Hybrid energy solutions for the optimization of a golf-course irrigation system

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Abstract

Water distribution and irrigation systems consume high quantities of energy that, in light of a sustainable future, needs to be recovered. The expenses necessary for water pumping are substantial and the need for solutions which can harness some of the system's energy is perceived as essential.

The excessive water pressure existing in these systems, creates a potential energy that can be harnessed by means of a pump working in turbine mode (PAT). This technology has been studied in hydraulic contexts and is a promising source of renewable energy which can also provide pressure control for the water systems. A laboratorial investigation on a PAT is carried out as well as the analysis of the machine's performance under different hydraulic and electric conditions.

In order to optimize a real case irrigation system, even though in a small scale, this dissertation analyses different sustainable solutions that can satisfy the electrical demands for pumping water from five local wells in a golf-course irrigation system. Two PATs with equivalent performance of the one from the laboratory tests are applied as replacement of existing pressure reducing valves (PRV). Other renewable energy sources are analysed, such as solar and wind hybrid technologies, and are implemented in the system to respond to the electrical need. A sustainable urban drainage system (SUDS) is also implemented with the purpose of overflow controlling and energy generation. An economic and environmental assessment is carried out to evaluate the feasibility of the solutions chosen.

Key words: Irrigation Systems (IS), Pump as Turbine (PAT), Water Distribution Networks (WDN), Hydropower Solution, Sustainability, Renewable Energy, Sustainable Urban Drainage System (SUDS)

Resumo

Os sistemas de irrigação e distribuição de água consomem grandes quantidades de energia que, com vista a um futuro sustentável, têm de ser recuperadas. Os custos necessários para bombear água são muito elevados e a necessidade de soluções de recuperação de energia potencial em sistemas hidráulicos é vista como essencial.

A excessiva pressão de água existente nestes sistemas cria energia potencial que pode ser recuperada por bombas a funcionar como turbinas (BT). Esta tecnologia, que também consegue controlar a pressão excessiva em sistemas hidráulicos, tem sido estudada nos últimos anos e é uma fonte promissora de energia renovável. Em virtude deste contexto, foi realizada uma análise laboratorial de uma BT de forma a analisar o seu desempenho sob diferentes condições hidráulicas e elétricas.

Tendo por objetivo a otimização de um sistema real de irrigação em pequena escala, esta dissertação analisa diferentes soluções sustentáveis de forma a satisfazer as condições elétricas de bombear cinco furos de captação de um sistema de irrigação de golfe. Duas BT, com desempenho equivalente à BT testada em laboratório, são implementadas como substituição de duas válvulas redutoras de pressão (VRP) existentes. Outras fontes de energia renovável, como soluções com aproveitamento da energia solar e eólica, foram também consideradas de forma a satisfazer a necessidade energética. Foi também implementado um sistema sustentável de drenagem urbana (SSDU) com o propósito de controlar potenciais alagamentos e produzir energia. Foi realizada uma análise económica e ambiental de modo a avaliar a viabilidade das soluções escolhidas.

Palavras-chave: Sistema de Irrigação, Bombas como Turbinas (BT), Sistema de Distribuição de Água, Hidroenergia, Sustentabilidade, Energia Renovável, Sistema Sustentável de Drenagem Urbana (SSDU)

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Abbreviations

BCC	Belas Clube de Campo
BEP	Best Efficiency Point
B/C	Benefit/Cost Ratio
CCI	Characteristic Curve of Installation
ER	Electrical Regulation
GC	Golf Course
GE	Green Economy
GHG	Greenhouse Gas
GS	Public Green Spaces
HER	Hydraulic and Electrical Regulation
HOMER	Hybrid Optimization Model for Electric Renewables
HR	Hydraulic Regulation
IG	Induction Generator
IRR	Internal Rate of Return
ITC	Information and Communication Technologies
NPC	Net Present Cost
NPV	Net Present Value
PAT	Pump as Turbine
PRV	Pressure Reduction Valve
PV	Photovoltaic System
SEIG	Self-Excited Induction Generator
SF	Smart Farming
SI	Smart Irrigation
SP	Submersible Pump
SWS	Smart Water System
SUDS	Sustainable Urban Drainage System
T	Payback Period
UFW	Unaccounted For Water
VOS	Variable Operating Strategy
WDS	Water Distribution System
WF	Water Footprint
WT	Wind Turbine

Notation and Symbols

A	Watershed Area
C	Capital Costs
c	Precipitation Losses
D	Internal Diameter
E	Energy Generated
E_{excess}	Excess Energy
E_h	Hydraulic Energy
g	Gravitational Acceleration
H	Nodal Head
H_i	Available Head
H_i^t	Head delivered by the PAT
H_{dn}	Downstream Head
H_{target}	Targeted Head
H_{up}	Upstream Head
I_s	Electric Current
i	Precipitation Intensity
L	Length
N	Rotational Speed
n	Period of years
O	Operational Costs
P	Reposition Costs
$P_{effective}$	Effective Precipitation
P_{hyd}	Hydraulic Power
P_{mec}	Mechanical Power
P_s	Active Power
P_u	Power
PF	Power Factor
Q	Flow Rate
Q_{in}	Inlet Discharge
Q_i^t	Turbinated Flow
Q_{out}	Outlet Discharge
Q_s	Reactive Power
R	Revenues
r	Discount rate
V_s	Voltage
V_{target}	Targeted Volume

γ	Specific weight of a fluid
η_{el}	SEIG (Generator) Efficiency
η_{global}	Global (PAT + Generator) Efficiency
η_i^t	Mechanical Efficiency
η_p	Plant Efficiency
η_{PAT}	PAT Efficiency
ρ	Mass density of a fluid
Δt	Time interval

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1. Introduction

1.1. Scope

Water, as the most vital and scarce resource, is seen as an opportunity for investing the growing knowledge and technologies in view of a sustainable future. From source until the user's tap, an efficient sustainable water management is regarded as a priority for the current aware societies. Not only access to clean and safe water is considered crucial but also to establish a reliable and inexpensive water supply and distribution network for the present generations and for the ones yet to come. To engage on a sustainable water management strategy, it is required a chain of thought that prioritize the process of planning ahead of the current needs and demands. The symbiotic relation between the practical know-how and the theoretical expertise of the modern world creates a thrilling environment for developing new technologies and achieving astonishing solutions.

This sustainable path creates a fundamental awareness, which is being revealed in the introduction of concepts, such as green economies or water footprints. To aim for the optimization of the use of the natural resources, so as to reduce their waste and increase their potential, is the key for a sustainable future.

Water supply and distribution systems have a significant dependency on energy. The interconnected role of water and energy creates a nexus, which is a structural consideration for a sustainable development. The increasing demand of the two resources is a major stress factor for present societies, although it also represents an opportunity for new technologies and solutions.

Renewable energy solutions have had an exponential growth over the past years and prospects of increasing. Solar and wind resources have been regarded together in order to form hybrid solutions so as to adapt to new systems, promoting more efficient networks. Solar and/or wind pumping are examples of new solutions that are being invested due to their feasibility and environmental impact.

Moreover, one of the most reliable alternative energy sources is hydropower. In the scope of small and micro hydropower solutions and in the point of view of optimizing the water supply and distribution systems, the concept of recovering energy, which is currently being wasted, emerges as an opportunity for not only to attain the sustainability but also the capitalization. Technological innovation such as pumps operating in reverse mode as a turbine (PAT) is a solution to harvest potential energy in water systems.

The future of sustainable water management of supply and distribution networks is through integrating renewable sources in smart water systems along with taking advantage of excessive energy available in water networks. A constant endeavour and critical thinking are revised as paramount in order to boost the current environmental standards to ones that allow and promote self-sustainable smart water networks.

1.2. Objectives

This dissertation aims to introduce, in a golf course irrigation system, a feasible solution with the highest renewable percentage viable in order to create a more efficient network then the one currently used. This sustainable project is analysed for three renewable power generation solutions: a hybrid solution to satisfy water pumping demands, a pump as turbine (PAT) solution to replace installed pressure reducing valves (PRV) while recovering dissipated energy, and a sustainable urban drainage system (SUDS) solution to collect rainfall, prevent overflowing situations in the lowest region of the case study, while generating power.

This study has the ambition of presenting an economic feasible solution which optimizes the stated elements, maximizes the energy generation and the system's efficiency.

1.3. Structure

This dissertation is structured in six chapters. The first chapter presents the general framework of the subject analysed and its relevance for the present sustainable world. It also introduces the aims and objectives of the study and how it was structured.

The second chapter presents an insight about the global and national water and energy consumption. Concepts such as Green Economy and Water Footprint were defined in the view of water management. A focus on hydropower generation was conducted, with particular interest in small-scale hydropower solutions such as pump as turbines. PATs development was then explained as well as its operation method. The concept of Smart Water Systems was also presented in this chapter.

The third chapter consists on the methodology used in this dissertation. This was structured in five arrows: (i) a capitalization concept is presented in order to quantify the potential energy that can be harnessed; (ii) an energy resource assessment explains the science behind the recovering of potential energy and the solutions chosen; (iii) it is presented the economic and environmental variables; (iv) a design guidance for the laboratorial assessment is displayed; (v) it is presented the support tools used in this study.

The fourth chapter displays the laboratorial conditions for a PAT Pilot Station, which was analysed and then presented its results in dimensionless units.

The fifth chapter introduces the case study. It presents the hydraulic elements and constraints as well as the systems characteristics. In this chapter, three different alternate solutions, which can operate at the same time, are analysed. These solutions are studied and the results displayed, aiming for a joined solution with the highest viable renewable percentage. Also, in this chapter, it is quantified the energy generated and it is carried out a sensitive analysis of the economic feasibility and environmental impact for this project.

The last chapter establishes a conclusion for the chosen solutions, bearing in mind the concept of sustainable development and the current reality. Future perspectives and recommendations are also defined in this chapter.

2. Background Review

2.1. Water Consumption Overview

Water is an essential need for mankind's health and a requirement for its survival. Although it covers around 70% of Earth's surface, water must not be perceived as an endless resource. In addition to the environmental factors that restrain the amount of water one can use as a supply, waste and careless use of it are critical wrongdoings for our societies [1], while entering in a generation that has to have water management and sustainability in its core and moto.

In the recent years, studies have shown that water scarcity is a reality within both developed and in developing countries [2, 3]. The amount of fresh water available is continuing to decrease and water harvesting has to be reviewed as a major concern in current societies [4].

It may seem abundant but of all Earth's water, about 97.5% is salt water, leaving only 2.5% for consumption. However, the issue has even deeper roots, as almost 70% of that fresh water available for consumption is frozen in icecaps, and the remainder is stored in underground aquifers or present as soil moisture. This leads to the conclusion that only approximately 1.3% of the total Earth's fresh water is available for direct human use [5, 6].

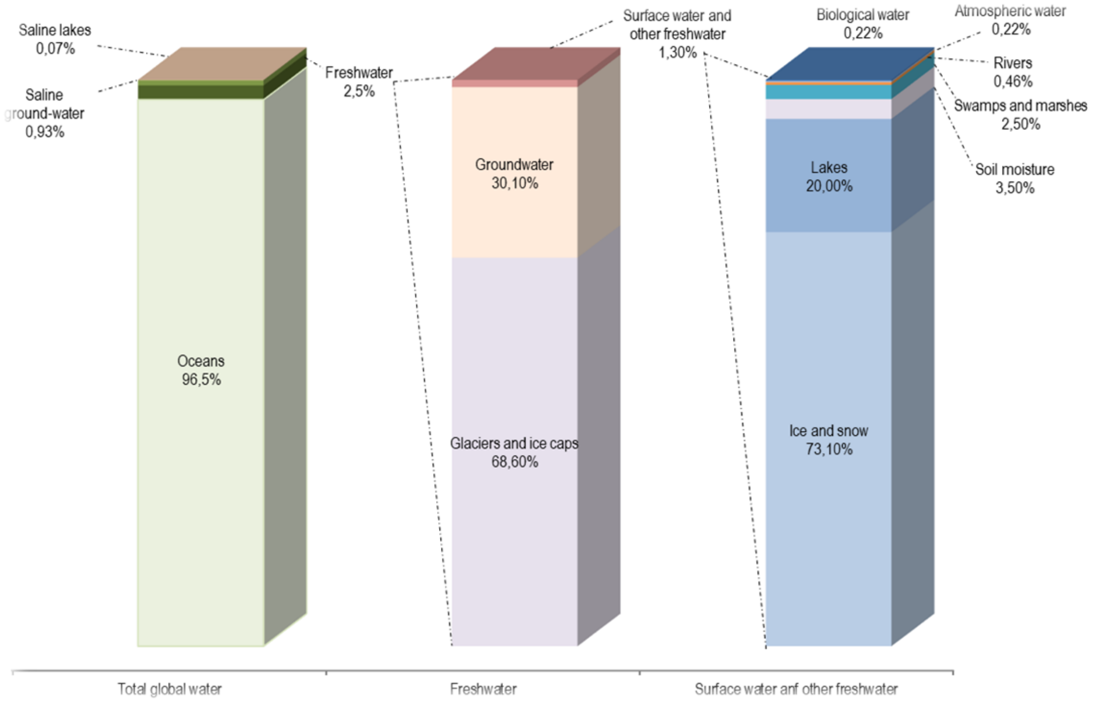


Figure 1 - Total water distribution based on data from [6]

Water has various fields of use such as drinking, drainage, irrigation, impoundment, energy production all having had a considerable impact in landscapes and water flows throughout the years [7]. In the beginning of societies, irrigated agriculture, with the purpose of growing crops for consumption, established the need for fresh water supplies. Nowadays, adding to that primary motivation, other sectors developed the need for more efficient water infrastructures.

The amount of water consumed for each sector is not equally distributed. Agriculture is, undoubtedly, the larger water consumer. In Portugal the water used for agriculture is approximately 3389 hm^3 per year, while the domestic, industrial and the tourism sector consume approximately 1150 hm^3 of water per year in Portugal, (Figure 2) [8]. In the tourism sector the golf-courses are responsible for approximately 47% of the consumed water. And as it is expected larger countries than Portugal, consume larger quantities of water, though the percentage for sector is still comparable. For instance, in Brazil, in 2010, the water withdrawal for agriculture represented 54% of the 74 830 hm^3 of water used, 23% for domestic use and 17% was used for industries [9].

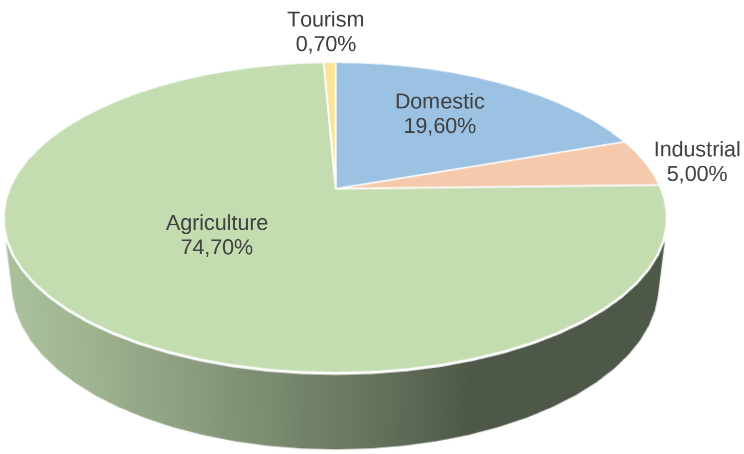


Figure 2 - Water use by sector in Portugal based on data from APA 2015 [8]

Within these percentages, there are water losses associated with each sector. Water losses represent a threat towards a better water management if not efficiently handled. These losses can be physical such as pipe breaks, leaks and storage overflows or commercial losses such as water thefts, metering errors and billing anomalies. These losses are an important factor to consider when focusing on optimizing water systems. Thus, the concept of unaccounted-for water (UFW), which is expressed as a percentage of net water production and represents the difference between the volume of water delivered into a network and the volume of water that can be accounted for by legitimate consumption, is essential for gaining knowledge of the amount of water being wasted in distribution and mishandling. These losses vary widely per country and UFW values can reach from 6% to 63% [10]. According to the Water and Sanitation Division of the World Bank, the acceptable rate of UFW in industrialized countries is less than 20%, however the average rate of UFW in developing countries is 37%.

As the increase of water waste, contamination and over-exploitation has the inclination to prevail, new technologies, methods and concepts had to be developed throughout the years in order to best manage this scarce resource. Along with quantifying the losses in water systems, there is the need to implement green initiatives and to achieve a worldwide consciousness that water is a social and economic good, which needs proper and efficient management. Thus, concepts such as Green Economy (GE) and Water Footprint (WF) are seen as essential in order to reach the sustainable atmosphere desired.

2.1.1. Water and the Green Economy

The water scarcity issue presents an opportunity for innovative ideologies, such as the one of a green economy in view of a sustainable future. A GE is defined by UNEP as an economy that achieves simultaneously an improved state of human well-being and lasting social fairness while decreasing radically the environmental threats and ecological scarcities for future generations [11]. Water management has a crucial role to play in this economy by developing more social and economic opportunities while preserving the freshwater ecosystems. Additionally, not only the issue of water supply but also the biodiversity present in water environments is considered a priority in a GE [11].

A GE has the aim of accomplishing a vast number of challenges in different sectors. One of the main concerns for reaching the sustainable level desired is to create feasible solutions to enhance water supply in a global scale. However, not only from a global perspective but also awareness and sensibility from a smaller scale is required for achieving the GE goals.

Table 1 - Challenges and opportunities in a Green Economy based by water sectors [12]

Water use sectors	Challenges and Opportunities for a Green Economy
Agriculture	Using less quantities of water and still achieving food security. Better water managements and considerable investments in innovation are in the core of this challenge.
Cities	In order to reduce the resource use, compact cities are analysed. Cities with concentrated population will require lower investments per capita in transportation and infrastructure. Thus, basic services will have the opportunity to be developed with higher efficiency.
Ecosystem Services	Not only safeguarding the ecosystems but also to recognize the important benefits of protecting them, is the path for sustainability, equality, water security and poverty decrease.
Green Jobs	To achieve social and economic prosperity by way of investments that manifest a concern in reducing pollution and carbon emissions, improving energy and water resources efficiency and avoid biodiversity losses.
Industry	Towards a better water management and practices, the industry sector in a green economy must focus on the prevention of contaminated waters and their overexploitation issues. The ideal ambition is one of zero discharges.
Water and Sanitation	It is essential to invest in efficient sanitation services and water supply infrastructures.
Renewable energies	Focusing on non-fuel energies as a way to develop the world with concern for future generation is the moto for a sustainable path. Recover the potential energy that is wasted in water system appears as a new source for renewable energies.

2.1.2. Water Footprint

The water footprint of a product is the volume of water used to produce it, since the beginning of the production chain and there are three elements (blue, green and grey), which can characterize a person or product water footprint. The green water footprint refers to the consumption of rainwater, the blue water footprint is the amount of irrigation water used in means of ground and surface water consumption and the grey water footprint quantifies the amount of fresh water that is needed to dilute pollution [13].

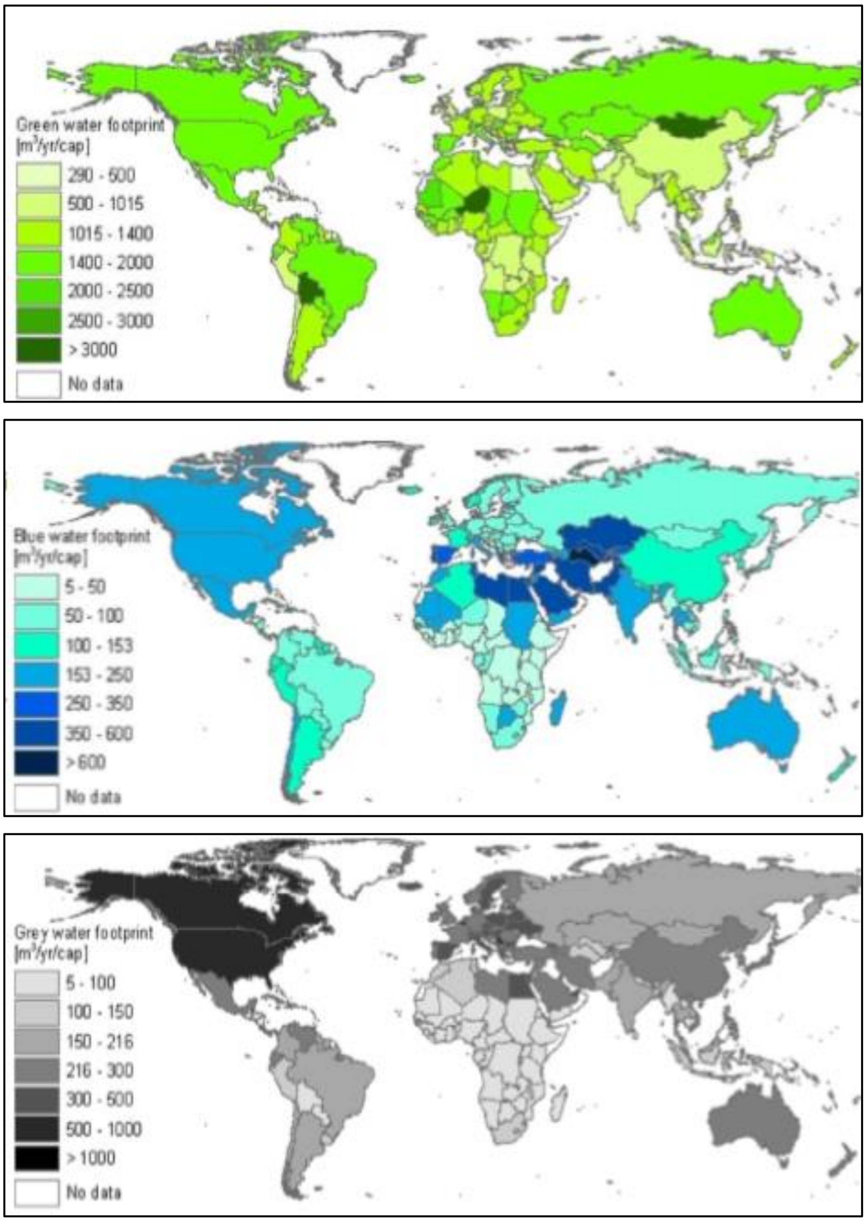


Figure 3 - Green, Blue and Grey Water footprint of national consumption per country (1996–2005) [14]

In total terms, the countries which have the largest total water footprint within their domain are China (1368 Gm^3 per year), India (1145 Gm^3 per year) and the United States of America (821 Gm^3 per year) [14]. However, countries with larger populations, will present a larger WF. Hence, it is more relevant to analyse the WF per capita. Figure 3 illustrates the green, blue and grey water footprints in the period of 1996 to 2005, in m^3 per capita per year.

Figures 4 and 5 depict that industrialised countries present WF per capita in the range of 1250-2850 m3/yr, whereas the WF per capita for developing countries varies much more (550-3800 m3/yr per capita). In the figures, it can be highlighted that both industrialised and developing countries are present in ranges of large WF per capita. The latter countries are present in that range not because of their relative large consumption, but due to their low water productivities, i.e. large WF per ton of product consumed. For instance, in Bolivia, the meat consumption is only 1.3 times higher than the global average, while the WF per ton of meat per capita is 5 times higher than the global average [14, 15].

From 1996-2005, the World's average water footprint in terms of national consumption was 1.385 m^3 per year per capita. Portugal had a consumption of 2.500 m^3 per year per capita contrasting with countries such as Sweden, which had a similar water footprint as the World's average (Figure 4 and 5) [15]. It is critical to highlight the different consumption between a southern and a northern European country since as stated by the DGEG in the *2017 JEC IV – Public Water*, the water availability in these regions will suffer a discrepancy throughout the following years. Reasons for this disparity is the water intensive tourism and an explosion of irrigated agriculture, which endanger the Mediterranean water resources [2]. Also, climate change is expecting to undermine efforts for sustainable development in the Mediterranean region as rainfall is predicted to diminish over the years [16]. On the other hand, the Scandinavia area is facing a more optimistic rainfall forecast which will contribute for an increasing opportunity for water storage. In addition, these Nordic countries have also a different consciousness regarding water management [1], which is reflected in their water footprint values.

