is the height of the bank above the highest water level anticipated. It is required to guard against overtopping by waves or unexpected rises in the water level.

2. **The side slope**: Is expressed as ratio, namely the vertical distance or height (h) to the horizontal distance or width (w), h:w.

3. **The bottom slope**: Is the division between the height difference and the horizontal distance. It is commonly expressed in percent (see Equation 1). The bottom slope will have a huge impact in water speed, so in the flow.

$$Bottom\ slope\ (\%) = \frac{height\ difference\ (m)}{horizontal\ distance\ (m)} \cdot 100 \quad \textbf{(1)}$$

**Figure 13 - Open irrigation channel in Alqueva**

According to the shape of their cross-section, open channels are called rectangular (a), triangular (b), trapezoidal (c), circular (d), parabolic (e), and irregular or natural (f) (see Figure 14). The most commonly used open channel cross-section in irrigation and drainage, is the trapezoidal cross-section.

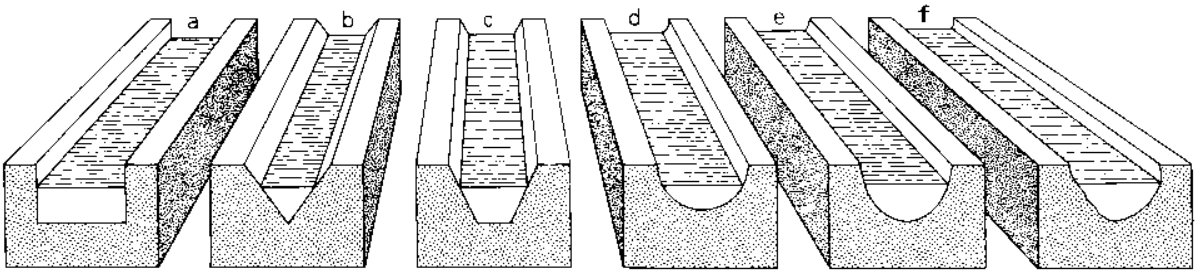



**Figure 14 - Different open channels cross-sections**

### 2.4.2. Scenario B - Pressurized irrigation system

For the Scenario B, the irrigation network of the study will be composed with pressurized flow. The pressurized irrigation systems are those in where water for agriculture travels throughout a system of connected pipes (Figure 15). The advantages of pressurized system over open channels are that they represent a less land use with energy savings, more flexibility in the control of the water discharge and no evaporation problems. Pressurized systems guarantee a better quality of the water and minimum loss if they are well designed.

**Figure 15 - Pressurized irrigation system in Alqueva**

In this kind of systems is really important to analyze and study the head and pressure. This two factors are crucial in terms of guarantee a discharge in certain points of the system. It is important that values out of the range of interest do not appear, because it could mean obtaining not desirable results.

In Figure 16 the various topologies of pressurized irrigation systems are presented. The branched network consists of continuous sections where there is only one possible route for the flow. This network has the advantage of being easy to scale and requires fewer accessories. In case of failure, the supply is interrupted downstream. The meshed network consists, as the name indicates, by knitting, which provides redundancy between the sections. Although more expensive and more demanding hydraulic calculations, the meshed network permits in case of damage or breakage, the section in question can be repaired without removing the supply to neighborhood.

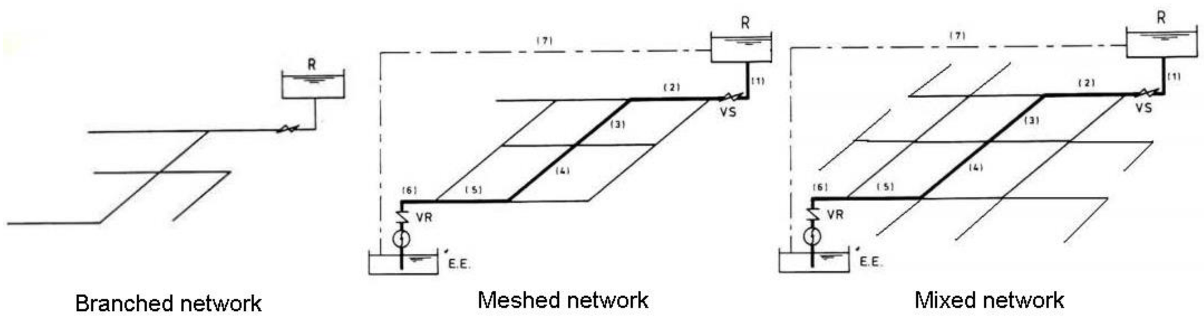



**Figure 16 - Topologies of pressurized networks**

## 2.5. Irrigation water consumption

The Alqueva region represents a vast irrigation land. This directly means a high water consumption due to agriculture. So it is essential to analyze the water needs to have an efficiency and optimal use, avoiding leakages and useless consumptions of water.

The water consumption in the AMP was determined based on previous studies by EDIA (2014), and the data of the *'Ministerio da Agricultura e do Mar'*. As water for the crops can be obtained from rainfall or irrigation, it is really important to know how much water we can save thanks to the rain. In the Table 4 it is shown the average rainfall in the Alqueva region.

**Table 4 - Average rainfall in the Alqueva region**

| Month | Precipitation [mm] | Rainfall days |
|---|---|---|
| January | 53.3 | 10 |
| February | 47.6 | 9 |
| March | 43.4 | 8 |
| April | 50.8 | 10 |
| May | 45.8 | 9 |
| June | 10.6 | 3 |
| July | 0.8 | 1 |
| August | 9.8 | 2 |
| September | 30.8 | 5 |
| October | 80.4 | 11 |
| November | 71.9 | 9 |
| December | 88 | 11 |

Evaporation plays also a really important role in irrigation, especially in summer months when it has a huge impact in the water consumption. In Table 5 is illustrated the monthly evaporation rate in the Alqueva region (Ferreira, 2014).

**Table 5 - Distribution of the monthly evaporation rate in the AMP**

| Monthly evaporation rate (mm) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Jan.** | **Fev.** | **Mar.** | **Abr.** | **Mai.** | **Jun.** | **Jul.** | **Ago.** | **Set.** | **Out.** | **Nov.** | **Dez.** |
| 33 | 44 | 87 | 116 | 168 | 204 | 167 | 244 | 164 | 97 | 50 | 26 |

The precipitation and evaporation are given in mm, it is necessary to pass from mm to a discharge value [l/s], to know how much water is necessary to supply from irrigation to the crops:

$$1\ mm = 1\ \frac{l}{m^2} \cdot \frac{10000\ m^2}{1\ ha} \cdot 68000\ ha \cdot \frac{1\ month}{30\ days} \cdot \frac{1\ day}{24\ hours} \cdot \frac{1 hour}{3600\ s} \tag{2}$$

Finally we only need to calculate the irrigation discharge as the discharge needed less the rain discharge, plus the looses of evaporation (Ferreira et al., 2014):

$$Irrigation = Crops\ needs - Rainfall + Evaporation \tag{3}$$

To calculate the discharge needed for each crop and the total one, it is first necessary to know the area that each crop occupies with the percentage it represents in the Alqueva region. Once the area it is known, it is only needed the amount of water that each crop demands to be harvested.

EDIA (2014) and COTR (2014) have made some studies regarding the water consumption for irrigation taking into account the rainfall and evaporation values. In Table 6 the results of these studies is shown, and also the average irrigation discharge that the crops need in one year.

**Table 6 - Crops needs**

| Crop | % | Area [ha] | $m^3$/(ha·year) | $m^3$/year x $10^6$ | Irrigation discharge [l/s] |
|---|---|---|---|---|---|
| Olive | 54.45% | 37026.00 | 2000 | 74.05 | 2348.17 |
| Corn | 12.36% | 8404.80 | 6000 | 50.43 | 1599.09 |
| Vineyard | 7.67% | 5215.60 | 1500 | 7.82 | 248.08 |
| Forage | 5.32% | 3617.60 | 5500 | 19.90 | 630.92 |
| Cereals | 3.78% | 2570.40 | 2000 | 5.14 | 163.01 |
| Others | 16.42% | 11165.60 | 2000 | 22.33 | 708.12 |
| **TOTAL** | **100.00%** | **68000** | **-** | **179.67** | **5697.32** |

Once it is calculated the irrigation discharge, then it can be calculated how much energy it is possible to extract from this flow. This flow will determine how much energy can be recovered with the two different scenarios.

# 3. HYDROMECHANICAL EQUIPMENTS

## 3.1. Hydropower plants

Hydropower is defined as the electricity produced from hydraulic machines that are acting by water. This kind of technology is versatile and flexible. It can be found in really different scales, from power a single home to its largest supplying the industry and the public with renewable electricity, on a national and even regional scale.

### 3.1.1. Classification of hydropower plants

Hydropower plants can be classified based on different factors (Ramos et al., 2000)(ESHA el al., 2004):

1. **Head**: Depends on the head hydropower plants can be classified as low (less than 50 m), medium (between 50 and 250 m) and high (greater than 250 m)
2. **Exploitation and storage**: Hydropower plants can have flow regulation, daily or seasonal, this would be the reservoir type, or they can also be without flow regulation, is the case of the run-of-the-river type.
3. **Conveyance system**: Pressurized (penstock); mixed circuit (canal and penstock).
4. **Type of turbines**: The turbine can be impulse, reaction or reversible.
5. **Powerhouse site**: Dam or diversion scheme
6. **Energy conversion mode**: The hydropower plant can obtain the energy just from turbining or from reversible pumping-turbining
7. **Installed power**: Depending on the installed power the hydropower plants are classified as micro ($Pt < 100$ kW), mini ($100 \text{ kW} < Pt < 500$ kW) and small ($500 \text{ kW} < Pt < 10$ MW).

The classification based on the power is very important because is an institutional and legislate reference (Ramos, 2000).

### 3.1.2. Types of hydropower plants

It is possible to classify the hydropower plants in four typologies depending on their characteristics:

- **Storage hydropower**: This kind of hydropower plants store water in a reservoir, normally it is a large system that uses a dam. When the water is released from the reservoir it goes through a turbine that produces electricity activating a generator. Storage hydropower are really useful in terms of producing electricity when the demand is higher, because the electricity production can be controlled by the water released. It can also offer enough storage capacity to operate independently of the hydrological inflow for many weeks or even months.

- **Pumped-storage hydropower**: Provides peak-load supply, harnessing water which is cycled between a lower and upper reservoir by pumps which use surplus energy from the system at times of low demand. These hydropower plants pump water in hours of low demand, when the energy is at low cost, and work as turbines producing energy when the energy is needed, at the highest price.
- **Run-of-river hydropower**: Run-of-river provides a continuous supply of electricity by directing the water from a river through a turbine. This type of scheme does not have an inflow regulation, it normally has some flexibility of operation for daily fluctuations in demand through water flow that is regulated by the facility. Typically a run-of-river project will have little or no storage facility.
- **Offshore hydropower**: Offshore hydropower is the less established but growing nowadays. They use tidal currents or the power of waves to generate electricity from seawater

In reality these technologies can often overlap (ESHA et al., 2004). For example, storage projects can often involve an element of pumping to supplement the water that flows into the reservoir naturally, and run-of-river projects may provide some storage capability.

## 3.2. Hydraulic machines

### 3.2.1. Main characteristics

Hydraulic machines are implemented in the hydraulic circuits in order to promote the exchange of mechanical energy between the fluid and the rotor, they make possible changes between mechanical and hydraulic energy through two processes of transformation, depending on the transmission direction, namely in pumps or turbines (Simão et al., 2009). These machines can be of many different types as they have complex characteristics. That allow their differentiation and classification, it can be classified as hydraulic turbo and volumetric engines from the mechanical point of view (Macintyre et al., 1983).

### 3.2.2. Volumetric machines

Volumetric machines or positive displacement machines, the exchange of energy is made with the variations of volume of the fluid when this is confined in a camera (Calado et al., 2014). Regarding the volumetric pumps or positive displacement pumps, the movement of the fluid is caused mainly by the action of the pump impulsion, which forces the fluid to make the same movement over and over again in alternating movements (Simão et al., 2009). In Figure 17 it is illustrated the operation of a gear pump.

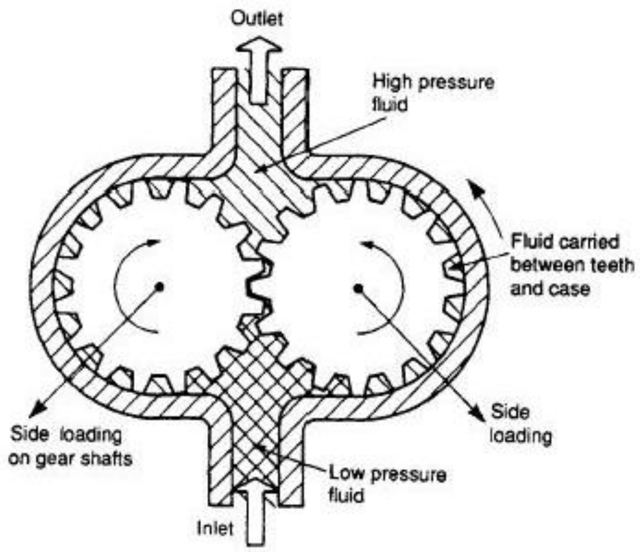



**Figure 17 - Gear pump operation**

The name volumetric it is given to this kind of pumps due to the volume occupied and evacuated by the fluid in the interior of the pump during the operation it is known. These pumps can also be sub-classified as rotating pumps (gears, lobes, vanes, helicoidal, bobbins, screws, peristaltic) and as pistons or alternative pumps (pistons, diaphragm, membrane) (Simão, 2009).

### 3.2.3. Turbo machines

In turbo machines the flow movement is made by the rotation of the runner, which causes forces developed by the fluid in the impeller blades (Simão et al., 2009).

Hydraulic turbo machines can be divided into (Quintela et al., 2005):

1. **Motor turbo machines**: This kind of turbo machines is characterized for receiving mechanical energy of the liquid, making it available on the shaft (turbines).
2. **Receptor turbo machines**: Transmit mechanical energy to the fluid received from the outside (pumps).

The turbo machines can also be classified by the liquid movement in relation to the wheel: Radial, axial or mixed (Quintela, 2005).

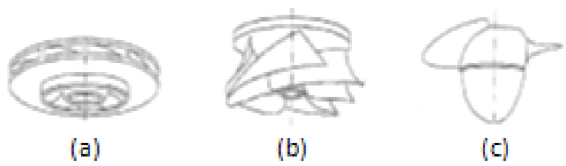



**Figure 18 - Pump impellers: (a) radial; (b) mixed; (c) axial impellers (adapted from Simão, 2009).**

The turbines, motor turbo machines, are characterized by two different groups:

1. **Action turbines**: The action or impulse turbines are characterized by fluid passing through the wheel is at atmospheric pressure (Macintyre et al., 1983). The best known turbines in this category are the Pelton (Figure 19). However, Turgo turbine and Cross-Flow turbine also are action turbines. The Turgo turbine supports greater variations in flow rates but their efficiency is lower.

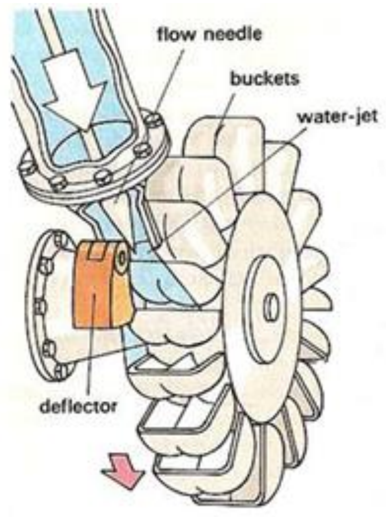



**Figure 19 - Pelton turbine**

2. **Reaction turbines**: When the propeller is inserted in the hydraulic circuit maintaining the flow pressure, the turbines are of reaction type (Quintela et al., 2005). In this group there are the radial-axial turbines, such as the Francis turbine (Figure 20), and axial turbines such as Kaplan and propeller. The Francis turbine is one of the most used turbines because they can work efficiently to a high variability drops and flow rates (Calado et al., 2014).

**Figure 20 - Francis turbine**

### 3.3. Similarity laws and specific speed in turbo machines

The turbo machinery behavior in a hydraulic engineering project involves the study of its type in the laboratory at a reduced scale. The Theory of Similarity governs the transposition into full-scale prototype of a reduced model (Simão et al., 2009).

This theory requires the verification of three similarity conditions: geometric similarity, kinematic similarity and dynamic similarity. They can be defined as (Quintela et al., 2005):

1. **Geometric similarity**: The dimension of the turbine cannot be reduced to a smaller scale which can induce scale effects in the prototype
2. **Kinematic similarity**: The triangle of speeds is equivalent in the inlet and outlet of the runner.
3. **Dynamic similarity:** The polygon of forces must be similar both in the prototype as in the model.

The similarities are related with homologous relationships in model and in prototype, in particular, to allow the definition of the specific speed of turbines, as an important parameter of each set of similar turbines that characterizes its dynamic behavior (Ramos, 2000). Based on similarity laws, a full description of the external and internal (inertia) forces balance acting on a control volume defined between inlet and outlet runner sections, through momentum equation, will provide the discharge variation.

