Energy recovery of urban water networks towards new park charging

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July 2020

Key-words: Pump as Turbine (PAT), Energy Recovery, Water Distribution Networks, Irrigation System, Green Mobility, Urban Sustainability

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Abstract

Water distribution networks have high values of energy consumption due to water pumping and treat. It's common that this huge energy usage it's not used efficiently in the whole network, which leads into excessive water pressures in the systems that, nowadays, is just lost commonly in pressure reducing valves (PRV) or at entrance to tanks or reservoirs. However, this problem leads into a potential energy that can be recovered, creating new steps into a more sustainable water network management and energy consumption. This can be harnessed by means of a pump working as a turbine (PAT), an innovative technology that has been deeply studied these last years with great results in terms of energy recovery of a renewable energy source.

This dissertation analyses a typical urban irrigation system in Lisbon in order to obtain and optimize energy recovery from the network with PATs technology. This generated energy is aimed to cover the demand of two electric bikes' charging Gira stations in Lisbon. A designing process is carried out to obtain maximum energy generating values from the system, and the main components to unify the solution with the charging system are implemented. This project contributes to renewable energy and green mobility, creating a more sustainable urban environment. An economic, environmental and social assessment is carried out with the objective of evaluating the feasibility and different impacts induced by the developed solutions.

1. Introduction

Nowadays, hydropower is one of the most reliable and mature renewable energy sources. It supports growth in some other renewable energy technologies such as wind and solar, whose generation characteristics can be variable depending on non-controllable external factors like sources availability [1]. Hydroelectricity has several advantages among other sources of electrical power: it has low operating and maintenance costs, it's cost-competitive, it has high efficiency (about 60% to 90% from waterpower to electricity conversion) with high-reliability levels and with the capacity to stabilize fluctuations and storage energy if necessary [2]. Regarding to hydraulic power generation, 2019 ended with 7111 MW of installed power, being the most important renewable source in Portugal. Figure 1 shows a full analysis of this evolution [3].

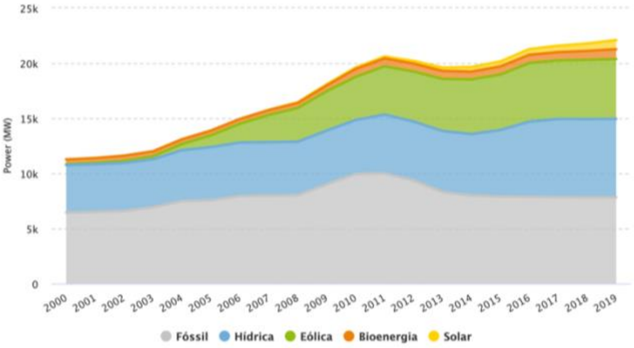

Figure 1. Evolution of the Installed Capacity of the Different Sources of Electricity Generation in Portugal between 2000 and 2019 [5]

Fossil fuels still supply most of the world's energy demand. Even though, Portugal's electricity production is mainly done with renewable energy resources. According to the APREN [4], the Portuguese Renewable Energy Association, the electricity generation in Mainland Portugal this January of 2020 has been covered with a 67.80% of renewable sources, showing the high capacity of non-fossil electric generation of the country. Indeed, of the total power generated, the 38.30% has been hydropower's.

Technological innovations keep appearing based on hydropower, using other technics and finding new approaches to the energy production. One representative example is the use of pumps in reverse mode: pumps as turbines (PATs), which have several applications in micro and pico hydropower energy production.

Water distribution networks have a strong dependency on energy, which creates a nexus between them. A sustainable management of this distribution system is becoming a main priority. PATs open a new world of harnessing energy and recover power from the water networks that, otherwise, would be lost. This new hydraulic renewable source used in smart water systems will lead to a better sustainable water supply management, representing a huge opportunity for this new technology'. Moreover, by taking advantage of excessive energy, it's not only beneficial for green energy generation, but also for controlling in a more optimal way the water supply networks.

This dissertation aims to study the potential of new energy generating technologies in the hydraulic field, in particular, PATs. An overview on the existing technologies will help to outstand the potential applications of these devices and to understand their characteristics. Then, this dissertation aims to study the introduction of a renewable energy solution based on PATs technology to fulfil the electric bikes stations' energy demand from GIRA's company in Lisbon. To do it, it's taken into consideration the energy recovery from the irrigation system. Energy generation, pressure and flow control is achieved with this solution, protecting the system from overpressures. The design is aimed to be optimal for energy recovery and compatible with the existing system. The proposed solution is technically, economically, environmentally and socially evaluated to decide if it's a feasible and beneficial option in these possible aspects.