These contrast exacerbates the European water gap in a way that southern countries, such as Portugal, will require to achieve higher efficiency gains in agricultural water usage (as well as other areas of water consumption) in order to prevent seasonal water shortages. Low rainfall, high population density and intensive agricultural and industrial activity will have to be taken into account as threatening issues for a desirable sustainable atmosphere [17].

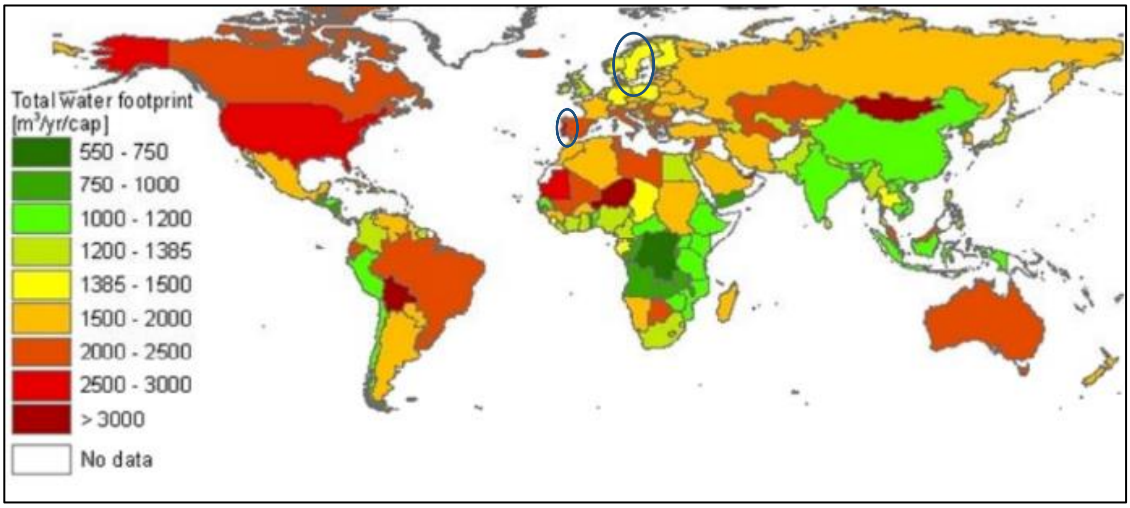


Figure 4 - Total water footprint of national consumption per countries. Green colour countries have a WF smaller than the global average whereas red countries present a WF larger than the global average [14, 15]

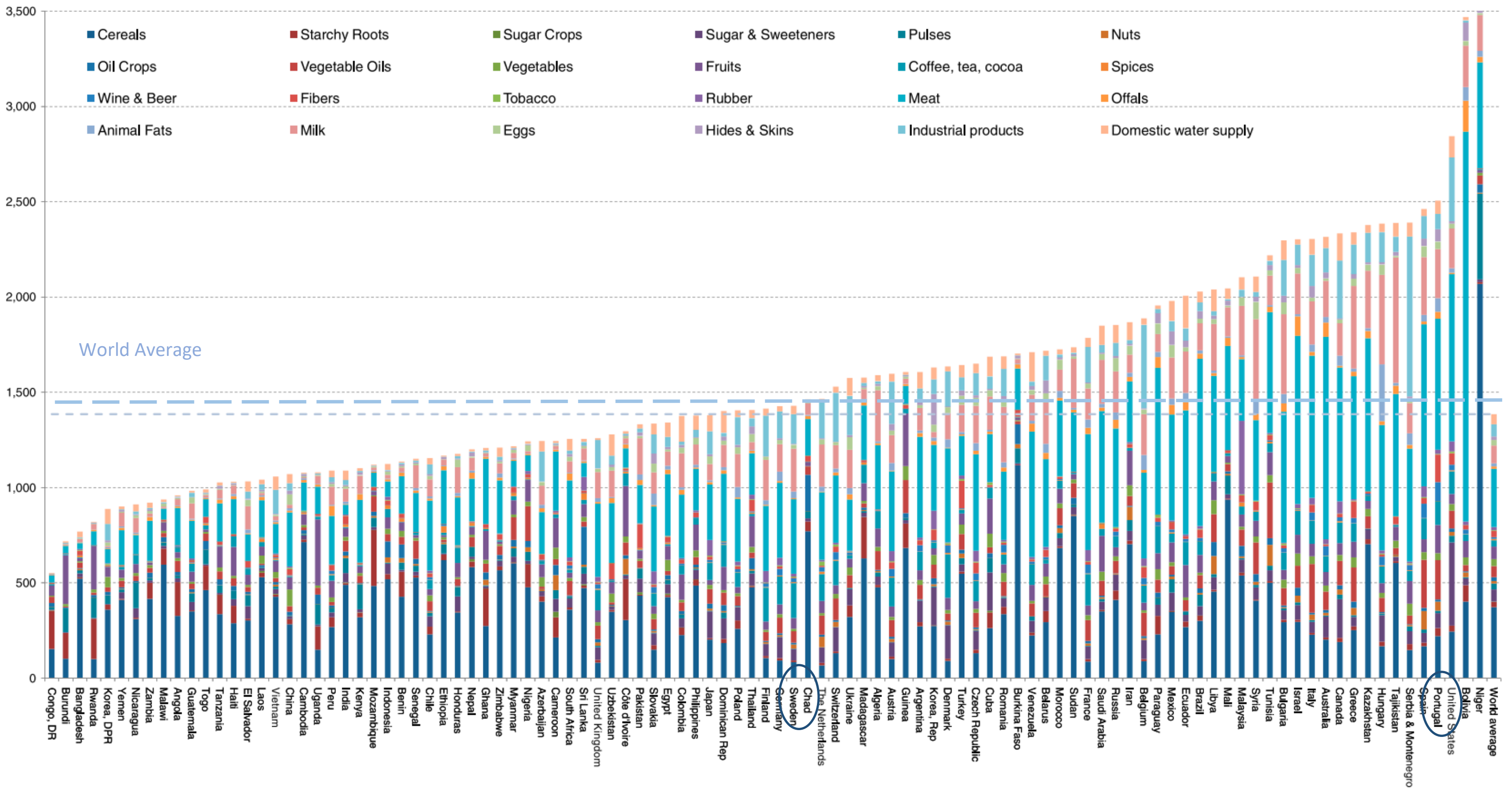


Figure 5 - WF of national consumption (m3/yr/cap) for countries with a population larger than 5 million from 1996 to 2005. Comparison between Portugal (Southern European country) and Sweden (Nordic European country) [14, 15]

2.2. Energy Consumption Overview

2.2.1. Energetic Dependency

The energy that a society consume has reached unprecedented levels. Focusing on the gap since 1997 until 2020, estimations were made and the global consumption will have a 76% increase, which means 22 000 TWh are expected to be consumed in 2020, rather than the 12 000 TWh in 1997 [18]. This escalation is due mostly to the population growth and the over excessive fossil fuels exploitation [19]. With this concerning increase of energy consumption in mind, a focus on renewable energies has been reviewed as critical in order to establish a sustainable path for future generations to come.

In Portugal, there is a high energy dependence and one of the main objectives from the current national energy department is to reduce this energy dependence from abroad [20]. Due to the lack of national production of fossil fuel such as petrol and natural gas, Portugal always had a high energetic dependence with values oscillating between 80% to 90%. Thus, an investment on renewable energies and energetic efficiency was crucial for lowering the level of energy dependence for values below 80%. However, the fluctuating conditions of the hydrologic atmosphere, associated with the large hydropower national generation, has negatively influenced the energetic dependence in draught years, such as 2005 and 2008 [20].

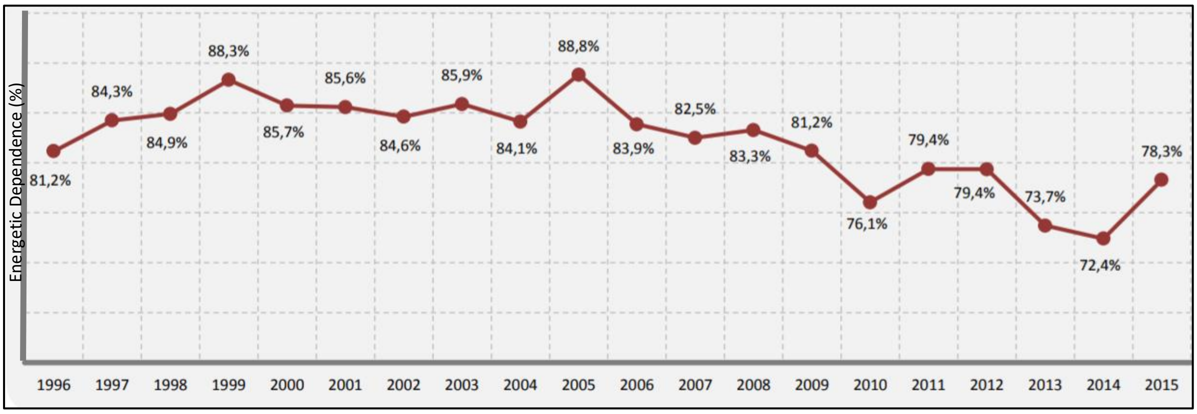


Figure 6 - Energetic dependence evolution in Portugal (%), adapted from [20]

In 2015 the energetic dependence was 78,3% which was a 5,9% increase regarding 2014. This escalation is due to the decrease of renewable energy production, especially hydroelectric and wind power, resulting on the increase of fossil fuel consumption, which generated a boost of importations [20]. As the 7th higher energetic dependent country in the EU-28, Portugal requires a greater investment in renewable energies in order to reduce the fossil fuel consumption [20].

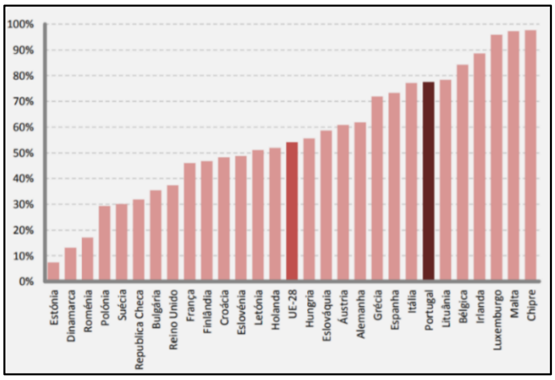


Figure 7 - Energetic Dependence in EU-28 in 2015

Hence, a better understanding on how renewable energies are produced, especially the hydroelectric, responsible for approximately 38% of the renewable energy production in Portugal in 2015 [20] and 47.7% in January 2018 [21], is of a paramount importance.

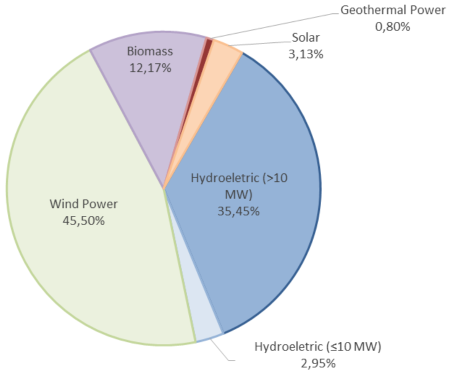


Figure 8 - Electric Production by Renewable Energies in Portugal, 2015 based on data from DGEG [20]

Being one of the most important clean energy sources in Portugal, the investment and development of new technologies and methods which can generate energy in hydraulic systems have been motivated. Different studies through the past years have been deliberating new solutions and techniques in order to recover the dissipated energy in these systems, and even creating it through means of small hydropower technology. Not only do these solutions appeal to the imperative environmental standards, but also economic advantages are displayed by these new scientific approaches [22].

2.2.2. Hydropower Generation

Hydropower generation, as a response to the stated issues, has been analysed over the past years [23]. As a renewable energy, hydropower supplied, in 2016, 16.4% of the planet's electricity and it leads the renewable sources for power generation as it, globally, provides about 71% of all electricity generated by non-fossil sources [24, 25]. It is estimated that the planet's feasible hydropower potential is around 14.370 TWh/year, which reveals the promising approaches surrounding hydroelectric technological solutions [26].

According to the World Energy Council (WEC) 2016 Report, approximately 160 countries in the world use hydropower generation for providing electricity to their national electric mixed grid [27]. The global production of hydropower, however, is focused on ten countries. The top four of this list, i.e. China, Canada, Brazil and USA, represent relatively 50% of the total electricity production [28].

Table 2 - The top ten countries with the most installed hydropower capacity, hydropower potential and electricity production in 2016, adapted from the WEC and IRENA [27, 28]

Country	Installed Capacity (GW)	Country	Total Potential (TWh)	Country	Electricity Production (TWh)	Share of the World total electricity production (%)
China	319	China	2 140	China	1 114	27.9
USA	102	Russia	1 670	Canada	381	9.5
Brazil	92	Canada	1 181	Brazil	360	9
Canada	79	Brazil	818	USA	271	6,8
India	52	India	660	Russia	169	4.3
Russia	51	USA	529	India	150	3.8
Japan	50	Indonesia	402	Norway	139	3.5
Norway	31	Peru	395	Japan	91	2.3
Turkey	26	Tajikistan	317	Venezuela	76	1.9
France	25	DR Congo	314	Sweden	75	1.9
Rest of the World	385			Rest of the World	1 170	29.3
World	1 212	World	14 370	World	3 996	100

There are different frames in which hydropower can be applied. Large, small, micro and pico hydropower solutions are used accordingly to the different contexts they are inserted. These contexts are mostly unique [29], since no two power developments are exactly alike, particularly due to the installations, since despite having the same installed capacity, the hydropower plant design is site-specific. Hence, it is important to understand the classification of hydropower projects so as to best consider the proper technology and application. Usually, hydropower projects depend on many factors such as head, available flow and the topography of the area [29]. Therefore the classifications vary in accordance with the installed capacity (Table 3), head (Low, medium or high), purpose (single or multi-purpose), facility (run-of-river, reservoir, in stream or pumped storage), hydrological relations (single or cascade) and the transmission system (isolated or connected to grid) [30]. Also, the classifications change from country to country since there is not a general agreement among countries and institutions of what should be the upper limit of a small-scale hydropower plant capacity [31].

Table 3 - Hydropower projects classification based on installed capacity and the different considerations for small-scale hydropower projects [31, 32].

Plant Type	Installed capacity (MW)	Applicability
Large	> 100	Large urban population centres
Medium	10 - 100	Medium urban population centres
Small	1 - 10~50	Small communities with possibility to supply the regional grid
Mini	0,100 - 1	Small factory or isolated communities
Micro	0,005 – 0,100	Small isolated communities
Pico	< 0,005	1 -2 houses

Country/Institution*	Small-scale hydropower classification as defined by installed capacity (MW)
Canada, China	≤ 50
India	≤ 25
USA, Brazil	≤ 30
UK	≤ 20
France, Norway, South Africa, **Portugal**, Spain, Ireland, Greece, Belgium, ESHA*, IEA*, WCD*	≤ 10
Sweden	≤ 1.5

*ESHA (European Small Hydropower Association), IEA – International Energy Agency, WCD (World Commission on Dams)

In a smaller scale, i.e. with a power output lower than 100kW, there are micro and pico hydropower solutions. One that has been studied in pressurized water networks as a sustainable and efficient energy recovery technology in water networks is a pump operating as a turbine (PAT).

2.3. Pump as Turbine (PAT)

2.3.1. PAT Development

To gain a better understanding of the overall functioning of a technology, first one is important to learn about its genesis and context. The first PAT started due to an unintentional conclusion reached by Thoma and Kittredge in 1931 – pumps running in turbine mode could work efficiently [33].Throughout the century, the necessity for supplying the high power demands change the concept of pumped hydroelectric energy storage, in a way PATs gain application in a wide range of fields, such as chemical industries or water networks [34]. In the first context, it was noticed that PATs could be economically applied in locations where there is a pressure letdown in chemical processes, for instance as it occurs in refineries. In the latter context, there were several circumstances that a PAT could be incorporated. Pipe networks, wastewater discharge at pressure, or even the common streams and reservoirs conceived an opportunity for incorporating PAT units [35]. The earlier issue, however, was that the technology required for using the PATs for electrical power generation was still to be envisioned. Only due to the progress in the electrical field of study, it was possible to handle a pump rotating in reverse mode in order to generate power. This framework motivated many authors to discover different insights in the PAT approach. It prompted numerous studies [36], where conventional pumps were tested in turbine mode. The upshot was that its peak efficiency was similar when in pump mode, its mechanical procedure was smoother and also the head and discharge had increased values at the best efficiency point (BEP) comparing to the pump mode.

2.3.2. PATs in Water Systems

In water networks is common to have excessive energy availability. Systems such as irrigation, water distribution, natural falls, drainage and sewage have this extra potential, which an efficient recovery is seen as an intervention renewable energy source [37]. PATs are an alternative solution, which has tremendous advantageous over the use of turbines. Lower costs of equipment and easier implementation are the main feature of PATs when comparing to turbines, but there are also many other advantages of having a pump running in turbine mode instead of the standard hydro-turbines – mass production, availability for a wide range of heads and flows, short delivery time, availability in a large number of standard sizes, ease of availability of spare parts, less complexity, etc [38].

Not only PATs represent an interesting alternative to hydro-turbines, but also to Pressure Reduction Valves (PRV) [39]. In WDS the main objective is to provide successfully the user demand required. Nevertheless, this demand can be largely fluctuant throughout the system, causing excessive pressure and consequently pipe damage, leading to water leakages [40]. In order to reduce the water losses, PRVs are an efficient solution, broadly used in this type of systems. By reducing the pressure, the installation of these valves avoid extra costs in pipe replacements. However, despite the positive impacts of this solution, researches had been trying to replace the PRVs with hydropower technology in order to decrease the high amount of energy consumed in WDS. PAT is, then, noticed as an efficient technology capable of reducing the water losses and generating power to balance out the high energy values consumed in these systems [41].

2.3.3. Selection of Appropriate Pumps as Turbines: Criteria Selection Overview

In order to use this technology, one has to study which are the types of pump that can be used in turbine mode appropriately. Since, when in this mode, the flow direction is the opposite comparing to the pump mode, there are some pumps that are not suitable for this task. The presence of non-return valves and overheating issues are some common obstacles that some pumps face to work as turbines. Hence, self-priming pumps, dry-motor submersible pumps and wet-motor submersible bore hole pumps, as examples, aren't advisable to use in this mode [42]. Nevertheless, recent studies [43] state that all centrifugal pumps, regardless of their specific speed, installation, split and stage can be adapted to work in turbine mode. PATs can be chosen depending on the head and discharge values one requires. For instance, axial flow pumps are more applicable when facing low head and high flow level values, while multistage radial flow pumps are more appropriate for a range set of higher heads and lower discharges, as illustrated in Figure 9. Therefore, the criteria for selecting pumps operating in reverse mode can be compiled in features such as the capacity range, the desired rotational speed, the pressure in the outlet and available head range [43].

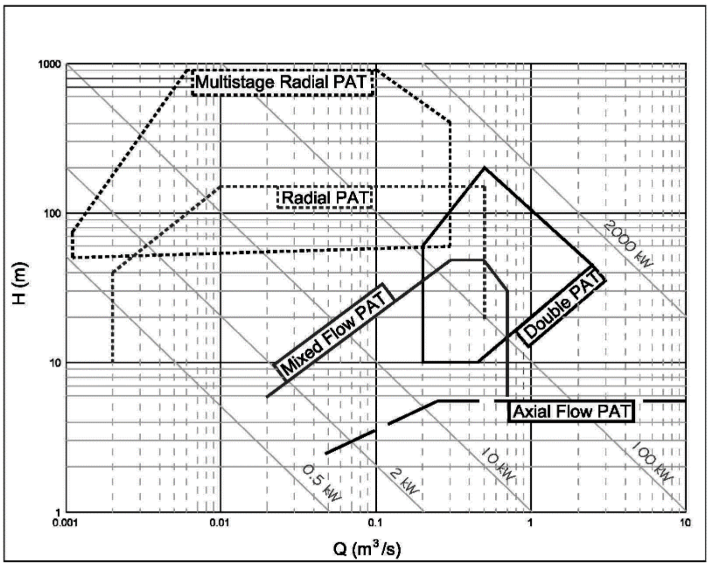


Figure 9 - Criteria for PAT selection [19]

When, in remote areas, the possibility of using micro-hydropower occurs, one has to analyse its context for proper installation of a PAT system. Pump working as turbine systems normally engage on using the induction motor found in the pump, as an AC generator in order to create power. Consequently, it is of the most importance to have the knowledge of the background concerning the installation, as will it be a supply-connected induction generator operation or a stand-alone induction generator operation. In the first case, working "On-Grid", the induction motors are normally interconnected directly to the electrical network, through means of a switch. The electrical network supplies a magnetizing current that establish a rotating field, as if it were a motor, and when the induction machine is driven above the synchronous speed, the slip becomes negative (rotor speed > speed of the rotating field), a torque is provided to the rotor and the machine operates as a generator, powering back the network. In the latter case, operating in a stand-alone installation, "Off-Grid", the system will require capacitors to provide the magnetizing current. The capacitors will act as the only external source that can supply reactive power, which enables the induction motor to create electricity [44].

2.4. Smart Water Systems

2.4.1. Smart Water Systems for Water Distribution System

In order to improve water systems' efficiency, there have been breakthroughs in the past years with new technology, such as smart water systems (SWS). In view of the stated concerns regarding water and energy overconsumption, the concept of SWS is revised as vital for the modern world. Moreover, the World Bank states that water losses have values around 45 billion m^3 per year, which have a significant impact on the economy, costing roughly € 11.9 billion around the world [45]. This water is lost by weak management and poor metering, leakages, corruption and unauthorized connections. SWS, thus, aim for the optimization of water grids in a way they can ensure a safer and more efficient water supply for end users [46]. SWS use Information and Communication Technologies (ICT) to achieve a constant grid monitoring of data such as water flow, pressure, moisture and water quality, with automated control so as to alarm the water manager in case of any malfunction or abnormality, such as water contamination [47].

The increasing investment in this field of study has been resulting in technological advances regarding smart water technology. These advances allow to efficiently detect and locate water bursts. A highly efficient leakage detection is crucial for WDS, since they are the main source for non-revenue water losses [48]. There are older and commonly used techniques such as, acoustic sensors, ground penetrating radars, infrared thermography and electromagnetic sensors [47], but these methods are rather limited regarding leakage detection. New technologies that were put in place are shown in Table 4.

Table 4 - Examples of SWS, how they operate and where were they tested

Smart water systems	*Characteristics*	*Tested in*	*Reference*
Decision support system (DSS)	Leakage assessment by flow and pressure sensors analysis and investigation of steady and dynamic properties of a WDS under PRV control	UK	[49]
Invert transient analysis (ITA)	Data collection of flow and pressure sensors. Gradual optimization of a leakage function, assumed to be Gaussian distributed in pipeline. This system can identify the burst of 7.7 l/s.	Dundee pipeline system, UK	[50]
Bottom-up approach	The analysis is carried out by installing flow meters and pressure transducers at some predefined points. Acoustic sensors are used to detect the water leakages. This approach allowed to reduce water losses by 40%, saving 63 500€.	Lisbon, PT	[51]
Prototype of a smart water network	Leakages identification through means of magnetic valves along with flow and pressure sensors.	Graz University, Austria	[52]
WaterWiSe	Pipe failures, i.e leaks or bursts, detection and prediction by managing and analysing data from a network of intelligent wireless sensor nodes. Hydraulic, acoustic and water quality parameters are continuously monitored.	Singapore	[53]
Kalman filter for hydraulic parameters prediction	Burst detection method by calculating difference between measured and predicted flow and pressure. This technique is computationally less complex and requires fewer amount of data. Useful to detect small leakages and small abrupt changes.	North England	[54]

There are other leakage identification techniques such as transient damping method (TDM) and impulse response analysis (IRA) but they are limited to simple pipeline architecture [47].

2.4.2. Smart Irrigation Systems

Smart irrigation (SI) will reduce the water and energy consumption in water systems. There are different fields of interest for this application such as agriculture (farming) or gardening (golf courses as an example). As for agriculture, smart farming (SF) is seen as essential since crop production needs to be increased by 70% until 2050 according to the UN Food and Agriculture Organization (FAO), in order to fulfil the food demand of the growing world population. This will require more water for crop cultivation. SF is composed by technologies, which are able to analyse soil qualities (moisture and humidity contents) and tell types of crops that can be grown ate given locations along the harvesting time. They also analyse the best time and place to sell those crops and earn a better revenue [47].