Under similarity operational conditions, the turbine speed, head and power, both in model and prototype, follow the general equation:

$$\frac{n}{n'} = \left(\frac{P'}{P}\right)^{1/2} \left(\frac{H}{H'}\right)^{5/4} \tag{4}$$

Specific speed of a turbine gives the geometrical proportion of a similar turbine to a known turbine, and it is defined as:

$$n_s = n\frac{P^{1/2}}{H^{5/4}} \tag{5}$$

where:

$n_s$ - Specific number of revolutions [m, kW]
$n$ – Nominal rotational speed [rev/min]

A complete similarity between runners of different dimensions is always difficult and “scale effects” can occur. For a machine model with the same dimensions of the prototype, the following relationships get verified (Quintela, 2005):

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

Instead of maintaining the size not varying the runner speed [rpm], the similarity laws correspond to (Quintela et al., 2005):

$$\frac{P}{P'} = \left(\frac{D}{D'}\right)^5 \qquad \left(\frac{D}{D'}\right)^2 = \frac{H}{H'} \qquad \left(\frac{D}{D'}\right)^3 = \frac{Q}{Q'} \tag{7}$$

The validation of these conditions gives a scientific approach to select the turbine that best adjusts to the project conditions (Simão et al., 2009).

## 3.4. Hydraulic modeling models

### 3.4.1. EPANET

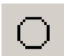
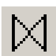
EPANET is a mathematical model that performs extended period simulation of hydraulic and water quality behavior within pressurized pipe networks. The Environmental Protection Agency of USA (EPA) created the EPANET model in 1993, since then it has been updated to its latest version, EPANET 2.0, September 2000, but some improvements have been incorporated among these last years (Arnalich et al., 2011). Although there is a wide range of hydraulic simulation programs like WaterGEMS, WaterCAD and Synergee Water, this program continues to be widely used by the trust of the results and also because it does not require license.

A network consists of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. EPANET tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of a chemical species throughout the network during a simulation period comprised of multiple time steps. In addition to chemical species, water age and source tracing can also be simulated (Rossman, 2000).

The complexity of network models calculations can be overwhelming, EPANET makes possible for people with little knowledge of fluid mechanics to study and evaluate the different networks (Arnalich et al., 2011). Starting with a geometric description of the pipe network, a set of initial conditions, estimates of water usage, and a set of rules for how the system is operated, EPANET predicts all flows, pressures, and water quality levels throughout the network during an extended period of operation.

The EPANET model through calibration process allows you to assign the same characteristics and mode of operation of a real supply system (Calado et al., 2014). Through simulations it is possible to evaluate the hydraulic behavior and water quality pressure supply systems (Rossman, 2000). Junctions, reservoirs, pipes, valves, tanks and pumps make the components of this model of the program. EPANET only recognizes these 6 types of objects found in the networks and it is vital to know them (Arnalich et al., 2011). The characteristics of the elements used in this study are described in Table 7.

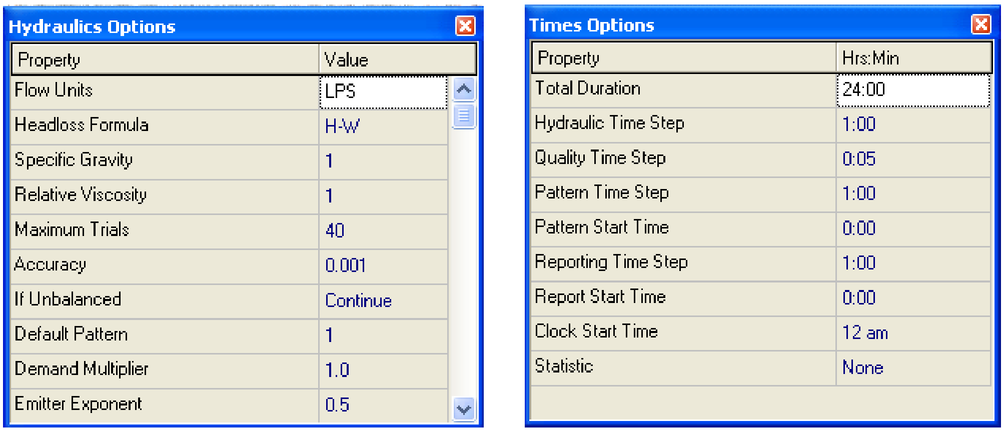
**Table 7 - Main characteristics of the elements of the network**

| Element | Symbol | Description |
|---|---|---|
| Junctions |  | Connect the sections to each other and is where water enters and leaves the network. These points are characterized by their height, consumer base and initial water quality. |
| Reservoirs |  | The reservoirs work as a drain or as water source. The volume, unlimited, remains constant regardless of water input and output, because of its huge dimension in comparison with the system. |
| Tanks |  | Have a limited capacity to store water, and the level changes if we fill or empty them. |
| Pipes |  | Transport water from one place to another. Are characterized by the initial and final node, the diameter, length and roughness coefficient. |
| Pumps |  | Pumps add energy to the water, which means that they lift it. |
| Valves |  | Limit the pressure and the discharge in a specific point of the network. They are characterized by the initial and final node, diameter, and state control parameter. |

### 3.4.2. Model calibration of Scenario B

The case study is an area of 68 ha, corresponding to 0.1% of the total area of the AMP, situated in the district of Beja. The area originally is composed with only olive crops, for our case study it has been separated in different fields, representing each one a kind of crop.

To start with the simulation with EPANET, firstly is necessary to define the hydraulic and time characteristics in which the model will be simulated (see Figure 21).



**Hydraulics Options**

| Property | 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 |
| Demand Multiplier | 1.0 |
| Emitter Exponent | 0.5 |

**Times Options**

| Property | Hrs:Min |
|---|---|
| Total Duration | 24:00 |
| 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 |
| Statistic | None |

**Figure 21 - Hydraulic and time properties**

The head losses in the pipes are determined based on the following expression (Rossman, 2000):

$$h_L = A \cdot q^B \tag{8}$$

where:

$h_L$ - Head loss [m]
$q$ - Flow rate [$m^3$/s]
$A$ - Resistance coefficient [-]
$B$ - Flow exponent. [-]

The head losses result from the work done by the resistant forces, and for the simulation is chosen the Hazen-Williams (H-W) formula, used in flow pressure and exclusively for water:

$$A = 10.7 \cdot C^{-1.852} \cdot d^{-4.871} \cdot L \qquad B = 1.852 \tag{9}$$

where:

$C$ - Hazen-Williams roughness coefficient [-]
$d$ - Pipe diameter [m]
$L$ - Pipe length [m]

**Junction 2**

| Property | Value |
|---|---|
| *Junction ID | 2 |
| X-Coordinate | 1020.89 |
| Y-Coordinate | 1739.53 |
| Description | |
| Tag | |
| *Elevation | 0 |
| Base Demand | 2.348 |
| Demand Pattern | |
| Demand Categories | 1 |
| Emitter Coeff. | |

**Pipe 1**

| Property | Value |
|---|---|
| *Pipe ID | 1 |
| *Start Node | 0 |
| *End Node | 1 |
| Description | |
| Tag | |
| *Length | 400 |
| *Diameter | 80 |
| *Roughness | 140 |
| Loss Coeff. | 0 |
| Initial Status | Open |

**Figure 22 - Junction and pipe configuration**

These three factors of the H-W formula have to be set up. The H-W roughness coefficient is taken 140 as value and regarding the pipe diameters and lengths, these varies depends on the system characteristics. These values were taken from real cases of EDIA and COTR and were adapted to this case study. The model calibration requires the knowledge of the base demand of each junction. This base demand has been calculated taking the irrigation needs average consumption of the crops.

The network of study is a branched irrigation pressurized system. Figure 22 illustrates an example of pipe and junction configuration. A tank at the beginning of the irrigation network supplies the water consumption. Each junction corresponds to a different type of crop with his particular flow (see Figure 23).

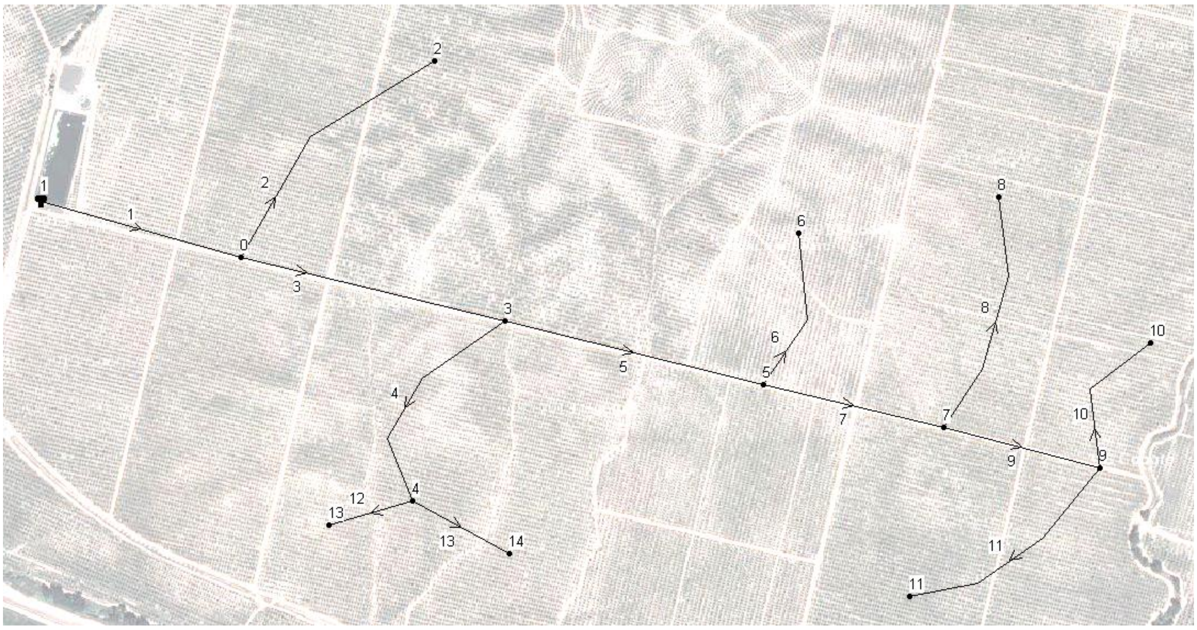


**Figure 23 - EPANET irrigation network**

Results from the simulation are shown in Table 8 and Table 9:

**Table 8 - Network nodes**

| Node ID | Demand [l/s] | Head [m] | Pressure [m] |
|---|---|---|---|
| **Junc 0** | 0 | 3.41 | 0.41 |
| **Junc 2** | 2.35 | 2.06 | 2.06 |
| **Junc 3** | 0 | 3.04 | 0.04 |
| **Junc 4** | 0.54 | 2.36 | 2.36 |
| **Junc 5** | 0 | 2.78 | 0.78 |
| **Junc 6** | 0.71 | 2.18 | 2.18 |
| **Junc 7** | 0 | 2.37 | 0.37 |
| **Junc 8** | 0.63 | 1.2 | 1.2 |
| **Junc 9** | 0 | 1.84 | 0.84 |
| **Junc 10** | 0.25 | 1.63 | 1.63 |
| **Junc 11** | 0.16 | 1.75 | 1.75 |
| **Junc 13** | 0.54 | 2.15 | 2.15 |
| **Junc 14** | 0.54 | 2.15 | 2.15 |
| **Tank 1** | -5.72 | 13 | 10 |

**Table 9 - Network pipes**

| Link ID | Flow [l/s] | Velocity [m/s] | Unit Headloss [m/km] | Friction Factor | Status |
|---|---|---|---|---|---|
| **Pipe 1** | 5.72 | 1.3 | 23.99 | 0.021 | Open |
| **Pipe 2** | 2.35 | 0.47 | 3.37 | 0.024 | Open |
| **Pipe 3** | 3.37 | 0.3 | 0.91 | 0.024 | Open |
| **Pipe 4** | 1.62 | 0.32 | 1.69 | 0.026 | Open |
| **Pipe 5** | 1.75 | 0.22 | 0.66 | 0.026 | Open |
| **Pipe 6** | 1.04 | 0.24 | 1.02 | 0.027 | Open |
| **Pipe 7** | 0.63 | 0.32 | 2.91 | 0.028 | Open |
| **Pipe 8** | 0.41 | 0.21 | 1.32 | 0.029 | Open |
| **Pipe 9** | 0.25 | 0.13 | 0.52 | 0.032 | Open |
| **Pipe 10** | 0.16 | 0.08 | 0.24 | 0.034 | Open |
| **Pipe 11** | 0.54 | 0.28 | 2.18 | 0.028 | Open |
| **Pipe 12** | 0.54 | 0.28 | 2.18 | 0.028 | Open |
| **Pipe 13** | 0.71 | 0.25 | 1.49 | 0.028 | Open |

As presented in Table 8 and Table 9 the results of the run analysis are shown. In all pipes the velocity and flow are always positive, that means that water flows in the right direction. Regarding the junctions the head and pressure are also positive which is desirable to assure the correct displacement of water. It is important to highlight that pressure values should be positive but not very high values as they may damage the system.

# 4. HYDROPOWER CONVERTERS FOR LOW POWER

## 4.1. Introduction

The development of hydropower converters for low power has been in progress under the European project HYLOW, where studies of new systems were gathered to exploit the energy created by small waterfalls or to take the advantage of non-negligible available flow energy in any water pipe system (Schneider et al., ?).

These new technologies can be applied to existing water systems, with the purpose of producing energy (Ramos et al., 2013), being the irrigation systems one example of possible applications. These converters have significant low-costs of installation and maintenance that makes them largely suitable and attractive as a sustainable solution.

The small hydropower plants can still occupy a relevant contribution around the world, existing a huge potential in existing structures or natural rivers for energy production (EC et al., 2015). In Table 10 is illustrated the impact evolution of small hydropower plants in Portugal. According to the National Renewable Energy Action Plan (NREAP), small hydropower should contribute 1511 GWh in 2020, corresponding to a total installed capacity of 750 MW in Portugal (Liu et al., 2013) .

**Table 10 - Evolution of small hydropower (adapted from ESHA, 2012)**

| Small hydropower | 2005 | 2007 | 2010 | 2020 |
|---|---|---|---|---|
| **Total installed capacity (MW)** | 340 | 399 | 450 | 750 |
| **Generation (GWh)** | 689 | 895 | 1370 | 2032 |
| **Number of power plants** | 100 | 137 | 155 | 250 |

Two of these hydropower converters for low power are shown in this thesis: first the Rotary Hydraulic Pressure Machine (RHPM), developed to work in open channel situations; second, the Pump-as-Turbine (PAT) as a solution for the pressurized pipes.

## 4.2. Rotary Hydraulic Pressure Machine (RHPM)

The Rotary Hydraulic Pressure Machine (RHPM) is a novel energy converter developed at the University of Southampton in the UK for exploiting very low head hydropower sites, with fall heights under 5m (see Figure 24). This kind of turbine is composed by 4 main components (Senior et al., 2008):

1. **The central hub**: This is a horizontal cylinder that spans the width of the machine, and has a diameter equal to the head of the site. The top of the hub is level with the upstream water surface and the bottom of the hub is level with the downstream water surface.
2. **The blades**: The blades are the surface on which the water's energy is extracted. Flowing water, when pass through the Hydraulic Turbine it strikes the blades of the turbine and makes the shaft rotate. They extend radially from the hub, whilst twisting as they progress across the width of the wheel. Overall they can be thought of as 'diagonally mounted', such that the termination of each blade coincides with the start of the subsequent blade on the other side of the wheel. This design is critical, allowing the large blades to enter and exit with minimal losses, and ensuring continual blade tip entry and exit from the water resulting in smooth consistent rotation.
3. **The shroud**: This curved section of riverbed ensures that at least one entire blade is enclosed within a close fitting channel. This prevents any leakage flow of water between and along the blades, entering from beneath the wheel.
4. **Sidewalls**: These not only provide a mounting for the wheel's bearings, but also prevent any leakage flow of water between the blades entering from the sides of the wheel. Importantly, the sidewalls do not extend up to the water surfaces or along the entire length of the wheel. Instead the sides of the wheel remain exposed to allow water to enter the compartments between the blades from the side of the wheel as well as the front. They also allow air to 'ventilate' the compartments from the side of the wheel. This process allows the water to drain from the compartments with ease once they have reached the downstream.

Regarding the Rotary Hydraulic Pressure Machine (RHPM), it is necessary to take into account that there are some important differences with the waterwheel. The theory for an ideal RHPM assumes that the diameter of the hub of the machine (D), equals the head difference (H) (Schneider et al., ?). The machine turns with a center velocity of the blade that corresponds to the downstream velocity, $v_2$ (Schneider, ?). The head difference of water creates a difference in forces acting on the blades ($F_1$ and $F_2$), as a result of the hydrostatic pressure on both sides of the blade (see Figure 24).The wheel rotates with angular velocity $\omega$ because of the drag effect created between the submersed blades and the flowing fluid (Senior et al., 2008).

