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)

1. Introduction

Water is the scarcest resource of our planet. Regarding the concept of sustainability, consciousness is required concerning water management and our on-going consumption of this precious resource. Concepts such as water footprint (WF) and green economies (GE) raise awareness for this issue in a local and global scope [1, 2]. In an European perspective, it is important to access the water gap between the Northern and Mediterranean countries, since it will be aggravated in the following years due to the upcoming climate changes. It is essential to keep an open line of communication between all European countries in order to exchange knowledge and technologies to face potential issues of water shortage.

Smart water systems strive for a better control of water, using information and communication technologies (ICT), in order to detect water leaks, to best control water pressure and to optimize the efficiency of hydraulic systems. Not only in water supply and distribution systems, but also in irrigation networks it is critical to assess the amount of water being consumed and lost in order to analyse and to implement new measures and feasible technologies for the better management of this natural resource. Hence, analysing the existing water systems, focusing on the better control of water consumption and on the sustainable maintenance of these networks is regarded as vital.

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. Hydropower was responsible for 47,7% of the renewable energy produced in Portugal in January 2018 [3]. In the scope of small and micro hydropower solutions, 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 [4, 5].

Moreover, 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 wind pumping are examples of new solutions that are being invested due to their feasibility and environmental impact [6].

This study aims to introduce, in a golf course irrigation system, a feasible sustainable solution in order to create a more efficient network then the one currently used. This project focus on three renewable power generation solutions:

- A pump as turbine (PAT) solution to replace installed pressure reducing valves (PRV) while recovering dissipated energy;
- A hybrid solution (solar and wind solutions) to satisfy water pumping demands;
- A sustainable urban drainage system (SUDS) solution to collect rainfall, prevent overflowing situations in the lowest region of the case study, while generating power.

2. Laboratorial Analysis for a PAT

A PAT performance in a small water system was assessed at IST-DECivil laboratory conditions in order to analyse how these machines could operate in a real water supply system. The laboratorial station was previously installed by a research team of Professor Ramos. In this dissertation, designed guidelines on how to operate this technology in an off-grid connection system and its hydraulic and electrical conditions were developed. Different hydraulic and electrical parameters in a pump running in reverse mode were tested so as to determine their efficiency, power output, reliability, and ability to control pressure in water systems.

Figure 1 - PAT Pilot Station

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 a Picoscope software) were the hydraulic tested variables. It was imposed a pressure of 3 bar in the pressurized air vessel and a centrifugal pump that would induce a flow through the pipe system.

In order to analyse 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, there was the need for an isolated self-behaviour element named as Self-Excited Induction Generator (SEIG). The SEIG is excited by the use of a bank of capacitors, which are able to excite the generator due to their reactive power. The electrical parameters were analysed according to the SEIG, global and PAT efficiencies in Equations 1-3:

$$\eta_{SEIG} = \frac{P_s}{P_{mec}} \quad (1)$$

$$\eta_{global} = \frac{P_s}{P_{hyd}} \quad (2)$$

$$\eta_{PAT} = \frac{\eta_{global}}{\eta_{SEIG}} \quad (3)$$

where P_s is the active power of the generator, which was directly obtained by a Fluke multimeter, P_{mec} is the mechanical power and P_{hyd} is the hydraulic power. The estimation of the efficiency of the SEIG, η_{SEIG}, can also be described as function of the rotational speed, N. Figure 2 depicts the electrical behaviour of the PAT station, where Q_s is the reactive power and IG refers to the induction generator, which is the SEIG.

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.

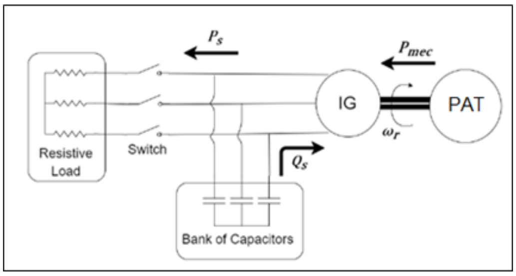

Figure 2 - Off-grid PAT electrical connection

The results in Figure 3 depict that 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.

