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Water-energy nexus management strategy towards sustainable mobility goal in smart cities.

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Author Contributions:

All the authors have participated in different steps of this research. Particularly a brief description is attached: Helena M. Ramos supervised the whole research and was mentor of the idea. Helena M. Ramos and Modesto Pérez-Sánchez wrote the introduction and the definition of the methodology. Modesto Pérez-Sánchez and Lluis Giralt developed the model and simulations. P. Amparo López-Jiménez has revised this research.

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Water distribution networks have high values of energy consumption from the source to the distribution. The use of pumps working as turbines to leverage the energy excess in consumption nodes is an innovative technology. The research proposes a new methodology, which couples the energy generation from water systems with other energy-consumption systems. The main goal is the development of energy communities, which will be self-sufficient to unify the solution with the mobility park charging systems. The optimization process is applied to an urban irrigation system in Lisbon to optimize the energy recovery from the network with PATs. This generated energy is used to cover the demand for two electric bikes' charging in Lisbon. This research contributes to both renewable energy and green mobility, creating a more sustainable and urban smart environment. An economic, environmental and social assessment is carried out evaluating the feasibility in global environmental terms.

Keywords: Energy recovery; Pump as Turbine (*PAT*); efficiency and sustainability; mobility park charging; water distribution networks (*WDN*); sustainable development goals (SDGs)

Introduction

United Nations adopted an action plan to consolidate sustainable development. This agreement was endorsed in 2015 and it was called Agenda 2030. The plan includes 17 sustainable development goals (SDGs), which contains 169 targets (Castor et al., 2020). All targets define a new framework to improve the sustainability of the world. It implies the targets are interrelated between them and the use of joint actions is key to reach these targets before 2030.

Water and energy are present in the majority of the targets of these SDGs, and therefore, the management improvement in the different social activities is crucial to increase sustainability (de Andrade Guerra et al., 2021). Currently, society becomes aware of the development of sustainable actions. It can be observed in the quotidian actions such as the use of bikes to move to work, use of public transport, use of renewable energies at home, among others. In this line, the increase of use of electric bikes in the cities caused an increase in energy demand for the municipalities. These electric points are located on bikes parking, which are near gardens, stations or public buildings commonly. Society should tackle the challenge to reach zero-net energy management in its activities of the city. In this line, one of the solutions to supply the electric demand is to install recovery systems in the water pressurized systems both supply and irrigation networks. Besides, this solution increases the use of renewable energies to reach zero-net energy management in these facilities (Giudicianni et al., 2020).

Different published researches proposed the use of energy recovery systems in the last years. These energy recovery solutions based on micro-hydropowers have increased the energy efficiency of the water distribution networks (WDNs). (Ramos and Borga, 1999) proposed the replacing of the dissipated energy in different pressure reduction valves (PRVs) by energy recovery. The applied technology of these recovery systems was the use of pump working as turbines (PATs). First researches were focused on the development of studies of the pump working as a turbine (PATs), analysing the operational and efficiency curves of these hydraulic machines when they operate in reverse mode. The knowledge of the technology, as well as the definition of the operation curve, increased by the published studies of (Paish, 2005, 2002; Rawal and Kshirsagar, 2007). (Yang et al., 2012) established an empirical method to estimate the best operation point as a turbine, when the water manager knows the best operation point as a pump (Barbarelli et al., 2017; Rosado et al., 2020). The need to develop regulation strategies to increase the recovered energy established the development of researches, which is focused on these strategies (Carravetta et al., 2013, 2012; Caxaria et al., 2011). Once, the operational curves were known, the researchers studied the analysis of theoretical recovered energy considering a constant flow. To increase energy generation, they proposed different regulation strategies when the flow change over time (Mdee et al., 2020). Some of these proposals included methodologies to optimize the location of the machine inside of the WDNs (Reca et al., 2008; Samora et al., 2016; Pérez-Sánchez et al., 2018). This maximization of the recovered energy established a new optimization approach by simulated annealing (Samora et al., 2016), multicriteria (Kandi et al., 2021), shorting genetic algorithm III based on Latin hypercube sampling and chaos theory (LCNSGA-III) (Zhang et al., 2019), Particle Swarm Optimization (Lima et al., 2017). The development of these strategies showed the need to analyse the behaviour of these recovery systems considering two different lines. The first approach was focused on the knowledge of analytical expressions, which allow water managers to know the characteristic curves of the PATs when they operate under variable rotational speed. (Fecarotta et al., 2016) defined modified affinity laws using experimental tests. In this line, (Delgado et al., 2019; Modesto Pérez-Sánchez et al., 2018; Tahani et al., 2020) established different expressions for other tested PATs, and finally, (Plua et al., 2021) defined new general analytical expressions, which defined the operation curves considering rotational speed if the best efficiency point of the machine was known. These expressions used 87 different curves for 15 different machines to develop the new model. The development of the second research line is aligned to the first since it analysed the behaviour of these recovery systems when they operated off-grid under variations of the rotational speed. (Capelo et al., 2017) started to analyse the influence between the self-excited induction generator (SEIG) and the hydraulic machine, considering the capacitance of the circuit. These analyses continued defining optimization models to maximize the global efficiency of the electro-hydraulic system (SEIG+PAT) (Fernandes et al., 2019) (Nikolic et al., 2021). This evolution of the PAT analysis establishes the need to link the energy efficiency of these recovery systems with other sustainability improvements to search for the self-consumption of the different public services in the urban areas.