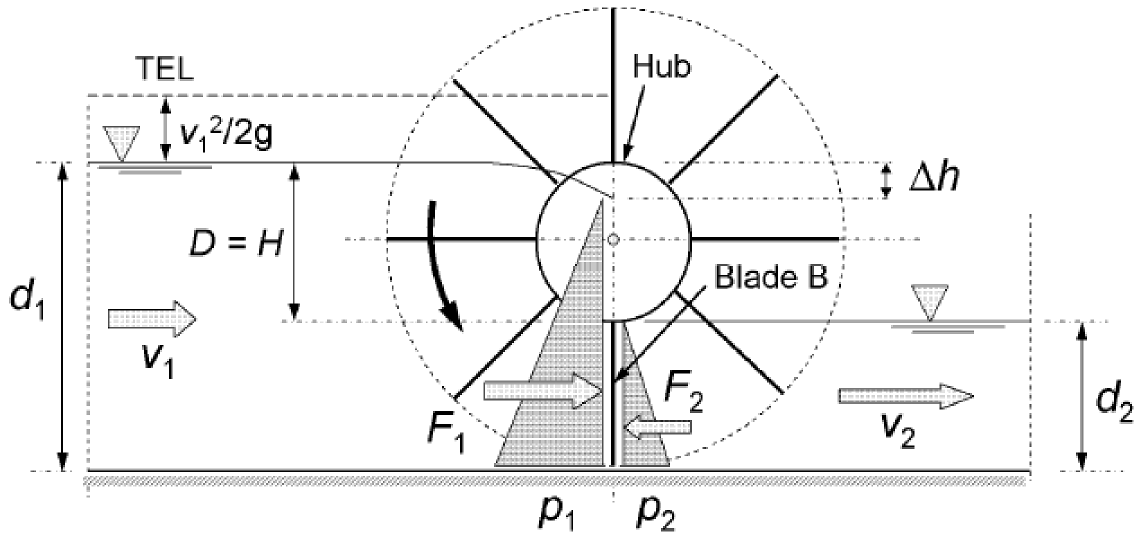



**Figure 24 - RHPM principle**

The RHPM works with a head difference of water, as a result of that, the Pressure (P), plays an important role to understand the operation of the turbine. This pressure is given by the liquid pressure formula (White, 2000):

$$P = h \cdot \rho \cdot g \quad \textbf{(10)}$$

where:

$P$ – Pressure [N/m$^2$]
$h$ – Depth of water [m]
$\rho$ – Fluid density [kg/m$^3$]
$g$ – Gravity [m/s$^2$]

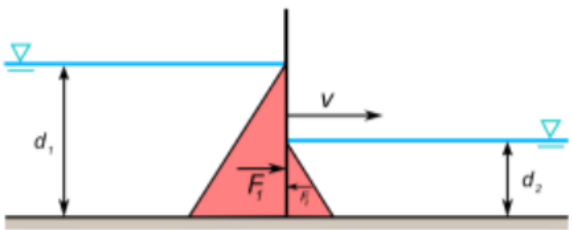



**Figure 25 - Pressure acting on a simple vertical plate**

Referring to Figure 25, consider a simple vertical plate, which separates two dissimilar depths of water, $d_1$ and $d_2$. The triangles represent the hydrostatic pressure (Senior et al., 2008). The forces on either side of this plate of width, W, are $F_1$ and $F_2$:

$$F_1 = \rho \cdot g \cdot \frac{d_1^2}{2} \cdot W \quad \textbf{(11)}$$

$$F_2 = \rho \cdot g \cdot \frac{d_2^2}{2} \cdot W \tag{12}$$

It can be seen that the force on the plate acting from the deeper water (Senior, 2008), $F_1$, is greater than $F_2$ from the shallower water, and the total force acting on the plate, F, in the direction of $F_1$ is:

$$F = F_1 - F_2 = \rho \cdot g \cdot \frac{(d_1^2 - d_2^2)}{2} \cdot W \tag{13}$$

In accordance with continuity (White et al., 2000), the velocity of the downstream water, $v_2$, is greater than that of the upstream water, $v_1$ (see Figure 26):

$$v_2 = \frac{d_1}{d_2} \cdot v_1 \tag{14}$$

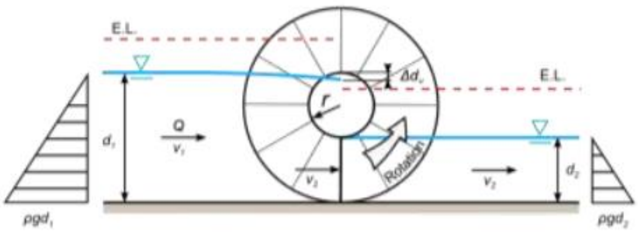



**Figure 26 - Operation of the RHPM**

The blades are mounted about an axis. This configuration adds additional complexity to the analysis as the water must flow from the deeper side of the Rotary Hydraulic Pressure Machine to the shallower side (Schneider, 2008). Therefore the water must undergo acceleration as it passes through the turbine (Senior et al., 2010). Assuming for simplicity that the channel width is equal to that of the wheel, application of the energy equation (White, 2000), gives the head drop associated with acceleration in the upstream, $\Delta d_u$ as:

$$\Delta d_u = \frac{v_2^2 - v_1^2}{2g} \tag{15}$$

Regarding the blade, using the theory described above, it is only necessary to take into account the pressure acting on the blade itself. The force on the blade ($F_p$), is a function of the pressure difference across the blade and the area of the blade, A:

$$F_P = \rho \cdot g \cdot (d_1 - d_2 - \Delta d_u) \cdot A \tag{16}$$

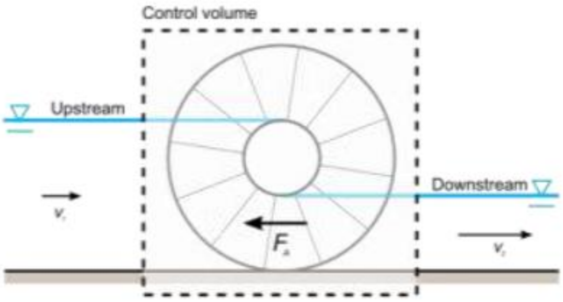



**Figure 27 - Reaction force**

The force resulting from the pressure difference between the differing water depths, $F_p$, is not the only force acting on the RHPM (Senior et al., 2008). A mass of water is accelerated from a lower speed, $v_1$, to a higher speed, $v_2$, so in accordance with Newton's second and third laws (White, 2000), this acceleration must result in a force (Schneider et al., 2008). This counteracting force to the acceleration, $F_A$ (see Figure 27), is quantified by calculating the momentum change of the water, equal to the mass flow rate, Q, multiplied by the velocity change (Senior, 2010):

$$F_A = \rho \cdot Q \cdot (v_2 - v_1) \tag{17}$$

Senior, 2008, assumed that all of the counteracting force to the acceleration of the water acts upon the blades, and that there are not losses such as friction and turbulence. So the theoretical power output, $P_{out\ ideal}$ is:

$$P_{out\ ideal} = (F_P - F_A) \cdot v_2 \tag{18}$$

Since turbulence losses are excluded in the theory described above, an empirical loss factor is established. The blades of the RHPM generate turbulent losses when interacting with water (Schneider et al., 2008). Those losses are expressed as a counteracting force: , which is a function of the loss coefficient $C_L$:

$$F_C = \frac{\rho}{2} \cdot C_L \cdot A_b \cdot v_b^3 \tag{19}$$

where:

$F_C$– Counteracting force [N]
$C_L$ – Loss coefficient [-]
$A_b$ – Area of the blade [m$^2$]
$v_b$– Velocity of the blade [m/s]

The RHPM of study is with fixed blades aligned perpendicularly to its axis that rotates around a main axle, perpendicular to the turbine plane. This kind of turbine is a Radial Flow Hydraulic Turbine, as the liquid flowing mainly in a plane perpendicular to the axis of rotation. The turbine is partially submersed in fluid, with a head difference between the two sides, while the remaining part is in contact with the air (see Figure 28).

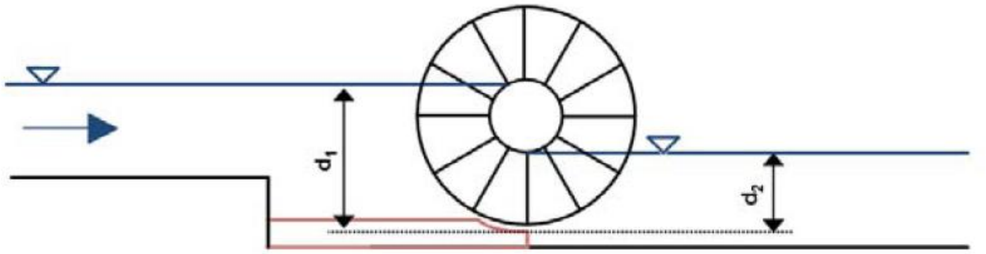



**Figure 28 - Head difference**

The first one tested by HYLOW project is a straight blades RHPM. The model has a diameter of 1200 mm and a width of 970 mm, while de diameter of the hub is 400 mm. (D = 1200 mm, $D_{hub}$ = 400 mm, W = 970 mm)

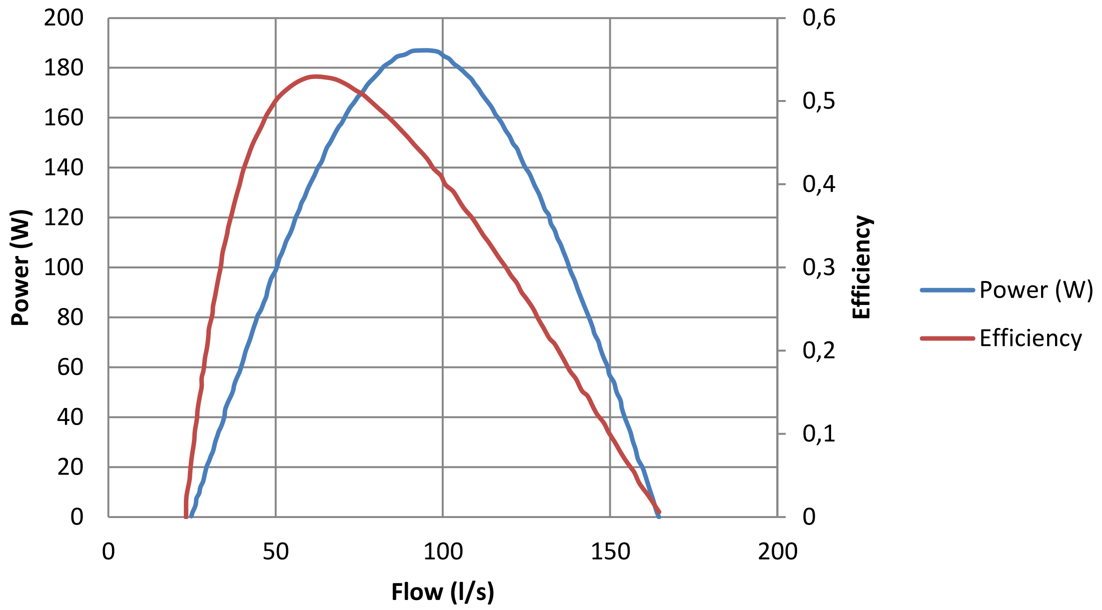



**Figure 29 - Straight blades RHPM results**

Those tests carried by HYLOW project gave a maximum power output of 186.7 W for a flow rate of 97.8 l/s and an efficiency of 49 %. The Best Efficiency Point (BEP), with and efficiency of 51 % was reached for a power output of 156.8 W and a flow rate of 78.5 l/s.

The second RHPM tested by HYLOW project also has rectangular shape blades, but twisting as they progress across the width of the wheel. And these helical blades are attached to radial axles (see

Figure 30). The model has a diameter of 450 mm and a width of 235 mm, while de diameter of the hub is 150 mm. (D = 450 mm, $D_{hub}$ = 150 mm, W = 235 mm)

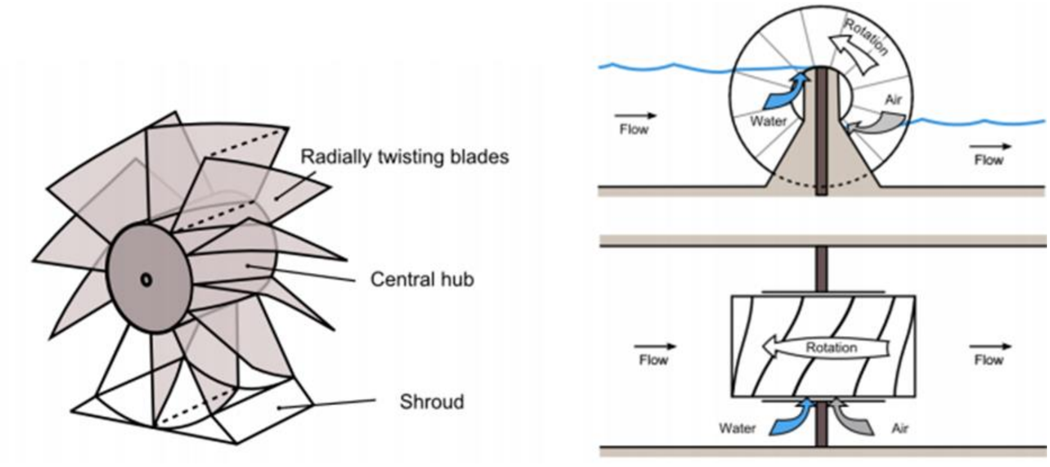



**Figure 30 - Depiction of helical blades RHPM**

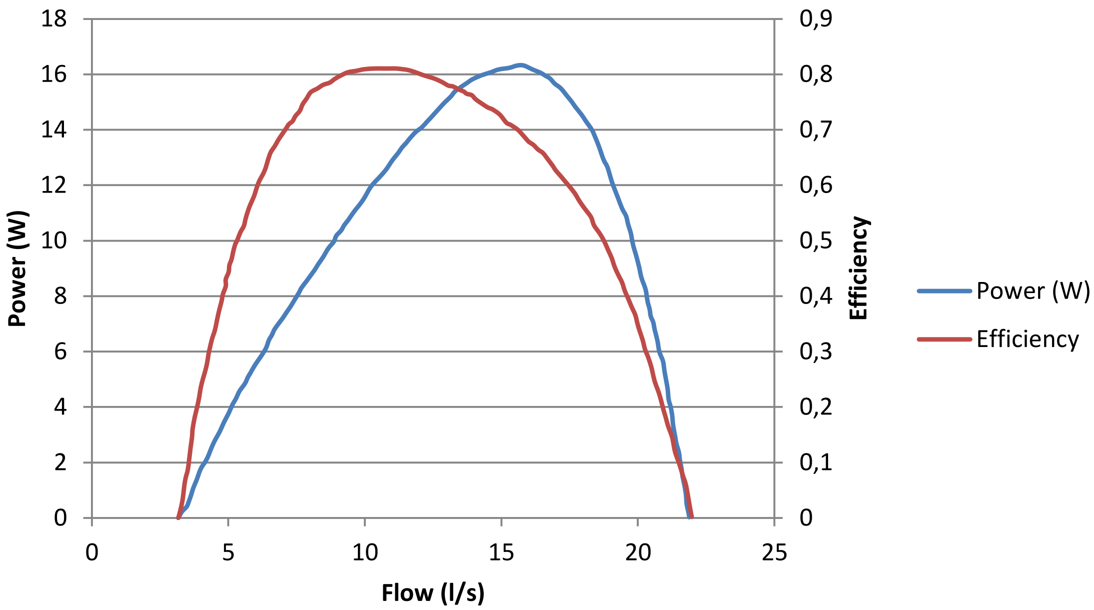



**Figure 31 – Helical blades RHPM results**

The maximum power output was 16.2 W for a flow rate of 14.3 l/s with an efficiency of 70 %. The maximum efficiency of 80.5 % was reached for a power output of 13.1 W and a flow rate of 10.8 l/s.

**Table 11 - Results of RHPM**

| Type of blades | Working point | [W] | [l/s] | Efficiency [%] |
|---|---|---|---|---|
| **Straight** | Maximum power | 186.7 | 97.8 | 49 |
| | BEP | 1568 | 78.5 | 51 |
| **Helical** | Maximum power | 16.2 | 14.3 | 70 |
| | BEP | 13.1 | 10.8 | 80.5 |

In Table 11 the following results are summarized. RHPM with helical blades were identified as the best combination of simple geometry and efficiency. So the RHPM with helical blades are the chosen ones to apply to our Scenario A to produce the energy. Even the power output for the straight blades is much bigger than the one obtained by the helical RHPM, it has to be highlighted that the straight turbine tested is much bigger than the helical ones, with a lower efficiency. So based in the similarity laws explained in the Chapter 3, it is obtained helical RHPM of bigger dimensions maintaining the efficiency.