2. From water to energy

Hydropower or waterpower is the conversion of energy from flowing water into energy, most commonly into electrical power. It's considered to be a renewable energy source due to the water cycle. To convert this energy into electricity, hydropower plants use hydraulic machines, which are specially designed to transform pressure and kinetic energy of a fluid into rotational mechanical energy. In this project, only rotodynamic machines with incompressible flux are treated.

2.1 Types of hydraulic machines

There exist several types of hydraulic machines in order to use for water energy available, and they can be classified, depending on the system where they are installed [6]. Consequently, we can divide them in different types.

- Pressurized water systems: divided into traditional machines and adapted machines. The first ones can be classified at the same time in reaction machines, whose hydraulic power is transmitted to the shaft by creating a pressure drop in the water flow (e.g., Francis and Kaplan); or action machines, that uses the kinetic power of the fluid at atmosphere pressure to transform hydraulic to mechanical energy (e.g., Pelton and Turgo). Adapted machines include hydraulic machines that usually work not as turbines but as pumps, and also positive displacement machines.
- Open channels hydraulic machines: they have been used traditionally to take advantage of waterfalls. They can be divided in three types according to the energy used: gravitational machines if they use potential energy, hydrostatic machines if they use pressure and kinetic machines if they use the kinetic energy of the water flow. Gravitational ones use water level differences to extract energy, whereas hydrostatic machines operate by hydrostatic pressure differences on the faces of the blades, and kinetic machines extract the energy from the velocity of the water flow. Each technology has developed several machines.

A full classification of all the hydraulic machines appears in Figure 2. When talking about micro and hydro hydropower plants, the more used ones are adapted machines, being usually installed in places where the energy is being dissipated for specific flow and pressure operating conditions. The best efficiencies vary between 40% and 70% [6].

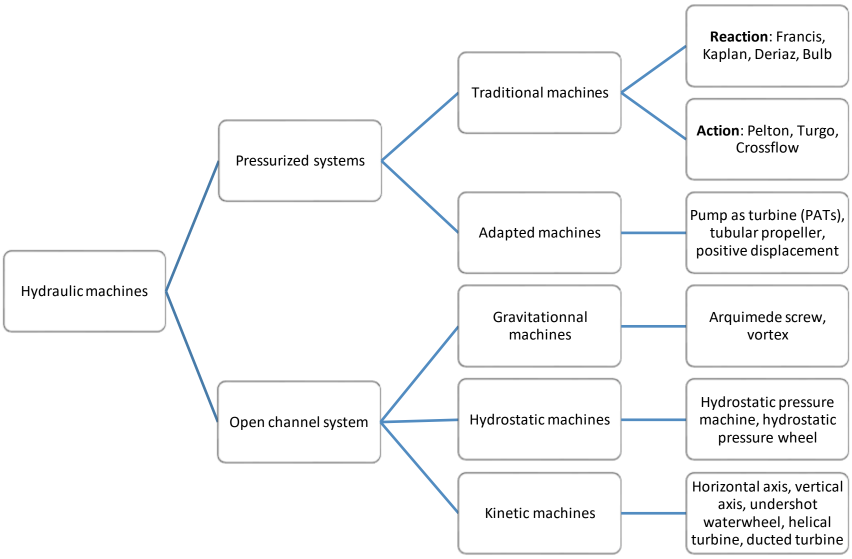

Figure 2. Classification of hydraulic machines (adapted from [6])

2.2 Pumps as turbines (PATs)

PATs are exactly what their names express: pumps working as turbines in order to generate electricity. The first one was introduced by Thoma and Kittredge in 1931, after reaching unintentional conclusions where they observed that a pump working as a turbine could reach good efficiency levels [7]. PATs have become an interesting solution for scenarios where conventional turbines wouldn't be suitable.

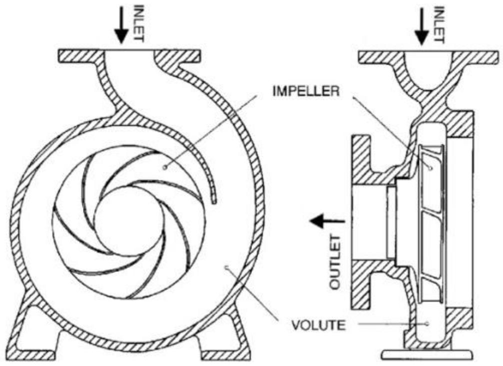

Figure 3. Pump as turbine scheme (adapted from [8])

PATs can reach peak efficiencies similar to pump mode, its mechanical procedure is smoother, and, at the best efficiency point (BEP), they increase discharge and head values compared to the pump mode [9]. They are becoming more and more popular due to their high availability, productivity, economical investments needed, easy maintenance, and reasonably good efficiencies in energy production. In this thesis, PATs are a main focus of study.