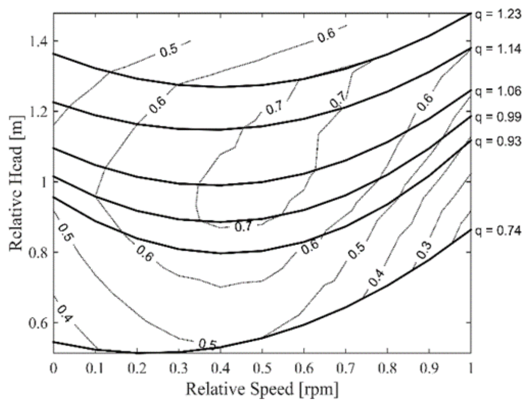

Figure 3 - Relative head, flow, rotational speed and PAT efficiency

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 4). The corresponding head varies from values from 1.3 to 1.4 of the PAT nominal head. Figure 4 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%).

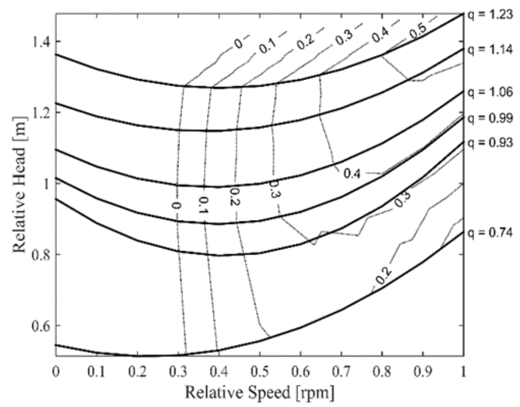

Figure 4 - Relative head, flow, rotational speed and global efficiency

The results reached by the PAT analysis in these laboratorial conditions permitted to extrapolate the working conditions of the machine to other scenarios. In the following case study analysis of a golf-course irrigation system, the two existing PRVs were substituted by two PATs, which are similar to the one analysed in the laboratory, although having different operating range conditions for each of the scenarios tested.

3. Case Study – Belas Clube de Campo

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. 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 5 by colours. The blue region has higher elevations than the orange region, and the green region has the lower elevations.

Figure 5 - Map of BCC

3.1. Storage Capacity, Demand and Pumping Wells

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 (V=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.

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 6). In this study, the analysis was done only for the summer months, where the demand is higher and more critical.

Since the demand on the dry season 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 5). For three of this pumping wells, there is a storage unit (Reservoir Tank) which can hold 380 m^3 of water.

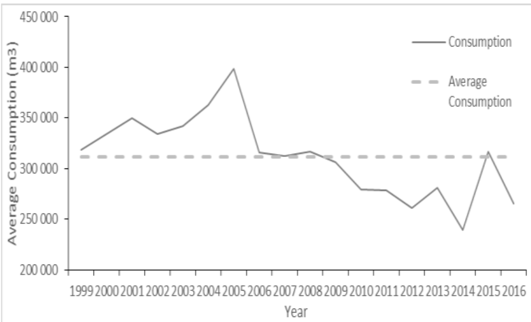

Figure 6 - Measured annual water consumption in BCC

3.2. Model Development

The software *WaterGEMS* was used in order to analyse the current hydraulic conditions of the case study. The input data such as demand patterns, pump characteristics, lake capacities and the system's elevation points were provided by BCC.

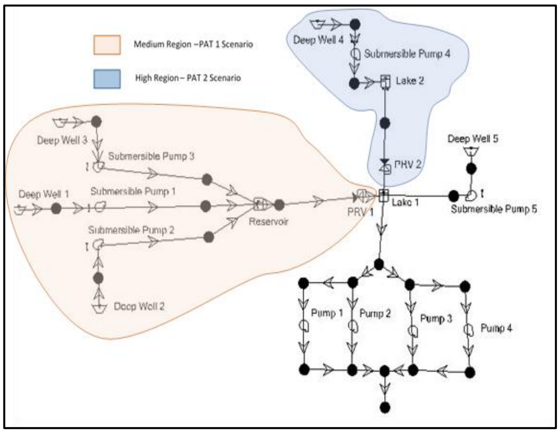

Figure 7 - Water Supply System of BCC

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) To fulfil this demand pattern, the submersible pumps (SP) 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,** from the Medium Region, operate from 00:00 until 16:00, **SP-4** from the High Region 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 depicted in Figure 8 and 9.