Currently, these systems try to get a sustainable development of the society in a new smart environment of future urban areas (EU, 2017). This development is linked to improving the social, cultural and environmental benefits, which is connected with the renewable energies mandatory (Miola and Schiltz, 2019; Scardigno, 2020). The use of this technology will allow water managers to improve and reach the sustainability key performance indicators (SKPIs) considering the previews cited benefits. These SKPIs enable to measure of the targets of the different sustainable development goals (SDGs) in which water engineering is influenced (Vanham et al., 2019). The SDG-6 Water and Sanitation and SDG-7 Energy are the main goals in which the water engineering is rolling, but indirectly, the water management has influenced too other important goals, such as SDG-4 Education, SDG-5 Gender Equality or SDG-11 Sustainable cities (Di Vaio et al., 2020).

This sustainable need causes new paradigms related to the management, which must be proposed, searching the generation of the energy communities, in which the energy consumption can be coupled (Balacco et al., 2021; Binetti et al., 2019). This coupling enables the use of renewable energy solution in water systems (e.g., water networks). The generated energy could use in other facilities of the city, which need locally available energy such as bike charging park or the use in the recharge of electric vehicles (Balacco et al., 2018). These alternatives are considered as green energy options in smart cities (Guo et al., 2014) and some research published different optimized solutions in their allocations (Conrow et al., 2018). The research is not focused on the optimization and modelling of the bike charging parks, which were developed using different methodologies (Caggiani et al., 2018; Li et al., 2016).

Hence, this research presents a procedure to select the best solution to create self-consumption energy communities by the analysis of a real case study in a water supply system. The procedure develops an iterative optimization where it chooses the number of the location where the recovery systems could be installed, defining the available characteristic operation curve in each location and establishing the best operation point of the recovery machine to guarantee the minimum service pressure in all consumption points and maximize the recovered energy. The procedure promotes its flexibility and feasibility applied to environmental benefits not only in energy but also in social and economic issues. In contrast, the use of these new technologies, which integrate different urban infrastructures, needs to implement transversal coordination logistic to guarantee their correct operation. The research considers an irrigation system, which presents a high difference of level in its irrigation area. Therefore, variability pressure can observe and the pressure excess can take advantage of energy recovery. However, the proposed methodology can be extended to any water system in which there are available pressure to be recovery. This approach studied the integrated use of these technologies (electrical and hydraulic), which are coupled to the electrical demand of the bikes parking. It improves other published researches, which only studied and defined the hydraulic behaviour of the installations, not defining the electrical system in the integration of the optimization.

Energy in water distribution networks

Particularly in the main pipelines of the WDNs, there is an excess of the hydraulic power, which is variable over time as a function of the flow and head (Chen and Chen, 2016).