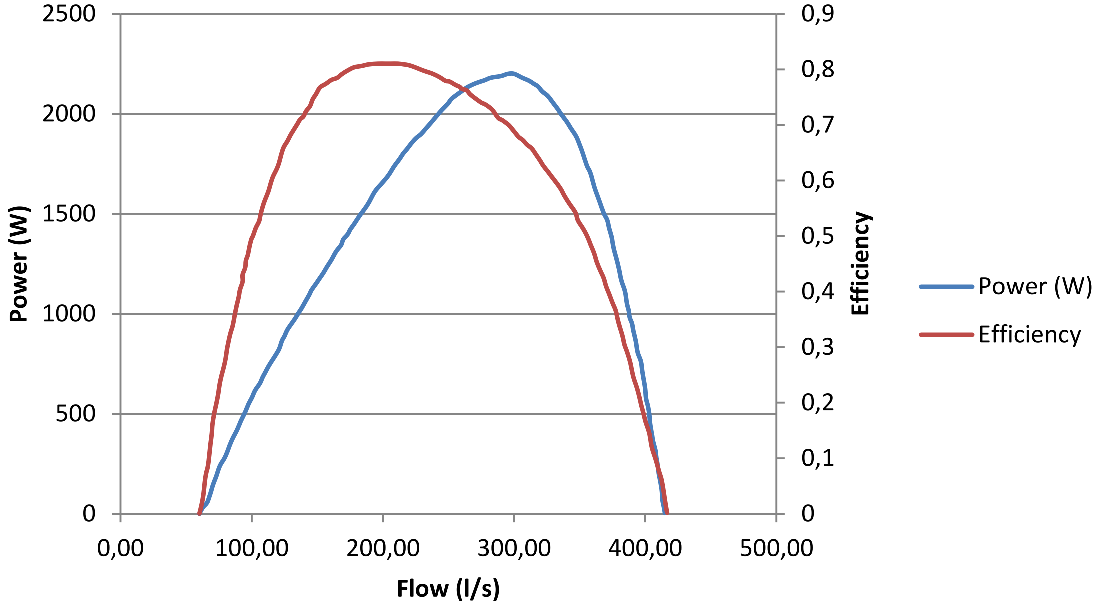



**Figure 32 - Helical blades RHPM with higher diameter**

In Figure 32 it is illustrated the new helical RHPM obtained with a diameter of 1.2 m instead of 0.45 m. Now the BEP gives an output power of 1.75 kW for a flow of 205.9 l/s. And the maximum power output is 2.2 kW reached with a flow of 295.95 l/s. The intersection between the power and efficiency curves is taken as the working point, with the values of 2.11 kW with an efficiency of 76.9% and a flow of 258.35 l/s.

### 4.3. Pump-as-Turbine (PAT)

When a pump induces a certain power to the flow, it is necessary that a quantity promotes the fluid pumping which in many cases cannot happen and can lead to an inverted rotation of the impeller, and consequently the change of the fluid direction, from downstream to upstream, to the suction line (KSB et al., 2005). PATs are centrifugal pumps running in reverse rotation mode, in order to produce instead of consuming energy (EC et al., 2015). This concept has been recognized by pump manufacturers for many years and within the water supply industry has been exploited to a limited degree as a means of generating power in locations where it is considered too expensive to purchase a hydro turbine (Calado et al., 2014).

A small pump operating as a turbine unit can be much more economically incorporated into traditional water transport systems and reservoirs, such as upstream of a pressure reducing valve to take the advantage of excess effective flow energy or in a pipeline service, in mountainous regions, to avoid excessive pressure, in wastewater pressure discharges and in any type of natural falls (Ramos et al., 2000a).

In the current world economic climate where reducing energy costs is becoming a high priority it is not surprising that PATs are starting to create significant interest (Calado et al., 2014), as the energy output can be higher than the energy input used to run it as a pump (Budris et al., 2011). When the pump is working as a turbine, it can handle a major volume of water, and this means that the energy coming out is also higher than when it is used in conventional pumping mode (Budris et al., 2011). PATs convert the pressure energy and the kinetic energy of the flow into mechanical energy in the rotor. Figure 33 shows a comparison between a turbine, where it receives hydraulic power, converting it into mechanical energy, and its operation as a pump, which is provided mechanical power for it to be converted into hydraulic power.

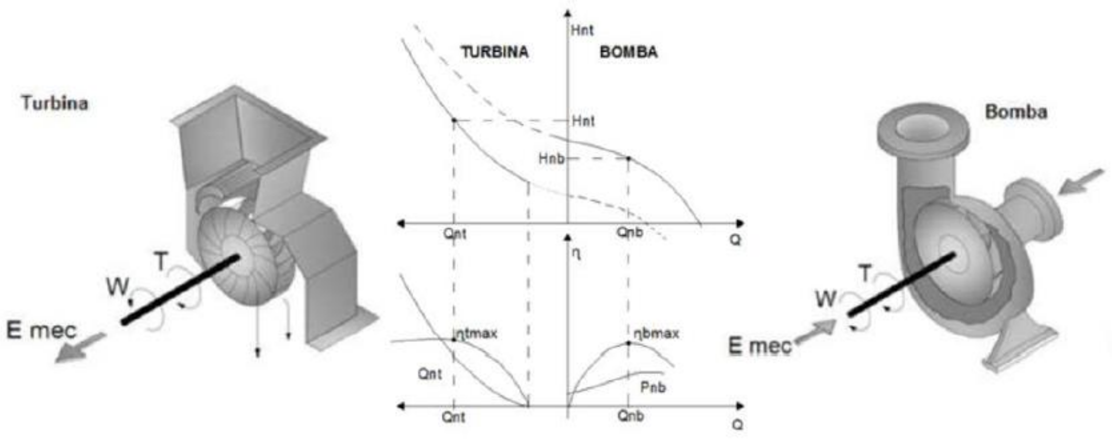



**Figure 33 - Scheme operation of a turbine and a pump (adapted from Ramos et al., 2000)**

Moreover, using the pumps as turbines we can achieve a higher efficiency. The operating range for ring section and volute casing pumps is illustrated in Figure 34.

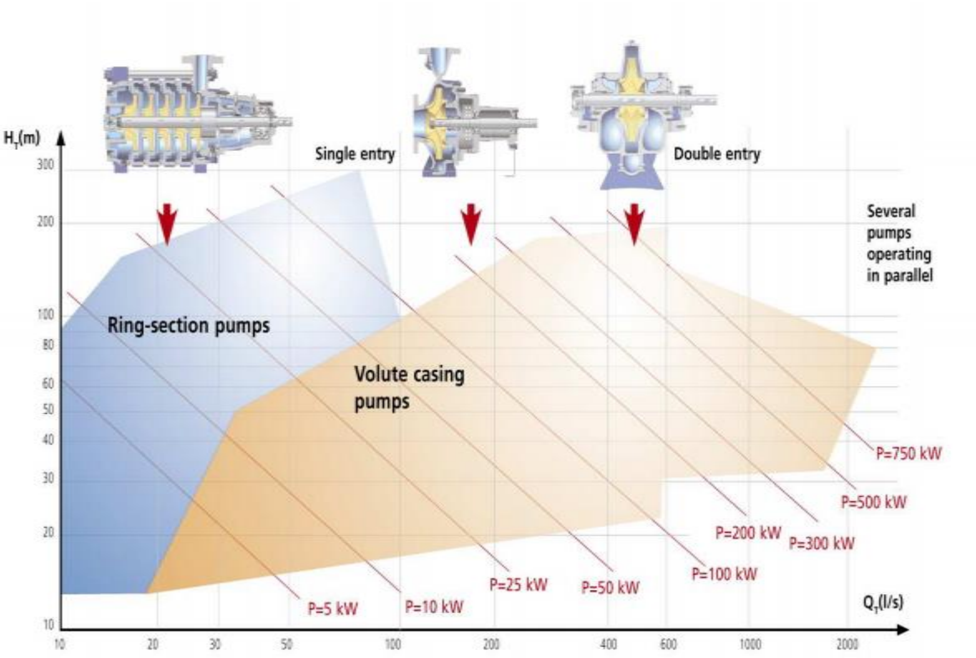



**Figure 34 - Application range of PATs (Budris, 2011)**

PATs became viable because they require low investment, maintenance and repairing costs, giving reasonable efficiency (EC, 2015). From the economic point of view a PAT installation with power between 5 - 500 kW should give investment return in 2 or 3 years (Calado et al., 2014). The main issue of this hydraulic machine is that the supplier doesn't provide the characteristic curves working as a turbine (Carravetta et al., 2012).

It has not gone unnoticed that running PATs is an efficient method of generating energy as well as recovering energy and contributing to energy savings (Budris et al., 2011). But the problem is that is not possible to maintain the efficiency of PATs, as they do not have any flow control device (EC et al., 2015). So finding the best efficiency point (BEP) of a PAT has been the focus of many studies, because losses by turbulence and friction the BEP of a PAT when working in pumping mode is not equal when working in turbine mode. Rodrigues et al., 2003, quoted by Calado (2014), studied the water mass displacement finding that 30% of the total losses are in the spiral case and 40% in the impellor.

The struggles to find a PAT adequate for the flow conditions and to maximize the production of energy, theoretical and experimental studies have been carried out to predict PAT performance. Some are based in the BEP and others in the specific speed $n_s$ (Carravetta et al., 2012). The relations between the BEP in pumping mode and in turbine mode are presented by correcting factor in relation to the flow and head (see Figure 35).

| S. no. | Name of investigator | Criteria | Head ratio ($H_t/H_p$) | Discharge ratio ($Q_t/Q_p$) | Remarks |
|---|---|---|---|---|---|
| 1. | Stepanoff | BEP | $\frac{1}{\eta_p}$ | $\frac{1}{\sqrt{\eta_p}}$ | Accurate for $N_s$ in the range of 40–60 |
| 2. | Alatorre-Frenk | BEP | $\frac{1}{0.85\eta_p{}^5+0.385}$ | $\frac{0.85\eta_p^5+0.385}{2\eta_p^{9.5}+0.205}$ | – |
| 3. | Schmiedl | BEP | $-1.4+\frac{2.5}{\eta_{hp}}$ | $-1.5+\frac{2.4}{\eta_{hp}^2}$ | – |
| 4. | Grover | Specific speed | $2.693-0.0229N_{st}$ | $2.379-0.0264N_{st}$ | Applied for $N_s$ in the range of 10–50 |
| 5. | Sharma | BEP | $\frac{1}{\eta_p^{1.2}}$ | $\frac{1}{\eta_p^{0.8}}$ | Accurate for $N_s$ in the range of 40–60 |
| 6. | Hergt | Specific speed | $1.3-\frac{6}{N_{st}-3}$ | $1.3-\frac{1.6}{N_{st}-5}$ | – |
| 7. | Childs | BEP | $\frac{1}{\eta_p}$ | $\frac{1}{\eta_p}$ | – |
| 8. | Hancock | BEP | $\frac{1}{\eta_t}$ | $\frac{1}{\eta_t}$ | – |

**Figure 35 - Development of PAT performance prediction methods (NAUTIYAL, 2010)**

$$h = \frac{H_t}{H_p} \qquad\qquad q = \frac{Q_t}{Q_p} \tag{20}$$

where:

$h$ – Head correction factor
$q$ – Flow correction factor

The hydraulic power is one of the main hydraulic characteristics of a PAT, and it is calculated as follows:

$$\mathrm{P_H} = \gamma \cdot \mathrm{Q_t} \cdot \mathrm{H_u} \tag{21}$$

where:

$\mathrm{P_H}$ – Hydraulic power [W]
$\gamma$ – Specific weight fluid [N/m$^3$]
$\mathrm{Q_t}$ – Discharge [l/s]
$\mathrm{H_u}$ – Net head [m]

The mechanical power is:

$$P_e = M \cdot \omega = \rho \cdot Q \cdot k \cdot \omega \tag{22}$$

where:

$\mathrm{P_e}$ – Engine or mechanical power [W]
$\mathrm{M}$ – Torque [W]
$\omega$ – Impeller rotational speed [Hz]
$\rho$ – Density [kg/m$^3$]
$k$ – Free-vortex constant

The efficiency (η) is obtained using the electric power and the hydraulic power

$$\eta = \frac{P_e}{P_h} \tag{23}$$

Calado (2014), said that in a turbine performance it must be defined two characteristic curves; the first corresponding to N=0, standstill curve, in which values of flow and head lower than this curve don't produce torque; and in the second, M=0, shows the values from which the torque isn't transmitted to the shaft (Figure 36).

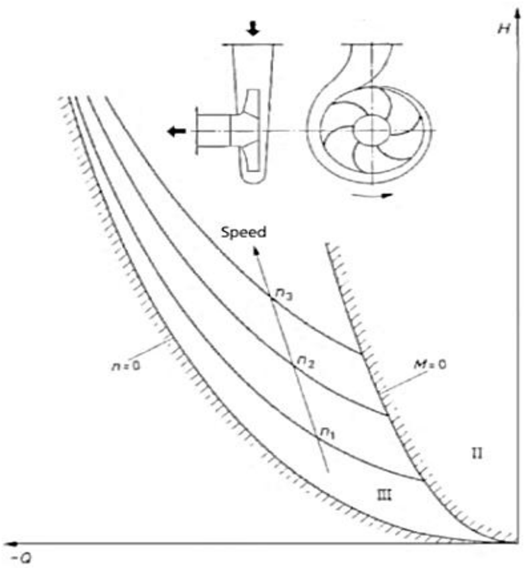



**Figure 36 - Turbine characteristic curves (KSB, 2005)**

The performance of a PAT, described by its characteristics curves, are difficult to define, as the manufacturers normally provide poor information on the PAT performance thus representing a limit for its wider diffusion (Carravetta et al., 2012). This characteristics curves can be obtained in three ways (Carravetta et al.,2012): experimentally, by computational fluid dynamics (CFD), and by any one-dimensional method.

In Figure 37, it is shown the characteristic curves of the PAT Etanorm 160.1-32, provided by the manufacturer KSB. It is possible to observe that this turbo machine can work with small flows but with a big head.

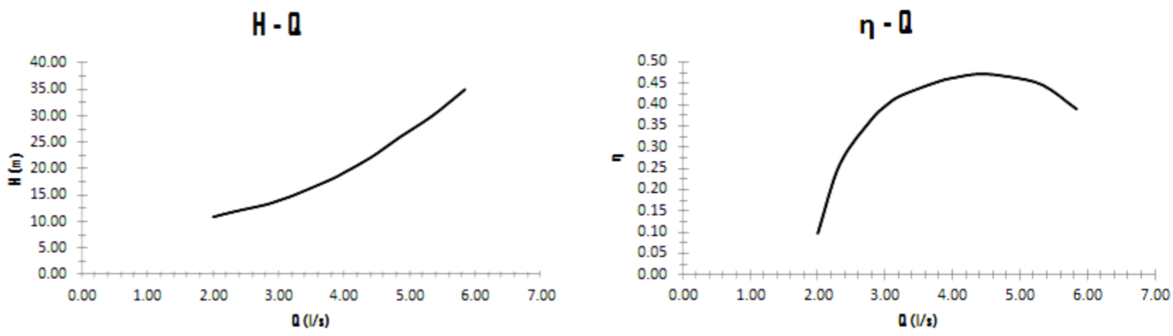



**Figure 37 - Characteristic and efficiency curve for Etanorm 32-160.1 of KSB**

Accordingly with the characteristic curves it has been calculated the turbine BEP (see Table 12).

**Table 12 - BEP of Etanorm 160.1-32**

| Q | $H_0$ | $P_H$ | $P_E$ | $\eta$ | N | $n_s$ |
|---|---|---|---|---|---|---|
| [l/s] | [m] | [W] | [W] | [-] | [rpm] | [m·kW] |
| 4.4 | 22.1 | 0.95 | 0.49 | 0.47 | 1520 | 21.04 |

Based on the theory of the hydraulic similarity (see Chapter 3), it is possible to calculate the characteristic curves for different rotational speeds (Figure 38). It is possible to visualize that increasing the rotational speed the head value increases too.

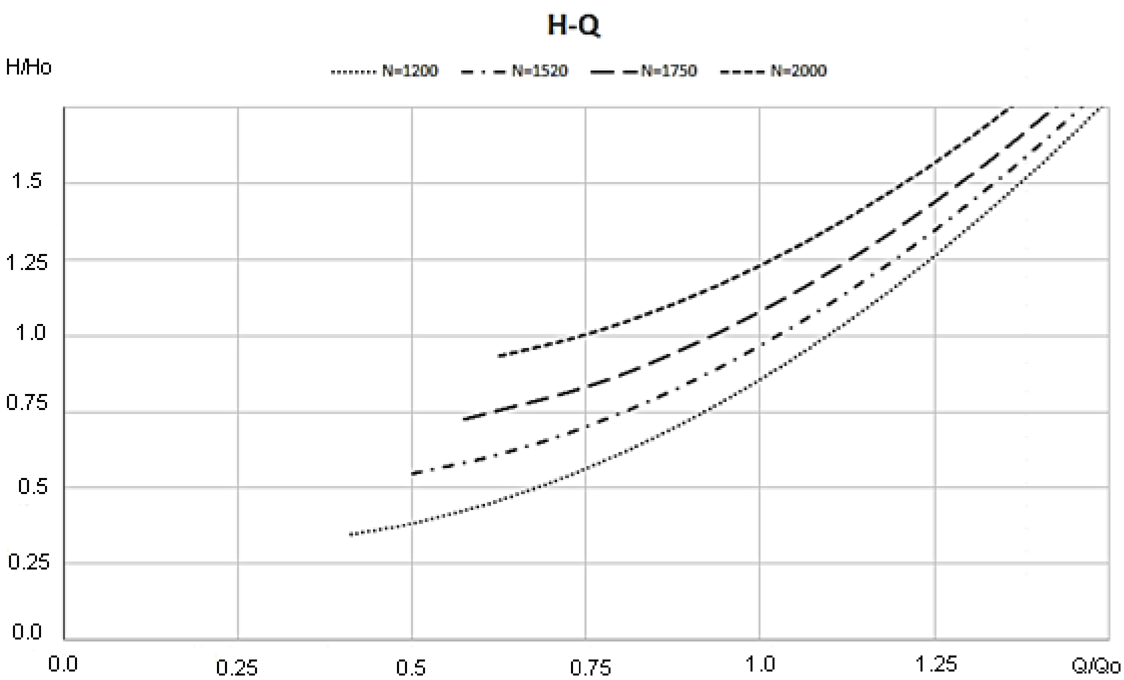



**Figure 38 - Characteristic curves for different rotational speeds**

The electric power, $P_e$ (Equation 22), and hydraulic power, $P_H$ (Equation 21) are calculated (Figure 39), using analytic equations with the torque.