Smart irrigation technologies in that context uses information and communication technology such as weather forecasting, mobile communication technology, GPS and moisture senses to provide data about watering, soil moisture, humidity, temperature, wind speed and direction and heat level [55, 56]. These characteristics are useful not only for agriculture but also for gardening areas.

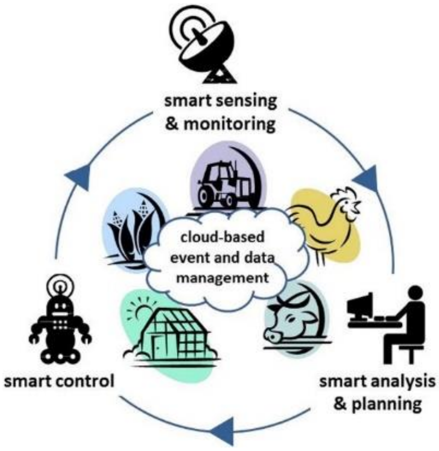


Figure 10 - Smart Farming [55]

To optimize the schedules of watering in green fields can result in the saving of water and energy. Moisture sensors are deployed in gardens and data is sent to a central location via radio module. Depending upon moisture content, watering to plants is scheduled, which results in reduction of water consumption for gardening. There have been other solutions such as autonomous gardening by plant recognition using neural networks. Acquired data and history allow future prediction that manage more effectively and efficiently the gardens [56]. However, sensor network consumes high energy and providing electricity to rural area is itself a challenging task. PATs appear to be a good solution for this issue.

Moreover, according to companies such as *Trigger Systems* [57], the control of the water use in irrigation systems can be manage with an efficient assessment methodology. Firstly, to analyse the existing irrigation system and its elements: it is common for gardening or farming systems to have poorly adjusted irrigation sprinklers, which are spending more water than they should. Figure 11 depicts the sprinklers covering area of a simple garden. The head of the sprinkler has to be well selected in order to best adjust the covering area it pretends to water. Corner sprinkler should not water more than 90º as an example, and the garden should have enough sprinklers to cover all of the area, which are conditions that can be poorly manage resulting on unnecessary water losses.

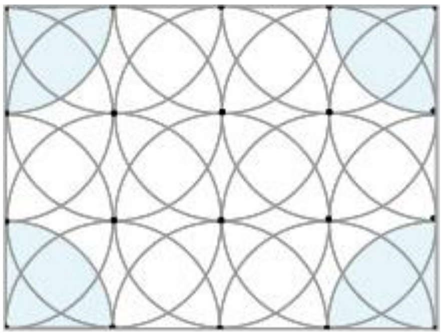


Figure 11 - Irrigation Sprinklers coverage area [57]

Secondly, it is crucial to do a resource control. This control can be achieved due to a method named stress watering. Instead of watering a constant excessive quantity, the watering process should be more adjusted to the evapotranspiration curve of the plants. Stress watering allows to water the plants by a more adjusted value, being able to reduce until 50% of water losses (area difference between the normal irrigation pattern and the evapotranspiration curve). This is possible since the plants use all of the water they are given, even if it is excessive. By forcing the plants on to a stress performing condition, the plants will still use the necessary water for its healthful growing, while not consuming avoidable water quantities. *Trigger Systems* has been proving the sustainability and efficiency of this technique [57].

Lastly, it is necessary a sustainable maintenance of these irrigation systems. Commonly, the irrigation schedule is done by a fixed time interval. With this technique the water does not flow into the deepen regions of the soil, since the low watering quantity is rapidly absorbed by the plants' roots. This results in the growth of more superficial roots. A different sustainable approach is to irrigate by volume and not time intervals. If a plant requires 25 litres of water in a 5 days' week, instead of watering 5 litres each day, by watering 20 litres on the first day, the plant will be forced to manage the water quantity until the next irrigation. This stress performing technique done by volume irrigation, forces the plant to grow its roots to a deepen area of the soil resulting not only in a more efficient irrigation but also in a more resistant plant [57].

3. Methods

3.1 Capitalization

This dissertation will firstly quantify the potential energy that can be recovered in a water system, such as the adapted case study of a golf course. Water distribution/irrigation systems have, commonly, an excess energy which require pressure control devices to dissipate it. Pressure reducing valves (PRV) are usually installed in these systems in high pressure points in order to satisfy the pressure required. However, as stated in Chapter 2.3, this excessive pressure could be transformed into electric power by means of a device which addresses the excessive pressure issue, while converting it to energy in a PAT, instead of dissipating it in a PRV. Hence, there is an energetic potential associated with this issue.

In order to gain the knowledge of the advantages of using energy recovering devices, one has to know how much one can capitalize from these energy extraction platforms. Focusing on a large water distribution system in Portugal, in the area covered by EPAL, it was captured approximately 219 Mm^3 of water in 2015, which supplied 2 842 185 end-users [58]. From the source to a supply, this water cycle consists on pumping, capturing, treating and distributing the water, which requires electricity (Table 5). Nevertheless, this cycle also represents an opportunity for micro generation of energy.

Table 5 - Economic and environmental performance indicators of EPAL, adapted from [58].

	2013		2014		2015	
	Water and Energy					
Water Captured (m^3)	218 251 646		211 732 490		218 908 035	
	kWh	GJ	kWh	GJ	kWh	GJ
Solar Energy Produced	72 560	261	72 618	261	77 907	280
Solar Energy Sold	51 454	185	49 415	178	57 719	208
Energy Consumption	125 326 389	451 175	118 796 944	427 669	124 506 667	448 224
Energetic Intensity (kJ/m^3)	2 067		2 020		2 048	
	Environment					
GHG Emissions (tCO_2)	42 407		40 734		51 546	
Emissions Intensity (kg CO_2/ m^3)	0,200		0,198		0,235	
GHG avoided by solar generation – Sold (kg CO_2)	7 306		6 051		25 339	
GHG avoided by solar generation – self-consumed (kg CO_2))	25 551		25 954		32 721	

In 2015, EPAL generated 77 907 kWh, which corresponded to 57 719 kWh of energy sold to the grid. This enabled a revenue of 22 500 € [58], excluding the economic value of the consumed energy. However, solar energy was the main source of this power generation. Hence, there is spare for more non-fossil fuel energy sources development, such as PATs, which would increase the revenues and the water systems' efficiencies. By contacting EPAL, it was possible to learn that, in the area of Lisbon (Portugal), EPAL have 39 PRV in 5 different elevation areas. As an example, one PRV located in Parque das Nações, has a flow of 78 m^3/h and a headloss of 11 meters of water column (m w.c.). If a PAT with an assumed efficiency of 60% was to be installed in the same location, under the same hydraulics conditions, an electricity production of 25,2 kWh per day would be possible if the machine worked for 18 hours. It is conspicuous that the other PRVs operate in different hydraulic conditions, with different flows and headlosses. However, for estimation purposes, assuming all of the 39 PRV operate in the same conditions, the daily electrical production would be 984 kWh, meaning approximately 359 081 kWh per year could be generated.

Moreover, in a smaller context, a PAT study made in a WDS in Loures (Portugal) established the conclusion that a PAT installed for 3,0 l/s, working for 13 hours a day, would generate 529 W, while a multicellular PAT for 4,0 l/s, running for 18 hours a day, would generate 992 W, depending of the hydraulic conditions [59]. Hence, PATs are undoubtedly advantageous as PRV's substitutes since not only they can control the pressures when there is flow, but also produce energy.

Focusing on irrigation water systems in Portugal, EDIA, while responsible for the construction and development of EFMA, is the responsible entity for managing the water resources and its necessary infrastructures in the Alqueva region [60]. EDIA, excluding EDP's power generation platforms in Alqueva, produced 4,99 GWh due to solar and mini-hydro power generation in 2015 (Table 6). The latter is responsible for 96% of this energy production [60].

Table 6 - Economic and environmental performance indicators of EDIA, adapted from [60].

	2015		
Water for irrigation (m^3)	107 050 623		Water
	kWh	GJ	Energy
Electricity produced	4 990 000	17 964	
Energy consumption	89 090 000	320 724	
Energetic intensity (kJ/m^3)	2996		
GHG emissions (tCO_2)	20 563		Environment
Emissions intensity ($kg\ CO_2/\ m^3$)	0,192		

In Valencia (Spain), another study was carried out. Pérez-Sánchez *et al.* (2016) [61] quantified the potential energy which could be recovered in a drip irrigation network in Vallada. It was concluded that the maximum estimated potential recoverable energy was 188 230 kWh/year considering all consumption points, for a water consumption of 925 427 m^3 [61]. Associating it with the 107 050 623 m^3 of water used for irrigation by EDIA in 2015, the same methodology would correspond to a potential recovery of 24,4% of the total energy consumed in that year by EDIA. It is clear the advantages of the investment in these power recovery technologies.

3.2 Energy Resources Assessment

3.2.1 Energy Recovery

Since water systems contain excessive pressure in different points across the network, this study produced an assessment that quantifies the energy available for micro hydropower technology to be exploited. In the proposed case study, the data analysed is of an irrigation network, where the energy recovery is assessed in pressure reducing valves (PRV) and storage reservoirs. The location of these components of the water infrastructure is determined together with data on flow and excess pressure at each location to enable assessment of the energy resources. In order to convert the available excess pressure and flow to hydraulic power and electrical power, the first step is to select the site and to identify the dissipation points.

In a steady flow regime, the total energy line in a pipe, at a certain time, is defined as a straight line between the available head from the upstream to downstream node. In each node, the head will be equal or higher than a minimum pressure, p_{min}, which is imposed for quality services purposes. Within the pipe, when the head is higher than the minimum pressure, an excess of energy exists, which will change along the time, since the network's demands also change with time. This will affect both the node's pressure and the pipe flow. Therefore, the available energy at a point, within a water network, can be defined as the excess energy, which can be extracted from the flow without compromising the system's pressure to drop below the imposed minimum value. So to assess the amount of this excess energy which is available for power generation, it is first required the identification of the excess energy points. These are located in a pipe system when the difference between the total energy and the minimum pressure is minimal but higher than zero [62].

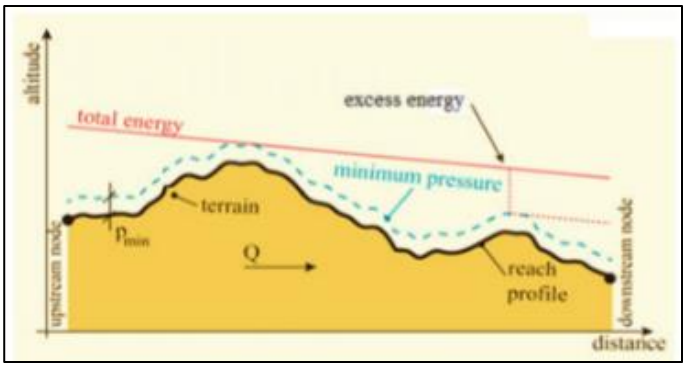


Figure 12 - Available energy which can be extracted in a pipe system [62]

$$E_h = \gamma Q H \Delta t \quad (1)$$

The hydraulic energy E_h (Wh) in any point of the pipe is defined as the Equation 1, where γ is the water volumetric weight (N/m^3), Q is the flow rate (m^3/s), H is the head (m), meaning the total energy subtracted from the elevation at that point and Δt (h) is the time interval. Hence, to estimate the excess energy in the upstream and downstream nodes Equation 2 is presented.

$$E_{excess} = \gamma Q_t (H_{up} - H_{dn}) \Delta t \quad (2)$$

The knowledge of the availability of power is a critical factor necessary to predict and identify the economic benefits of converting energy dissipation into energy production. The growth of interest in exploiting water for drinking and irrigation purposes to produce electricity has resulted in considerable research projects. Recurrent situations within the water systems, from which energy can be potentially recovered, have been identified in Table 7 [62].

Table 7- Recurrent situations in water networks, from which energy can be potentially recovered

Excessive pressure in correspondence with inlet duct leading into storage reservoirs
Excessive pressure within gravity-fed water conveyance pipes
The replacement of PRVs with PATs
Dissipated potential within irrigation systems
Sites at the inlet or outlet of wastewater treatment plants characterized by low available net heads, albeit showing significant and constant flow rates throughout the day

The experience of some authors, such as Carravetta, Houreh and Ramos [62], has led to the conclusion that the most favourable location in water systems for power generation are the replacements of PRVs and the paths of the highest available heads and discharge flows. This is the reason why the highlighted situations in Table 7 were the scenarios analysed in the proposed case study. Hence, it is necessary to understand the science behind these scenarios.

3.2.2. Pressure Reducing Valves (PRV) and Pump as Turbines (PAT)

In water networks, PRVs are used to satisfy the pressure limitations and to control it, dividing the water grid into pressure areas with respect to the network's topography. PRVs' manoeuvring creates a local headloss with hydraulic dissipation, due to the decrease in the outlet pressure. The areas that PRVs create have controlled flow and pressure, which allow an easier monitoring of the water losses by improving the location identification and the response. The PRVs behaviour can be divided in three types:

1. PRV active – If the pressure outlet is higher than the set value, the value closes creating a headloss
2. PRV passive open – if the pressure inlet is lower than the set value, the valve opens, decreasing the headloss.
3. PRV passive closed – if the outlet pressure is higher than the inlet pressure, the valve closes (working as a retention valve)

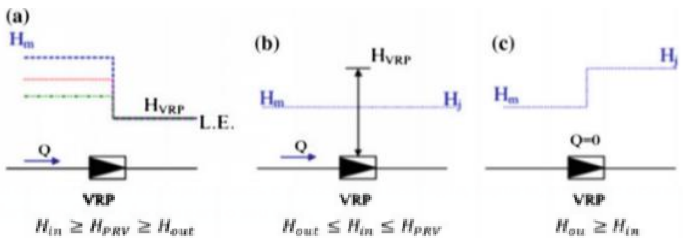


Figure 13 -PRV behaviour: a) Active, b) Passive open, c) Passive closed [63]

In the scope of renewable energies, PATs can harness the dissipated potential for energy generation present in PRVs, in WDS. PRVs and PATs have a similar behaviour under uniform regime, however, PATs are an alternative source for producing clean energy with low costs and environmental impacts [39], harnessing the excess energy which otherwise would be dissipated through a PRV. PATs are also able to control the pressure in WDS in the same manner as PRVs while increasing the flexibility of the system [64]. However, one of the largest challenges within this technology is not having any flow control device, which disables its optimum efficiency when the flow oscillates which is usual in WDS [59].

3.2.3. PAT Regulations

As a set difficulty for a PAT implementation, the variation of the hydraulic conditions with different flows and pressure values, corresponding to the different demand patterns throughout the day, has been analysed and has now a solution. A new design procedure, named Variable Operating Strategy (VOS) has been analysed [65]. To overcome the variable operating conditions in water demand daily patterns, it is required a control system for enhancing the PATs energy recovering performance. VOS is then applied in three regulation modes.

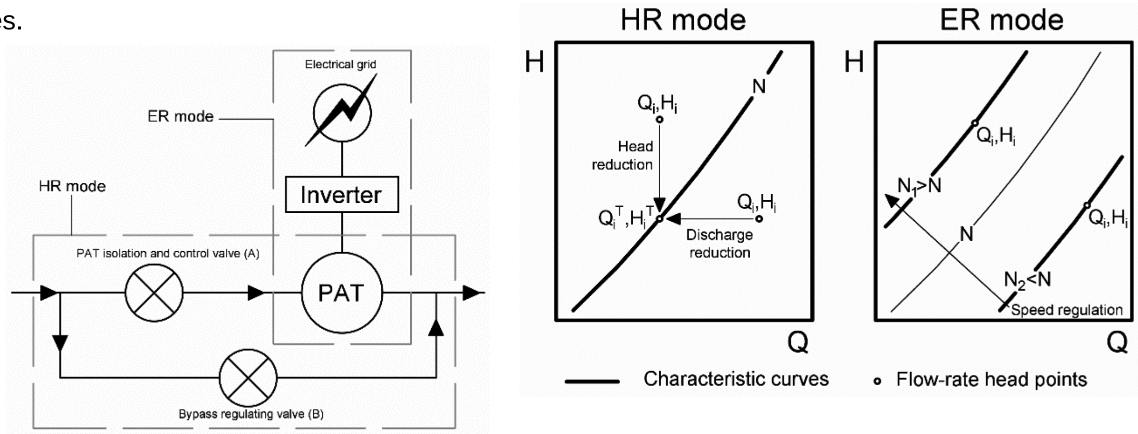


Figure 14 - Hydraulic or Electric Regulations (HR/ER) PAT installation scheme and operating conditions [66]

In hydraulic regulation mode (**HR**), the installation scheme is divided in two: firstly, a control valve and a PAT are set in series, which correspond to the dissipation and production elements. Secondly, it is installed another control valve, which functions as a bypass regulated element (Figure 14). In HR mode, if the available head, H_i, is higher than the head delivered by the PAT, H_t (region above the PAT characteristic curve in Figure 14 and Figure 15), the valve set in series (A) dissipates the pressure in excess. Moreover, if the discharge, Q_i, is higher (points below the PAT characteristic curve, Figure 14 and Figure 15), the PAT will produce a head higher than the available head, opening the second control valve (B) to reduce the flow within the PAT from Q_i to Q_t. This bypass (valve B) prevents the PAT to produce a head higher than the one available, optimizing its efficiency values. In electrical regulation mode (**ER**), the installation scheme is composed by a PAT and an inverter (Figure 14). In this mode, the operating speed of the generator (which establishes the PAT characteristic curve) is set to equal the actual flow discharge and available head (Figure 14 and Figure 15). In hydraulic and electrical regulation mode (**HER**), both previous techniques are combined by valve (flow) and operating speed controlling in order to achieve the desired high drop [62, 66].

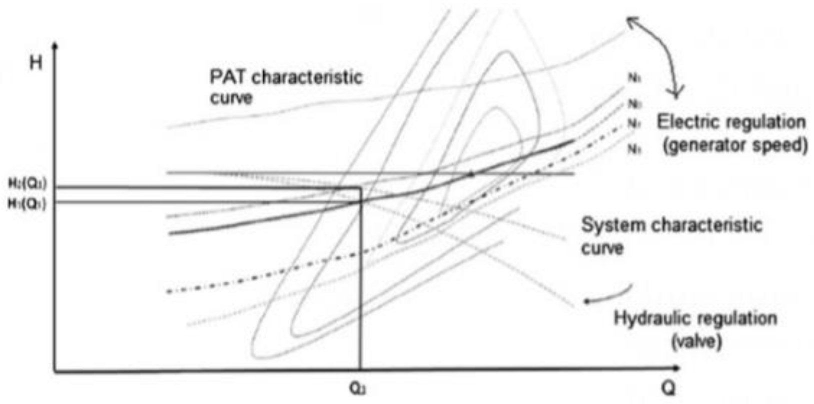


Figure 15 - Hydraulic and Electric Regulation (HR/ER/HER) in a hill diagram [62]

The advantage of working in HR mode is that the dissipation valve (A) and the bypass (B) allow the PAT to operate constantly in BEP. However, it has the downside of not converting all of the excess energy into electrical power. In ER mode, all of the energy is transformed in the PAT, having the disadvantage of not working in the BEP region. In HER mode both previous methods are combined. There is also the possibility of conceiving the PAT installation scheme without any regulation, which would be the same as a current PRV installation [66].

The selection of the PAT and which regulation mode is more suitable is based on the best plant efficiency (Eq. 3). The plant efficiency is defined by the amount of hydraulic energy available in the network that can be converted into electrical power [64].

$$\eta_p = \frac{\sum_{i=1}^{n} H_i^T Q_i^T \eta_i^T \Delta t_i}{\sum_{i=1}^{n} H_i Q_i \Delta t_i} \quad , Q_i^T \leq Q_i, H_i^T \leq H_i \tag{3}$$

where, H_i^T is the head delivered by the PAT (m), H_i is the available head (m), Q_i^T is the turbinated flow (m³/s), Q_i is the flow discharge (m³/s), η_i^T is the mechanical efficiency and Δt_i is the duration of the time interval with constant hydraulic parameters (h) [64].

Studies focusing on the application of VOS in water distribution networks enabled the selection of the best PAT geometry for both HR and ER mode. A comparison between the two regulations has led to the conclusion that the HR mode is economically more advantageous and it is generally more flexible and efficient when there are fluctuations in the working conditions from the design values [66].

3.2.4. Hybrid System

In view of a self-sustainable system, alternative sources will also be analysed. The power necessary for satisfying the electrical demands of WDS' pumps throughout a day is higher than the electricity produced in the energy recovery technologies, such as PATs. Depending on the number of PATs that are feasible to introduce in the system, for a higher renewable percentage system solution, other renewable power sources have to be taken into consideration. For this reason, a wind/solar hybrid solution consisting on PV panels and small wind turbines will be studied to complement the energy recovery technology in order to satisfy all electrical demands and thus to achieve a self-sustainable atmosphere.

A hybrid power solution (Figure 16) is defined as a system that has more than one resource. Single energy source systems can be oversized when the only resource is less available. This consists on a limitation that hybrid systems can upgrade. When one of the resources is not available, the other can compensate, increasing the reliability of the system [67]. This complementarity is undoubtedly advantageous for energy systems users.

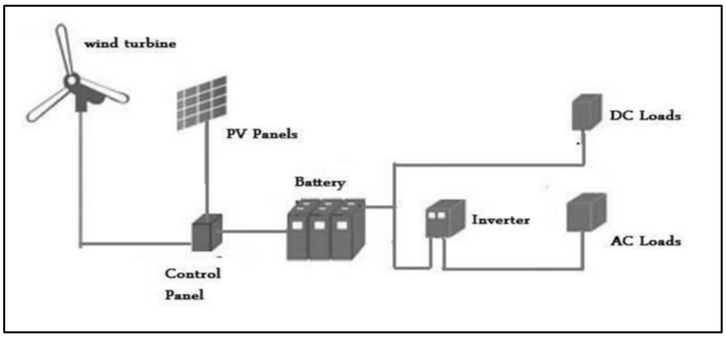


Figure 16 - (PV + WT) Hybrid power system [68]

Photovoltaics systems (PV) are being used as renewable sources for supplying water pumps (Figure 17) [67, 69]. This technology, described as Solar Pumping as different types in the current market, is more and more utilized [69]. For these systems to be operational, the elements required are a PV array (Wp), a controller, over current protection devices and an inverter when an AC pump motor is being used. Depending on the power demand, different capacities for the PV arrays have to be considered. These solutions can also include a battery bank for harnessing the produced energy and to supply it when there is no sunlight.

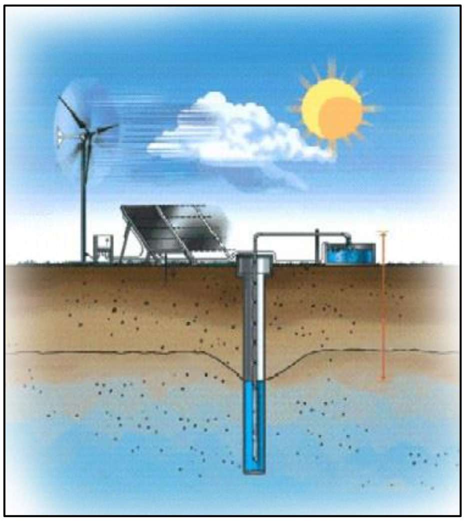


Figure 17 - Hybrid pump system scheme [70]

The PV solution is currently a very reliable and high-developed technology. A high life expectancy of pumps and solar cells, ranging from 25 to 30 years, is currently an advantage with the little maintenance they require. Moreover, the pumps designed for these systems have good efficiencies that enable smaller solar array sizes, which means that the upfront cost is lower [69].

Other common solution for sustainable water pumping is a wind pump, which can provide durable solutions with simplistic technological features [71]. The combination of the wind source with solar pumping has a great advantage, as mentioned, however the cost effective prices for installations, especially the wind turbines, can be a challenge for the implementation of these systems. Therefore, another realistic solution, despite not being completely self-sustainable, can be a grid-connected hybrid solution, which only uses the grid power for back-up purposes.