One main difference in pumps working in reverse mode towards a conventional turbine is the lack of discharge control to maintain efficiency. Therefore, it's needed a proper selection of the device to extract the maximum power of the flow. These hydraulic machines don't have the same head when working in pump mode as in turbine mode. The same happens with its efficiency: their maxim value is not the same in both operating modes and they have different head and discharge values in that point. This optimal point is called Best Efficiency Point (BEP) [10].

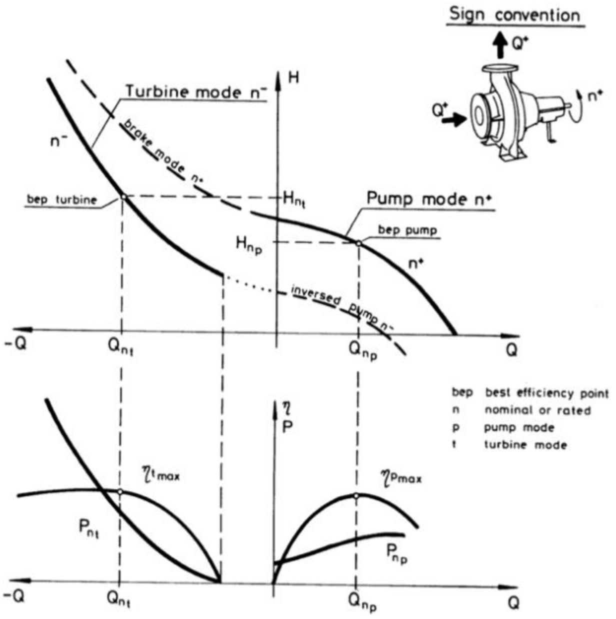

Figure 4. Operating curves in turbine and pump mode (adapted from [10])

3. Case study: Energy recovery of water networks towards new park charging

This case study consists on the creation and development of an energy recovery hydraulic power plant capable of fulfilling the energy necessities of the electrical bike stations of Gira. This project follows the new energy solutions proposed by REDAWN. REDAWN (Reducing Energy Dependency in Atlantic areas Water Networks) is a project that aims to improve the energy efficiency of water networks through the installation of innovative micro-hydropower (MHP) technology [11].

Gira Bicicletas de Lisboa is a public service offered by EMEL company since September 2017. The users can move around the city with their bikes during their operational schedule of 20 hours per day, from 6:00 am to 2:00 am [38]. The charging stations feed the bikes with a tension of 42±0.1 V and an electric current of 6250 mAh. The batteries have a nominal tension of 37 V and a nominal capacity of 12800 mAh. It was decided that the power energy plant designed would try to fulfil the necessities of the two stations nearer to the park: the stations 307 and 308, located at *Marquês de Pombal*. Data was recollected by checking Gira's consultation, where there is a real-time counter on each station of the used or the empty spots. Due to the created scenarios for all the model simulations, a safety coefficient of 1.3 was applied to ensure that the dimensioning of the power plant would be correct. It was concluded that these two stations had an estimated energy consumption of 31.2 kWh per day.

3.1 Hydraulic model

Due to the lack of information found about the irrigation systems of these two parks (and also due to the lack of time and the exceptionality caused by COVID-19 which made more difficult the research itself), an approximated model based on other irrigation systems and general average values found on the available expert literature has been created to do the study. Consequently, a sensitivity analysis of the model was also developed in order to provide as much information and conclusions as possible.

The irrigation system studied is located in the center of Lisbon, in Parque Eduardo VII and Jardim Amália Rodrigues, with a total surface area of 31.6 ha. The highest point, where the reservoir that supplies the water to the installation is located, is at 105 m from the sea datum level; and the lowest point is at 60 m. Taking this into account, the irrigation system was designed based on similar irrigation projects. It consists of a mesh that divides the parks into 12 different main points of demand, which supply water to the irrigation area. Figure 5 shows the irrigation scheme.

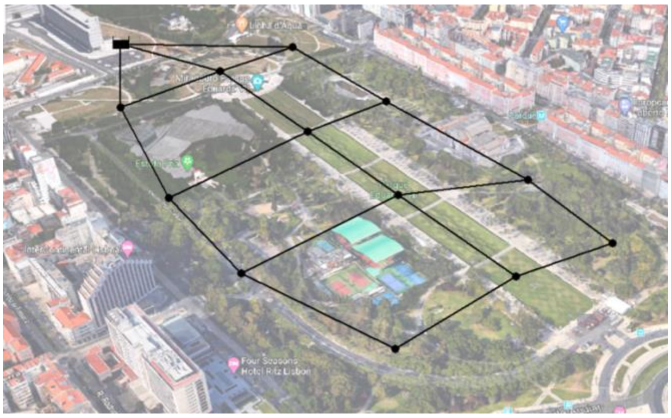

Figure 5. Irrigation scheme

The project's aim was to analyse the irrigation network of these gardens in order to develop a hydraulic energy recovery system based on pumps as turbines (PATs). Consequently, the software EPANET was used as hydraulic simulator for system behaviour and selection of the best hydraulic solution