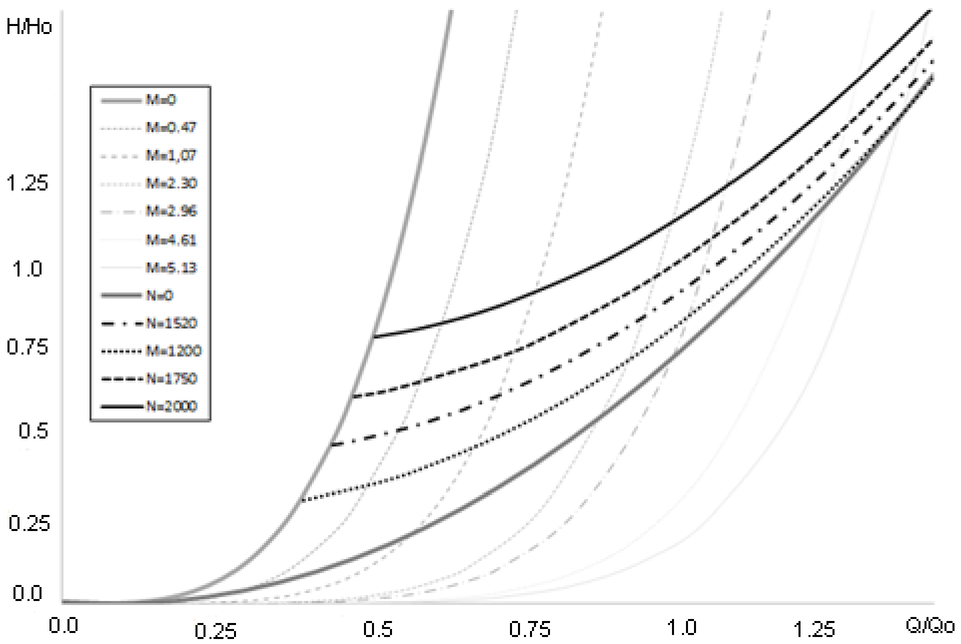



**Figure 39 - Torque curves**

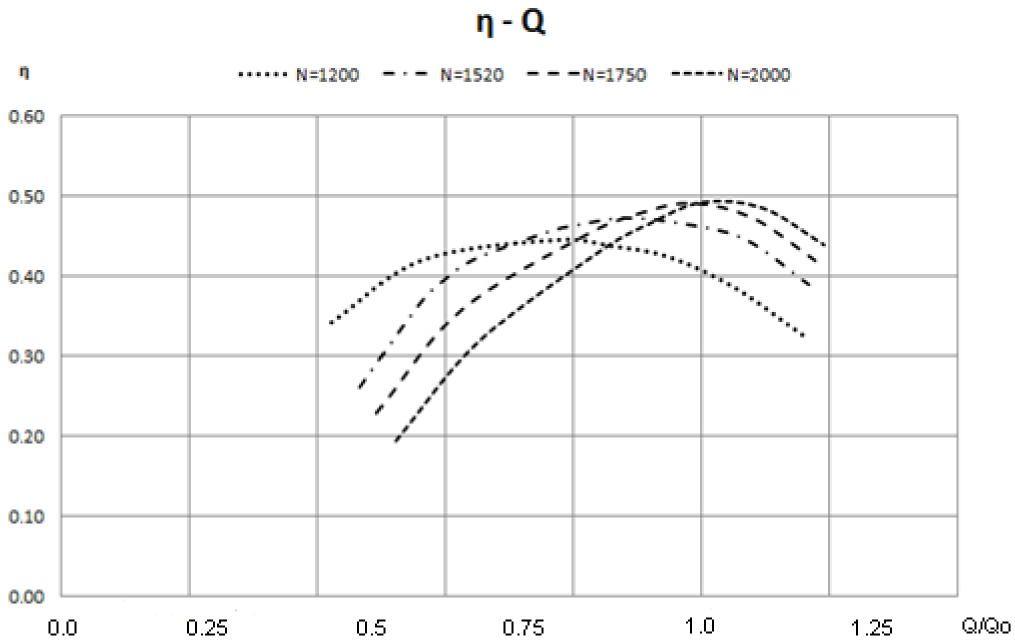



**Figure 40 - Efficiency curves for different rotational speeds**

The relationship between the hydraulic power and mechanical power allows obtaining the several efficiency points (Figure 40). Thus finding the PAT efficiency for different rotational speeds it can be construct the hill diagram (Figure 41).

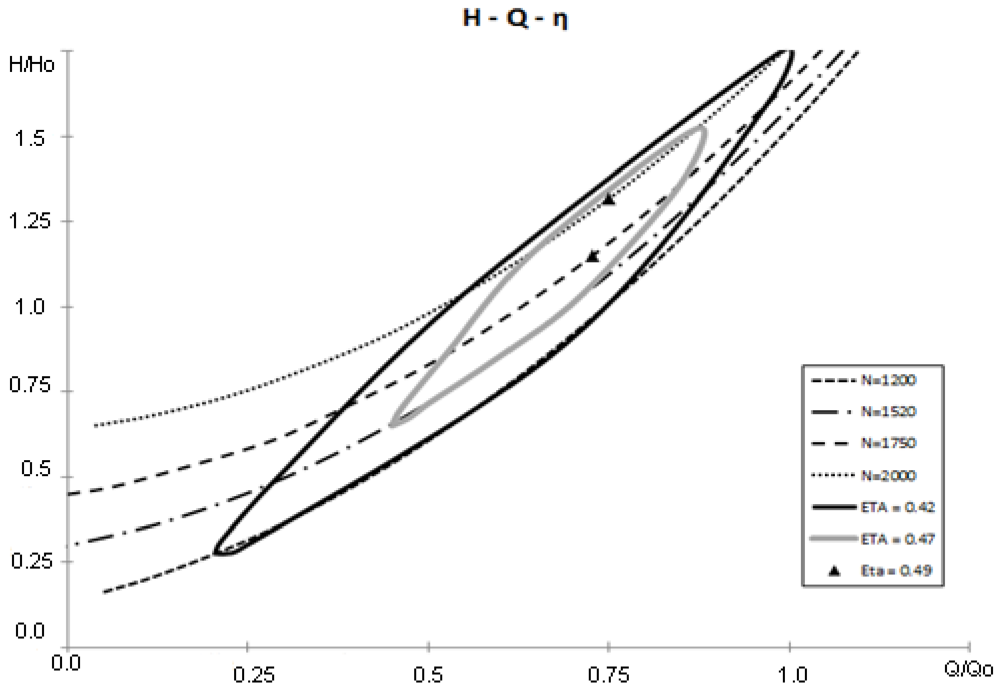



**Figure 41 - Etanorm hill diagram**

In order to avoid instability situations from turbine zone operating, the pump might operate in the point of the characteristic curve correspondent to the maximum power, normally close to the maximum efficiency (Ramos et al., 2000b). The reason of instabilities occurrence can be explained through the interception between the characteristic curve of the hydraulic system and the line of equal power, which means, for each power value, that would have two possible operating points (Ramos et al, 2000a). Schematically, in Figure 42 is represented the operating point, supposing the output power control, characterized through the dash line, correspondent to $p_{max}$, which has only one solution (in the peak of relative power curves (p)), so the operating point is the intersection between the characteristic curves of the hydraulic system and the machine.

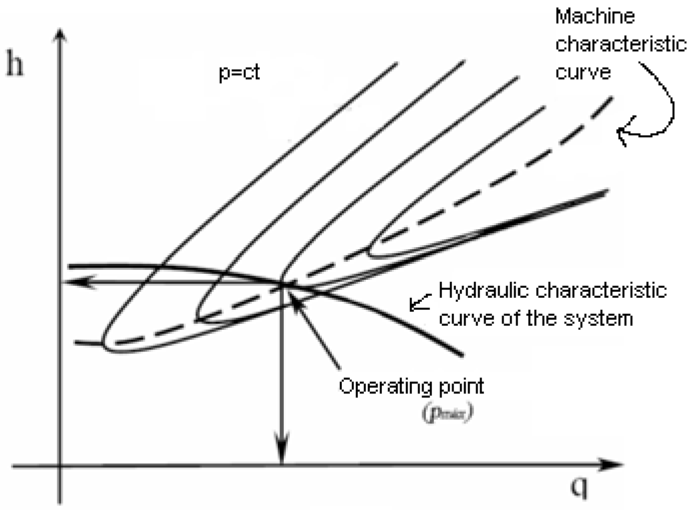



**Figure 42 - Operating point of a pump in turbine zone (adapted from Ramos et al, 2000b)**

Using the model EPANET the working point for the PAT is directly obtained for our specific situation, as the conditions of head and flow are constant. PAT will be placed in the pipe 1, between the tank and junction 0 (Figure 23). The available head is the difference between the tank head and the junction 0 head, and the flow will correspond to the flow that passes throughout the pipe 1 (see Table 8 and Table 9). Once the flow and head are known, the efficiency is determined with the help of the characteristic curves of the PAT. For the PAT the working point is illustrated in Table 13:

**Table 13 - PAT working point**

| [l/s] | Head [m] | Efficiency [%] |
|---|---|---|
| 5.72 | 9.6 | 45 |

# 5. ENERGY, ENVIRONMENTAL AND SOCIAL ANALYSIS

## 5.1. Introduction

Hydroelectricity is the term referring to electricity generated by hydropower; the production of electrical power through the use of the gravitational force of falling or flowing water. The two vital factors to take into account to calculate the total amount of available hydropower are the flow and the available head of the system.

The energy evaluation in a irrigation water distribution system depends on the volume of consumptions (Ramos et al., 1999). Known the quantity of volume needed for irrigation for each system presented in Chapter 2, it is important to define a flow capable of being powered. In terms of economic evaluation, the turbinable flow is what induces more advantage in terms of energy production and energy sales for a given time interval. An analysis for the two possible scenarios (A ans B) is provided in order to know the available energy of the system.

Once the energy analysis is done, it is possible to calculate the advantages of producing hydropower energy with an important renewable source against fossil fuels, and the social impact that one installation like the AMP has in the society.

## 5.2. Energy production

The energy that the Alqueva Multipurpose Project can produce is a function of time over which it is able to mobilize a given power.

$$E = \sum (P_u \Delta t) \tag{24}$$

where:

E – Energy [kWh]
$P_u$ – Power [kW]
Δt – Time interval [h]

In Chapter 2, a study of the irrigation needs for the Scenarios A and B are provided. It is obtained the volume of water needs for the irrigation of all the Alqueva irrigation system. With the volume of water needed per year it is calculated the annual flow (see Equation 25):

$$Q_{annual} = \frac{volume\ m^3}{year} \cdot \frac{1\ year}{365\ days} \cdot \frac{1\ day}{24\ hours} \cdot \frac{1 hour}{3600\ s} \tag{25}$$

Regarding the annual installed power, this is calculated as function of the annual flow and the available head of the system. The installed power can be calculated as:

$$P_{annual} = \eta \cdot \rho \cdot g \cdot Q_{annual} \cdot H \tag{26}$$

where:

$P_{annual}$ – Annual installed power [W]
$\eta$ – Efficiency
$\rho$ – Water density [kg/ m$^3$]
$g$ – Gravity acceleration [m/ s$^2$]
$Q_{annual}$ – Annual flow [m$^3$/s]
$H$ – Head [m]

#### 5.2.1. Scenario A - Open irrigation channels

In the open irrigation channels is it possible to produce energy using the Rotary Hydraulic Pressure Machine (RHPM) designed by the HYLOW project in the University of Southampton, UK . In Chapter 4 it is defined the main characteristics and the working point of the RHPM (see Table 14).

**Table 14 - RHPM working point**

| Flow [m$^3$/s] | Efficiency [%] | [kW] |
|---|---|---|
| 0.26 | 76.9 | 2.11 |

Once the discharge needed for irrigation is known, it is easy to determine how many RHPM it is possible to apply to the system and calculate the quantity of energy, (Equation 24), that can be produced based on the working point (see Table 15).

**Table 15 - Energy production RHPM**

| Irrigation needs [m$^3$/s] | Number of RHPM | Installed power [kW] | Energy production [MWh] |
|---|---|---|---|
| 5.70 | 22 | 46.42 | 406.64 |

#### 5.2.2. Scenario B - Pressurized irrigation system

Pressurized irrigation pipes are used by PATs in terms of energy production. Once know the working point of the PAT (see Table 16), the annual installed power is calculated as function of the available head of the system and the annual flow that can be turbined by the PAT.

**Table 16 - PAT working point and energy production**

| Flow [l/s] | Head [m] | Efficiency [%] | Installed power [kW] | Energy production [kWh] |
|---|---|---|---|---|
| 5.72 | 9.6 | 45 | 0.24 | 2124 |

In Table 16 the results for the energy production of the PAT for the area of the case study of the EPANET are shown. As the case study of the pressurized system is not all the Alqueva region, the total irrigation area can produce 2124 MWh by the PAT in the Scenario B.

### 5.3. Environmental benefits

Taking actions to reduce greenhouse gas emissions, they yield important economic benefits. These benefits are from the reduced risk to human health and welfare that results from lower emissions of greenhouse gases and less global warming and consequently climate change contribution.

Since $CO_2$ emissions are one important concern associated with the energy production process, an estimation of benefits of the implementation of an environmental solution based on available data was also analyzed. Hydropower does not burn fossil fuels, nor directly produce $CO_2$. While some carbon dioxide is produced during manufacture and construction of the project, this is a tiny fraction of the operating emissions of equivalent fossil-fuel electricity generation (Ramos et al., 2000).

One measurement of greenhouse gas related and other externality comparison between energy sources can be found in the study realized by Spadaro (2000). In this study it is calculated the total $CO_2$ equivalent emission for different energy sources. In Table 17 this calculus are shown. These include both direct emissions from burning and indirect emissions from the life cycle.

**Table 17 - Grams of $CO_2$ equivalent emission per kWh for different energy sources**

| Energy source | $CO_2$ equivalent emission (g/(kW·h)) | | |
|---|---|---|---|
| | Maximum | Minimum | Average |
| Coal | 1 306 | 966 | 1 136 |
| Gas | 688 | 439 | 564 |
| Solar PV | 280 | 100 | 190 |
| Hydro | 236 | 4 | 120 |
| Wind | 48 | 10 | 29 |
| Nuclear | 21 | 9 | 15 |

The hydropower energy production is not completely $CO_2$ emission-free, and an average of 120 g/(kWh) of $CO_2$ equivalent can be generated, using the average value for hydropower production from Table 17. If the same amount of energy were produced by coal and gas, assuming an average value between the two sources from Table 17, 850 g/(kWh) of $CO_2$ equivalent would be emitted to the atmosphere.

**Table 18 - $CO_2$ released**

| Energy source | Scenario | $CO_2$ equivalent emissions [g/kWh] | MWh produced | $CO_2$ released [kg] |
|---|---|---|---|---|
| Hydro | Scenario A | 120 | 406.64 | 48797 |
| | Scenario B | | 2124 | 254880 |
| Coal and gas | Scenario A | 850 | 406.64 | 345644 |
| | Scenario B | | 2124 | 1805400 |

In Table 18 the results of the $CO_2$ released for each scenario and energy source are presented. It is clear the difference between the hydro energy source against the coal and gas. For the Scenario A, where the energy is produced by the RHPM, the difference of $CO_2$ released by the two energies sources is 296847 kg of $CO_2$. And for the Scenario B, where the energy is produced by the PAT, the difference is 1550520 kg of $CO_2$. These amounts of $CO_2$ that it is not emitted by the implementation of the renewable energies suppose a benefit for the environment and human health, when investing in a sustainable solution.

### 5.4. Social impact

Alqueva Multipurpose Project (AMP) has been for many years the motor of all regional development in Alentejo, a burst of new opportunities and development in the region. A number of both positive and negative social impacts can be evaluated.

The major social impact is the increase in the agricultural land, creating plenty of new opportunities and renewing the agriculture in Alentejo to irrigated crops and opening the doors to agro-industry.

Alqueva has promoted the construction of a number of public works, such as roads, museums, sports facilities, health centers and other public utilities, contributing to the area many more facilities and services. It has also attracted the investment towards the Alentejo area, increasing the employment and the tourisms in the region. This has created an increase in the trade of regional products such as olives, olive oil, wine, cheese, black pork and other animal products.

Although the employment has increased, is important to point out that hardly any local workers were employed in the construction of the dam, a pattern common to major public works.

During the construction of the dam some villages were totally resettled near the reservoir, to the point of maintaining neighborhood relationships. The quality of the buildings and equipments is much better in the new villages, as shown in the Figure 43. It had been an expected thing for many years, and there was no real opposition to the transfer, which was conducted with great care; but it was nevertheless quite traumatic for the people involved. It is curious to note that one of the most difficult issues was the transfer of the graveyard, because of psychological and religious implications.

**Figure 43 - Nova Aldeia da Luz**

The flooding has provoked also the loss of cultural heritage, with the disappearance of hundreds of archaeological sites, including some of the most interesting Paleolithic rock engravings in Portugal and Spain. Many potentially interesting sites are probably lost forever, with superficial signs revealing erased by water and sediment, but the benefit to that region in terms of agriculture and availability of water largely compensate all these losses.