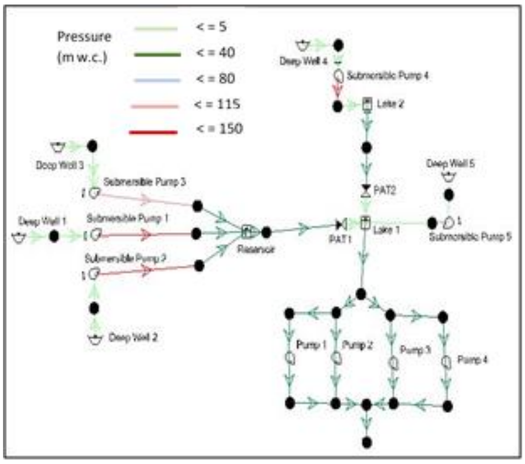

Figure 8 - Pressure in the network at 07:00

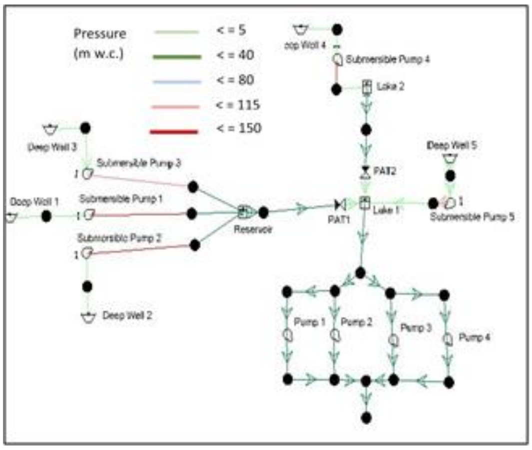

Figure 9 - Pressure in the network at 17:00

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.

3.3. Pump as Turbine Application

PAT Scenario 1

In the first scenario (Figure 10a and 10b), the PRV substitution is located under the hydraulic conditions of the Medium Region of the WDS (Figure 5). 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 10a). 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.

The water flows from the tank and have its discharge in the Lake 1 (Figure 10b). 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%.

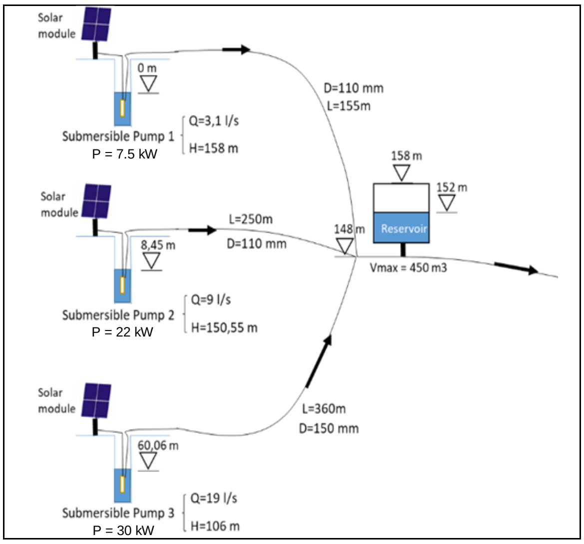

Figure 10a - Medium Region of BCC WDS – Submersible Pumps to Reservoir tank

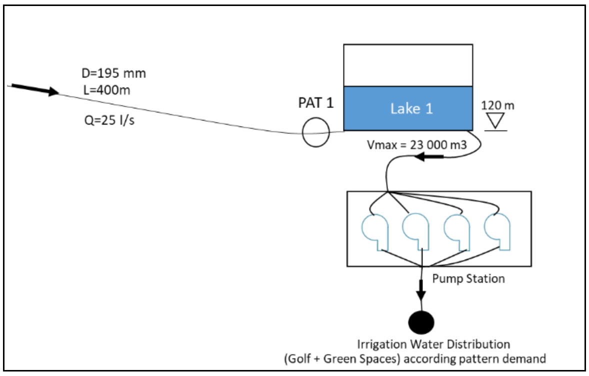

Figure 10b - Medium Region of BCC WDS – Reservoir tank to Storage Lake

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.

Moreover, three regulations were studied: hydraulic regulation, HR, electric regulation, ER and hydraulic and electric regulation, HER, in order to optimize the PAT’s behavior. The first regulation is done for a fixed operational speed and by adjusting the flow through a valve. ER 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.