Regarding the water consumption of the area that has to be irrigated, it was needed to create different scenarios to have a demand estimation to insert as input data in EPANET. The water needed per m_2 and per day depend on lots of variables like the type of plants, the type of terrain or the weather of the zone, among others. After an extensive research, two estimated values, 11 l/m_2/day during the winter and 14 l/m_2/day during the summer, were chosen as reasonable values to carry on the calculations. As a result, it was obtained that the water demand for each point was of 364000 l/day and 286000 l/day, respectively for the season mentioned before. The designed water demand pattern distributes the water supply during a time period of 6 hours, from1:00 to 7:00. Consequently, the initial pattern used for the study, for each node, resulted in a 6 hours constant demand with a value of 13 l/s during the winter and 17 l/s during the summer. An extended period analysis of 24 hours was carried out in every simulation to extract the results.

3.1.1 Model development

Two processes were executed in order to develop the simulation model and design the energy production system. First of all, a study to decide the location and the number of PATs that could be installed in the irrigation system.

Secondly, an iterative optimization process process to design the PATs that would provide the best results to the energy recovery system.

PATs location on the model

Once all the input data is in the model, the first calculations were developed in order to see the original pressure and discharges of the installation with the two demand patterns. With this, a first approach to the PATs possible locations was analysed in order to obtain as much energy production as possible. It was observed then the best localizations were in the upstream pipes of the three demand points highlighted in Figure 6, due to their discharge and head values.

Figure 6. EPANET results for a nominal demand of 13 l/s at PAT's locations.

Three different models were created to estimate the energy production capacities in the irrigation system for the nominal demands. In this step, pressure regulation valves (PRV) were used, with an outlet pressure consign of 5 mwc., which is similar to the expected outlet pressure when using the PATs on the irrigation system. The behaviour scenario of the three models were compared and it was concluded that the best alternative for more efficient charging performance was the scenario with the tree PATs. This option presented several advantages among the other possible ones. The main reason and most important result is the useful hydraulic energy is higher with three PATs operating at the same time. The power output given by a turbine [13] is defined with the following equation, in which η is the efficiency of the hydraulic machine, ρ is the fluid density, g is the gravitational acceleration, Q is the nominal flow rate and H is the head.

$$\boldsymbol{P = \eta\, \rho\, g\, Q\, H} \tag{1}$$

In this case, without taking into consideration the machine efficiency, 9.91 kW of available hydraulic power was obtained for the 3 Pats scenario, versus 1.41 kW for one PAT and 5.61 kW for two PATs. Moreover, when putting only one or two PATs on the installation, the discharge of each pipe changes through the hydraulic balance caused by the flow resistance induced by the turbine installation, making even lower the energy production and more difficult the discharge control.

PATs design on the model

The turbomachine used to design the PAT for the irrigation system was the Etanorm 32-160 turbine, with a nominal rotational speed of 1520 rpm. The company, KSB, provides the operational curves of the turbine, represented on Figure 7. Based on the characteristic curves, the best efficiency point (BEP) can be defined as shown in Table 2.

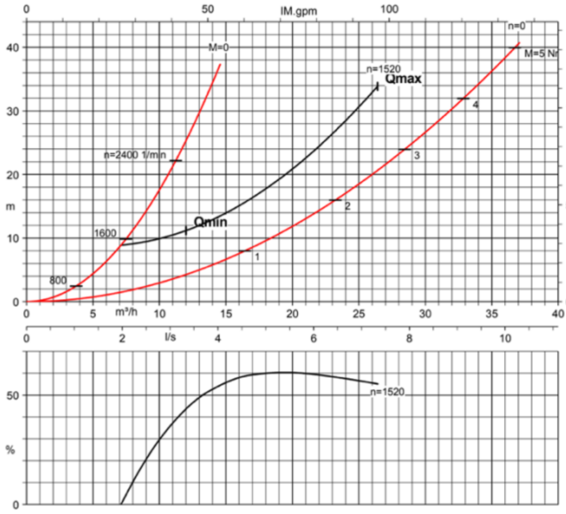

Figure 7. Characteristic curves for Etanorm 32-160 PAT

Table 1. Best efficiency point (BEP) for the Etanorm 160-32 PAT

Q [l/s]	H [m]	Ph [kW]	Pe [kW]	η	N	Ns
5.4	21	1.11	0.68	61 %	1520	27.88

This machine doesn't suit to the discharges and pressure drops needed for the installation studied in this case, but by using non-dimensional analysis it's possible to adapt the characteristic curves to a similar PAT. To do this adaptation, first, it was defined the characteristic curve of the installation (CCI) for the three locations of PATs, to know exactly the operation points. The CCI is a curve that shows the discharge and head available in a specific network location while modifying the water needs of a demand pattern.