# 6. ECONOMIC ANALYSIS

## 6.1. Introduction

An energy production project must be accompanied by an economic analysis in order to verify its viability. The country's current situation requires that investors should become more discerning in the analysis of economic and financial risks that can arise in a new project.

The final decision on whether or not a small hydropower scheme should be constructed, or the selection among alternative design solutions for the same is generally based on the comparison of the expected costs and benefits for the useful life of the project, by means of economic criteria. The analysis should be performed in the first stages of the design (along with the feasibility study) as nothing ensures that a project suitable from a technical point of view is also advantageous from an economic point of view (Portela et al., 1988).

In order to evaluate the profitability of the project, it should be created several operating systems, making sure that which is the one that leads to more benefits. The profitability of the project is determined by the evaluation of costs and benefits, translated by the economic analysis. This type of analysis includes economic indicators of reference, which make possible calculate the payback time of the investment and profits for the project time horizon.

Ramos (2000) defined that the costs of a small hydropower scheme can be grouped in the three following categories as illustrated in Table 19:

**Table 19 - Costs of a small hydropower scheme**

| | |
|---|---|
| **Capital cost** | Studies and design<br>Supervision during the execution<br>Civil works<br>Equipment<br>Land acquisition<br>Contingencies or unforeseen cost |
| **Annual operation costs** | Exploitation<br>Maintenance<br>Spare parts<br>Grant of permission |
| **Reposition costs** | |

The capital costs **c**an be defined as the sum of all expenditures required to bring the project to completion. These costs occur during the construction period and are composed by the next components (Ramos et al., 2000):

- The studies and design and the supervision costs result from agreements between the investor and the consulting firms.
- The civil work costs are evaluated from the design, by measuring the work quantities relative to the different components of the scheme. To evaluate the equipment costs, budget prices from the suppliers should also be obtained.
- The cost of the acquisition of the land that will be occupied by the scheme depends namely on the land valorization.
- The contingencies or unforeseen cost are the ones that represents expenditures that are possible but not certain or yet foreseen. This costs come from the lack of the information of the project or the site where is going to be constructed. It is important to take them into account because they can have a big impact because the capital costs of the project can raise.

The annual operation costs result from the exploitation and maintenance of the scheme during its useful live. They can be divided as (Portela et al., 1988):

- The exploitation costs are caused by the staff that promotes the use of the system, which in this case is required the permanent presence of the operator.
- The maintenance costs are the costs of maintenance works and equipment, usually evaluated in terms of percentages of investment costs to which they relate.
- The cost of spare parts are the costs with the reposition of the material that is necessary to keep in stock in order to perform the maintenance of the hydropower scheme or to execute small repairs in the same.
- The grant of permission costs occurs once the scheme starts to operate and represent the annual payments due for the scheme license and for the water utilization. In terms of economic analysis they can be treated as fixed percentages of the energy incomes.

The reposition costs are produced by the substitution of the equipment having a useful live lesser than the one of the scheme

Apart from the costs, the project should have some benefits, in order to make it profitable. The revenues are created by the sale of the energy produced to the company in charge of the exploitation of the public net, in this case the EDP.

The main problem of the economic analysis is to conceive a scenario for the future evolution of the inflation (Ramos et al., 2000).

It is defined Cash Flow (CF) for the annual difference between the cost and the benefits. The Net Present Value (NPV) takes into account the time value of money and therefore should be subject to CF at an adjustment factor. This criterion is reflected in the calculation of the sum of annual CF, updated with the discount rate (r).

According to the discount rate concept and as represented in Figure 44, one monetary unit of today will be changed in year n by $(1+r)^n$ monetary units and one monetary unit of year n will be changed today by $1/(1+r)^n$ units.

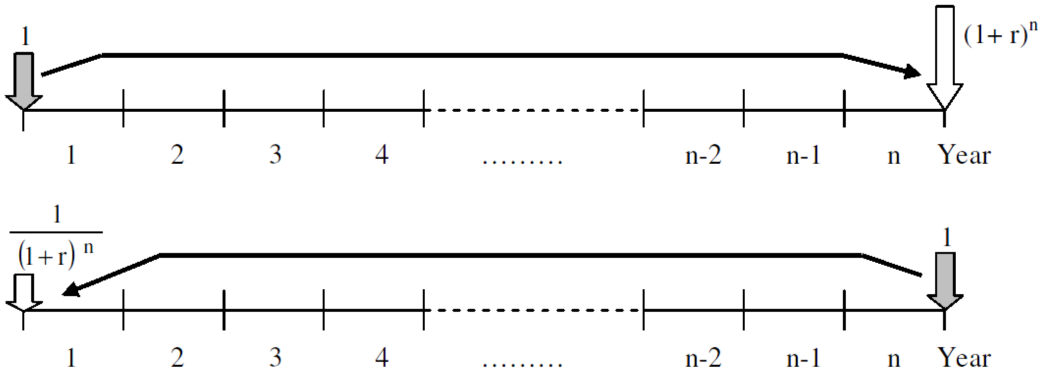



**Figure 44 - Transference of unitary monetary fluxes by means of the discount rate.**

So, to calculate the NPV, it is used the Equation 27:

$$NPV = \sum_{k=0}^{N} \frac{CF_k}{(1+r)^k} \tag{27}$$

where:

$NPV$ – Net Present Value [€]
$CF_k$ – Cash Flow of year K [€]
$N$ – Number of years of the investment project [years]
$r$ – Discount Rate [%]

The Discount Rate is also known for the opportunity cost of capital or minimum rate of project profitability. There is the minimum that investors require to implement an investment project and will serve to update the Cash Flows generated by it.

The higher the Discount Rate is, the lower will be the NPV, since we are demanding a higher return on investment project, so it requires more profitability to be achieved with the implementation of the investment project. The opposite is also true; a project has the higher NPV when the Discount Rate is lower. It is inevitable to analyze the Discount Rate, as estimated in this component linked to the future, by inserting thus an element of uncertainty. It should be pointed out that the discount rate (r) is assumed to be constant during the n years period under analysis.

The Internal Rate of Return (IRR) is the interest rate at which the NPV of all the CF (both positive and negative) from a project or investment equal zero. It represents an interest rate that makes that the invested capital placed at that rate, the final rate of return would have the same value . In other words, it is no more than the discount rate that, at the end of the project life period, equals the NPV to zero. From the moment the profitability of investment projects is known, the decision criteria on investment is to accept those with a higher IRR. With the Equation 28 it is possible to calculate the IRR:

$$NPV = \frac{\sum_{i=1}^{m-n} \frac{1}{(1+IRR)^i}(R_i - O_i)}{(1+IRR)^m} - \sum_{k=0}^{m} \frac{1}{(1+IRR)^i} C_i - \frac{S_i}{(1+IRR)^i} = 0 \tag{28}$$

where:

$C_i$ – Capital costs in year i [€]
$O_i$ – Operation and maintenance costs in year i [€]
$S_i$ – Reposition costs in year i [€]
$R_i$ – Energy revenues in year i [€]
$IRR$ – Internal Rate of Return [%]

In the result of the IRR value, three situations may occur:

- IRR> r: implies that the NPV> 0; the project can generate a rate of return greater than the cost of capital opportunity, so we are facing an economically viable project.
- IRR <r: implies that the NPV <0; the project fails to generate a rate of return greater than the cost of capital opportunity, so we have a project uneconomical.
- IRR=r: Implies that the NPV=0; the project generates a rate of return equal to the cost of capital opportunity.

The index Benefit/Cost (B/C) represents the present value of the wealth generated by the project, by updated source unit used (Portela et al., 1988). This index is defined as the ratio between present values of the net annual benefits and of the capital and reposition costs (Equation 29).

$$\frac{B}{C} = \frac{R-O}{C+S} \tag{29}$$

The B/C parameter has much popular appeal since it gives an immediate indication of the “degree” of desirability of a project. If the B/C is less than one, the project is unprofitable. If it is exactly one the project has a marginal interest and if it is greater than one, its implementation would seem justified and as much as B/C is higher.

The payback period or recovery period (T), can be defined either on a discounted or without discount basis and represents the number of years it takes before cumulative forecasted cash flows equal the initial investment. Its value is provided by the year when the cumulative cash flow changes from a negative value to a positive value.

In this study the period of economic analysis is 20 years. The analysis is performed based on the Constant Market Price System referred to the year of start-up. This system prevents, to some extent, consideration inflation assuming that it affects equally all project components (Portela, 1988).

## 6.2. Economic analysis

Once we have the installed power, it is important to calculate the price to implement this power. The Total Investment Costs (TIC) is the total money that needs to be invested for the production of a certain power. The TIC (Equation 30), is just the multiplication of the Installed Cost (IC) for the power.

$$TIC = P \cdot IC \quad \textbf{(30)}$$

where:

$TIC$ – Total Investment Costs [€]
$P$ – Installed power [kW]
$IC$ – Installed Cost [€/kW]

**Table 20 - Installed Cost (adapted from Frantzis, 2009)**

| Hydropower Technology | MW Range | Installed Cost (€/kW) |
|---|---|---|
| Conventional Hydro (impoundment) | 50 (average) | 900 - 4490 |
| Micro-hydro | < 0.1 | 3590 - 5390 |
| Run of River (diversion) | Approx. 10 | 1350 - 5390 |
| Pumped Storage | >500 | 910 - 4040 |

In Table 20 it is shown the Installed Cost (IC) for different hydropower technologies. As in this thesis micro-hydropower is the energy source, is taken the IC range value of 3590 to 5390 €/kW.

Applying the Equation 31, it is obtained the total energy produced, multiplying this energy for the unit cost of energy it is obtained the Gross benefit (GB):

$$GB = Energy \cdot c \quad \textbf{(31)}$$

where:

$GB$ – Gross Benefit [€]
$c$ – Unit cost of energy [€ / kWh]

For lack of information on remuneration schemes applied to micro-hydropower, was defined as the price of energy sales or unit cost of energy (c) of 0.11, 0.125 and 0.15 €/kWh. A sensitivity analysis of the obtained results is made.

To obtain the Net benefit (NB) it is necessary to multiply the GB for the percentage of benefits that it is obtained from that quantity of money:

$$NB = \eta \cdot GB \tag{32}$$

where:

$NB$ – Net Benefit [€]
$\eta$ – Percentage [%]
$GB$ – Gross Benefit [€]

Due to the time value of money, to calculate the NB updated, it is necessary first to define the factor update (F) as:

$$F = \left( \frac{1 - \frac{1}{(1+r)^n}}{1 + \frac{1}{1+r}} \right) \tag{33}$$

where:

$F$ – Factor update [-]
$r$ – Discount rate [%]
$n$ – Number of years [years]

Multiplying the NB for the factor update the NB updated is obtained:

$$NB_{updated} = F \cdot NB \tag{34}$$

The Benefit/Cost ratio (B/C) is calculated as:

$$B/C = \frac{NB_{updated}}{TIC} \tag{35}$$

and finally, to know which is the Cash Flow of the year, we have to make the rest between the NB updated minus the TIC:

$$Cash\ Flow = NB_{updated} - TIC \tag{36}$$

A more detailed economic analysis of the two different scenarios is made, to see the viability of the different MHP solution used to produce the energy. The cost of both Scenarios was determined based on previous studies of similar systems and information provided by the hydrodynamic companies (Ramos, 2010; Calado, 2014; KSB, 2015; Schneider, 2015; Wiemann, 2008; Frantzis, 2009; EDIA, 2015, COTR, 2015)

### 6.2.1. Scenario A - Open irrigation channels

In the Scenario A, the rotary hydraulic pressure machines designed by HYLOW project make the energy production. For this case it is easy to make the economic analysis in order to determine if it is a profitable option.

The economic analysis is presented with more detail in the Appendix B. In the Table 21 it is possible to observe a resume of the NPV, the IRR, the B/C and the Payback of the Scenario A for different discount rates and unit costs of energy.

**Table 21 - Resume table of the economic analysis of the Scenario A**

| €/kWh | 0.15 | | | 0.125 | | | 0.11 | | |
|---|---|---|---|---|---|---|---|---|---|
| IRR (%) | 25.27 % | | | 20.68 % | | | 17.82 % | | |
| Discount rate (r) | 2.00% | 6.00% | 8.00% | 2.00% | 6.00% | 8.00% | 2.00% | 6.00% | 8.00% |
| NPV (€) | 702498 | 412977 | 317696 | 539529 | 302974 | 225279 | 441748 | 236972 | 169828 |
| F | 16.68 | 12.16 | 10.60 | 16.68 | 12.16 | 10.60 | 16.68 | 12.16 | 10.60 |
| B/C (-) | 4.574 | 3.434 | 3.038 | 3.755 | 2.819 | 2.494 | 3.263 | 2.450 | 2.167 |
| Payback (years) | 4 | 5 | 5 | 5 | 6 | 6 | 6 | 7 | 8 |

In general, the results are quite interesting. In any analysis the IRR is always greater than the discount rate. There is not in any case a negative NPV value or index B/C below the unit. The payback period is really small, so what is really desirable in terms of viability and economic benefits. For the worst case, with the sale of kWh as 0.11 €, the payback period is 8 years for a 8% discount rate, what it is still a really small payback period, so the Scenario A with the incorporation of the RHPM to produce energy is viable.

### 6.2.2. Scenario B - Pressurized irrigation system

For the pressurized irrigation system the PATs are the responsible of producing the electricity and so the economic benefits.

The economic analysis is presented with more detail in the Appendix C. In the Table 22 it is possible to observe a resume of the NPV, the IRR, the B/C and the Payback of the Scenario B, with a sensitive analysis for different discount rates and unit costs of energy:

**Table 22 - Resume table of the economic analysis of the Scenario B**

| €/kWh | 0.15 | | | 0.125 | | | 0.11 | | |
|---|---|---|---|---|---|---|---|---|---|
| IRR (%) | 23.34 % | | | 18.80 % | | | 15.97 % | | |
| Discount rate (r) | 2.00% | 6.00% | 8.00% | 2.00% | 6.00% | 8.00% | 2.00% | 6.00% | 8.00% |
| NPV (€) | 3451953 | 1988822 | 1508810 | 2604279 | 1416649 | 1028105 | 2095675 | 1073345 | 739682 |
| F | 17.35 | 12.47 | 10.82 | 17.35 | 12.47 | 10.82 | 17.35 | 12.47 | 10.82 |
| B/C (-) | 4.259 | 3.171 | 2.799 | 3.479 | 2.591 | 2.286 | 3.011 | 2.242 | 1.979 |
| Payback (years) | 5 | 5 | 6 | 6 | 7 | 7 | 7 | 8 | 9 |

The results obtained in the Scenario B are also very promising. The IRR is always greater than the discount rate. The payback period is smaller when the energy is sold at 0.15 €/kWh with the best case of 5 years payback period for a discount rate of 2% and 6%. In the other hand, the worst case is with a discount rate of 8% and energy revenues of 0.11 €/kWh where the payback period is 9 years. The NPV is never negative and the B/C ratio is always higher than the unit. The energy production with PATs in the pressurized irrigation system of the Alqueva Multipurpose Project turns to be feasible.

# 7. CONCLUSIONS AND FUTURE WORK

## 7.1. General considerations

Due to high world energy dependence, particularly to countries with no oil or coal, to seek new alternative methods of energy production irrigation systems (or water supply systems) can be a new base solution of the utmost importance. This study seeks to determine the hydraulic and economic feasibility of installing Rotary Hydraulic Pressure Machines (RHPM) and pumps operating as turbines (PAT) in irrigation systems, particularly in the irrigation network of the Alqueva Multipurpose Project (AMP).

To reach the main objective of this work, a comprehensive methodology was developed to evaluate the implementation of micro-hydropower solutions in water existing networks, taking into account factors associated to technological developments the economy, the social-demography, the climate and government policies.

Using the EPANET model and the data provided by EDIA and COTR, an analysis of the studied area was developed, in order to define the main hydraulic parameters. It was also important to analyze the different MHP solutions to know the variables that affect them in order to seek maximum efficiency.

This methodology was applied to two case studies of irrigation water distribution systems. One composed by open irrigation channels and another by pressurized irrigation system. In the open irrigation channels was applied the Rotary Hydraulic Pressure Machine (RHPM) developed at the University of Southampton in the UK for the energy production. In the pressurized irrigation system the PAT Etanorm 160.1-32 developed by KSB was applied .

Results show that a large potential for energy recovery or production in irrigation water distribution systems exist as well as the feasibility of implementing micro-hydropower solutions in water systems. In the two scenarios studied the economic analysis is positive and promising with great benefits after each payback period.

The study comprised the major components associated with the micro power generation and irrigation systems helping on how to promote clean energy without carbon emissions in hydraulic systems with a guaranteed almost 24 hour flow.

## 7.2. Future developments

In the present work was carried out a full analysis of the technical and economic feasibility of the implementation of MHP in a water irrigation distribution network in two different scenarios. The initial conditions of low flow rate and low head caused constraints in the choice of a MHP solution for the scenario of pressurized system. In order to strengthen this methodology the following proposals for future work is suggested:

- The extension of the irrigation water consumption by adding more variables, such as differences in consumption regarding the hours of the day.
- The incorporation of water losses.
- Improves in the simulation by EPANET taking into consideration variable water demand along the day and the year.