However, these parameters have significant variations in the consumption nodes. The knowledge of the available power is a critical factor. It is necessary to predict and define the economic benefits of converting flow energy dissipation into electric energy production (Carravetta *et al.,* 2012, (Giudicianni et al., 2020)).

Figure 1. Optimization procedure of the bike park charging solution

The methodology established several specific issues:

A. Considering the garden irrigation systems, Step A develops a model based on Epanet software. This model considers the irrigations needs of the garden as well as the topology of the water network (Rossman, 2000).
B. For the irrigation pattern, hydraulic simulations were developed to identify all hydraulic constraints about pressure and flow over time. In step B, the proposal simulates different PRVs firstly to know the maximum losses. The valves settings should guarantee the minimum value of pressure (P_{min}) along with the water network. This minimum pressure depends on the water system characteristics, in which the theoretical recoverable energy is defined in the system by the following equation (1):

$$E_{TR} = \sum \rho g (P_i - P_{\min}) \Delta t \tag{1}$$

with E_{TR} the theoretical recoverable energy in kWh, P_i the pressure upstream of the PRV in each time in $\mathrm{m\,w.c.}$, P_{min} the minimum pressure to guarantee the quality service in $\mathrm{m\,w.c.}$, and Δt the time interval in h.

C. The strategy defines two different phases once the best location of recovery points and the number of PATs are defined. The phases are: (i) the definition of the characteristic curves of the hydraulic installation (CCI) and (ii) the definition of the characteristic curve of the PAT (CPAT). The definition of the CCIs depends on the function of the flow as well as the number of installed PAT systems. Using a tested machine (i.e., PAT, which will be described their characteristics in the following section) and applying the affinity laws (i.e., geometrically, kinematic and dynamic similarities), the model develops different iterations to search the best efficiency point of the machine (BEP) within possible operational points. This iteration process optimizes the recovered energy considering different irrigation strategies satisfying the water demand of the city garden. A PAT analysis is necessary to obtain the CPATs. In the analyzed case, the proposal considers different coefficients in the PAT systems to develop the PAT adaptation to the operation point, using different schemes (Carravetta et al., 2014b). These coefficients are: head (C_H), flow (C_Q) and power (C_P) coefficients. They are constant for any value of the machine and they are defined by the following equations (Mataix, 2009):

$$C_H = \frac{n\,D}{H^{\frac{1}{2}}} \tag{1}$$

$$C_Q = \frac{Q}{nD^3} \tag{2}$$

$$C_P = \frac{P}{n^3 D^5} \tag{3}$$

where: n is the rotational speed in rpm; D is the diameter of the impeller in m; H is the head in m w.c.; Q is the flow in m^3/s; P is the power in kW.

The use of these non-dimensional numbers, which are applied to the best efficiency point (BEP) of the machine enables the definition of the specific speed number (n_s). This parameter classifies the type of the turbine as defined by the following equation:

$$n_s = n_{BEP}\frac{P_{BEP}^{\frac{1}{2}}}{H_{BEP}^{5/4}} \tag{3}$$

where: n_{BEP} is the nominal rotational speed in rpm; P_{BEP} is the power in kW; and H_{BEP} is the recovered head in the best efficiency point in m w.c.

Similarity machines can be defined knowing n_s. Therefore, the non-dimensional numbers (i.e., flow, *q*, head, *h*, speed, *n*, and torque, *t*,) are defined according to the BEP operation point of the machine.

$$q = \frac{Q_i}{Q_{BEP}} \tag{4}$$

$$h = \frac{H_i}{H_{BEP}} \tag{5}$$

$$n = \frac{n_i}{n_{BEP}} \tag{6}$$

$$t = \frac{T_i}{T_{BEP}} \tag{7}$$

where: Q_i is a flow value in m^3/s; H_i is the recovered head value in m w.c.; n_i is the rotational speed of the machine for the values Q_i and H_i in rpm; T_i is the mechanical torque for the values Q_i and H_i in Nm.

Applying for the non-dimensional numbers, the proposal runs different iterations to choose the best machine, which maximizes the energy recovery considering the irrigation times, as well as proposing/adapting new irrigation times to improve the recoverable energy.