3.2.5. Sustainable Urban Drainage System (SUDS)

In order to take advantage of other renewable sources for complementing the self-sustainable system, a Sustainable Urban Drainage System (SUDS) solution was also taken in account. Although SUDS primary goal is to act as a flood control technology [72], in association with a small hydropower technology, it is an excellent energy recovery opportunity.

The system consists in using the precipitation collected in a pond, lake or storage reservoir and its volume and water height to produce energy by connecting it to a micro-hydropower, such as a PAT. The power output is calculated as function of the outlet discharge and the net head created from the elevation of the PAT until the water level inside the lake.

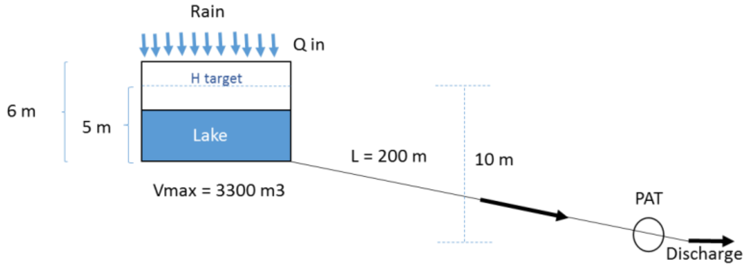


Figure 18- Sustainable Urban Drainage System (SUDS) scheme

The inlet discharge, Q_{in}, which flows into the lake, is calculated by analysing the precipitation values (mm) of the catchment area in a year. The Q_{in} (m^3/s) is then evaluated for each month, according to the watershed area **A**, a coefficient that considers precipitation losses **c** (0,8), and the precipitation intensity **i** (mm/h), which can be obtained by dividing the effective rainfall by the number of hours and days that has rained in that specific month.

$$I(mm * h^{-1}) = \frac{Peffective}{Nº rainy\ hours * Nº\ rainy\ days} \tag{4}$$

$$Q_{in}\ (m^3 * s^{-1}) = c * i * A \tag{5}$$

After analysing the inlet discharge, a constant head target is considered for the PAT station. When the water reaches a specific water level inside the lake (head target), a valve opens allowing the excess water to be discharged to another reservoir/lake. The discharged flow, Q_{out} is controlled by the user.

The number of hours to reach the water level that satisfies the head target (H_{target}) is then estimated by considering an initial volume. With this input, it is possible to estimate how many hours will the water flow through the discharge pipe (water level higher than the head target) and hence the energy production per month.

$$P\ (kW) = \rho * g * Q_{out} * H_{target} * \eta PAT \tag{6}$$

$$E\ (kW * month) = P\ (kW) * Nº hours\ (water\ level\ \geq\ H_{target}) * Nº\ rainy\ days \tag{7}$$

3.3 Economic and Environmental Impacts

The impact of the solutions chosen on the operation costs of water supply will be analysed. Moreover, an assessment of the economic feasibility of converting the available resources to electricity in terms of return on investment and annual income was carried out.

3.3.1 Economic Analysis

In order to evaluate the feasibility of the proposed solutions, an economic analysis was assessed. According to Ramos *et al* (2000), a daily demand law of a water system is required for an energetic assessment [73]. The usable flow for producing energy can be defined due to the established demand patterns. The total energy produced can be obtain by Equation 8.

$$E = \sum(Pu\Delta t) \tag{8}$$

where E represents the energy in kWh, Pu the power in kW and Δt the time interval in hours.

The feasibility of the project is analysed by considering the costs such as of pipes, valves, PATs, and all the civil construction operation and the revenues generated by the sold electricity. The costs of the project are divided into different categories:

- Capital costs (C)
- Operational costs (O)
- Reposition costs (P)

Future costs and benefits were assessed based on an analysis of the current market prices. This study is based on the concept of constant market prices, which does not account for inflation. The discount rate, r, establish a value for the monetary flux which occurs in different instants. The present value (P_V) allows to analyse the sequence of these monetary fluxes referred to the first year of the analysis period [73].

$$P_V = C\sum_{i=1}^{n}\frac{1}{(1+r)^i} = C\frac{(1+r)^n - 1}{(1+r)^n r} \tag{9}$$

where n is the period of n years.

The economic viability of the project is measured by four parameters: the net present value (NPV), which represents the cumulative sum of all benefits excluding all costs, expected during the lifetime of the project, at a discount rate (Eq. 14); the benefit/cost radio (B/C), which represents the ratio between the present value of benefits and total costs (Eq. 15); the IRR, internal rate of return, which is the discount rate for which NPV equals zero (Eq. 16); and the payback period (T), which is the number of years required for the cumulative cash flows to equal the first investment (to reach zero) [73, 74, 75].

A project with a high NPV is more interesting than one with a low NPV. A negative NPV means that the overall cost over the lifetime of a project is higher than the revenues and thus it should be disregarded. The higher the B/C (over than one) the more economically viable is a project. When B/C is equal to one, it means the NPV is zero, which represents an equality between the costs and the expected profits. B/C lower than one should not be considered. In addition, choosing from different projects with different IRR, the higher the IRR the better the project. A project with a discount rate such as the IRR is a project that has B/C as one and NPV equal to zero [73, 74, 75].

Table 8 - Economic parameters and the corresponding formulas [75]

Parameters	Formulas	
Capital costs	$C = \sum_{i=1}^{k} \frac{C_i}{(1+r)^i}$	(10)
Operational costs	$O = \frac{\sum_{j=k+1}^{n} \frac{O_j}{(1+r)^j}}{(1+r)^k}$	(11)
Revenues	$R = \frac{\sum_{j=k+1}^{n} \frac{R_j}{(1+r)^j}}{(1+r)^k}$	(12)
Reposition costs	$P = \frac{P_m}{(1+r)^m}$	(13)
Net Present Value (NPV)	$NPV = R - C - O - P$	(14)
Benefit/cost ratio (B/C)	$B/C = \frac{R - O}{C + P}$	(15)
Internal rate of return (IRR)	$NPV = \frac{\sum_{j=k+1}^{n} \frac{1}{(1+IRR)^j}(R_j - O_j)}{(1+IRR)^k} - \sum_{i=1}^{k} \frac{1}{(1+IRR)^i} C_i - \frac{P_m}{(1+IRR)^m} = 0$	(16)

3.3.2. Environmental Analysis

To achieve the desired sustainability status, it is required a decrease of the gases which contribute to the global warming, hence lowering the use of non-renewable resources. By knowing how much greenhouse gas (GHG) emissions would the fossil sources release into the atmosphere, we can estimate how much pollution the renewable technologies chosen can avoid [76].

As part of sustainability analysis in water systems, different studies acknowledge the importance of environmental criteria [77, 78]. Therefore, aiming for a sustainable future, it is thought essential to have an environmental analysis on this project proposal.

The software model, *WaterGEMS,* allows to input the value of CO_2 emissions, associating it to the consumed electricity in the grid. In this dissertation it was considered emissions of 600 g CO_2/kWh of produced energy [67]. Moreover, another software model (HOMER) establishes the amount of electricity needed from the grid in case of non-total renewable solutions, quantifying the grid purchases and sales. The comparison between the current network energy demand and the solutions applied with view of sustainability allow to estimate the saved emissions.

In the case of a 100% renewable network the full comparison between the previous system and the new, self-sustainable, one establishes the environmental value of the project.

3.4 Design Guidance

A PAT performance in a small water system was assessed at IST-DECivil laboratory conditions. Designed guidelines on how to operate this technology in an off-grid connection system and its hydraulic and electrical conditions were developed. This work involved testing different hydraulic and electrical parameters in a pump running in reverse mode, so as to determine their efficiency, power output, reliability, and ability to control pressure in water systems.

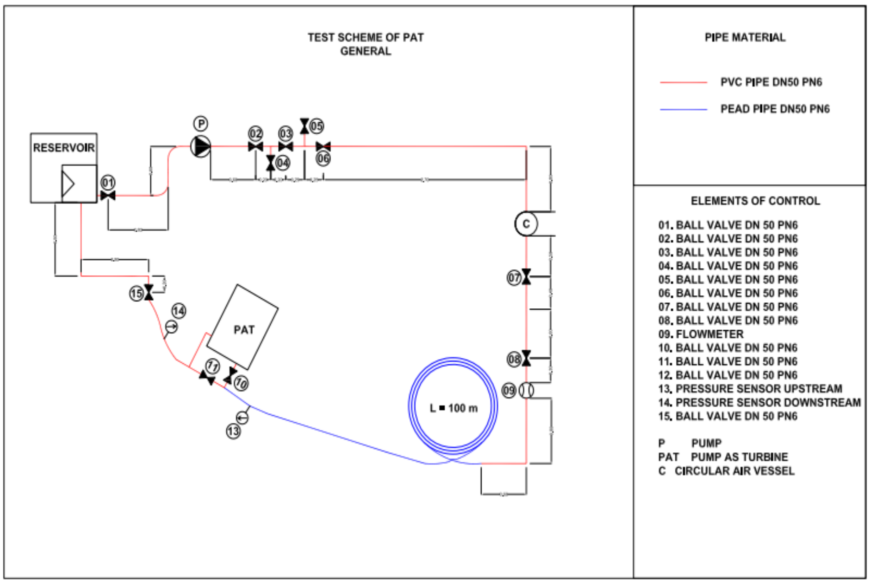
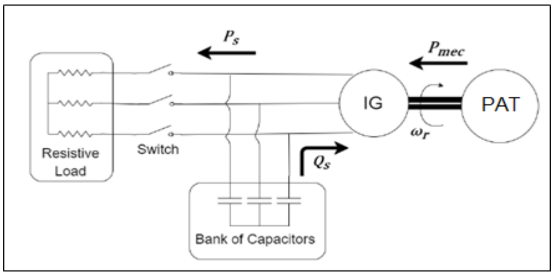


Figure 19 - PAT pilot station scheme

Hence, to simulate a real energy recovery device in a WDS, a PAT Pilot Station with the configuration of Figure 19 was created. With this facility it is possible to evaluate the PAT performance along different hydraulic and electrical conditions. So as to recreate the normal operating conditions of a water distribution network, some hydraulic parameters were established. It was imposed a pressure of 3 bar in the pressurized air vessel and a centrifugal pump would induce a flow through the pipe system.

Different trials were performed for different hydraulic and electrical parameters. The flow (Q – measured with an electromagnetic flow-meter), the pressure up and downstream the PAT (Pup and Pdown, both measured with pressure transducers with connection to the Picoscope software) were the hydraulic tested variables. The electrical parameters were the rotation of the shaft that connects the PAT to the generator (measured with an optical tachometer in rpm), the voltage (V_s), the current (I_s), active power (P_s) and power factor (PF) corresponding to the generator energy production. These latter variables were measured with a Fluke multimeter.

The study had the purpose of analysing an off-grid connection system which meant to simulate a stand-alone power generation system that could fulfil a certain load or supply an energy storage device. For this type of isolated self-behaviour, there is a need of using a bank of capacitors to excite the generator, named as Self-Excited Induction Generator (SEIG). The electrical parameters had then to be analysed. It was used adjustable resistors to simulate the load for each of the three phases in a star connection. The capacitors were able to excite the generator due to their reactive power.



- Ps - Active Power (W);
- Qs - Reactive Power (Var);
- Pmec - Mechanical Power (W);
- PAT – Pump as Turbine
- IG – Induction Generator

Figure 20 - Off-grid PAT electrical connection

$$\eta_{SEIG} = \frac{P_s}{P_{mec}} \approx \eta_{SEIG}\,(N) = -5 * 10^{-5} * N^2 + 0{,}1445 * N - 36{,}185 \quad (17)$$

$$\begin{cases} P_s = 3 * V_s * I_s * cos\varphi & (18) \\ P_{mec} = P_{DC} - P_{loss} & (19) \end{cases}$$

The estimation of the efficiency of the SEIG, η_{SEIG}, is described by the Equation 17 as function of the rotational speed, N. In Equation 18, the P_s is the active power of the generator, which was directly obtained by a Fluke multimeter by measuring the voltage, V_s, and current, I_s. P_{mec} is the mechanical power, which is given by the total power in the dc motor, P_{DC}, excluding all associated losses, P_{loss} (Equation 19). A previous study in the same system established that the maximum efficiencies of the SEIG depended on the load applied and rotational speed occurred [79]. After an analysis of the different values of the generator efficiency, the previous study established an average electrical efficiency equation (Equation 17) depending only on the rotational speed values. In the present study, the SEIG performance was analysed considering that the equation for a constant load of 175 Ohm for each one of the three phases.

$$\eta_{global} = \frac{P_s}{P_{hyd}} \quad (20)$$

$$\begin{cases} P_s = 3 * V_s * I_s * cos\varphi & (21) \\ P_{hyd} = \rho * g * Q_i * H_i & (22) \end{cases}$$

The global efficiency of the system was then calculated by Equation 20. The active power, P_s, was obtained by the Fluke multimeter and the available hydraulic power P_{hyd} was measured by analysing the different flows and the corresponding head values.

$$\eta_{PAT} = \frac{\eta_{global}}{\eta_{SEIG}} \quad (23)$$

The PAT performance is then estimated. The electrical efficiency is defined as function of the rotational speed (N), while the global efficiency is expressed as function of the flow rate. The PAT efficiency is also as function of the flow rate, which is the factor that influences the most performance of the turbine.

3.5 Support Tools

Two computer softwares were used in this dissertation: a support tool such as a hydraulic modelling software, WaterGEMS, and the Hybrid Optimization Model for Electric Renewables (HOMER).

WaterGEMS is an application for WDS with advanced interoperability, geospatial model building, optimization, and asset management tools. It provides the necessary tools to analyse, design and optimize WDS and it is also able to analyse the energy consumption and the capital costs management [80]. WaterGEMS was used to analyse and compare the PAT computed results with the experimental ones obtained in the laboratory. Also, it allowed to model the water system of the case study.

HOMER allows to easily evaluate both off-grid and grid-connected designs of power systems for a wide range of applications. It considers a large number of technologies, the variation in their costs and allows to input resources availability. Due to an optimization algorithm and sensitivity analysis, HOMER establish various scenarios of hybrid combinations and allows the user to easily choose the more feasible one. The scenarios are tested and presented in a list of configurations that is sorted by net present cost (NPC), which is the present value of all costs minus the present value of all the revenues (NPC= -NPV). This tool simplifies the evaluation of a hybrid system configuration [81].

This study, by means of the methods discussed, intends to integrate PATs in a WDS and analyse the implementation of renewable technological systems in order to maximize the energy generation and to achieve a state of self-sustainability.

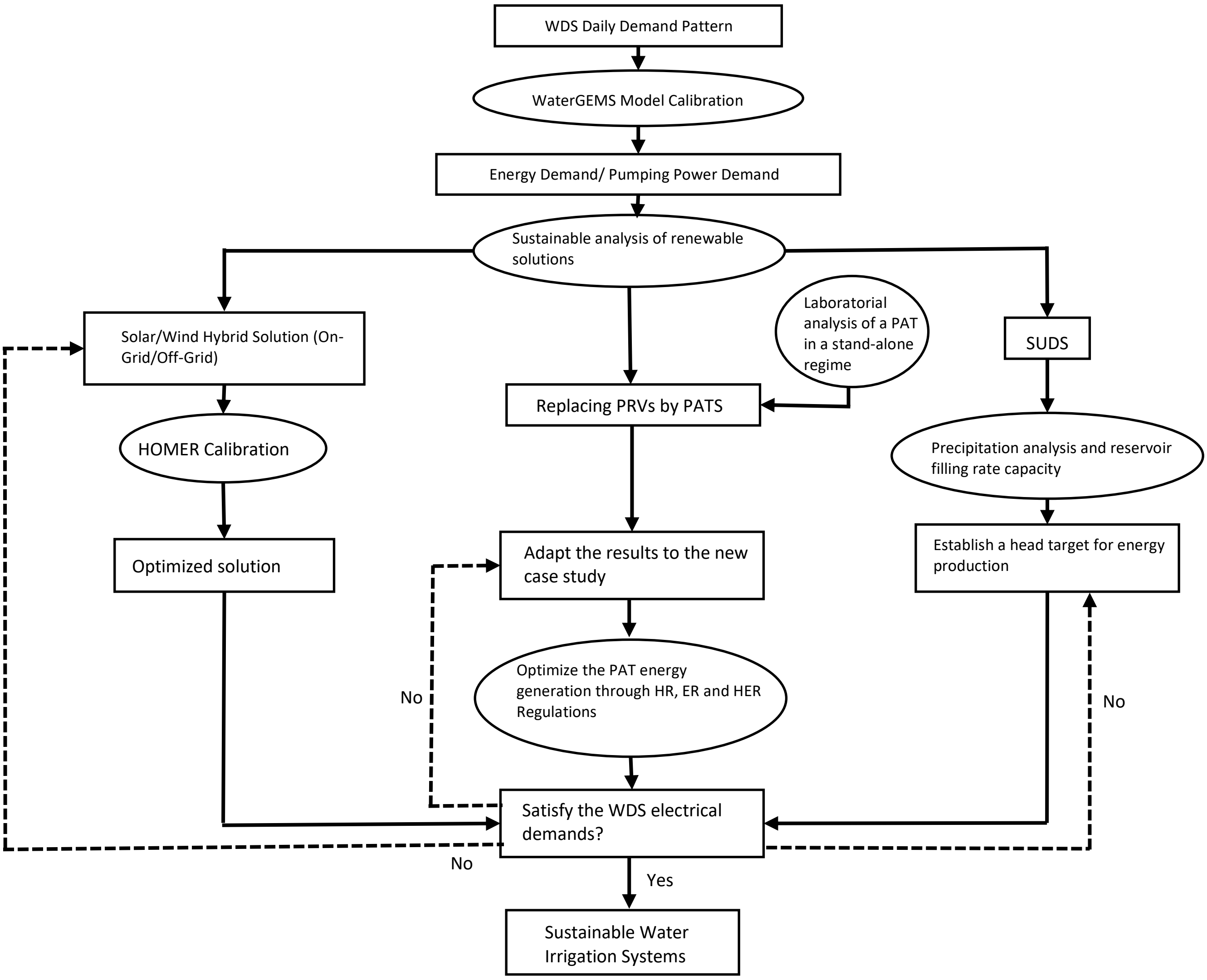


Figure 21 - Optimization model

4. Laboratorial Analysis for a PAT

To simulate a real energy recovery device in a water supply network, it was analysed a PAT Pilot Station. The laboratorial station was previously installed by a research team of Professor Ramos. With this facility, an evaluation of the PAT performance along different hydraulic and electrical conditions was assessed.

Figure 22 - PAT pilot station

The trials were performed for a constant pressure in the network of 3 bars, for different flow conditions, which depended on the number of hydrants opened or closed. The relation between the flow and the number of hydrants was determined.

Table 9 - Hydrants opening relation with flow

Hydrants	Flow (l/s)
2.5	3.117
3	3.314
3.5	3.525
4	3.818

It was evaluated the relation between the head, flow, rotational speed, the PAT and global efficiency relative to the Best Efficiency Point (BEP) values provided by the manufacturer datasheet. These BEP values are the following: PAT (**Q_{BEP}= 3.36 l/s** ; **H_{BEP}= 4 m** ; **n_{BEP}= 1020 rpm**; **$\eta_{PAT,BEP}$= 60%**) ; SEIG (**$\eta_{SEIG,BEP}$= 67.5%**). These nominal values allowed to generate dimensionless relations between the different parameters.

Figure 23 - Electrical components of the PAT Pilot Station

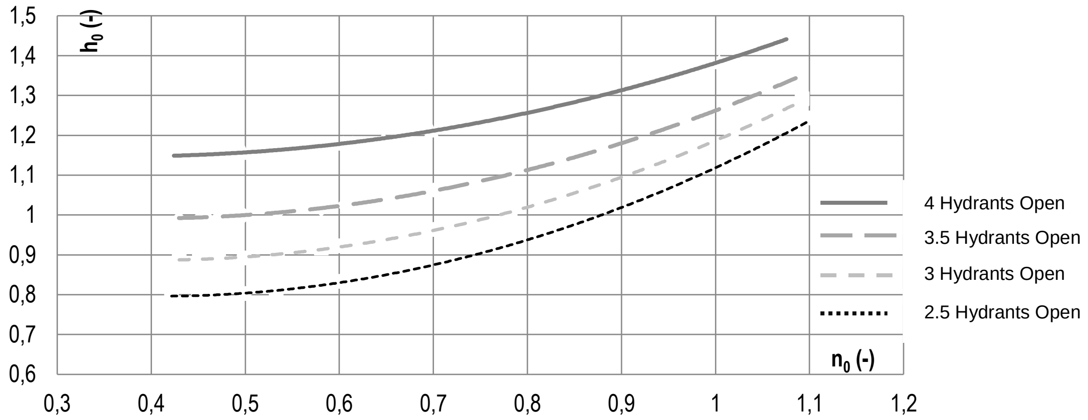


Figure 24 – Relative head by relative imposed nominal rotation

The relation between the PAT head for different rotational speeds was analysed (Figure 24). The results showed that the head is proportional to the rotational speed of the generator. More data was collected for lower rotational speed values (higher capacitance applied) since it was only considered the points in which power was being generated.

The Self-Excited Induction Motor's performance was analysed by calculating its efficiency. Different flows and capacitance values allowed to obtain different rotational speeds, which by application of Equation 17, enabled the estimation of the electrical efficiency. For a nominal efficiency of 67.5% ($\eta_{SEIG,BEP}$,) the efficiency of the SEIG achieved the maximum values for higher rotational speeds.

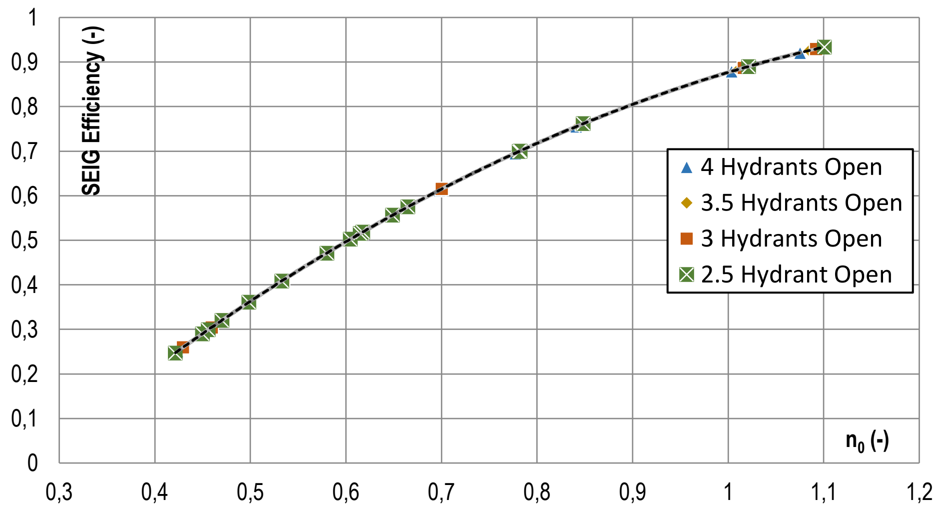


Figure 25 - SEIG (electrical) efficiency by relative imposed rotational speed

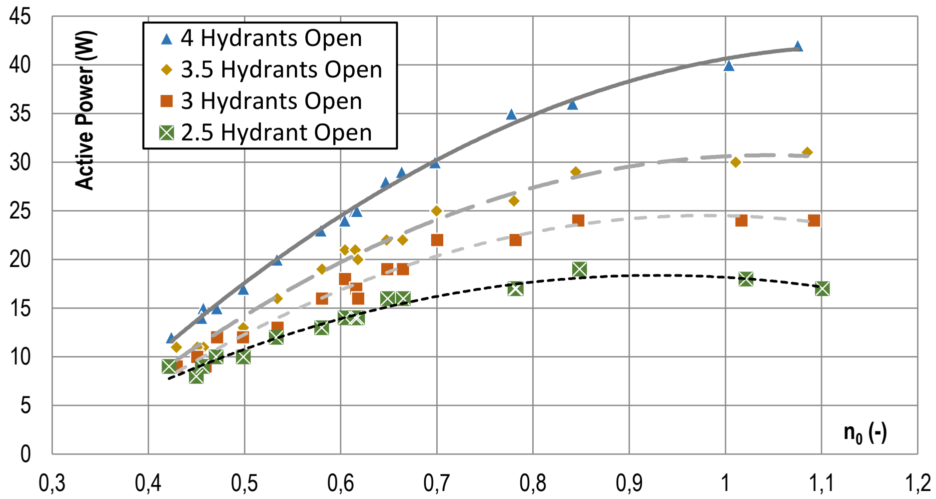


Figure 26 - Active Power by relative imposed rotational speed

It was also measured the amount of active power which could be extracted in these conditions (Figure 26). The global efficiency was then determined by the relation between the output active power and the input hydraulic power (Equation 20). Figure 27 depicts the global efficiency for four different flow scenarios. The results showed that the global performance is proportional to the flow. For the four different flow scenarios, the maximum experimental efficiency obtained in laboratory was approximately 20%. The maximum efficiencies of the turbine are obtained for different rotational speeds comparing to the ones that optimize the efficiency of the SEIG. Hence, the maximum efficiency areas of the SEIG and the PAT are different, thus the system is not optimized, resulting in a maximum experimental global efficiency of half of the nominal global efficiency ($\eta_{global,BEP} = \eta_{SEIG,BEP} * \eta_{PAT,BEP}$ = 40,5%).