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## APPENDIX A - Specifications ETANORM 32-160.1

### Structure and method of operation:

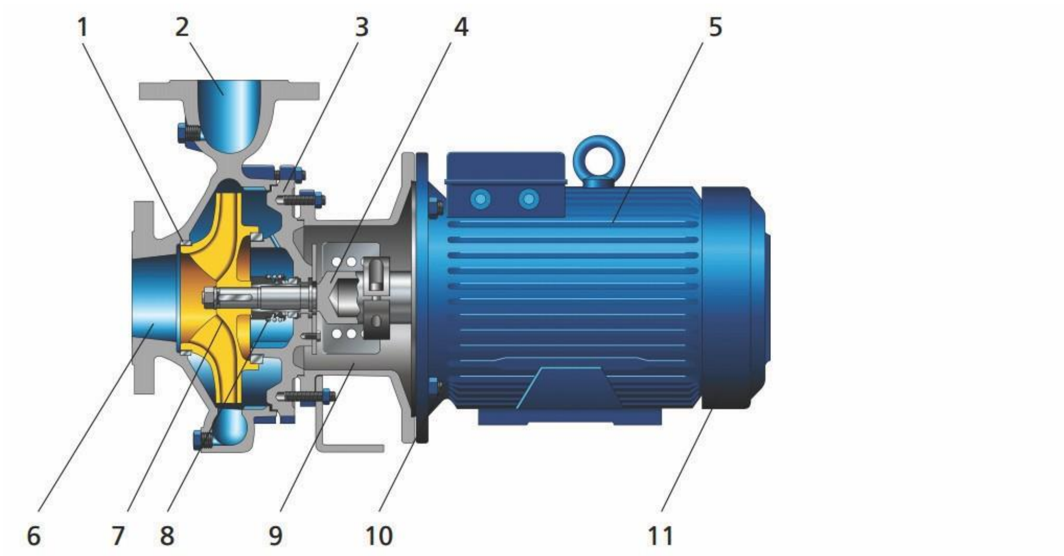
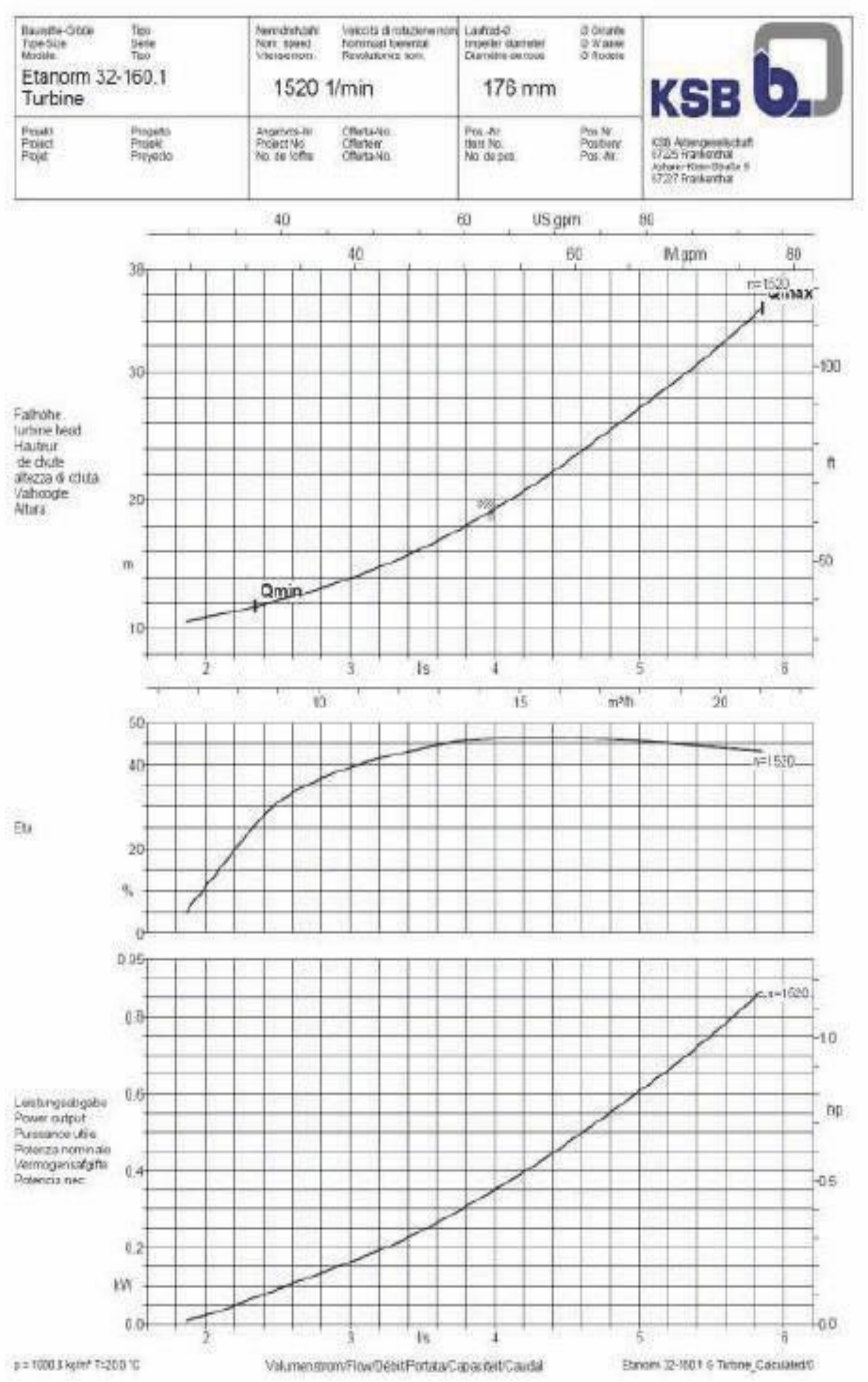



**Table 23 - Cutting scheme**

| | | | |
|---|---|---|---|
| 1 | Tolerance | 2 | Nozzle |
| 3 | Housing cover | 4 | Shaft |
| 5 | Motor casing | 6 | Pump suction pipe |
| 7 | Impeller | 8 | Shaft seal |
| 9 | Drive flashlight | 10 | Roller bearing |
| 11 | Roller bearing | | |

The pumped fluid enters the pump through the pump suction pipe (6) and is accelerated outward by the impeller (7). At the edge of the pump body current, the kinetic energy of the pumped fluid is transformed into pressure energy and the pumped fluid is led to the discharge nozzle (2) through which exits the pump. It prevented the return of the pumped fluid from the body to the suction pipe of the pump via a tolerance (1). The hydraulic system is limited, the back side of the impeller, a housing cover (3), through which the shaft (4) passes. The passage of the shaft by the cap is sealed to the environment through a dynamic shaft seal (8). The shaft is housed in roller bearings (10 and 11), which in turn are housed in a motor casing (5), which is connected to the casing or housing cover (3) through the drive flashlight (9).

**Characteristic curve and installation plan:**



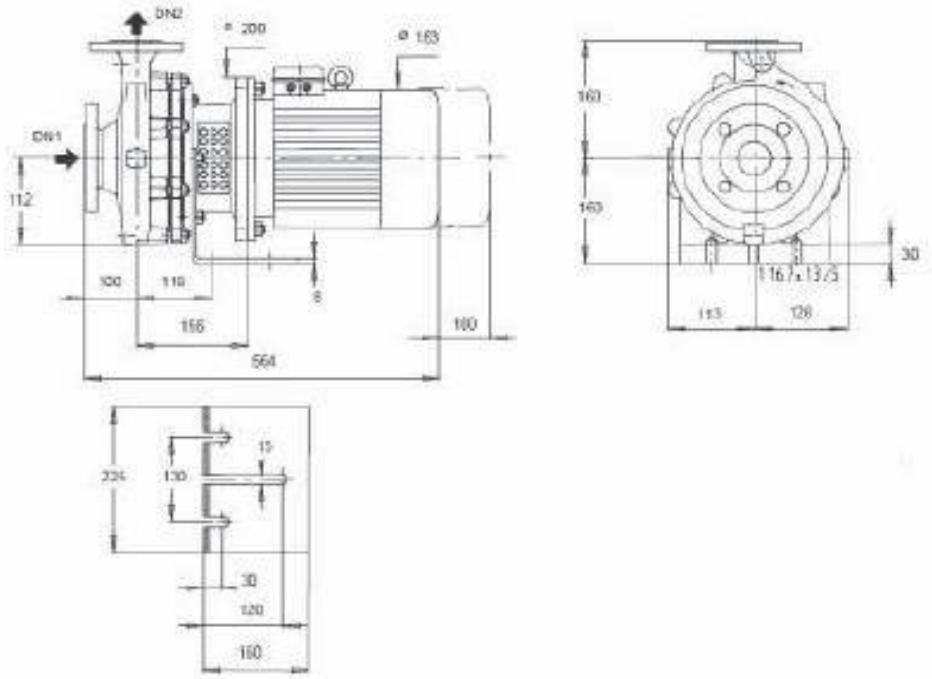
## Installation plan

Customer item no.:Customer item (pump)
Order dated: 29/06/2009
Order no.: Technical University of Lisbon
Quantity: 1

Number:
Item no.: 200
Date: 29/06/2009
Page: 1 / 2

Version no.: 1

**Etabloc GN 050-125/154 G11**
Close-coupled pump




*Drawing is not to scale*

*Dimensions in mm*

**Motor**

| | |
|---|---|
| Motor manufacturer | KSB |
| Motor size | 90L |
| Motor power | 1.50 kW |
| Speed of rotation | 1440 rpm |
| Position of terminal box | 0°/360° (top) |

**Connections**

| | |
|---|---|
| Suction nominal size DN1 | DN 65 / EN 1092-2 |
| Discharge nominal size DN2 | DN 50 / EN 1092-2 |
| Nominal pressure suct. | PN 16 |
| Rated pressure disch. | PN 16 |

Flanges DN 65 will be drilled with 4 holes

**Weight net**

| | |
|---|---|
| Pump | 32 kg |
| Motor | 18 kg |
| Total | 50 kg |

**Connect pipes without stress or strain!**

| | |
|---|---|
| Dimensional tolerances for shaft axis height: | DIN 747 |
| Dimensions without tolerances, middle tolerances to: | ISO 2768-m |
| Connection dimensions for pumps: | EN735 |
| Dimensions without tolerances - welded parts: | ISO 13920-B |
| Dimensions without tolerances - gray cast iron parts: | ISO 8062-CT9 |

**For auxiliary connections see separate drawing.**

# APPENDIX B – Economic analysis RHPM (Scenario A)

| CAPITAL COSTS (€) | YEAR -2 | YEAR -1 | YEAR 1 | …. | | …. | YEAR 10 | …. | YEAR 20 |
|---|---|---|---|---|---|---|---|---|---|
| 1 - Studies and designs (2/3 + 1/3) | 2000 | 1000 | | | | | | | |
| 2 - Supervision and consultancy (1/3 + 2/3) | 5000 | 10000 | | | | | | | |
| 3 - Civil works, cw **(30% year -2 + 70% year -1)** | | | | | | | | | |
| 3.1 - Adaptation works | 30000 | 70000 | | | | | | | |
| TOTAL PARCIAL | 30000 | 70000 | | | | | | | |
| 4 - Equipment, eq | | | | | | | | | |
| 4.1 - Hydromechanic equipment | | 77000 | | | | | | | |
| TOTAL PARCIAL | | 77000 | | | | | | | |
| 6 - Land adquisition | 0 | 0 | | | | | | | |
| 7 - Contingencies or unforeseen cost (15.0% cw; **70% year -2 + 30% year -1**) | 10500 | 4500 | | | | | | | |
| **TOTAL CAPITAL COSTS (€)** | 47500 | 162500 | | | | | | | |
| **OPERATION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| 1 - Operation, care and maintenance | | | | | | | | | |
| 1.1 - Operating costs | | | | ... | | ... | | ... | |
| 1.2 - Conservation / maintenance construction (1.0% cw) | -- | -- | 1000 | | | | 1000 | | 1000 |
| 1.3 - Conservation / maintenance equipment (2.5% eq) | -- | -- | 1925 | | | | 1925 | | 1925 |
| 2 - Administrative costs ( 7500€ / MW) | -- | -- | 348 | | | | 348 | | 348 |
| **TOTAL OPERATION COSTS (€/years)** | | | 3273 | | | | 3273 | | 3273 |
| **REPOSITION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| TOTAL REPOSITION COSTS (€/years) | | | 1000 | | | | 1000 | | 1000 |
| **ENERGY REVENUES (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| 1 - Energy production | | | | | | | | | |
| 1.1 - Average annual production (GWh) | -- | -- | 0.41 | | | | 0.41 | | 0.41 |
| 1.2 - kWh value (€ / kWh) | -- | -- | 0.150 | …. | | …. | 0.150 | …. | 0.150 |
| 1.3 - Value of average annual production (€ / year) | -- | -- | 60996 | | | | 60996 | | 60996 |

| **IRR (%)** | **25.27%** | | |
|---|---|---|---|
| | **Discount rate (r)** | | |
| | 2.0% | 6.0% | 8.0% |
| **NPV (€)** | **702498** | **412977** | **317696** |
| **F** | **16.68** | **12.16** | **10.60** |
| **B/C (-)** | **4.574** | **3.434** | **3.038** |
| **Year** | TOTAL CASH FLOW UPDATED | | |
| -2 | -47500 | -47500 | -47500 |
| -1 | -206814 | -200802 | -197963 |
| 1 | -152294 | -150319 | -149332 |
| 2 | -98843 | -102693 | -104304 |
| 3 | -46439 | -57764 | -62611 |
| 4 | 4936 | -15377 | -24007 |
| 5 | 55304 | 24610 | 11738 |
| 6 | 104685 | 62334 | 44836 |
| 7 | 153097 | 97923 | 75481 |
| 8 | 200560 | 131497 | 103857 |
| 9 | 247092 | 163170 | 130130 |
| 10 | 292712 | 193051 | 154458 |
| 11 | 337438 | 221241 | 176983 |
| 12 | 381286 | 247834 | 197840 |
| 13 | 424275 | 272923 | 217152 |
| 14 | 466421 | 296591 | 235033 |
| 15 | 507740 | 318920 | 251590 |
| 16 | 548250 | 339985 | 266920 |
| 17 | 587965 | 359857 | 281115 |
| 18 | 626901 | 378605 | 294258 |
| 19 | 665074 | 396291 | 306428 |
| 20 | 702498 | 412977 | 317696 |

| CAPITAL COSTS (€) | YEAR -2 | YEAR -1 | YEAR 1 | …. | | …. | YEAR 10 | …. | YEAR 20 |
|---|---|---|---|---|---|---|---|---|---|
| 1 - Studies and designs (2/3 + 1/3) | 2000 | 1000 | | | | | | | |
| 2 - Supervision and consultancy (1/3 + 2/3) | 5000 | 10000 | | | | | | | |
| 3 - Civil works, cw **(30% year -2 + 70% year -1)** | | | | | | | | | |
| 3.1 - Adaptation works | 30000 | 70000 | | | | | | | |
| TOTAL PARCIAL | 30000 | 70000 | | | | | | | |
| 4 - Equipment, eq | | | | | | | | | |
| 4.1 - Hydromechanic equipment | | 77000 | | | | | | | |
| TOTAL PARCIAL | | 77000 | | | | | | | |
| 6 - Land adquisition | 0 | 0 | | | | | | | |
| 7 - Contingencies or unforeseen cost (15.0% cw; **70% year -2 + 30% year -1**) | 10500 | 4500 | | | | | | | |
| **TOTAL CAPITAL COSTS (€)** | 47500 | 162500 | | | | | | | |
| **OPERATION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| 1 - Operation, care and maintenance | | | | | | | | | |
| 1.1 - Operating costs | | | | ... | | ... | | ... | |
| 1.2 - Conservation / maintenance construction (1.0% cw) | -- | -- | 1000 | | | | 1000 | | 1000 |
| 1.3 - Conservation / maintenance equipment (2.5% eq) | -- | -- | 1925 | | | | 1925 | | 1925 |
| 2 - Administrative costs ( 7500€ / MW) | -- | -- | 348 | | | | 348 | | 348 |
| **TOTAL OPERATION COSTS (€/years)** | | | 3273 | | | | 3273 | | 3273 |
| **REPOSITION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| TOTAL REPOSITION COSTS (€/years) | | | 1000 | | | | 1000 | | 1000 |
| **ENERGY REVENUES (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| 1 - Energy production | | | | | | | | | |
| 1.1 - Average annual production (GWh) | -- | -- | 0.41 | | | | 0.41 | | 0.41 |
| 1.2 - kWh value (€ / kWh) | -- | -- | 0.125 | …. | | …. | 0.125 | …. | 0.125 |
| 1.3 - Value of average annual production (€ / year) | -- | -- | 50830 | | | | 50830 | | 50830 |