Then, by using the equation (1), it's possible to represent the available hydraulic energy for pair of discharge and head values of the CCIs. With this representation, it was observed the point with best performance characteristic to design the operational curve of the PAT, which leads the maximum in the power curve. In conclusion, for a discharge value of 26.5 l/s and a head of 18 m approximately we obtain the maximum power available in the installation. These characteristics appear when the demand of the nodes is equal to 13 l/s, which is useful because is one of the nominal demand values. Therefore, that was the first design point for adapting the PAT curve to the installation.

To adapt the Etanorm 32-160 turbine curve to the operational values of the installation studied, an iteration process was carried out. This process was done based in non-dimensional curves in order to maintain the geometrical, kinetic and dynamic similarities between the original machine and the adapted ones [14]. First of all, the original curve values of discharge and head were transformed into non-dimensional with the BEP as a reference point. Then, the iteration process started and consisted of 3 steps. The 3 adapted curves and the efficiency curves obtained appear in Figure 8.

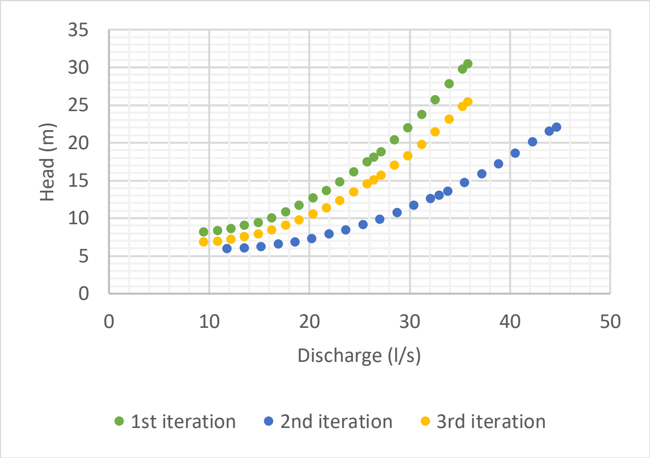

Figure 8. PAT curve for each iteration

The design process was developed following these procedures:

- **1st iteration**: BEP transformation into the point of higher energy available of the CCIs: its BEP was translated to the maximum point of available energy obtained with the CCIs: 26.5 l/s of discharge and 18 m of head. It was obtained maximum values of power generation. However, the pressure outlets have such small values that a slight change on the demand values can create negative pressures on the EPANET model. Similarly, it's almost impossible to change the rotational speed to modify the power obtained: if the rotational speed is increased, the pressure drop on the PATs may create negative pressures on the outlets. This PAT was not suitable for the installation due to its lack of operation flexibility
- **2nd step:** BEP transformation into the point of the CCIs for a maximum demand (17 l/s): The main pro achieved in this procedure was the wide range of operational points where the PATs can be used: they can perform with demands from the 13 l/s to over 16 l/s in each irrigation zone. However, for low demand levels, such as 13 l/s where the available energy is maximum, the energy produced is much lower than in the first step. Moreover, in high demand levels the system isn't able to reach high value of energy recovery due to the losses in the pipes.
- **3rd step:** optimization of the previous procedures: the design point used was that with the maximum amount of energy in the CCIs, but with a reduction on the head to widen the range of operation: 26.5 l/s of discharge and 15 m of head (instead of 18 m). It was observed that this model is capable of reaching high power generating values, as good as in the first iteration, due to the exploitation of the available energy in the irrigation system. At the same time, the range of operation has been widened as it was needed, although is not as large as in the former optimization step.

To conclude, thanks to all the benefits provided by the curve designed in this last optimization step, it was decided to be the defined adopted PAT curve, which optimizes the energy production, the time of operation, wet garden conditions in the day period, the use of bikes and the visiting of garden parks. In addition, it was decided that the irrigation times would be modified in order to optimize the energy production of the PATs.