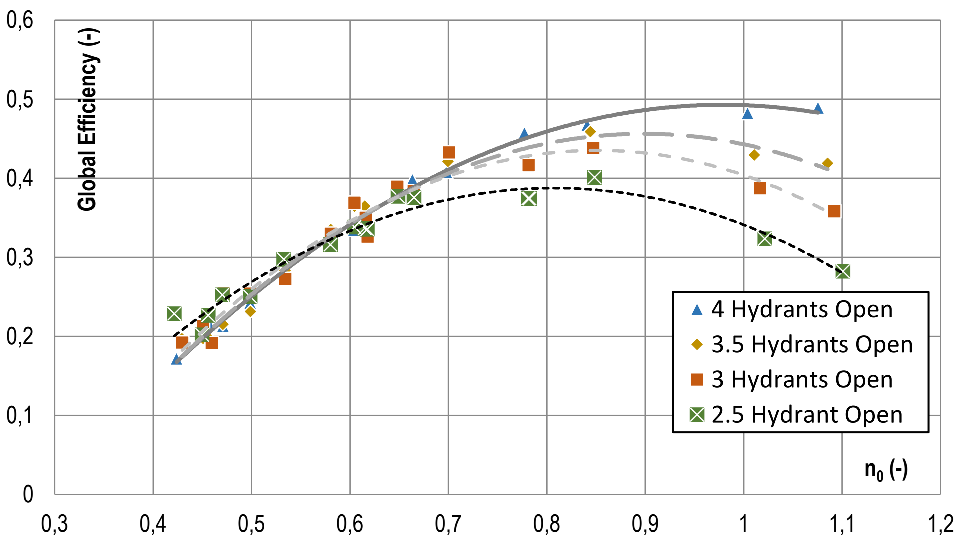


Figure 27 - Global efficiency by relative imposed nominal rotation for different flows

The PAT efficiency was obtained by Equation 23 for different flow and imposed rotational speed (Figure 28). The efficiency is proportional to the flow and so it presents its higher values for higher flows (four hydrants open scenario).

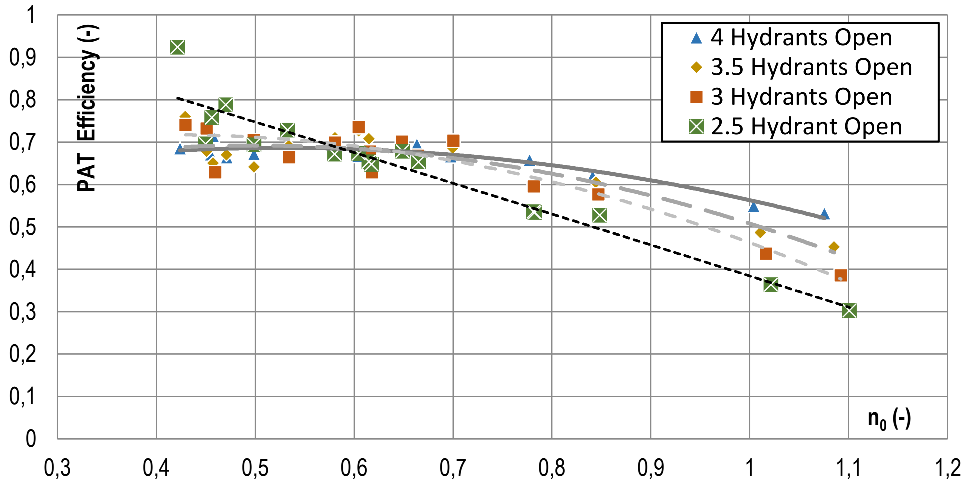


Figure 28 - PAT efficiency by imposed nominal rotation for different flows

A different analysis is showed in Figure 29 and in Figure 30. On the Figure 29, PAT efficiencies are obtained for values around 0.4 to 0.7 of the nominal efficiency of the PAT ($\eta_{PAT,BEP}$= 60%). The best PAT performances are achieved for relative speeds of 0.35 to 0.7 of the nominal speed (N_{BEP}= 1020 rpm) and around 0.9 and 1.3 of its nominal head (H_{BEP}= 4). Also, between 0.99 and 1.23 of the nominal PAT's flow (Q_{BEP}= 3.36 l/s), the best efficiencies are obtained (Figure 29).

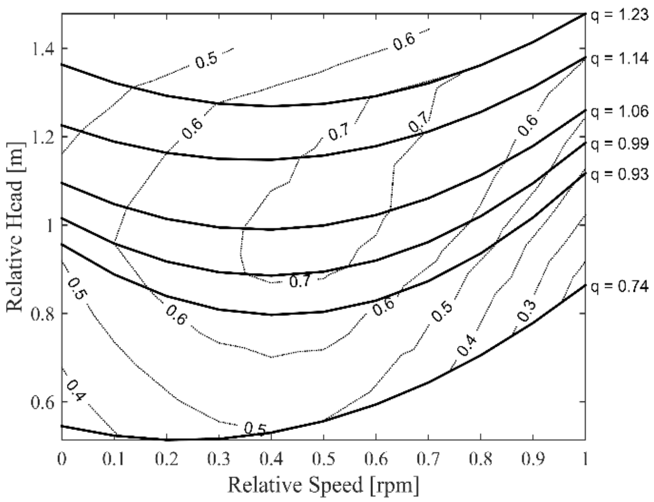


Figure 29 - Relative head, flow, rotational speed and PAT efficiency

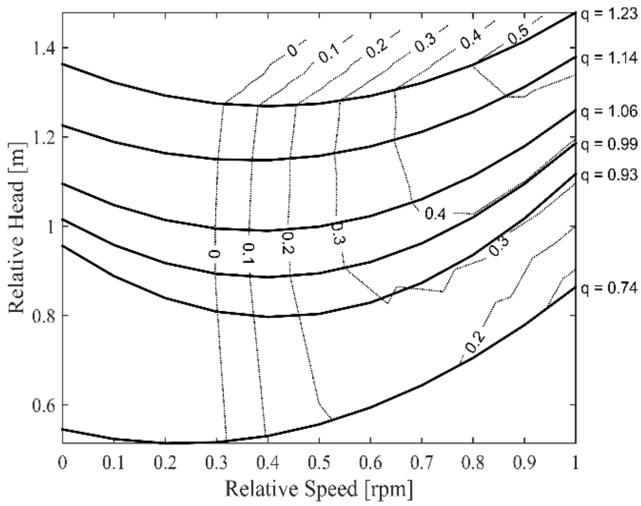


Figure 30 - Relative head, flow, rotational speed and global efficiency

The global efficiency (PAT + SEIG) achieved the highest values for 0.8 to 1.0 of the PAT nominal speed and between 1.14 and 1.23 of its nominal flow (Figure 30). The corresponding head varies from values from 1.3 to 1.4 of the PAT nominal head. Figure 30 also depicts that the global system can obtain a maximum efficiency of 0.5 of the nominal global efficiency as stated before ($\eta_{global,BEP}$= 40,5%).

5. Case Study – Belas Clube de Campo

5.1 Project Description

Located on the proximities of Sintra, Belas Clube de Campo (BCC) is an estate where a private community was built under the principle of sustainability. Managed by the *Planbelas, Sociedade Imobiliaria, SA*, within the *André Jordan Group*, the project was first founded in the 90's. The project's ambition was to protect an area of green field while acclimating it into an urban project, where all previous environmental features remained rigorously conserved. BCC is then composed by a real estate area with low density housing surrounded by a natural landscape and an 18-hole golf course.

The area analysed was divided in three regions, High, Medium and Low, which correspond to the topographic levels in BCC. There are different elevation levels in the area, which are highlighted in Figure 31 by colours. The blue region has higher elevations than the orange region, and the green region has the lower elevations.

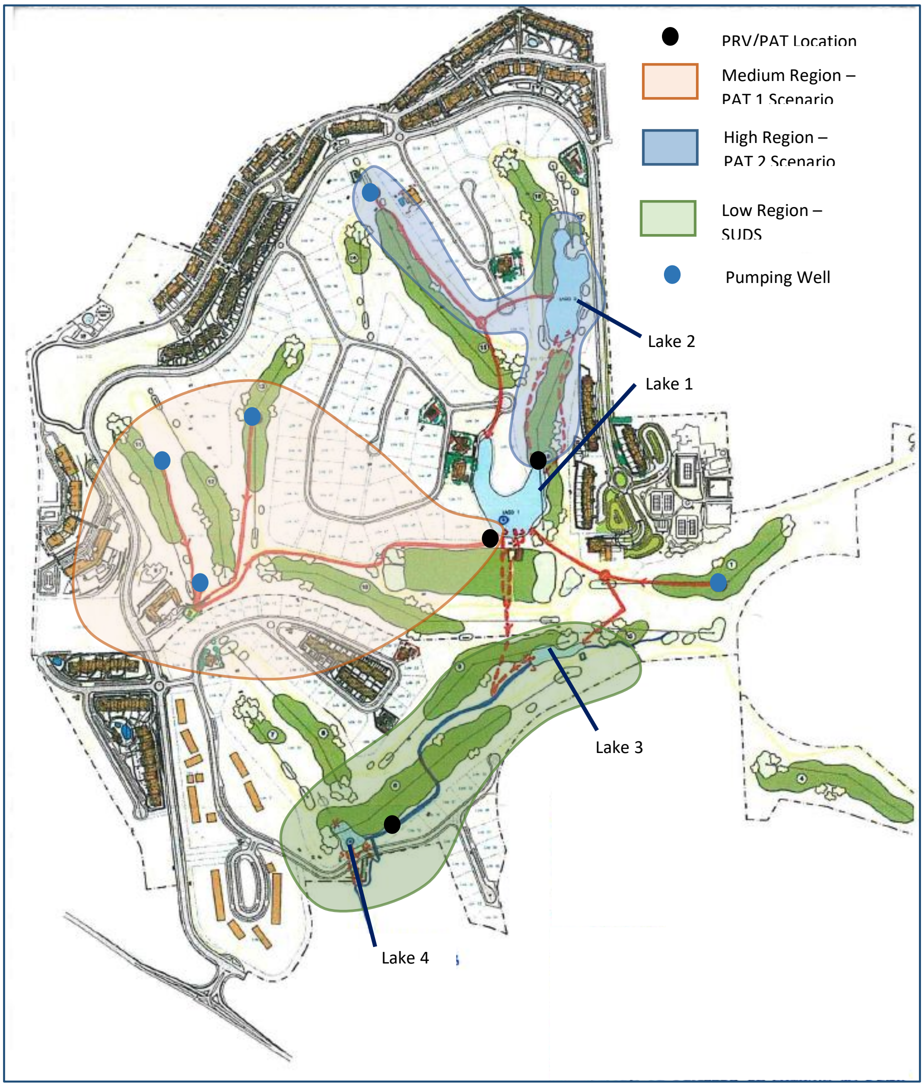


Figure 31 - Map of BCC

5.1.1. Storage Capacity

The BCC water irrigation system is divided into two sections: the public green spaces (GS) throughout the area and the golf course (GC). What connects both sections is the source of water, which is a storage lake (Lake 1), being the main supplier for both sections demands. Besides the storage lake, which can gather until 23 000 m^3, there are other three lakes, where two of them are merely decorative with a capacity of approximately 3 000 m^3 each one (Lake 3 and 4). The remaining lake (Lake 2), which has 18 000 m^3 of water capacity, is located in a higher elevation than the storage lake and it is connected with this one.

Table 10 - BCC's lakes characteristics

	Lake 1	Lake 2	Lake 3	Lake 4
Maximum Capacity (m^3)	23 000	18 000	3 300	3 000
Maximum Depth (m)	8	8	6	6
Watershed area (km^2)	0,49	0,18	0,15	0,12

5.1.2 Demand

From the same pump station there is a demand for the GS and for the GC. From 22h until 06h it is used an average of 1 500m^3 per day in the Summer months and 40m^3 per day in the Winter months for watering the GC. From 07h until 20h the demand of 250 m^3 per day is used for watering the GS in the non-raining months (dry season) and 5m^3 per day in the rainy season. The average consumption in an annual basis is approximately 311 932 m^3 (Figure 32). In this case study, the analysis was done only for the summer months, where the demand is higher and more critical. The water demand per months in the last 18 years is in *Appendix I*.

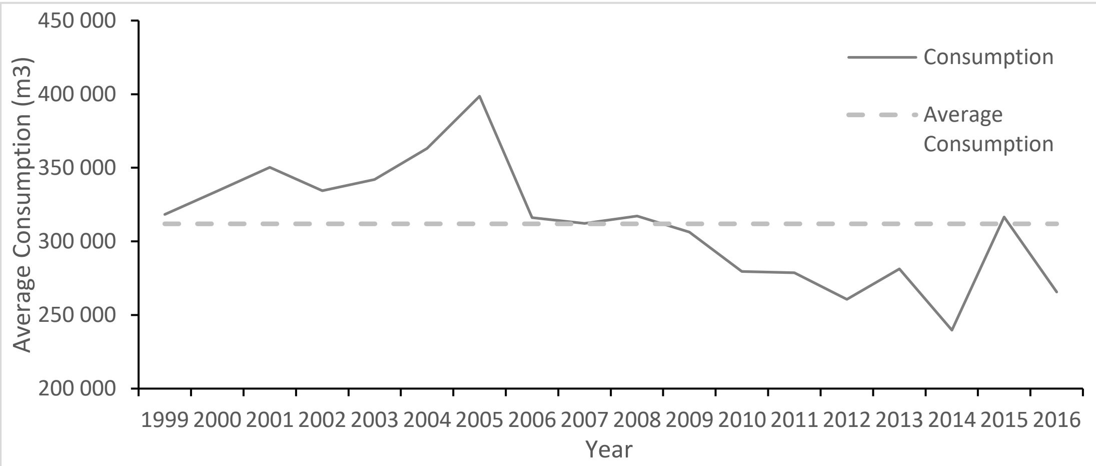


Figure 32 - Measured annual water consumption in BCC.

5.1.3 Pumping Wells

Since the demand on the dry season (54 410 m^3 on August 2016 for example) is higher than the water storage capacity provided by the lakes, there is an issue of water shortage. Hence, pumping wells were made in order to capture the groundwater stored in the aquifers underneath BCC's natural landscape. Five pumping wells with a capacity to extract approximately $65, 50, 40, 30 \text{ and } 10 \text{ m}^3/\text{h}$ from the aquifers were made (Figure 33). For three of this pumping wells, there is a storage unit (Reservoir Tank) which can hold 380 m^3 of water.

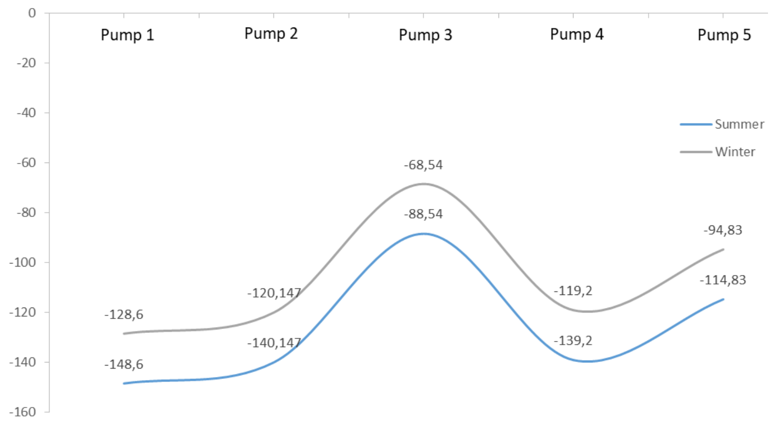


Figure 33 - Average Aquifer Level in summer and winter months for each of the pumping wells based on data from Appendix II.

5.2 Model Development

A simulation on *WaterGEMS* was carried out in order to analyse the current hydraulic conditions of a real water supply system. The objective was to access the present conditions and to further improve its management and efficiencies towards a sustainable grid. The input data such as demand patterns, pump characteristics, lake capacities and the system's elevation points were provided by BCC.

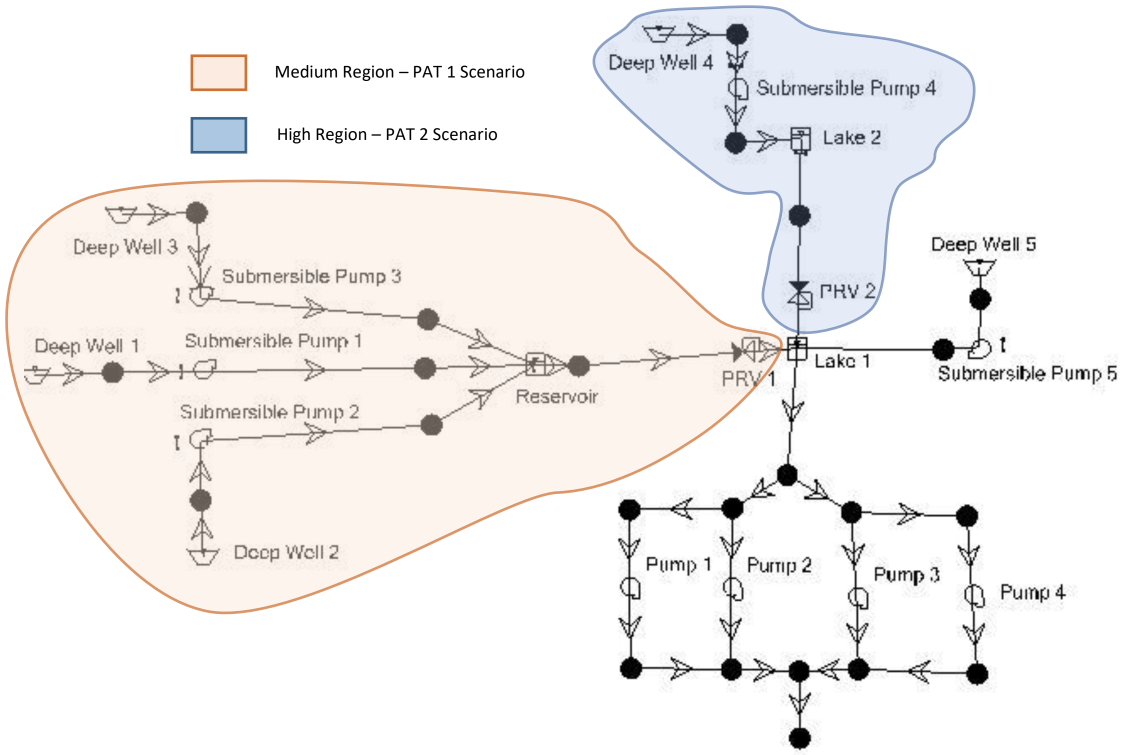


Figure 34 - Water Supply System of BCC

The model construction was made according to Figure 31 and its limitations. The data provided allowed to establish demand patterns such as the one depicted in Figure 32, which permitted to determine the pressure distribution in the network. According to BCC, the water demand of the warmest season is usually higher than the supply, hence, the analysis presented in this dissertation is in the scope of the Summer months.

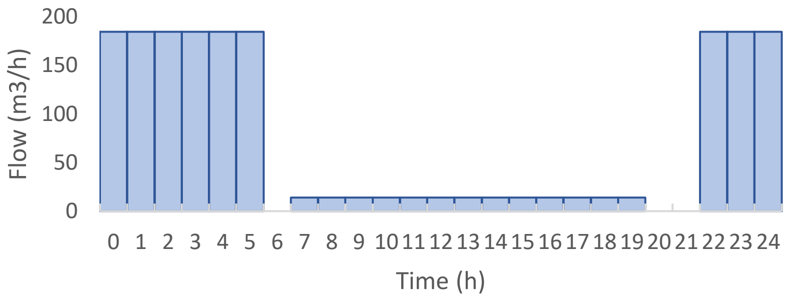


Figure 35 - Water Irrigation Demand Pattern in BCC (dry season).

The daily irrigation schedule consists on watering the GC from 22:00 until 06:00 (187,5 m^3/h) and then watering the GS from 07:00 until 20:00 (19,2 m^3/h) (Figure 35). To fulfil this demand pattern, the submersible pumps operate in different schedules hours so as to optimize the water gathering and to have a continuously movement in the network to avoid water stagnation. **SP-1**, **SP-2**, **SP-3** operate from 00:00 until 16:00, **SP-4** works from 00:00 until 08:00 and **SP-5** is turned on at 17:00 and turned off at 24:00. This pumping schedule in combination with the daily water demand leads to a pressure distribution network as shown in Figure 36. With the objective of controlling the pressure in the supply system while using the excess for energy generation, the pressure network is presented with two installed PATs instead of the two existing PRVs.

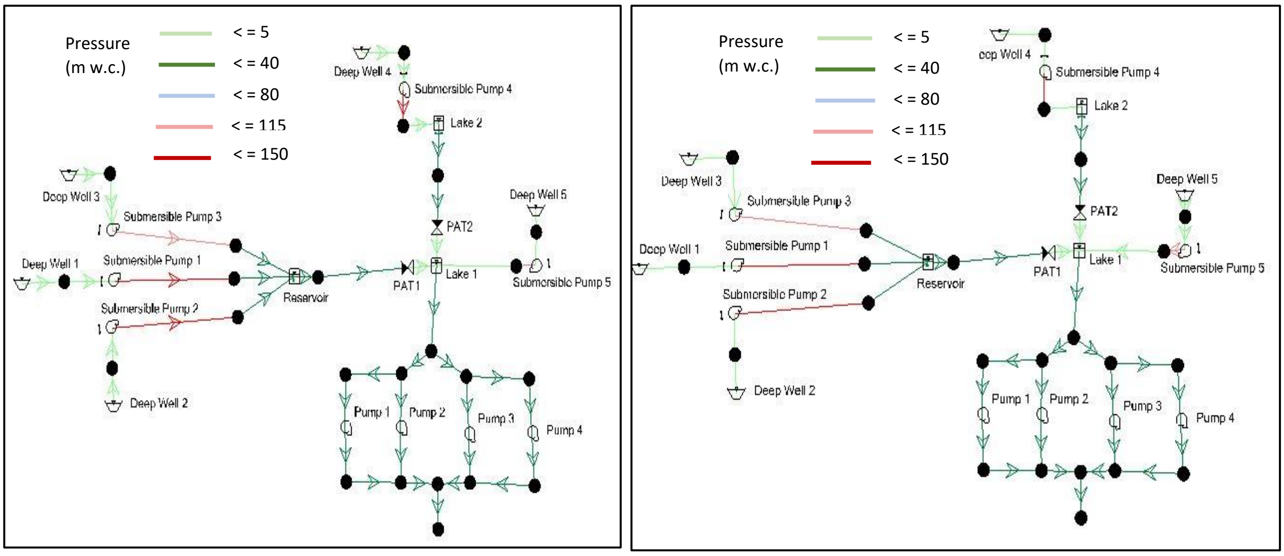


Figure 36 - Pressure in the network at 07:00 (left) and at 17:00 (right).