| **IRR (%)** | **20.68%** | | |
|---|---|---|---|
| | **Discount rate (r)** | | |
| | 2.0% | 6.0% | 8.0% |
| **NPV (€)** | **539529** | **302974** | **225279** |
| **F** | **16.68** | **12.16** | **10.60** |
| **B/C (-)** | **3.755** | **2.819** | **2.494** |
| **Year** | TOTAL CASH FLOW UPDATED | | |
| -2 | -47500 | -47500 | -47500 |
| -1 | -206814 | -200802 | -197963 |
| 1 | -162065 | -159367 | -158048 |
| 2 | -118193 | -120277 | -121090 |
| 3 | -75182 | -83399 | -86869 |
| 4 | -33014 | -48609 | -55183 |
| 5 | 8327 | -15789 | -25845 |
| 6 | 48857 | 15174 | 1321 |
| 7 | 88593 | 44384 | 26474 |
| 8 | 127550 | 71941 | 49764 |
| 9 | 165742 | 97938 | 71329 |
| 10 | 203186 | 122464 | 91296 |
| 11 | 239896 | 145601 | 109784 |
| 12 | 275886 | 167429 | 126903 |
| 13 | 311170 | 188021 | 142754 |
| 14 | 345762 | 207447 | 157430 |
| 15 | 379676 | 225774 | 171020 |
| 16 | 412926 | 243064 | 183603 |
| 17 | 445523 | 259375 | 195254 |
| 18 | 477481 | 274762 | 206041 |
| 19 | 508812 | 289279 | 216030 |
| 20 | 539529 | 302974 | 225279 |

| CAPITAL COSTS (€) | YEAR -2 | YEAR -1 | YEAR 1 | .... | | .... | YEAR 10 | .... | YEAR 20 |
|---|---|---|---|---|---|---|---|---|---|
| 1 - Studies and designs (2/3 + 1/3) | 2000 | 1000 | | | | | | | |
| 2 - Supervision and consultancy (1/3 + 2/3) | 5000 | 10000 | | | | | | | |
| 3 - Civil works, cw **(30% year -2 + 70% year -1)** | | | | | | | | | |
| 3.1 - Adaptation works | 30000 | 70000 | | | | | | | |
| TOTAL PARCIAL | 30000 | 70000 | | | | | | | |
| 4 - Equipment, eq | | | | | | | | | |
| 4.1 - Hydromechanic equipment | | 77000 | | | | | | | |
| TOTAL PARCIAL | | 77000 | | | | | | | |
| 6 - Land adquisition | 0 | 0 | | | | | | | |
| 7 - Contingencies or unforeseen cost (15.0% cw; **70% year -2 + 30% year -1**) | 10500 | 4500 | | | | | | | |
| **TOTAL CAPITAL COSTS (€)** | 47500 | 162500 | | | | | | | |
| **OPERATION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **....** | | **....** | **YEAR 10** | **....** | **YEAR 20** |
| 1 - Operation, care and maintenance | | | | | | | | | |
| 1.1 - Operating costs | | | | ... | | ... | | ... | |
| 1.2 - Conservation / maintenance construction (1.0% cw) | -- | -- | 1000 | | | | 1000 | | 1000 |
| 1.3 - Conservation / maintenance equipment (2.5% eq) | -- | -- | 1925 | | | | 1925 | | 1925 |
| 2 - Administrative costs ( 7500€ / MW) | -- | -- | 348 | | | | 348 | | 348 |
| **TOTAL OPERATION COSTS (€/years)** | | | 3273 | | | | 3273 | | 3273 |
| **REPOSITION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **....** | | **....** | **YEAR 10** | **....** | **YEAR 20** |
| TOTAL REPOSITION COSTS (€/years) | | | 1000 | | | | 1000 | | 1000 |
| **ENERGY REVENUES (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **....** | | **....** | **YEAR 10** | **....** | **YEAR 20** |
| 1 - Energy production | | | | | | | | | |
| 1.1 - Average annual production (GWh) | -- | -- | 0.41 | | | | 0.41 | | 0.41 |
| 1.2 - kWh value (€ / kWh) | -- | -- | 0.110 | .... | | .... | 0.110 | .... | 0.110 |
| 1.3 - Value of average annual production (€ / year) | -- | -- | 44730 | | | | 44730 | | 44730 |

| **IRR (%)** | **17.82%** | | |
|---|---|---|---|
| | **Discount rate (r)** | | |
| | 2.0% | 6.0% | 8.0% |
| **NPV (€)** | **441748** | **236972** | **169828** |
| **F** | **16.68** | **12.16** | **10.60** |
| **B/C (-)** | **3.263** | **2.450** | **2.167** |
| **Year** | TOTAL CASH FLOW UPDATED | | |
| -2 | -47500 | -47500 | -47500 |
| -1 | -206814 | -200802 | -197963 |
| 1 | -167928 | -164795 | -163277 |
| 2 | -129804 | -130827 | -131161 |
| 3 | -92428 | -98781 | -101424 |
| 4 | -55784 | -68549 | -73890 |
| 5 | -19860 | -40028 | -48395 |
| 6 | 15361 | -13122 | -24788 |
| 7 | 49891 | 12262 | -2931 |
| 8 | 83743 | 36208 | 17308 |
| 9 | 116932 | 58799 | 36048 |
| 10 | 149470 | 80112 | 53399 |
| 11 | 181371 | 100218 | 69465 |
| 12 | 212645 | 119185 | 84341 |
| 13 | 243307 | 137080 | 98115 |
| 14 | 273367 | 153961 | 110869 |
| 15 | 302838 | 169887 | 122678 |
| 16 | 331731 | 184911 | 133612 |
| 17 | 360057 | 199085 | 143737 |
| 18 | 387828 | 212457 | 153111 |
| 19 | 415055 | 225071 | 161791 |
| 20 | 441748 | 236972 | 169828 |

## APPENDIX C – Economic analysis PAT (Scenario B)

| **CAPITAL COSTS (€)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
|---|---|---|---|---|---|---|---|---|---|
| 1 - Studies and designs (2/3 + 1/3) | 2000 | 1000 | | | | | | | |
| 2 - Supervision and consultancy (1/3 + 2/3) | 5000 | 10000 | | | | | | | |
| 3 - Civil works, cw **(30% year -2 + 70% year -1)** | | | | | | | | | |
| 3.1 - Adaptation works | 60000 | 140000 | | | | | | | |
| TOTAL PARCIAL | 60000 | 140000 | | | | | | | |
| 4 - Equipment, eq | | | | | | | | | |
| 4.1 - Hydromechanic equipment | | 950000 | | | | | | | |
| TOTAL PARCIAL | | 950000 | | | | | | | |
| 6 - Land adquisition | 0 | 0 | | | | | | | |
| 7 - Contingencies or unforeseen cost (15.0% cw; **70% year -2 + 30% year -1**) | 21000 | 9000 | | | | | | | |
| **TOTAL CAPITAL COSTS (€)** | 88000 | 1110000 | | | | | | | |
| **OPERATION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| 1 - Operation, care and maintenance | | | | | | | | | |
| 1.1 - Operating costs | | | | ... | | ... | | ... | |
| 1.2 - Conservation / maintenance construction (1.0% cw) | -- | -- | 2000 | | | | 2000 | | 2000 |
| 1.3 - Conservation / maintenance equipment (2.5% eq) | -- | -- | 23750 | | | | 23750 | | 23750 |
| 2 - Administrative costs ( 7500€ / MW) | -- | -- | 1811 | | | | 1811 | | 1811 |
| **TOTAL OPERATION COSTS (€/years)** | | | 27561 | | | | 27561 | | 27561 |
| **REPOSITION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| TOTAL REPOSITION COSTS (€/years) | | | 1000 | | | | 1000 | | 1000 |
| **ENERGY REVENUES (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| 1 - Energy production | | | | | | | | | |
| 1.1 - Average annual production (GWh) | -- | -- | 2.12 | | | | 2.12 | | 2.12 |
| 1.2 - kWh value (€ / kWh) | -- | -- | 0.150 | .... | | .... | 0.150 | .... | 0.150 |
| 1.3 - Value of average annual production (€ / year) | -- | -- | 317267 | | | | 317267 | | 317267 |

| **IRR (%)** | **23.34%** | | |
|---|---|---|---|
| | **Discount rate (r)** | | |
| | 2.0% | 6.0% | 8.0% |
| **NPV (€)** | **3451953** | **1988822** | **1508810** |
| **F** | **17.35** | **12.47** | **10.82** |
| **B/C (-)** | **4.259** | **3.171** | **2.799** |
| **Year** | TOTAL CASH FLOW UPDATED | | |
| -2 | -88000 | -88000 | -88000 |
| -1 | -1176235 | -1135170 | -1115778 |
| 1 | -898740 | -878223 | -868259 |
| 2 | -626687 | -635820 | -639075 |
| 3 | -359967 | -407138 | -426868 |
| 4 | -98477 | -191400 | -230380 |
| 5 | 157885 | 12126 | -48446 |
| 6 | 409221 | 204132 | 120011 |
| 7 | 655628 | 385269 | 275990 |
| 8 | 897204 | 556154 | 420414 |
| 9 | 1134043 | 717365 | 554141 |
| 10 | 1366239 | 869452 | 677962 |
| 11 | 1593881 | 1012930 | 792611 |
| 12 | 1817060 | 1148286 | 898767 |
| 13 | 2035863 | 1275981 | 997060 |
| 14 | 2250376 | 1396448 | 1088072 |
| 15 | 2460682 | 1510096 | 1172343 |
| 16 | 2666865 | 1617311 | 1250371 |
| 17 | 2869005 | 1718457 | 1322619 |
| 18 | 3067181 | 1813878 | 1389516 |
| 19 | 3261472 | 1903898 | 1451457 |
| 20 | 3451953 | 1988822 | 1508810 |

| CAPITAL COSTS (€) | YEAR -2 | YEAR -1 | YEAR 1 | …. | | …. | YEAR 10 | …. | YEAR 20 |
|---|---|---|---|---|---|---|---|---|---|
| 1 - Studies and designs (2/3 + 1/3) | 2000 | 1000 | | | | | | | |
| 2 - Supervision and consultancy (1/3 + 2/3) | 5000 | 10000 | | | | | | | |
| 3 - Civil works, cw **(30% year -2 + 70% year -1)** | | | | | | | | | |
| 3.1 - Adaptation works | 60000 | 140000 | | | | | | | |
| TOTAL PARCIAL | 60000 | 140000 | | | | | | | |
| 4 - Equipment, eq | | | | | | | | | |
| 4.1 - Hydromechanic equipment | | 950000 | | | | | | | |
| TOTAL PARCIAL | | 950000 | | | | | | | |
| 6 - Land adquisition | 0 | 0 | | | | | | | |
| 7 - Contingencies or unforeseen cost (15.0% cw; **70% year -2 + 30% year -1**) | 21000 | 9000 | | | | | | | |
| **TOTAL CAPITAL COSTS (€)** | 88000 | 1110000 | | | | | | | |
| **OPERATION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| 1 - Operation, care and maintenance | | | | | | | | | |
| 1.1 - Operating costs | | | | ... | | ... | | ... | |
| 1.2 - Conservation / maintenance construction (1.0% cw) | -- | -- | 2000 | | | | 2000 | | 2000 |
| 1.3 - Conservation / maintenance equipment (2.5% eq) | -- | -- | 23750 | | | | 23750 | | 23750 |
| 2 - Administrative costs ( 7500€ / MW) | -- | -- | 1811 | | | | 1811 | | 1811 |
| **TOTAL OPERATION COSTS (€/years)** | | | 27561 | | | | 27561 | | 27561 |
| **REPOSITION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| TOTAL REPOSITION COSTS (€/years) | | | 1000 | | | | 1000 | | 1000 |
| **ENERGY REVENUES (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| 1 - Energy production | | | | | | | | | |
| 1.1 - Average annual production (GWh) | -- | -- | 2.12 | | | | 2.12 | | 2.12 |
| 1.2 - kWh value (€ / kWh) | -- | -- | 0.125 | .... | | .... | 0.125 | .... | 0.125 |
| 1.3 - Value of average annual production (€ / year) | -- | -- | 264389 | | | | 264389 | | 264389 |

| **IRR (%)** | **18.80%** | | |
|---|---|---|---|
| | **Discount rate (r)** | | |
| | 2.0% | 6.0% | 8.0% |
| **NPV (€)** | **2604279** | **1416649** | **1028105** |
| **F** | **17.35** | **12.47** | **10.82** |
| **B/C (-)** | **3.479** | **2.591** | **2.286** |
| **Year** | TOTAL CASH FLOW UPDATED | | |
| -2 | -88000 | -88000 | -88000 |
| -1 | -1176235 | -1135170 | -1115778 |
| 1 | -949565 | -925284 | -913593 |
| 2 | -727339 | -727278 | -726386 |
| 3 | -509470 | -540480 | -553045 |
| 4 | -295874 | -364256 | -392544 |
| 5 | -86465 | -198007 | -243933 |
| 6 | 118837 | -41167 | -106329 |
| 7 | 320114 | 106794 | 21081 |
| 8 | 517444 | 246380 | 139054 |
| 9 | 710905 | 378065 | 248288 |
| 10 | 900573 | 502296 | 349430 |
| 11 | 1086522 | 619496 | 443081 |
| 12 | 1268824 | 730061 | 529794 |
| 13 | 1447553 | 834368 | 610084 |
| 14 | 1622776 | 932771 | 684427 |
| 15 | 1794564 | 1025603 | 753263 |
| 16 | 1962984 | 1113182 | 817000 |
| 17 | 2128101 | 1195802 | 876016 |
| 18 | 2289980 | 1273747 | 930660 |
| 19 | 2448686 | 1347279 | 981256 |
| 20 | 2604279 | 1416649 | 1028105 |

| CAPITAL COSTS (€) | YEAR -2 | YEAR -1 | YEAR 1 | …. | | …. | YEAR 10 | …. | YEAR 20 |
|---|---|---|---|---|---|---|---|---|---|
| 1 - Studies and designs (2/3 + 1/3) | 2000 | 1000 | | | | | | | |
| 2 - Supervision and consultancy (1/3 + 2/3) | 5000 | 10000 | | | | | | | |
| 3 - Civil works, cw **(30% year -2 + 70% year -1)** | | | | | | | | | |
| 3.1 - Adaptation works | 60000 | 140000 | | | | | | | |
| TOTAL PARCIAL | 60000 | 140000 | | | | | | | |
| 4 - Equipment, eq | | | | | | | | | |
| 4.1 - Hydromechanic equipment | | 950000 | | | | | | | |
| TOTAL PARCIAL | | 950000 | | | | | | | |
| 6 - Land adquisition | 0 | 0 | | | | | | | |
| 7 - Contingencies or unforeseen cost (15.0% cw; **70% year -2 + 30% year -1**) | 21000 | 9000 | | | | | | | |
| **TOTAL CAPITAL COSTS (€)** | 88000 | 1110000 | | | | | | | |
| **OPERATION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| 1 - Operation, care and maintenance | | | | | | | | | |
| 1.1 - Operating costs | | | | ... | | ... | | ... | |
| 1.2 - Conservation / maintenance construction (1.0% cw) | -- | -- | 2000 | | | | 2000 | | 2000 |
| 1.3 - Conservation / maintenance equipment (2.5% eq) | -- | -- | 23750 | | | | 23750 | | 23750 |
| 2 - Administrative costs ( 7500€ / MW) | -- | -- | 1811 | | | | 1811 | | 1811 |
| **TOTAL OPERATION COSTS (€/years)** | | | 27561 | | | | 27561 | | 27561 |
| **REPOSITION COSTS (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| TOTAL REPOSITION COSTS (€/years) | | | 1000 | | | | 1000 | | 1000 |
| **ENERGY REVENUES (€/year)** | **YEAR -2** | **YEAR -1** | **YEAR 1** | **….** | | **….** | **YEAR 10** | **….** | **YEAR 20** |
| 1 - Energy production | | | | | | | | | |
| 1.1 - Average annual production (GWh) | -- | -- | 2.12 | | | | 2.12 | | 2.12 |
| 1.2 - kWh value (€ / kWh) | -- | -- | 0.110 | …. | | …. | 0.110 | …. | 0.110 |
| 1.3 - Value of average annual production (€ / year) | -- | -- | 232662 | | | | 232662 | | 232662 |

| **IRR (%)** | **15.97%** | | |
|---|---|---|---|
| | **Discount rate (r)** | | |
| | 2.0% | 6.0% | 8.0% |
| **NPV (€)** | **2095675** | **1073345** | **739682** |
| **F** | **17.35** | **12.47** | **10.82** |
| **B/C (-)** | **3.011** | **2.242** | **1.979** |
| **Year** | TOTAL CASH FLOW UPDATED | | |
| -2 | -88000 | -88000 | -88000 |
| -1 | -1176235 | -1135170 | -1115778 |
| 1 | -980060 | -953520 | -940794 |
| 2 | -787730 | -782153 | -778772 |
| 3 | -599172 | -620486 | -628751 |
| 4 | -414311 | -467969 | -489843 |
| 5 | -233075 | -324086 | -361225 |
| 6 | -55393 | -188347 | -242134 |
| 7 | 118806 | -60291 | -131864 |
| 8 | 289588 | 60516 | -29763 |
| 9 | 457022 | 174485 | 64776 |
| 10 | 621174 | 282003 | 152311 |
| 11 | 782106 | 383435 | 233363 |
| 12 | 939883 | 479126 | 308410 |
| 13 | 1094566 | 569400 | 377899 |
| 14 | 1246217 | 654564 | 442240 |
| 15 | 1394893 | 734908 | 501815 |
| 16 | 1540655 | 810704 | 556978 |
| 17 | 1683558 | 882210 | 608054 |
| 18 | 1823660 | 949668 | 655346 |
| 19 | 1961014 | 1013307 | 699136 |
| 20 | 2095675 | 1073345 | 739682 |