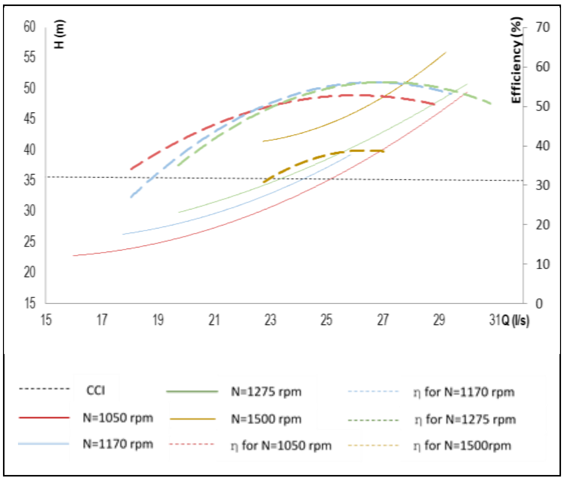

Figure 11 - PAT 1 operating conditions for different rotational speed - Head/Flow/Efficiency analysis

The results showed that by using ER or HER the maximum energy production is 105,38 kWh/day for the rotational speed of N=1275rpm. However, the best rotational speed in the HR mode is N=1170 rpm being able to produce a maximum of 102,82 kWh/day.

PAT Scenario 2

In the second scenario, the PAT implementation is located under the hydraulic conditions of the High Region of the WDS (Figure 12), 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. Between Lake 1 and 2 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%.

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 13, 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.

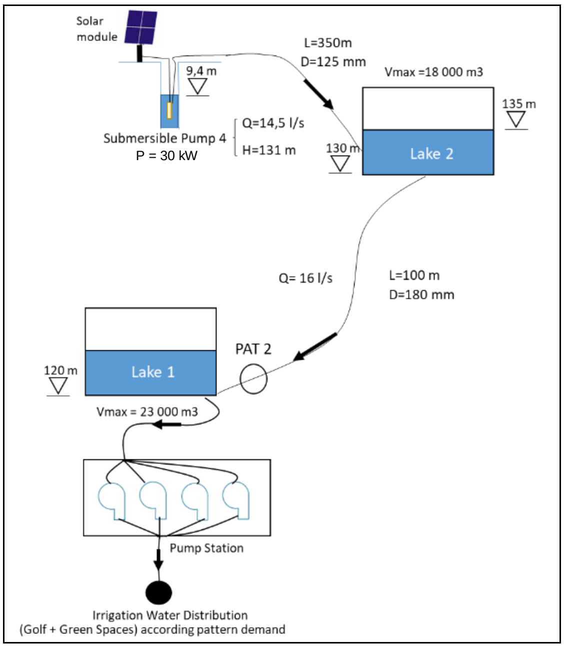

Figure 12 - High Region of BCC WDS - PAT 2 scenario schematic design

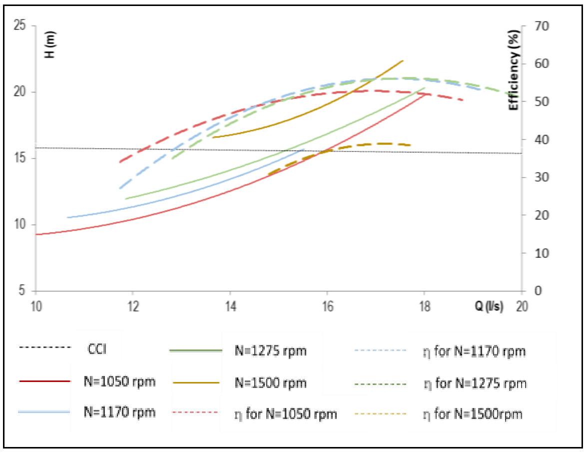

Figure 13 - PAT 2 operating conditions for different rotational speed - Head/Flow/Efficiency analysis

The HER and ER mode are able to produce a maximum energy of 37,38 kW/day for the rotational speed of N=1275 rpm. The best rotational speed for the HR mode is also N=1275 rpm, since for lower flows (by valve control) it is able to generate more energy than the other rotational speed tested.

3.4. 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. The solar data and the wind monthly speed were collected by the *HOMER* software for the local under analysis. Table 1 presents the costs for the PV modules, Wind Turbine (WT) and Converter.

Table 1 - Capital, operational and maintenance costs for the system configuration [6, 7]

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

For considering a WT it is also necessary an On-Grid controller (765 € - *Aeolos*) and a hub height of 12 m (2 150 € - *Aeolos*). The WT chosen had to be small so it would not interfere with the golfers' practices.