The two installed PATs control the pressure in the corresponding pipes in an equivalent way as the existing PRVs. However, it is now possible to harness the surplus of energy caused by the elevation gap between the Reservoir tank and Lake 1, for PAT 1, and between Lake 2 and Lake 1, for PAT 2. The next chapter shows how to exploit this methodology as well as a deepen explanation of the physical and hydraulic characteristics of each PAT scenario.

5.3. Pump as Turbine (PAT) Application

The results reached by the PAT analyzed in Chapter 4 permitted to extrapolate the working conditions of the machine to other scenarios. In the analysis of the BCC irrigation system the two existing PRVs were substituted by two PATs with different operating range conditions. The hydraulic conditions were assessed with the *WaterGEMS* software.

PAT Scenario 1

In the first scenario, the PRV substitution is located under the hydraulic conditions of the Medium Region of the WDS (Figure 37). In this area, there are three wells with submersible pumps (**SP-1**, **SP-2**, **SP-3**). These SPs work 16 hours per day, filling up a reservoir that gathers the collected water (Figure 38). This Reservoir Tank opens its outlet pipe at 16:00 until 20:00. The water flows from the tank and have its discharge in the Lake 1. The pipe distance between these two elements is 400 m, with a diameter of 195 mm, corresponding to an average flow of 25 l/s. The existing PRV is located near the discharge point in Lake 1 and it is substituted by a PAT in order to harness the most energy possible from the energy line. The BEP of the PAT 1 is Q_{BEP}= 25 l/s ; H_{BEP}= 35 m ; n_{BEP}= 1020 rpm; $\eta_{PAT,BEP}$= 60%.

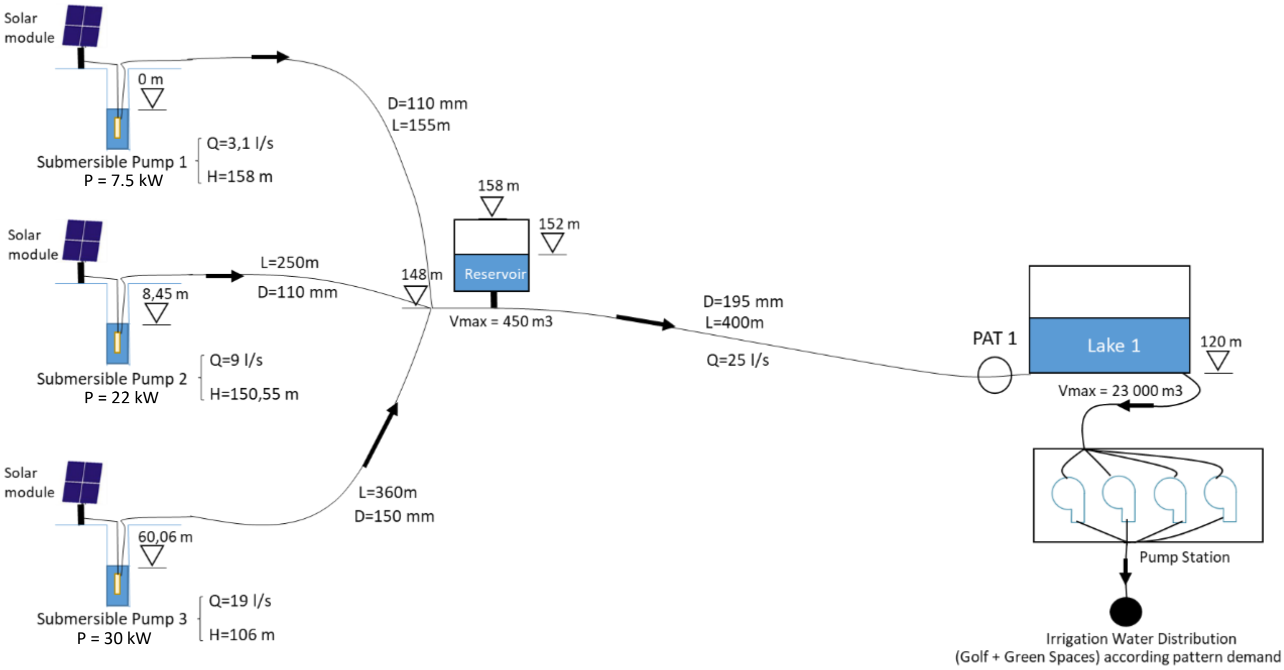


Figure 37 - Medium Region of BCC WDS - PAT 1 scenario schematic design.

The water demand pattern is the one depicted in Figure 35. In the actual BCC, the Reservoir Tank is not elevated. In the case study one solution discussed was to elevate this reservoir so it would be able to produce more energy. For analyzing the PAT performance, it is necessary to study the fluctuation of the energy line caused by the variation of the water level inside the reservoir (Figure 38). The reservoir filling behavior is one of increasing until 16:00, when the SPs stop working. After this period, the water flows in a pressurized gravitic system. The maximum energy that could be extracted from the PAT is when the reservoir is almost filled, reaching a head difference of 36 m.

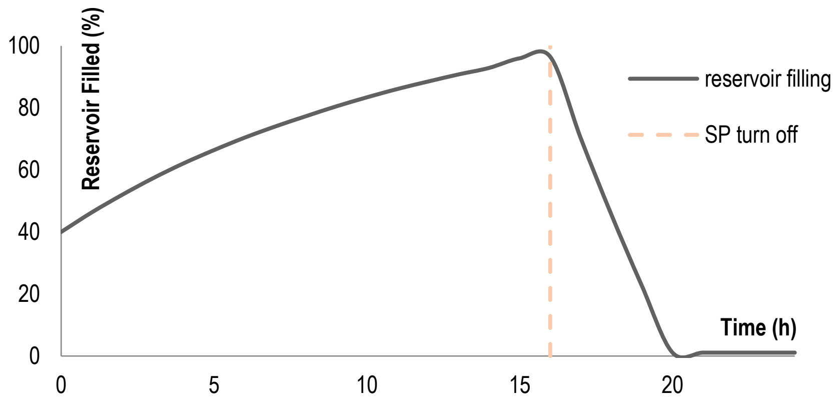


Figure 38 - Reservoir from the Medium Region filling rate

The PAT operating range was then analyzed for an installation curve with a maximum head of 36 m. Different PAT rotation speeds (**N=1050 rpm, N=1170 rpm, N=1275 rpm, N=1500 rpm**) were assessed in order to establish the best operating conditions (Figure 39).

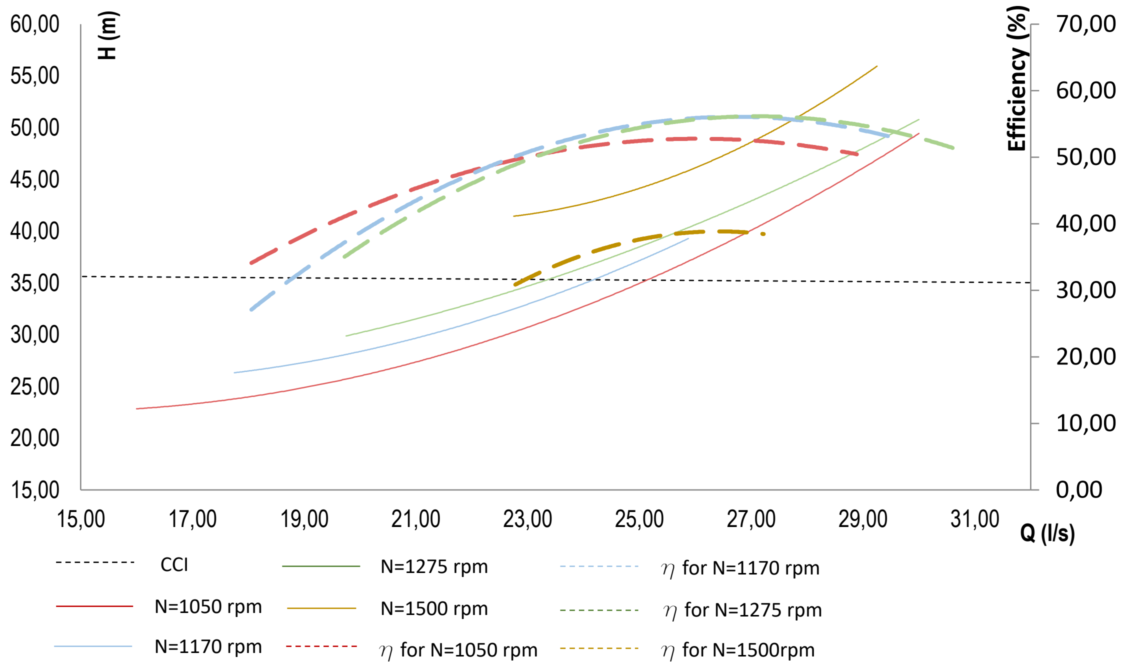


Figure 39 - PAT 1 operating conditions for different rotational speed - Head/Flow/Efficiency analysis

In Figure 39 it can be concluded that for the hydraulic condition of this scenario (CCI), different rotational speeds would produce different levels of energy according to their PAT curves, efficiency curves and the flow levels. As stated in Chapter 3.2.3., three regulations were studied HR, ER and HER, in order to optimize the PAT's behavior. The first regulation is done for the nominal operational speed and by adjusting the flow through a valve. The second one is done by testing different PAT curves and comparing each scenario for maximum energy production. The latter regulation, HER, is done by mixing the methods of both previous regulations.

Table 11 - PAT 1 energy production by HR, ER and HER regulation

			Electric Regulation (by control of the PAT's rotational speed) **Energy Production (kWh per day)**			
		Q average (L/s)	**N=1050rpm**	**N=1170rpm**	**N=1275rpm**	**N=1500rpm**
Hydraulic Regulation (by a flow control valve)	CCI original	25,3	92,32	102,82	105,38	83,52
	CCI 2	23,2	71,22	77,58	79,83	61,70
	CCI 3	20,4	46,67	47,61	31,91	19,40
	CCI 4	18	22,82	24,42	11,77	0

The HER mode consists on the optimization of these two modes, analyzing for each hour which flow and rotational speed would produce the maximum energy. This optimization shows the maximum energy production is 105,38 kWh/day. In *Appendix III* it is presented a table for a daily energy production for the original flow (no valve regulation) and for the best rotational speed in this condition (N=1275rpm). The best rotational speed in the HR mode is N=1170 rpm.

PAT Scenario 2

In the second scenario, the PAT implementation is located under the hydraulic conditions of the High Region of the WDS (Figure 40), which is also the area with higher elevation. In this area, there is one well with a SP (**SP-4**), which is connected to the most elevated lake in BCC, Lake 2. This lake connects with the main lake (Lake 1) through 100 m of PVC pipe, with a diameter of 180 mm, corresponding to an average flow of 16 l/s. Between both lakes there is an elevation gap of 10 m, adding the water level in Lake 2. The SP-4 works for the first 8 hours of the day, discharging its water in Lake 1. The current PRV is located near the discharge point in Lake 1 and its substitution by a PAT is done in the same manner it was done for *PAT Scenario 1*. The BEP of the PAT 2 is Q_{BEP}= 15 L/s ; H_{BEP}= 14 m ; n_{BEP}= 1020 rpm; $\eta_{PAT,BEP}$= 60%.

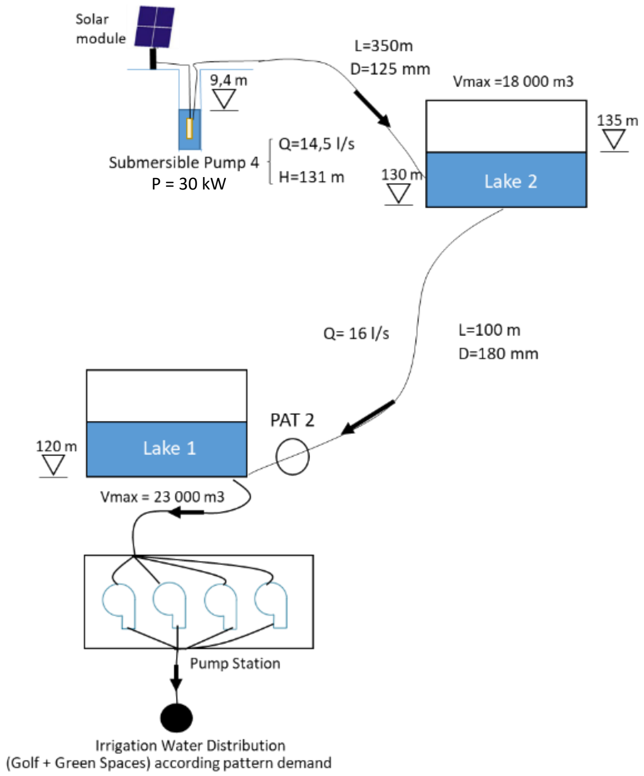


Figure 40 - High Region of BCC WDS - PAT 2 scenario schematic design.

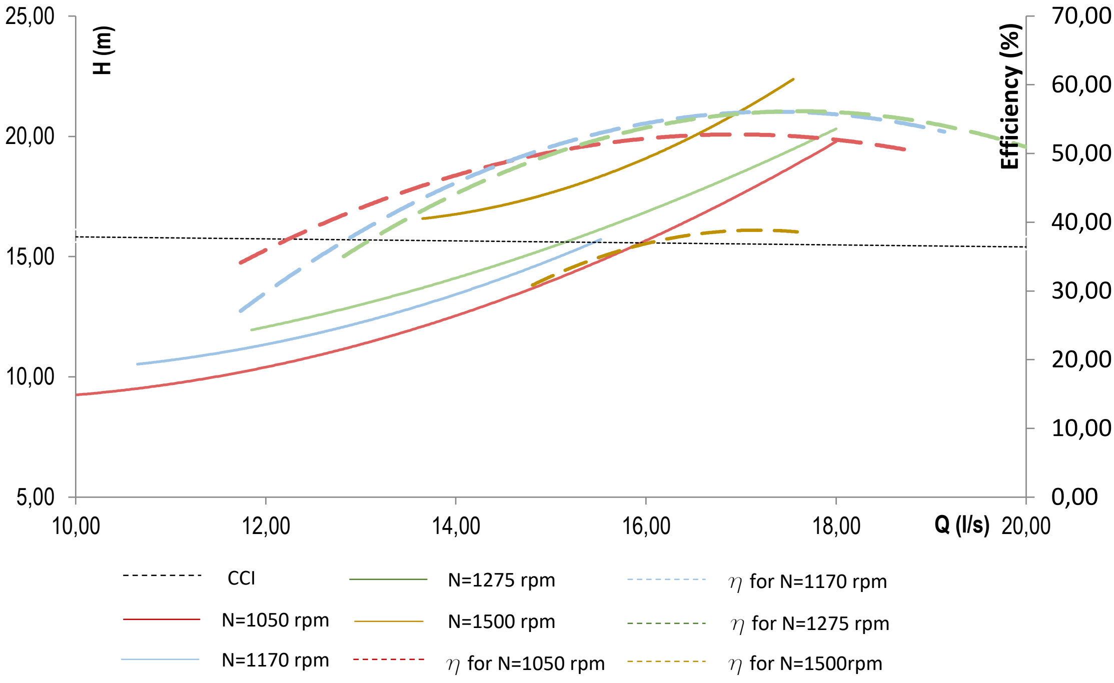


Figure 41 - PAT 2 operating conditions for different rotational speed - Head/Flow/Efficiency analysis

The operating range of PAT 2 was studied for an installation curve with a maximum head of 16 m. The same rotational speeds were tested as in *PAT Scenario 1* (**N=1050 rpm, N=1170 rpm, N=1275 rpm, N=1500 rpm**). In Figure 41, it is depicted the PAT curves for each rotational speed and its corresponding efficiency curves. So as to optimize the energy generation process, HR, ER and HER regulation methods were also applied (Table 12).

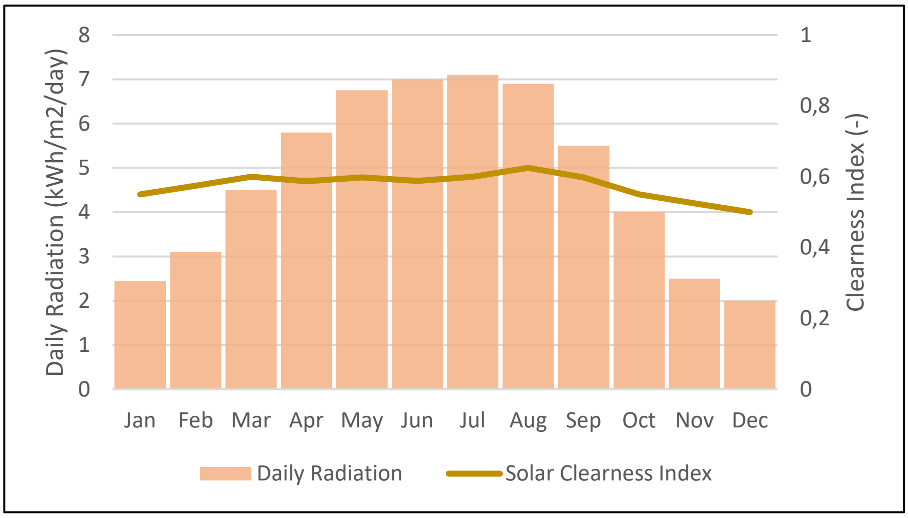
Table 12 - PAT 2 energy production by HR, ER and HER regulation

			Electric Regulation (by control of the PAT's rotational speed)			
			Energy Production (kWh per day)			
		Q average (L/s)	**N=1050rpm**	**N=1170rpm**	**N=1275rpm**	**N=1500rpm**
Hydraulic Regulation (by a flow control valve)	CCI original	16,3	33,71	37,22	37,38	29,22
	CCI 2	15,1	26,49	28,65	29,01	21,57
	CCI 3	14,1	20,47	17,75	21,75	14,42
	CCI 4	13,2	16,12	16,18	16,30	8,77

The HER mode was analyzed considering each hour of energy generation and each table (*Appendix III*) of different rotational speeds and CCI, obtaining the maximum energy produced. The HER mode is the optimization of the HR and ER modes and the maximum energy produced under these conditions was 37,38 kW/day. The best rotational speed for in the HR mode is N=1275 rpm, since for lower flows (by valve control) it is able to generate more energy than the other rotational speed tested.

5.4. Hybrid Solution

In order to satisfy the electrical demands of the submersible pumps needed for water collection, a modelling analysis on the software *HOMER* was carried out to find a hybrid solution. Solar and Wind technologies were the focus of this analysis and so, it was first necessary to gather information about the solar and wind resources in BCC (Figure 42). The solar data and the wind monthly speed were collected by the HOMER software for the local under analysis. Inputs such as PV modules, Wind Turbine (WT) and Converter costs were required as stated in Table 13.



	Wind Average (m/s)
Jan	3,59
Feb	3,68
Mar	3,49
Apr	3,56
May	4,22
Jun	5,21
Jul	4,69
Aug	4,3
Sep	4,4
Oct	4,56
Nov	4,57
Dec	4,09

Figure 42 – Daily Radiation, Solar Clearness and Wind Speed in BCC throughout the year.

Table 13 - Capital, operational and maintenance costs for the system configuration [67, 82].

	Capital Cost	Operation and Maintenance Cost
PV modules (*Heckert Solar*)	430 €/kW p	50 €/yr/kW p
Wind Turbine of 3kW (*Aeolos*)	1060€/kW	50 €/yr/kW
Converter (DC → AC)	500 €/kW	5 €/yr/kW

The converter has a lifetime of 15 years and serves the purpose of transforming the DC current in AC and vice versa. *HOMER* also has a list of wind turbines. It was chosen an *Aeolos* WT with a capacity of 3 kW (the power curve can be found in *Appendix IV*). It is also necessary an On-Grid controller for the WT and it costs 765 € (*Aeolos*). The hub height considered was 12 m and it costs 2 150 € (*Aeolos*). The WT chosen had to be small so it would not interfere with the golfers' practices. It was assumed an efficiency of 85% and a lifetime expectancy of 25 years. The solar component chosen was a generic flat plate PV and *HOMER* establishes its capacity based on the energy demand. The PV array inputs are 53º (latitude plus 15º), a ground reflectance of 20%, azimuth of 0º and the lifetime expectancy for the PV plates were considered to be 25 years [67]. The PV module price was considered to be 0,43 €/W, since it is the retail price for the German made models from *Heckert Solar.* A current oversupply and technological progress are the responsible elements for the decrease of prices of imported and European solar modules, hence the low PV module price [82].

After the input parameters, the software runs an analysis based on multiple variables, both economic and energetic, based on the resources data and the system configuration. A feasible solution was chosen in order to satisfy the electrical demands for water pumping in the five existing pumping wells. Table 14 presents the SP characteristics and energy demand based on an energy analysis carried out on *WaterGEMS*.

Table 14 - Submersible Pumps of BCC characteristics, electrical demand, costs and carbon emissions

Submersible Pumps	**SP1**	**SP2**	**SP3**	**SP4**	**SP5**
Flow (L/s)	2,8	8,3	18,4	13,9	8,0
Head (m)	167,4	158,9	108,3	141	88,0
Working Hours	0h-16h	0h-16h	0h-16h	0h-8h	16h-24h
Energy Demand per day (kWh)	136,1	315,0	425,8	209,8	86,1
Energy Cost per day (€)	20,2	46,7	63,1	21,0	15,0
Carbon emissions per day (Kg CO_2)	81,7	189,1	255,5	125,9	51,6

Based on this electrical demand, a renewable hybrid solution was chosen in order to create a self-sustainable atmosphere for BCC water pumping. Thus, a solution was determined for an average pumping load of 1 000 kWh/day (Table 15), which represents an average sum of the electrical needs of the five SPs.

Table 15 - Analysis for a load of 1 000 kWh/d in HOMER

		Stand-alone solution	
	Renewable Percentage	**100%**	
System Configuration	Nº Wind Turbines	1	
	PV power (kW p)	243	
	Converter (kW)	37,7	
Energy Production	*Heckert Solar* Flat Plate PV (kWh/yr)	396733	99,8%
	Aeolos Wind Turbine 3kW (kW/yr)	918	0,2%
	Total (kWh.yr)	397651	100%
	Total (kWh.day)	1089,5	
GHG Emissions	CO_2 (Kg/kWh/yr)	0	

The current submersible pumps in BCC represent a low renewable percentage since their energy consumption is supplied from the electrical grid. *WaterGEMS* establishes this demand, based on the hydraulic conditions present in the WDS. All of the SP require an electric daily demand of 1 173 kWh for water pumping in the conditions depicted on Table 14. Since, the irrigation for the GC is done by the night period, in which the irrigation volume is almost ten times higher than for watering the GS in the day time, EDP allows to establish two tariffs, one for the day time (8h-22h) and other for the night time (22h-8h). The first is 0,1981 €/kWh and the latter is 0,1023 €/kWh [83]. *WaterGEMS* allows to input these tariffs into the hydraulic model. Hence, the cost for the water pumping of the five wells is 166 € per day.

In the following Chapter 5.6, the economic analysis of this project is presented, based on the solution presented in Table 15, plus the PATs chosen for each one of the two hydraulic scenarios and for the SUDS (Chapter 5.5). This economic analysis is done for a project lifetime of 25 years. According to Table 14, and to the daily pumping cost of 166 €, the upshot of maintaining the present non-renewable scenarios is that, in 25 years, around 1 515 000 € will be spent by BCC in water pumping. The sustainable solutions chosen pretend to change these costs into revenues by energy generation, while at the same time reducing the CO_2 emissions, which are currently 703,8 Kg CO_2 per day, corresponding approximately to 257 tons of CO_2 per year.

5.5. Sustainable Urban Drainage System (SUDS)

In a sustainable view of a smart water grid, it was analysed another complementary solution to recover more energy from the water network. Hence, it was considered the issue of urban flooding as a result of excessive water collection, in a way to re-utilize and harvest this water with the purpose of energy recovery in a sustainable urban drainage system (SUDS).