3.1.2 Final model simulation and results.

After all the previous analyses and the support decisions criteria taken, the final optimized model was defined. With the PAT obtained in the third step, and by introducing the real operational characteristics, it was possible to get the final results and extract the real power output. As the model was created with some possible scenarios due to the lack of data, a sensitivity analysis was developed. Non-dimensional analysis was used to modify the characteristic curves into different rotational speeds of the runner. With the called specific quantities, used in analysing performance parameters of homologous turbines, it's possible to predict the behaviour of a prototype based on the results of a model [15]. These are the specific rate flow (Q_{11}), the specific power (P_{11}) and the defined double unit speed (N_{11}). In this equation, *Q* is the flow, *D* is the diameter of the pipe, *H* is the head, *P* is the power output and *N* the rotational speed.

$$\boldsymbol{Q_{11} = \frac{Q}{D^2\sqrt{H}}} \tag{2}$$

$$\boldsymbol{P_{11} = \frac{P}{H^{3/2}D^2}} \tag{3}$$

$$\boldsymbol{N_{11} = \frac{ND}{\sqrt{H}}} \tag{4}$$

Different PAT rotational speeds were assessed (N=1690, N=1520 being the original one, N=1350 and N=1180) and the demands from the nodes were modified (from 11.5 l/s to 14.5 l/s in steps of 0.5 l/s, being 13 l/s the nominal demand) in each step simulation. By using non-dimensional analysis, with equations (2), (3) and (4), the operation curve and efficiency curve were adapted to these new conditions, as presented in Figure 9 and 10.

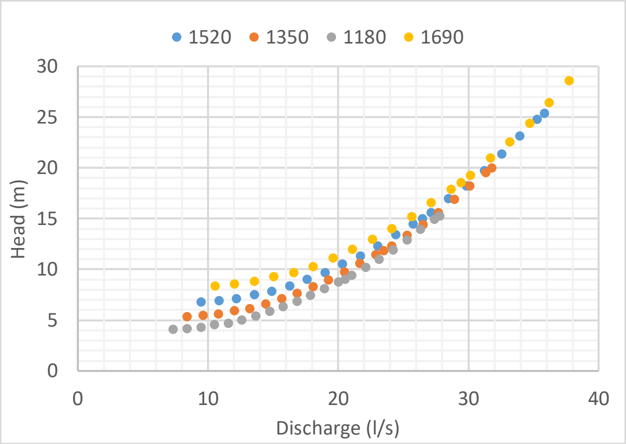

Figure 9. PAT performance curve for each rotation speed

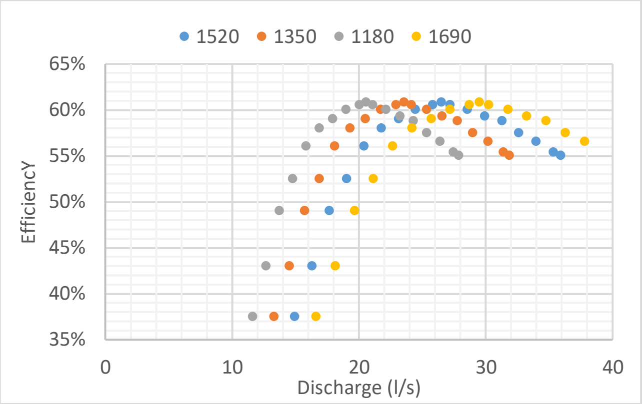

Figure 10. PAT efficiency for each rotation speed

All the curves defined in the hydraulic model and simulations were developed for each rotational speed and nodal demand. Later, the efficiency of each PAT for each simulation was found to calculate the power output by using equation (1). The final results of the power output are shown in Table 2. When a negative pressure is detected in any node of the installation, it was represented with the sign "-". Negative pressures on the EPANET model means that the piezometric line cuts the pipe profile, which means the occurrence of cavitation.

Table 2. Power output for each nodal demand and rotation speed

Power output (kW)		**Nodal demand (l/s)**					
		11.5	**12**	**12.5**	**13**	**13.5**	**14**
Rotation speed (rpm)	**1690**	5.08	5.67	6.31	7.02	7.81	-
	1520	4.87	5.53	6.13	6.77	7.41	8.14
	1350	4.70	5.20	5.78	6.36	6.95	7.53
	1180	4.35	4.86	5.33	5.88	6.46	6.96

With this optimization process, it's simple to know the energy production during the summer and the winter, by multiplying the power output by its irrigation time. This time is considered an average of 6 hours for the winter period and an average of ~8 hours for summer (which corresponds to the same nominal nodal demand of 13 l/s). In these two cases, the demand is modified considering changes in water necessities. The results are in Table 3.