An energy analysis carried out on *WaterGEMS* enabled to quantify the electrical demand, cost and emissions for the water pumping. All of the SPs require an electric daily demand of 1 173 kWh for water pumping. 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 [8]. Hence, the cost for the water pumping of the five wells is 166 € per day. Moreover, considering emissions of 600 g CO_2/kWh of produced energy [6] the SPs are currently releasing 703,8 Kg of CO_2 per day.

Based on the electrical demand, a renewable hybrid solution was chosen in order to create a self-sustainable atmosphere for BCC water pumping.

Table 2 – Hybrid Solution 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	

3.5 Sustainable Urban Drainage System

In a sustainable view of a smart water grid, 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 (Figure 5), which is an area with two decorative lakes. In order to control the water excess in the lower sector of BCC 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.

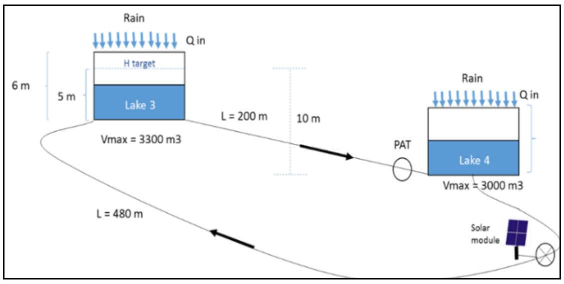

Figure 14 - Scheme of the SUDS in BCC (Low Region of BCC)

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.

For the analysis it was considered the rainfall of the year 2014, which was the year with the most precipitation (1505 mm) and it was estimated that, with a head target inside the lake of 5m, the SUDS annual energy production would be 1679 kW (Figure 15). It was considered 20% of precipitation losses.

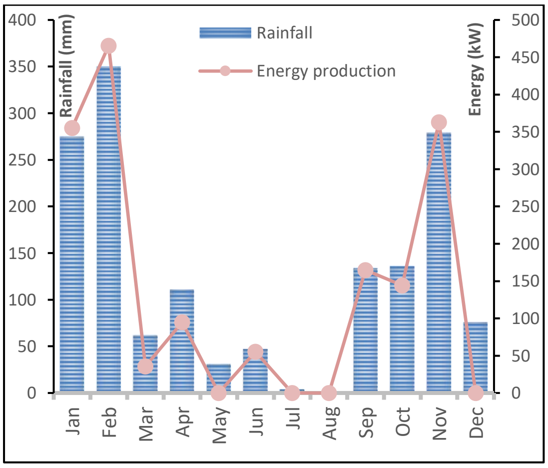

Figure 15 - Energy production for the year 2014 based on a SUDS and PAT technology

3.5. 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.

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. Nevertheless, the three PATs energy generation combined with the energy produced by the hybrid system is 0,4505 GWh/year (Table 3).

Table 3 - Energy Generation by solution chosen

PAT 1 (GWh per year)	PAT 2 (GWh per year)	PAT_{SUDS} (GWh per year)	Hybrid System (GWh per year)
0,0375	0,0136	0,0017	0,3977
Total Energy Production (GWh per year)		0,4505	

The energy generated by the solutions chosen is sold to the national electric grid by a sellback ratio of 0,09 €/kW.

Considering a discount rate of 8%, it would only be necessary 6 years for a 25 years 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).

Moreover, 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. Hence, a sensitivity analysis was carried out in *HOMER* between the cost, the load demand and the renewable percentage of a project solution, from 80% to 100%. It revealed 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 (i.e. battery storage).

4. Conclusion

Targeting a feasible self-sustainable environment, an analysis of a golf-course irrigation system was carried out. Firstly, a laboratorial assessment of a radial PAT performance in a small-scale water system enabled to gain the knowledge on how these machines can harness the dissipated energy present in most water supply systems. Also, it allowed the adaptation of the laboratorial PAT to the real hydraulic conditions of the case study.

PAT regulations were analysed and the HR mode was the best regulation under an economic point of view. The ER and HER have too expensive costs associated with the inverter. Hence, 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, a hybrid solution (solar and wind) 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, by harnessing 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, SUDS can generate 1 679 kW per year with a precipitation volume of 1 505 mm, such as the year of 2014.

In an off-grid scenario with electric storage in batteries and zero trade-off with the electric grid it was assessed that there are still too many costs for having an 100% renewable solution.The reason is mainly due to the high costs of renewable equipment, especially the WT. However, PV solar modules capital costs have been decreasing due to its high development rate and the same is expected to occur with WT.

This project is found to be relevant to be applied in Portugal, since golf courses are a major component of the national tourism.

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