This study proposes the implementation of SUDS in the Low Region of BCC, which is an area with two decorative lakes. In order to control the water excess in the lower sector of Belas catchment area and to use the existing elevation gap between the two lakes to produce electricity by means of introducing a small hydropower technology, such as a PAT, in-between the two lakes. In order to implement a self-sustainable solution, a solar pump is installed in the outlet of Lake 4 to pump the water back to Lake 3 in order to avoid water stagnation and thus the formation of microbiological ecosystems in the water (Figure 43).

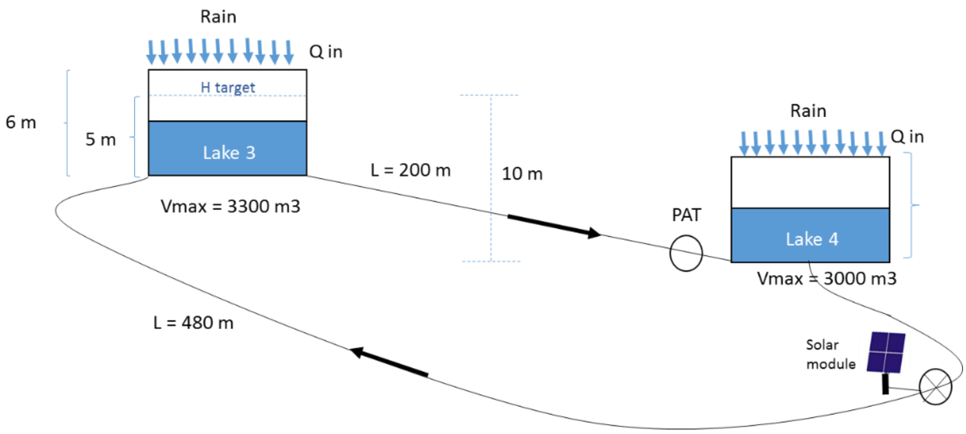


Figure 43 - Scheme of the SUDS technological solution implemented in the two decorative lakes in BCC (Low Region of BCC).

Firstly, it is necessary to analyse the rainfall in the area in order to evaluate the lake's filling capacity. Considering the year 2014, which was the year with the most precipitation (1505 mm), which can be seen in *Appendix V,* it was estimated that, with a head target inside the lake of 5m, the SUDS annual energy production would be 1679 kW (Figure 44). It was considered 20% of precipitation losses.

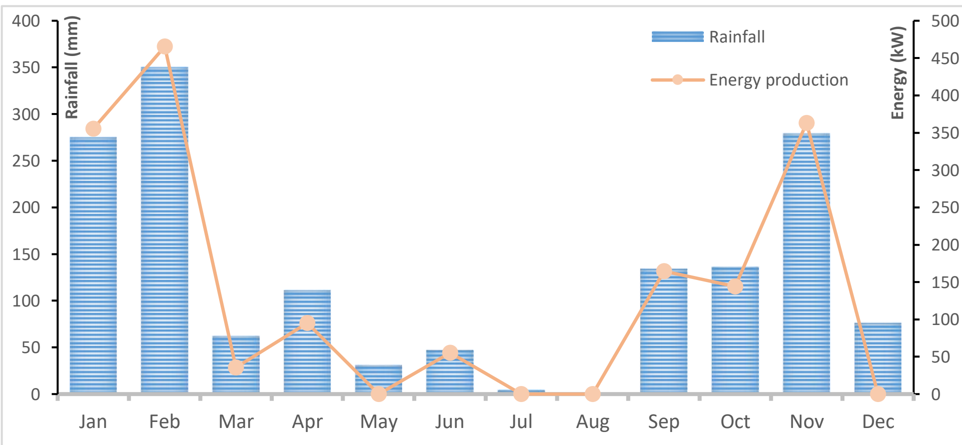


Figure 44 - Energy production for the year 2014 based on a SUDS and PAT technology

Table 16 - Precipitation and energy analysis for SUDS based on rainfall data for the year 2014 in BCC.

Month	Rainfall (mm)	Nº Rainy Days	I (mm/h)	Q_{in} (m3/s)	Nº hours to reach V_{target}	Nº discharge hours	E (kW) per rainy day	E (kW) per month
Jan	275	15	2,292	0,076	2,7	5,3	23,68	355,25
Feb	350	18	1,944	0,065	3,2	6,8	25,86	465,5
Mar	62	7	1,476	0,049	4,2	1,8	5,11	35,77
Apr	111	10	1,586	0,053	3,9	3,1	9,51	95,06
May	31	6	0,738	0,025	8,5	0,0	0,00	0**
Jun	47	3	1,567	0,052	4,0	6,0	18,46	55,37
Jul	4	2	0,333	0,011	18,8	0,0	0,00	0**
*Ago	0	0	0,000	0,000	0,0	0,0	0,00	0*
Sep	134	8	1,861	0,062	3,4	5,6	20,58	164,64
Oct	136	10	1,511	0,050	4,1	4,9	14,41	144,06
Nov	279	15	2,325	0,078	2,7	5,3	24,21	363,09
Dec	76	10	1,267	0,042	4,9	0,0	0,00	0**
Total	1505						**Total (kW)**	**1 678,74**

Lake 3		
Lake 3	Total Volume (m^3)	3 300
	Initial Volume (m^3)	2 000
	Head Target (m)	5
	Volume Target (m^3)	2 750
	Watershed Area (m^2)	150 000

* - Did not rain this month, energy production is zero.

** - In this month it did not rain enough to reach the V_{target} and thus there was no discharge to the other lake, which means there was no energy generated.

The discharged flow considered between the two lakes was the same as Q_{in} (Table 16). The PAT considered, PAT_{SUDS}, is assumed to have 60% of efficiency. In order to pump back the water from Lake 4 to Lake 3, it is considered a pump from Grundfos [84] with the following characteristics: H = 12m; Q = 18 l/s. The retail cost of this pump is 6 841 €.

The results in Table 16 allow the conclusion that a new renewable energy source could be implemented in the Low region of BCC. This technology is evidently dependent on the precipitation values, therefore in days with low or no rainfall, there will be low or no energy generation. Although SUDS may not be the higher energy generating platform, its purpose goes beyond the energy production. The main purpose of SUDS is flood control. Since the Low Region of the BCC represents an area with lower altitudes, when there is more precipitation, a concentration of water occurs in this region, which can lead to floods in a near residential area. Hence, SUDS act as a prevention technology. Moreover, the Lakes 3 and 4 are currently decorative lakes in BCC. By implementing this technology, not only it is possible to generate energy in a non-utilized area, but also it allows the water circulation between lakes, avoiding the creation of plant pests by water stagnation.

5.6. Economic and Environmental Analysis

The economic analysis was carried out by considering the three working solutions (PAT, Hybrid and SUDS) as the project as a whole. The investment for having these three operational solutions was analysed for a lifespan of 25 years.

Currently, there is few data on PAT market prices in European scope [85]. The information available is often inconsistent and outdated. As an example, in 2009, Ramos *et al.* [86] established the investment for a PAT would be from 200 to 400 €/kW for a nominal power below 40 kW. In 2013, Carravetta *et al*. [66] calculated the PAT cost as the sum of two elements: the multiplication of 230 €/kW by the nominal power, considering the turbine alone, plus the multiplication of 115 €/kW by the maximum PAT power considering the generator's cost. In addition, in 2014, De Marchis *et al.* [87], estimated a singular PAT unit cost of 2 000 €/kW for an assembled turbine and generator PAT. Hence, a new cost model for PATs was considered in this study [85].

Novara *at al.* [85], proposed several equations, which correlate the PAT cost with their nominal values of head, H_{BEP} (m), and flow, Q_{BEP} (m^3/s), depending on the number of magnetic poles. In this dissertation, the PATs considered are radial PATs with three magnetic poles. Therefore, Equation 24 presents the cost for these conditions according to Novara *at al.* (2018).

$$C_{PAT+gen} = 15{,}485 * Q\sqrt{H} + 1{,}173 \tag{24}$$

In HR and HER modes, the bypass regulation valve cost is considered to be 500 €. In ER and HER mode the price of the inverter depends on the maximum power and it is considered to be 200 €/kW. The most feasible regulation mode in the scenarios analysed is the HR mode, hence being the one selected.

The maintenance costs considered are the ones stated in Table 13 plus the following percentages applied to the investment costs: 2,5% for the electrical equipment, 0,5% for civil constructions and 1,5% for the mechanical equipment. The discount rates considered for this economic analysis are 6%, 8% and 10%.

An initial investment of 160 869 € would be necessary due to the cost of 243 kW PV panels, one 3kW WT, a system converter, 3 PATs with different Q and H conditions, a pump for the SUDS, plus civil construction equipment, PAT accessories and the cost of connecting to the electrical grid (*Appendix VI*).

Nevertheless, the three PATs energy generation combined with the energy produced by the hybrid system is 0,4505 GWh/year, in Table 17.

Table 17 - Energy Generation by solution chosen

PAT 1		PAT 2		PAT_{SUDS}		Hybrid System	
Energy/ **day** (kWh)	102,82	Energy/ **day** (kWh)	37,38	Energy/ **day** (kWh)	4,60	Energy/ **day** (kWh): PV panels + WT	1089,45
Energy/ **year** (GWh)	0,0375	Energy/ **year** (GWh)	0,0136	Energy/ **year** (GWh)	0,0017	Energy/ **year** (GWh)	0,3977
Total Energy Production (GWh per year)					0,4505		

In *Appendix VI* it is presented the cumulative discounted cash-flow. The energy generated by the solutions chosen is sold to the national electric grid by a sellback ratio of 0,09 €/kW. In Table 18 the results of the economic analysis are presented.

Table 18 - Main parameters of the economic analysis

Discount Rate (%)	6%	8%	10%
Total Investment (€)	160 869		
Total Energy Generation (kWh per day)	1 234		
Total Energy Generation (kWh per year)	450 503		
IRR (%)	23,6		
NPV (€)	**318 754**	**238 328**	**177 378**
B/C (-)	2,996	2,513	2,142
T (years)	6	6	6

The economic analysis allows to calculate the net present value (NPV) for a lifespan of 25 years, the amount of time that is needed for the project to reach its initial investment, the benefit/cost ratio (B/C) and the internal rate of return (IRR). Since the project has a positive NPV, the project is profitable. Considering a discount rate of 8%, it would only be necessary 6 years for the project to generate revenues equal to the first investment. After 25 years, the cumulative discounted cash-flow presents a positive balance of 238 328€, which means BCC would save almost 240 000 € of energy costs in the lifespan of the project. However, after 6 years, the initial investment is completely paid, so BCC could stop selling the generated energy and start to consume it (self-sustainability), saving approximately 1 151 210 € from EDP (water pumping cost for 19 years).

Although the economic analysis is undoubtedly important for studying the feasibility of a project, an environmental assessment is regarded as paramount in today's world for a sustainable approach. In BCC, the present fossil fuelled water pumping system is releasing approximately 257 tons of CO_2 into the environment every year. This study analyses a system with three green solutions, which means that these three solutions have a zero CO_2 emissions rate, enabling savings 257 tons of CO_2 per year.

Nevertheless, it is important to assess not only a 100% renewable solution, but also other renewable percentages in order to establish the current feasibility of stand-alone and grid connected solutions. In Table 19, a sensitivity analysis is presented, in which the stand-alone solution is considered not to sell any energy generated but to collect it into batteries. The grid connected solution is considered by consuming some energy from the electric grid and by selling some with a sellback ratio of 0,09 €/kWh.

Table 19 - Sensitivity analysis based on the renewable percentage for a 100 kWh load.

		Stand-alone solution		Grid connected solution					
	Renewable Percentage	**100%**		**95%**		**90%**		**80%**	
System Configuration	Nº Wind Turbines	-		-		-		-	
	PV power (kW p)	75,9		210		107		51	
	Battery (strings)	374		-		-		-	
	Converter (kW)	20,9		143		73,5		35,3	
Energy Production	Flat Plate PV (kWh.yr)	123 775	100%	342 437	95,4%	174 325	90,7%	83 100	81,3%
	Grid Consumption (kW.yr)	-	-	16 604	4,6%	17 844	9,3%	19 169	18,7%
	Total (kW.yr)	123 775	100%	359 041	100%	192 170	100%	102 269	100%
Economic analysis	Grid Sales (kWh.yr))	-		295 601		142 229		59 493	
	NPC (€)	369 015		139 704		99 284		77 848	
GHG Emissions	CO_2 (Kg/kWh.yr)	0		9 962		10 707		11 502	

The components selected are the same of Chapter 5.4 adding a storage component (batteries). *HOMER* has a list of batteries, which already contain the electrical information. The chosen battery was a generic 12 volt lead acid battery that has a storage capacity of 1 kWh. The lifetime of this battery is 10 years.

The NPC, the present value of all costs minus the present value of all the revenues (the opposite of the NPV), reveals that for having a 100% renewable solution the cost is almost five times (4.7) higher than if the solution is 80% renewable. This leads to the conclusion that, the price for having these hybrid technologies working in a stand-alone regime is not yet competitive enough if one does not sell the energy to the grid. The four solutions (for each of the renewable percentages), in Table 19, were chosen as representative optimized solutions, since *HOMER* establishes countless others based on different system configuration values. These solutions were the ones with the most competitive values with capacity to satisfy an average 100 kWh electrical load demand.

Figure 44 depicts a sensitivity analysis between the NPC, the load demand, from 100 to 500 kWh per day (x-axis), and the renewable percentage of a project solution, from 80% to 100% (y-axis). The figure is divided into 3 colours, which represent 3 solutions. These are the optimal solutions (lower NPC) which can satisfy the renewable percentage and load required. The blue area represents a solution consisted of solar panels and batteries, the green area is a solution with solar panels, wind turbines and batteries, and the orange area represent a solution with solar panels with connection to the grid.

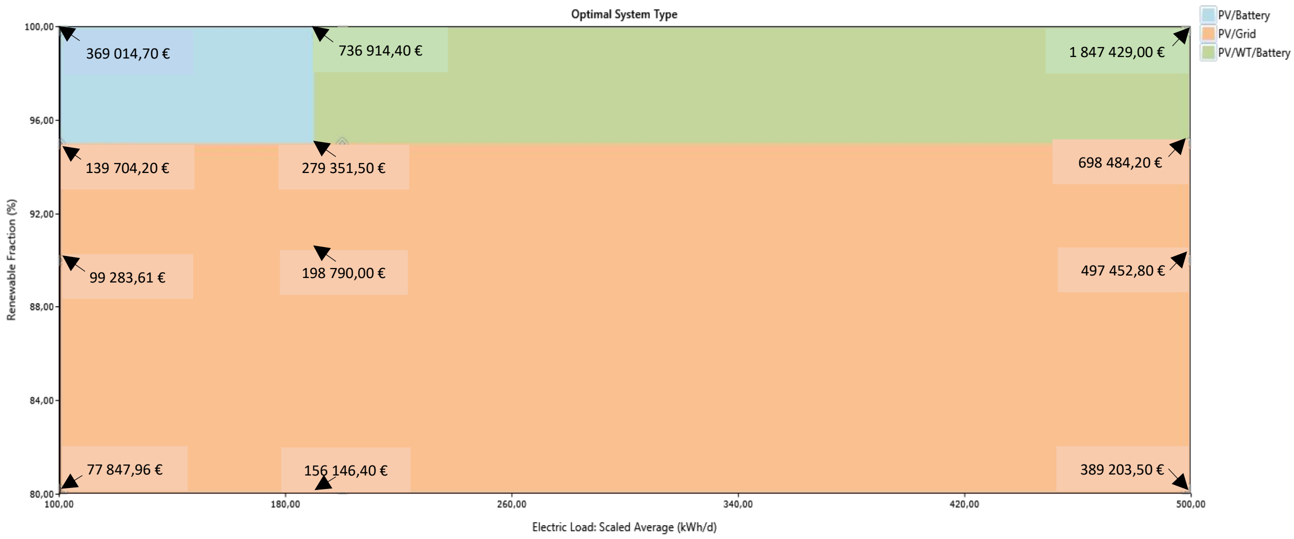


Figure 45 – Optimized system configuration for a sensitivity analysis based on the renewable percentage and the electric load

It can be depicted from the figure that the cost (NPC) for having a higher renewable percentage solution is higher than lower renewable percentage solutions, since it harnesses the produced electricity in batteries, instead of selling the energy to the grid. Moreover, it can be concluded from the figure that for a solution with a renewable percentage above 95%, a wind turbine will only be feasible to be included in the solution for electric loads above 190 kWh per day.

WT are still too expensive comparing to solar modules for low electric demands. The PV modules have had a high development rate in recent years and the cost per kW of output has been decreasing and is expected to continue in this path in the near future. Nevertheless, with scientific advances and resilient investigations and investments, the same is expected to happen to WT. Figure 46, 47 and 48 depict the optimized solutions configuration for a variation in WT cost, according to an established renewable percentage.

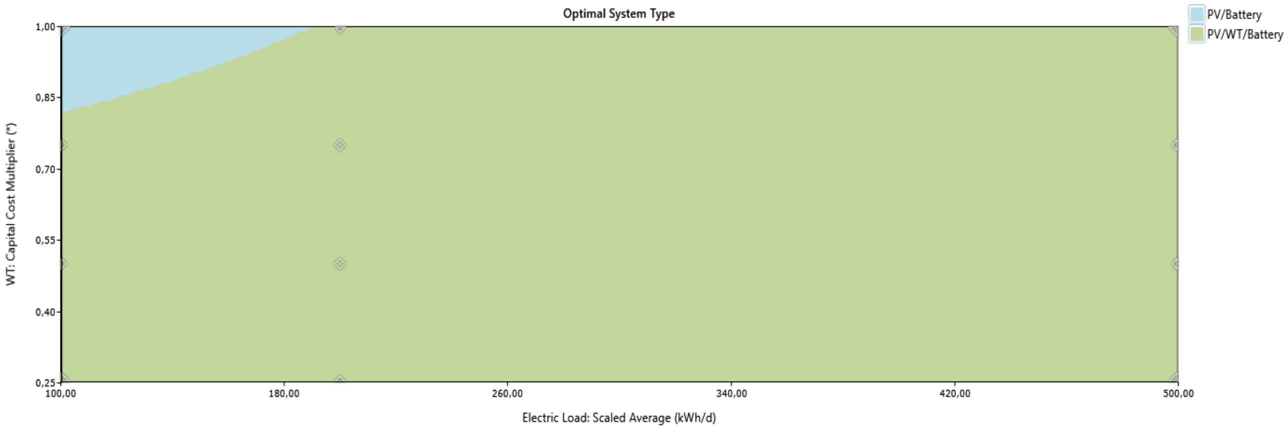


Figure 46 - Off-grid (100% renewable) optimized system configuration for different electric needs and WT cost multiplier values

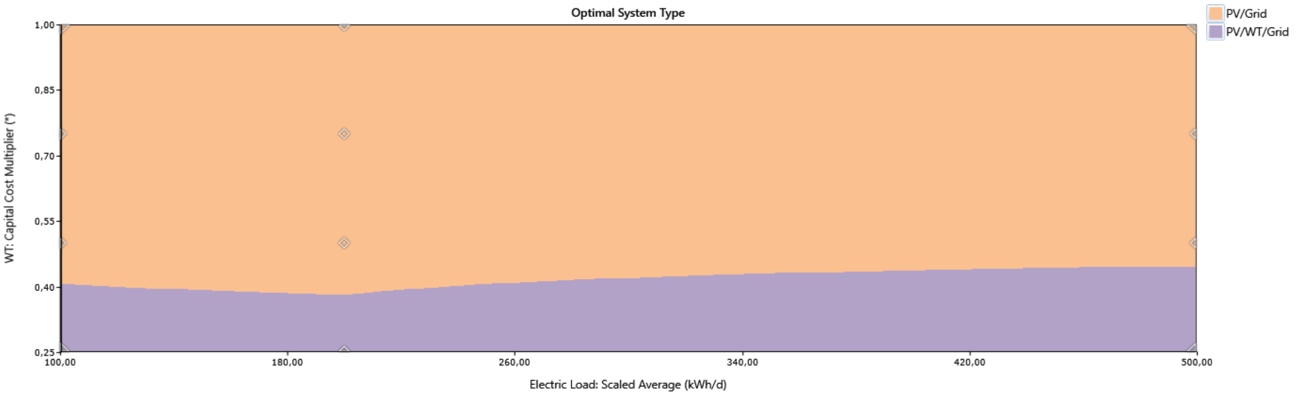


Figure 47 - On-grid (90% renewable) optimized system configuration for different electric needs and WT cost multiplier values

In Figure 46 it can be concluded that if the capital costs of WT reduce approximately 20%, the optimized off-grid solution, could have a WT incorporated even for low electric needs (100 kWh per day). However, in Figure 47, for a solution connected to the grid in a way that 90% of the proposed project is renewable, then the WT capital cost would have to decrease approximately 60% for it to be feasible to incorporate the optimized system configuration.

6. Final Conclusions and Recommendations
6.1. Final Conclusions

In this dissertation, a laboratorial assessment of a radial PAT performance in a small-scale water system was first analysed before advancing to a real case study. Testing the machine's output for different hydraulic and electrical conditions, the PAT was analysed by working in a stand-alone regime. There were some conclusions to extract from this assessment: the presence of the bank of capacitors allows the adjustment of the machine's rotational speed; the lower the capacitance, the higher the rotational speed; the generator's efficiency increases with the imposed rotational speed (lower capacitance); the global efficiency and active power generated increase with the flow and also with the imposed rotational speed of the generator; and the head drop obtained in the PAT increases with the flow and with the rotational speed imposed in the generator.

Hence, a real case study, a golf-course irrigation system in *Belas Clube de Campo* (BCC), was analysed. Due to concerns regarding water shortage, five pumping wells exist in the hydraulic system. This dissertation aimed to satisfy the electrical demands for pumping the necessary water, targeting a feasible self-sustainable environment. Hence, calculations were made in order to adjust two PATs to two different hydraulic regions of BCC. The PATs selected are similar to the one analysed in the laboratory.

Moreover, PAT regulations were analysed in order to maximize the energy recovering process. In the hydraulic regions studied, both HER and ER mode obtained the highest values of energy generation. However, the inverter costs in these modes are too expensive for a feasible solution. This high investment cost indicates that for this analysis, the HR mode is the best regulation under an economic point of view. The significant economic impact that ER and HER modes have in the project does not compensate the extra value of energy generated. Therefore, with HR mode selected, in Scenario 1, the PAT was able to produce 102,8 kWh per day for a rotational speed of 1170 rpm whereas in Scenario 2, the PAT generated 37,4 kWh per day for a rotational speed of 1275 rpm.

Furthermore, solar and wind energy technologies were analysed for energy production. The software *HOMER* allowed to input the electrical load that the system required, with the output of the analysis being the system that would need to have for satisfying the load demand. Hence, a hybrid solution consisting of PV panels with a power of 243 kW, a wind turbine of 3 kW and a converter of 37,7 kW was selected. This green solution is able to generate 1089,5 kWh per day.

Additionally, in the lower region of BCC, the presence of two decorative lakes with different elevations, allowed the creation of an additional circuit, which harnessed the precipitation volume of BCC, control the flood risk in the lower level of a residential area and due to the presence of a PAT, generated some electricity. This technology named sustainable urban drainage system (SUDS) and is able to produce 1 679 kW per year with a precipitation volume of 1 505 mm, such as the year of 2014.

These three solutions consist on a project that aimed for satisfying the electrical demands (1 173 kWh per day) for pumping a daily 1 750 m^3 of water in the dry season, while at the same time reducing the CO_2 emissions in value. The upshot of the economic analysis is that, with a discount rate of 8%, a project with a lifespan of 25 years would had revenues of approximately 240 000 €. Also, the initial investment would cost 160 869 € and the return period would be 6 years, which means after this period BCC can work in a self-sustainable environment, saving around 1 151 210 € in 19 years of water pumping costs from EDP. Moreover, since the solutions chosen are renewable (without CO_2 emissions), the environmental analysis concludes that 257 000 kg of CO_2 per year would be avoided.