Table 3. Energy output for a constant irrigation time and variable demand

Energy output (kWh) Constant irrigation time, variable water needs			**Nodal demand (l/s)**					
			11.5	**12**	**12.5**	**13**	**13.5**	**14**
Winter	**Rotation speed (rpm)**	**1690**	30.48	34.02	37.86	42.12	46.86	-
		1520	29.22	33.18	36.78	40.62	44.46	48.84
		1350	28.20	31.20	34.68	38.16	41.70	45.18
		1180	26.10	29.16	31.98	35.28	38.76	41.76
Summer		**1690**	39.37	43.94	48.90	54.41	60.53	-
		1520	37.74	42.86	47.51	52.47	57.43	63.09
		1350	36.43	40.30	44.80	49.29	53.86	58.36
		1180	33.71	37.67	41.31	45.57	50.07	53.94

Table 4. Energy output for a constant water needs in the gardens

Energy output (kWh) Constant water needs, variable irrigation time			**Nodal demand (l/s)**					
			11.5	**12**	**12.5**	**13**	**13.5**	**14**
Winter	**Rotation speed (rpm)**	**1690**	34.46	36.86	39.37	42.12	45.12	-
		1520	33.03	35.95	38.25	40.62	42.81	45.35
		1350	31.88	33.80	36.07	38.16	40.16	41.95
		1180	29.05	31.59	33.26	35.28	37.32	38.78
Summer		**1690**	44.51	47.60	50.86	54.41	58.29	-
		1520	42.67	46.43	49.41	52.47	55.30	58.58
		1350	41.18	43.66	46.59	49.29	51.87	54.19
		1180	38.11	40.80	42.96	45.57	48.21	50.09

Another way of interpreting the results would be by considering that the water needs of the garden are not modified, so the irrigation time has to adapt to the nodal demand (see Table 4).

It's clear that the optimum operating point corresponds to a nodal demand of 14 l/s and a rotation speed of the PAT of 1520 rpm. In these conditions, it's possible to generate 45.35 kWh in winter and 58.58 kWh in summer with a constant water need of the garden.

3.2 Implementation of the power plant to the charging stations

Energy production takes place during the night, while the consumption is done for the day period. Consequently, there was a need for creating a system to meet the generation and the consumption, even with changes on the values used in the design of the installation. The following solution is proposed.

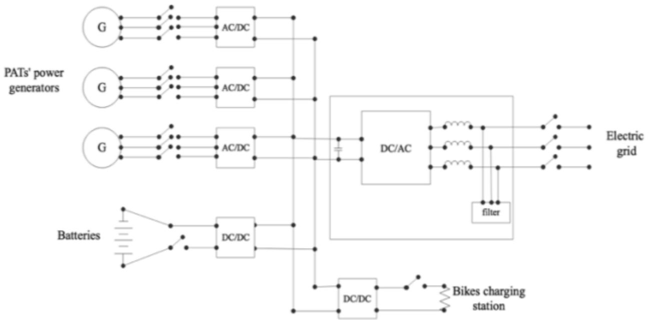

Figure 11. Basic electrical scheme of the charging system

Based on this scheme, the equipment needed was selected in order to make the budged of the installation. As one of the most expensive things are the batteries, two different options were proposed based on different technologies. Option 1 was conformed with a lead-acid set of batteries, while for the Option 2 it was selected a set of lithium ones. These two models have enormous differences on the prices, lifetime and environmental impact mainly. Because of this, they both were studied as possible options.

3.3 Economic, social and environmental analysis

To know the initial investment costs of the project it has to be taken into account all the stages and the resources required. Also, the resources that could be provided by the public administration and municipal services, so they will help to reduce the final inversion costs. For Option 1, it was estimated an initial investment of 16750 €, while Option 2 needed an inversion of 28930 € due to the elevated monetary value of the lithium battery. It has to be taken into account some more investments, associated with maintenance of all the installation and the equipment. The estimated costs related to the renovation of the equipment of a lead-acid battery, is up to 133 €/kWh, including in this the costs and benefits related to environmental impact, recycling and waste disposal [16]. Therefore, it was considered a 4655 € cost every 6 years for Option 1. Regarding the lithium batteries, they have a lower recycling rate, due to some components that can only be used as downcycling materials. However, big improvements in this technology and its recycling cycle, in addition to the long lifecycle of this equipment, lead into costs values that are being reduced progressively. It's estimated a 222 €/kWh cost for the renovation of a lithium battery [16]. In this project, it's considered a cost of 7770 € every 18 years (OPTION 2). In addition, an estimated value of 125 €/year is considered in concept of maintenance of the installations.