In addition, a sensitivity analysis was carried out in *HOMER* in order to assess the optimized solution configuration according to its renewable percentage and electric load demand. It allowed the conclusion that the cost for having an 80% renewable solution is approximately five (4.7) times lower than to have a 100% renewable one (in an off-grid scenario with electric storage in batteries and zero trade-off with the electric grid). The reason is mainly due to the high costs of renewable equipment, especially the WT. PV solar modules capital costs have been decreasing due to its high development rate and the same is expected to occur with WT. Hence, a sensitivity analysis was also carried out to establish the economic value that a WT have to reach to become feasible its integration in a 100% and 90% renewable optimized solution configuration. The results showed that a 20% decrease in WT costs would be enough for a WT to be incorporated in an off-grid optimized solution configuration, whereas a 60% decrease in its capital cost would be the required price drop for a 90% renewable optimized solution consisted of PV panels, Grid and WT.

This project is found to be relevant to be applied in Portugal, since golf courses are a major component of the national tourism. Focusing on the optimization of these systems by the application of renewable energies and recovering energy would have a huge environmental impact, while ate the same time being economically advantageous.

6.2. Future Work

This dissertation could be complemented with an analysis on the water distribution system of Belas Clube de Campo to use these renewable solutions for optimization of the residential water supply network. With the purpose of being a self-sustainable residential area with an optimized golf-course irrigation system.

In addition, future work could focus on the development of optimization analysis of multi-variable in terms of technical, economic and environmental factors, type of regulations and water-energy balance. Investigations on the type of energy converters would also be advantageous as well as a more elaborated study of the water needs in BCC.

An analysis of the PAT's behaviour in transient regimes could also be developed in order to avoid pipe burst events.

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Appendix

Appendix I – Water consumption for golf irrigation in the past 18 years in BCC

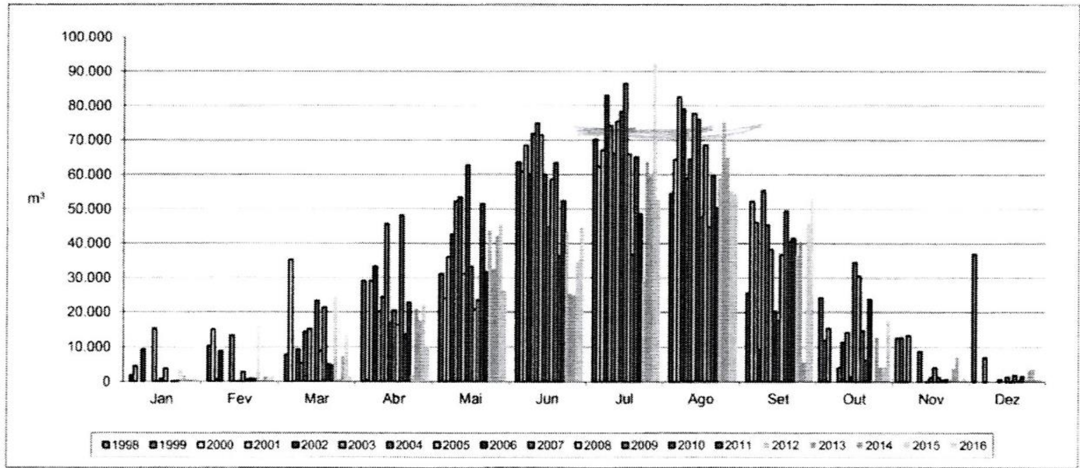
Consumo de Água para Rega no Campo de Golfe (m^3)

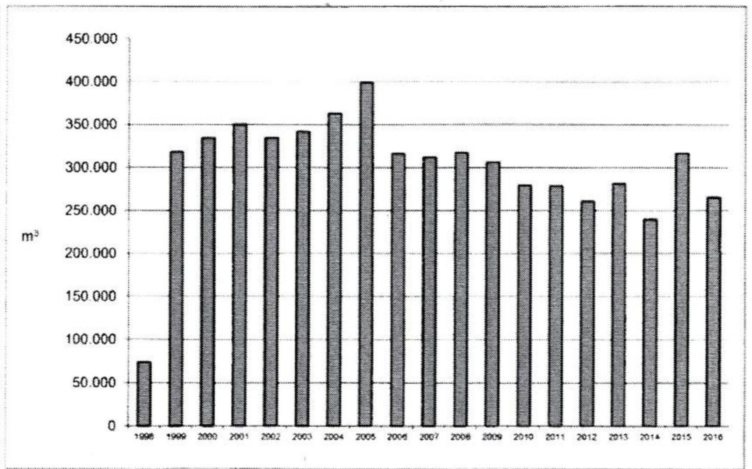
	1998	1999	2000	2001	2002	2003	2004	2005	2006
Jan		1.800	4.470	0	9.300	0	0	15.320	50
Fev		10.320	15.040	630	8.800	0	0	13.290	60
Mar		7.810	35.180	40	9.210	5.320	14.400	15.230	60
Abr		29.050	380	29.030	33.340	20.130	24.460	45.700	17.020
Mai		31.160	23.970	36.020	42.530	52.190	53.430	31.110	62.710
Jun		63.550	60.820	68.530	60.030	71.880	74.870	71.490	60.070
Jul		70.210	62.300	67.060	82.970	74.160	66.090	75.380	78.310
Ago		54.380	64.280	82.470	79.010	58.880	64.380	77.750	76.070
Set		25.460	52.190	46.140	9.260	55.340	45.350	38.310	20.300
Out	24.280	11.780	15.450	0	0	4.030	11.350	14.280	1.450
Nov	12.610	12.690	140	13.290	0	0	8.810	0	10
Dez	36.890	0	0	7.000	0	0	0	750	0
TOTAL	**73.780**	**318.210**	**334.220**	**350.210**	**334.450**	**341.930**	**363.140**	**398.610**	**316.110**

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Jan	830	3.830	0	64	114	3.610	1.580	790	910	1.270
Fev	120	2.860	590	880	820	16.180	590	1.530	990	1.930
Mar	23.340	8.920	21.380	5.110	4.660	24.670	830	7.300	13.340	1.640
Abr	20.530	16.270	48.260	13.660	22.850	2.000	20.950	17.610	22.120	10.230
Mai	33.250	20.710	23.600	51.450	31.660	43.610	32.550	42.110	45.590	26.260
Jun	44.820	58.610	63.467	36.420	52.350	43.540	25.340	24.950	34.870	44.680
Jul	86.470	65.910	36.840	65.090	48.570	28.910	63.740	59.420	92.350	52.680
Ago	47.850	68.520	44.810	59.630	50.300	59.190	75.280	64.900	55.110	54.410
Set	17.730	36.740	49.420	40.440	41.460	36.540	40.520	5.670	45.860	53.040
Out	34.560	30.520	14.660	6.230	23.720	440	12.850	4.210	4.350	17.550
Nov	1.230	4.110	1.320	440	680	850	3.745	7.370	290	1.200
Dez	1.450	120	1.910	150	1.540	1.130	3.396	3.840	840	800
TOTAL	**312.180**	**317.120**	**306.257**	**279.564**	**278.724**	**260.670**	**281.371**	**239.700**	**316.620**	**265.690**

Média últimos 10 anos (mês Junho), por substituição do contador

Avaria durante a instalação nova bombagem - Média anos anteriores



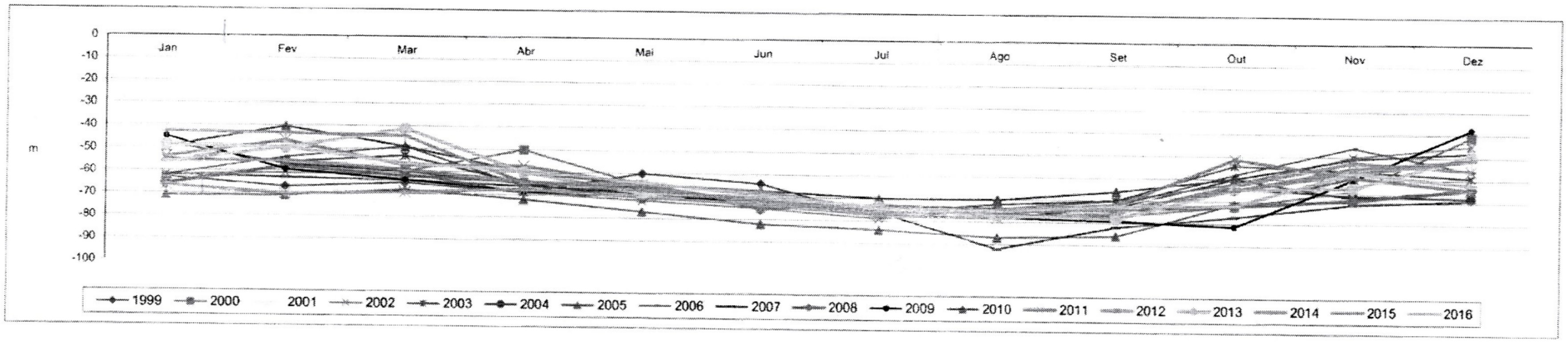


Appendix II – Comparison between the aquifer levels over the past 18 years in BCC

Comparação dos Niveis Freáticos dos Furos (m)

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	(*) 2015	2016
Jan	-63	-65	-50	-62	-55	-48	-71	-62	-62	-66	-45	-50	-54	-67	-49	-43	-56	-56
Fev	-67		-42	-61	-56	-57	-71	-54	-63	-58	-59	-41	-47	-70	-50	-43	-56	-50
Mar	-65	-60	-62	-61	-53	-60	-68	-49	-64	-62	-64	-49	-57	-69	-41	-44	-59	-56
Abr	-69	-50	-65	-69	-65	-65	-72	-66	-66	-64	-68	-60	-57	-67	-60	-65	-64	-59
Mai	-60	-65	-70	-72	-67	-71	-77	-68	-69	-66	-71	-65	-65	-70	-69	-65	-67	-64
Jun	-64	-72	-72	-75	-74	-73	-82	-71	-72	-75	-71	-67	-73	-73	-70	-67	-71	-69
Jul	-78	-73	-75	-79	-76	-75	-84	-74	-76	-73	-77	-70	-76	-77	-74	-75	-75	-74
Ago	-78	-76	-76	-74	-72	-76	-87	-76	-92	-74	-78	-70	-74	-78	-77	-75	-75	-75
Set	-73	-77	-71	-70	-70	-74	-86	-72	-82	-74	-79	-66	-72	-76	-78	-74	-74	-73
Out	-60	-72	-65	-62	-54	-64	-71	-58	-77	-72	-81	-60	-51	-63	-65	-65	-65	-72
Nov	-68	-65	-66	-50	-56	-67	-59	-46	-71	-69	-60	-51	-59	-52	-64	-55	-57	-57
Dez	-64	-41	-67	-45	-59	-68	-64	-56	-69	-64	-38	-48	-64	-56	-49	-51	-51	-62
Valor Médio	**-67**	**-60**	**-65**	**-65**	**-63**	**-67**	**-74**	**-63**	**-72**	**-68**	**-66**	**-58**	**-63**	**-68**	**-62**	**-60**	**-64**	**-64**

(*) 2015 - Média dos últimos 7 anos por impossibilidade de leitura - Fita presa no SE 2



Appendix III – Maximum Daily Energy Generation for each scenario

PAT Scenario 1

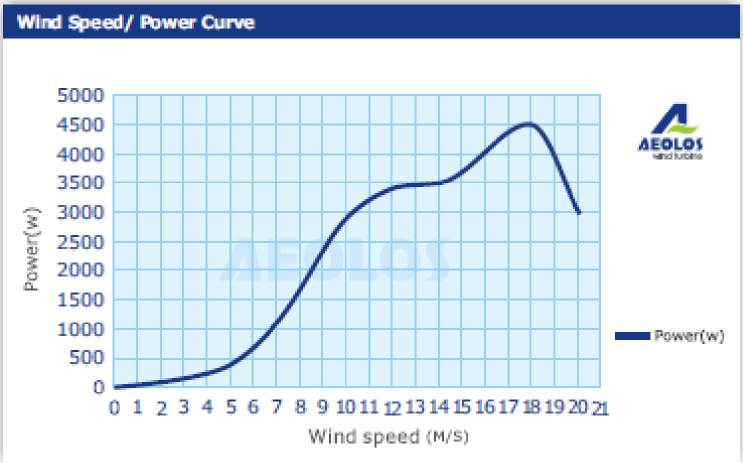
T (h)	Flow			Head	η	Energy
	(L/s)	m3/s	m3/h	m	%	Kwh
0	25,14	0,02514	90,504	38,78	54,63	5,22
1	25,17	0,02517	90,612	38,84	54,67	5,24
2	25,21	0,02521	90,756	38,92	54,73	5,26
3	25,24	0,02524	90,864	38,99	54,78	5,28
4	25,27	0,02527	90,972	39,05	54,82	5,30
5	25,3	0,0253	91,08	39,11	54,86	5,32
6	25,33	0,02533	91,188	39,17	54,90	5,34
7	25,32	0,02532	91,152	39,15	54,89	5,33
8	25,31	0,02531	91,116	39,13	54,87	5,33
9	25,3	0,0253	91,08	39,11	54,86	5,32
10	25,29	0,02529	91,044	39,09	54,85	5,31
11	25,29	0,02529	91,044	39,09	54,85	5,31
12	25,28	0,02528	91,008	39,07	54,83	5,31
13	25,28	0,02528	91,008	39,07	54,83	5,31
14	25,28	0,02528	91,008	39,07	54,83	5,31
15	25,27	0,02527	90,972	39,05	54,82	5,30
16	25,27	0,02527	90,972	39,05	54,82	5,30
17	25,11	0,02511	90,396	38,71	54,58	5,20
18	24,94	0,02494	89,784	38,36	54,31	5,09
19	24,78	0,02478	89,208	38,04	54,03	4,99
20	0	0	0	-	-	
21	0	0	0	-	-	
22	0	0	0	-	-	
23	0	0	0	-	-	
24	0	0	0	-	-	
					TOTAL Kwh.day	105,38

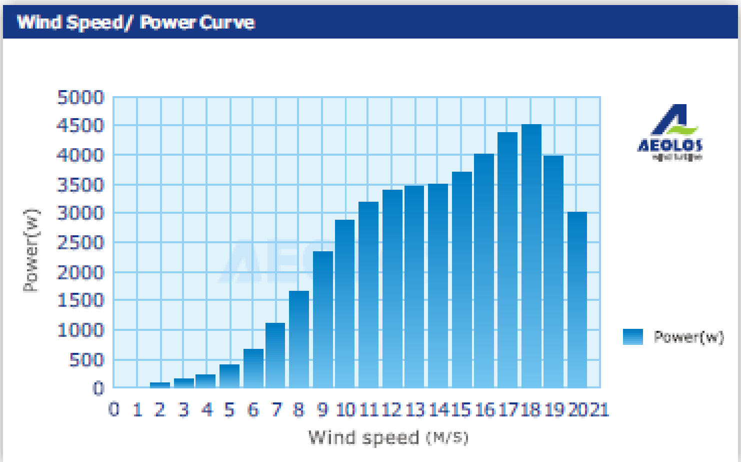
PAT Scenario 2

T (h)	Flow			Head	η	Energy
	(L/s)	m3/s	m3/h	m	%	Kwh
0	16,68	0,01668	60,048	17,96	55,34	1,62
1	16,66	0,01666	59,976	17,92	55,31	1,62
2	16,67	0,01667	60,012	17,94	55,33	1,62
3	16,68	0,01668	60,048	17,96	55,34	1,62
4	16,69	0,01669	60,084	17,97	55,36	1,63
5	16,69	0,01669	60,084	17,97	55,36	1,63
6	16,7	0,0167	60,12	17,99	55,38	1,63
7	16,64	0,01664	59,904	17,89	55,27	1,61
8	16,6	0,0166	59,76	17,82	55,20	1,60
9	16,53	0,01653	59,508	17,71	55,06	1,58
10	16,46	0,01646	59,256	17,59	54,92	1,56
11	16,39	0,01639	59,004	17,48	54,77	1,54
12	16,32	0,01632	58,752	17,37	54,61	1,52
13	16,25	0,01625	58,5	17,25	54,43	1,50
14	16,18	0,01618	58,248	17,14	54,25	1,47
15	16,12	0,01612	58,032	17,05	54,09	1,46
16	16,05	0,01605	57,78	16,94	53,90	1,44
17	15,96	0,01596	57,456	16,80	53,63	1,41
18	15,88	0,01588	57,168	16,68	53,38	1,39
19	15,8	0,0158	56,88	16,55	53,12	1,36
20	15,73	0,01573	56,628	16,45	52,88	1,34
21	15,67	0,01567	56,412	16,36	52,67	1,32
22	15,61	0,01561	56,196	16,27	52,45	1,31
23	15,62	0,01562	56,232	16,28	52,49	1,31
24	15,62	0,01562	56,232	16,28	52,49	1,31
					TOTAL Kwh.day	37,38

Appendix IV - Characteristics of the Wind Turbine (WT) considered

Aeolos-H 3kW





Aeolos-H 3kW Wind Turbine Output

Wind Speed(m/s)	3	4	5	6	7	8	9	10
Generator Power(w)	110	210	400	720	1100	1650	2300	2900
Annual Energy Output(kwh)	964	1840	3504	6307	9636	14454	20148	25404

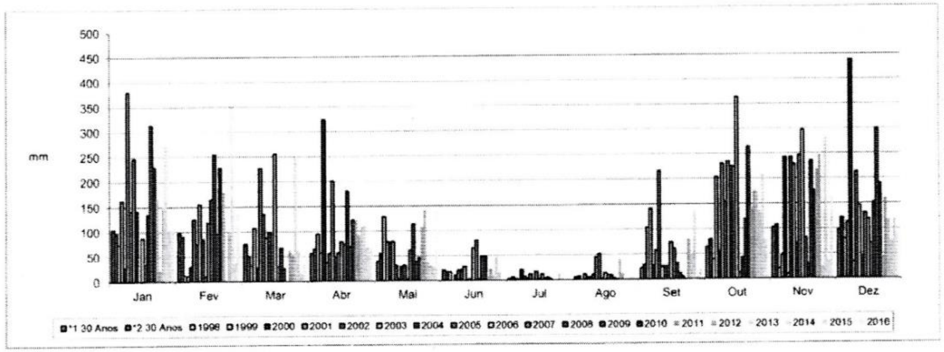
Appendix V – Precipitation data for the past 18 years in BCC

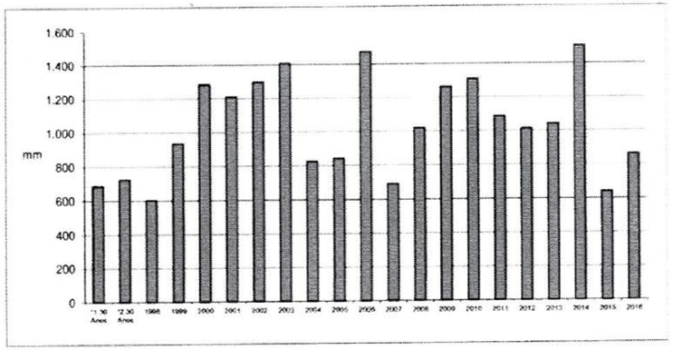
Pluviosidade no Belas Clube de Campo (mm)

	*[1] 30 Anos	*[2] 30 Anos	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Jan	104	96,8	74	162	27	380	141	246	142	0	87	35	134	314	229	167	22	152	275	103	144
Fev	98	90,2	12	12	29	125	75	155	85	10	118	164	254	96	227	179	4	101	350	37	134
Mar	75	51,2	31	107	27	226	135	87	99	95	255	30	67	25	0	61	54	253	62	15	34
Abr	56	64,7	95	57	324	37	56	200	50	57	79	74	180	69	122	121	92	109	111	69	65
Mai	39	55,6	129	79	77	79	31	4	29	31	3	61	114	38	46	108	142	37	31	27	138
Jun	21	17,2	17	0	10	21	22	28	1	3	65	81	3	48	49	7	23	9	47	16	1
Jul	3	6,1	3	2	21	7	3	12	0	17	2	12	4	5	2	0	0	14	4	1	0
Ago	5	6,8	0	11	5	5	10	45	52	2	13	9	9	3	1	39	12	0	0	4	0
Set	22	28,5	104	141	28	58	216	24	26	26	74	61	31	12	5	0	80	51	134	6	18
Out	64	79,8	39	204	55	230	154	234	225	224	363	13	43	119	264	141	176	174	136	208	78
Nov	102	107,1	20	47	242	9	242	228	72	246	297	82	29	235	176	218	247	23	279	35	161
Dez	97	121,8	79	113	438	33	213	146	44	131	119	70	152	299	189	45	161	117	76	120	89
TOTAL	**686**	**726**	**603**	**935**	**1.283**	**1.210**	**1.298**	**1.409**	**825**	**842**	**1.475**	**692**	**1.020**	**1.263**	**1.310**	**1.086**	**1.013**	**1.040**	**1.505**	**641**	**862**

*[1] Valores de precipitação média no periodo de 1961 a 1990

*[2] Valores de precipitação média no periodo de 1971 a 2000 para Lisboa (Geofisico)





Appendix VI – Economic analysis

INVESTMENT COST (euro)	**YEAR -1**	**YEAR 1**	**....**		**....**	**YEAR 15**	**....**	**YEAR 25**
1 - CIVIL CONSTRUCTION								
1.1 - Pipes and acessories	5000							
2 - Equipament for PAT system								
2.1 - PAT Scenario 1	3462,98							
2.2 - PAT Scenario 2	2041,8							
2.3 - PAT SUDS	3474,2							
2.4- Valve, bypass and speed multiplier	5500							
3 - Equipment for Hybrid System								
3.1 - Generic Flat Plate PV (243kW p)	104612							
3.2 - 3 Generic Wind Turbine (3kW)	6095							
3.3 - System Converter	18842					7994		7994
3.4 - Pump for SUDS (Grundfos)	6841							
3 - Connection to electrical grid	5000							
INVESTMENT COST (euros)	160869							7994
EXPLORATION COST (euros/year)	**YEAR -1**	**YEAR 1**	**....**		**....**	**YEAR 15**	**....**	**YEAR 25**
1 - Maintenance		2401						
1.1 - Generic Flat Plate PV								
1.2 - Generic Wind Turbine								
1.3 - System Converter								
RECEITAS	**YEAR -1**	**YEAR 1**	**....**		**....**	**YEAR 10**	**....**	**YEAR 25**
1 - Energy Generation								
1.1 - Anual Generation (GWh)	--	0,4505						
1.2 - Sellback Ratio (€/kWh)	--	0,090	....		....	0,090	....	0,090
1.3 - Energy Generation value (euros/year)	--	40545						

*(adaptation PORTELA, 2011)

IRR (%)	**23,6%**			
	Taxa de actualização			
	6,0%	8,0%	10,0%	23,6%
NPV (€)	**318754**	**238323**	**177378**	**0**
f	**12,783**	**10,675**	**9,077**	**4,217**
B/C (-)	**2,996**	**2,513**	**2,142**	**1,000**
ANO	CASH-FLOW ACUMULADO ACTUALIZADO			
-1	-160869,22	-160869,22	-160869,22	-160869,22
1	-124883,64	-125550,04	-126192,21	-130005,99
2	-90934,99	-92847,10	-94667,66	-105034,27
3	-58907,95	-62566,60	-66008,97	-84829,43
4	-28693,77	-34529,10	-39955,62	-68481,51
5	-189,83	-8568,46	-16270,76	-55254,26
6	26700,69	15469,18	5260,93	-44551,98
7	52069,10	37726,25	24835,20	-35892,66
8	76001,56	58334,65	42629,99	-28886,33
9	98579,35	77416,50	58807,07	-23217,45
10	119879,16	95084,88	73513,51	-18630,70
11	139973,32	111444,49	86882,99	-14919,52
12	158930,07	126592,28	99037,07	-11916,77
13	176813,79	140618,01	110086,24	-9487,22
14	193685,24	153604,80	120130,93	-7521,45
15	201607,69	157635,60	121268,47	-5930,93
16	216623,21	168769,68	129569,87	-4644,02
17	230788,80	179079,01	137116,60	-3602,78
18	244152,56	188624,69	143977,26	-2760,29
19	256759,88	197463,28	150214,22	-2078,63
20	268653,58	205647,15	155884,19	-1527,10
21	279874,06	213224,82	161038,71	-1080,84
22	290459,41	220241,18	165724,63	-719,77
23	300445,59	226737,80	169984,56	-427,63
24	309866,51	232753,20	173857,23	-191,25
25	318754,18	238323,01	177377,83	0,00