This project will create economic benefits directly related to the energy generation of the PATs. Each year, the installation will produce 18980 kWh that will be divided into two different purposes. 67% of this energy will be directly used by the charging station, while the other 33% will be sold to the grid to extract the maximum benefit Therefore, the total income received for energy generation will be of 2480 €/year. The CO_2 emissions reduction produce money input for several reasons. In one hand, this reduction is caused by the generation of electric energy with renewable energy. The recovered 1890 kWh from the water network can be resulted into a reduction of 13.42 tCO$_2$e [17]. Taking into consideration that a medium car emits 0.133 kgCO$_2$/km [18] it can be concluded that 14.56 tCO$_2$e are reduced due to this green mobility. In total, a 636 € income is estimated due to this CO$_2$ reduction. Finally, there is also a fuel consumption reduction of 5110 l/year, that can be considered as a benefit of 6900 €. In total, the project produces 10016 € per year.

Economic profitability indicators can be used for seeing the viability of the project. In conclusion, Since the NPV is positive for every estimated values of discount rates, and the IRR is greater than zero (see Table 5), it's concluded that the project is profitable. Option 1 would have revenues up to 92000€ with a discount rate of 8% in a lifespan of 35 years, an IRR value of 58.43 % and an estimated payback time of 2 years. Option 2 would create revenues up to 85000 € with the same considered conditions, an IRR value of 34.14 % and a return period of 4 years. In conclusion, both options are economically profitable, although the lead-acid battery solution may result in better economical results. Moreover, apart from economic benefits, the installation would create other positive effects related to urban sustainability and energy recovery, provoking high positive impacts.

Table 5. Economic analysis results

	OPTION 1			**OPTION 2**		
Investment (€)	16750			28930		
IRR	58.43%			34.14%		
Discount rate	10%	8%	6%	10%	8%	6%
NPV (€)	72953	91382	117466	65063	84401	111750
Payback (years)	1.94	1.9	1.84	3.64	3.47	3.32

The social impact evaluates the effects caused in economical, technical, cultural, institutional and environmental factors, causing a positive change on the people [19]. It's clear that the reduction of equivalent CO$_2$ emissions to the atmosphere, in addition to the incomes created by the electricity generation and green mobility, are both inducing social benefits. The utilization of renewable energy in public facilities and non-polluting mobility promotes and spreads the green culture and generates satisfaction among citizens. It can serve as inspiration for other similar projects, public or private, that may contribute to eco-friendlier electricity consumption. Furthermore, it also serves as an inspiration to an eco-friendly green mobility consciousness that creates less pollution by reducing fuel consumption. About employment generation, some direct job positions would be created for the development of the idea, the construction and the publicity campaign. The estimated associated benefit of this employment creation is around 44250 €. this project may inspire some new similar green installations, more resembling teams of developers and builders will be needed in the future. Furthermore, innovation to improve the installations' performance would increase competitivity in companies working with these new technologies, which would lead to even better solutions.

4. Conclusions

In this dissertation, an analysis of the hydropower and energy generation was carried out before advancing into a case study. It was extensively analysed the pumps working as turbines (PATs) due to their applicability and potential benefits in the case study. These devices are interesting for their high availability, productivity, easy maintenance, and reasonably good efficiencies in energy production.

Hence, a real case study was evaluated based on the information collected. It was inspired on the REDAWN project, and it consisted on the analysis of an irrigation system on *Parque Eduardo VII* and *Jardim Amália Rodrigues* in order to achieve energy recovery from the water network. The aim of the designed system was to cope with the electric demand of GIRA's company electric bikes' stations located in *Praça Marquês de Pombal*. Calculations were made to obtain the maximum available energy from the irrigation system and accomplish good control of the installation. PATs were selected as the devices to carry out this task.

A design process was developed, in order to optimize the energy recovery and ensure the project's feasibility. Then, a sensitivity was carried out to obtain more results for other possible scenarios, changing the water consumption of the system and the rotational speed of the hydraulic machines. As a conclusion, the designed system is capable of coping with the demand goal of 31.2 kWh/day of the bikes stations, and the surplus energy can be sold to the grid. It was estimated that the installation was able to produce a total electric energy of 18980 kWh per year.

The two different solutions proposed were economically profitable as the viability analysis shown and, moreover, the project also contributes on reducing the CO$_2$ emissions to the atmosphere with the renewable energy production and the green mobility stimulation.

The project developed in this thesis is found to be relevant due to its economical and environmental benefits, contributing to make Lisbon a green energy role model and creating a path to be a sustainable city. Using renewable energies and the energy recovery in water systems is vital to improve and optimize the system efficiency and the energy utilization, in addition to help the energy transition from conventional to green energy sources. This will cause huge positive environmental impact. Furthermore, the associated green mobility caused may contribute to an eco-friendlier way of moving around the city.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Professor Helena M. Ramos, for the help provided to develop my thesis, improving my knowledge and rising it. Thank you very much for your guidance, recommendations and advices. I would also like to thank my family, especially to my parents and my brother, for the unconditional support and help during this semester and all my life.

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