D. This stage analyzes the recovered energy considering the different scenarios comparing to the demanded energy to charge the bike parking. The step develops both hydraulic simulation as well as energy analysis. The procedure develops the simulation considering the hydraulic regulation of the machine. This regulation changes to reach the maximum recovered energy for the available head, the flow discharge and the efficiency of the machine. The developed analysis needs the improvement of an electric scheme to consider the charge and accumulation of the energy in batteries to supply the bikes' station when there is no irrigation.

E. Once the hydraulic simulations are developed, the proposal develops a feasibility analysis, considering different technological solutions. It considers both the investment in the facilities and maintenance costs, evaluating different scenarios (Ramos and Almeida, 2000). The feasibility study considers the following indexes: (i) net present value (NPV), (ii) benefit/cost ratio (B/C), (iii) internal rate of return (IRR), and (iv) payback period (T). The following equatons define the different used indexes:

$$NPV = R - C - O - P \tag{8}$$

$$B/_{C} = \frac{R - O}{C + P} \tag{9}$$

where: R are the revenues, C are the capital costs, O are the operation costs and P are the reposition costs. All variables are in €. The solutions are viable when NPV is greater than zero. B/C is the ratio between benefit and costs. If a project is viable, B/C should be greater than 1.

The third index is the Internal Rate of Return (IRR), which is the discount rate that makes NPV equal to zero. The last index is the payback period, T, which represents the number of years needed to recover the initial investment.

F. The last step of the model proposes a sustainable analysis. It establishes the strategy for the reduction of CO_2 emissions, the improvement of different environmental and social indicators. The procedure enables managers to compare the impact of these technologies in some SDGs. The social impact evaluates the effects caused by economical, technical, cultural, institutional and environmental factors. These indexes cause a positive change in the people (Cohen and Martínez, 2005). It is clear 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 methodology measures different targets of the SDGs:

(i) Generated green energy in kWh/year. This parameter measures the target 6.4.1 established by the UN (UN, 2018; Vanham and Mekonnen, 2021). This indicator establishes the change in water-use efficiency over time.

(ii) CO_2 emissions reduction linked to energy generation using renewable energies. Target 7.2.1 establishes the renewable energy share in the total final energy consumption (Eisenmenger et al., 2020). The reduction of fossil energies can extrapolate to the reduction of CO_2 emissions (Epa and Change Division, 2019).

(iii) Social impact, which is evaluated in terms related to economical, technical, cultural, institutional and environmental factors. These cause a positive change in the people (Cohen and Martínez, 2005). The social impact is measured in economic, social mobility and employment terms. This impact is related to SDG-11, called *"Sustainable cities and communities"* (McCarton et al., 2021). This goal tackles the need to develop cities where the grown will be sustainable and the use of resources does not support by non-renewable resources. It implies the use of renewable technologies, which reduce the carbon footprint of the different processes and activities of the communities and cities, increasing their inclusive, safe, resilient and sustainable. It is focused on target 11.3, which enhances inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries.

Case study and results

Case study

This case study consists on the creation and development of an energy recovery hydraulic power plant capable of fulfilling the energy necessities of two electrical bike stations of Gira, Lisbon town. 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. 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, called 307 and 308 respectively, and they are near the park charging. These stations are located at Marquês de Pombal in Lisbon (Portugal). The energy study concluded these two stations had an estimated energy consumption equal to 31.2 kWh/day. Figure 2a shows the hourly demanded power. It can be observed that the maximum power that the charging station has to provide is around 3500 W. Figure 2 shows there are hours, in which there is no activity on Gira’s bikes, particularly from 2:00 to 6:00, there is no need for supplying energy to any bike. As the public gardens are irrigated during the night-time, the recoverable energy will take place during the night and the consumption during the rest of the day. This situation establishes the need to propose a new irrigation schedule to closer the electrical need and the possibility to use hydraulic recovery systems.

Figure 2.

The studied irrigation system is located in the centre of Lisbon, in Edward VII Park and Amalia Rodrigues Gardens (Figure 2b) with a total surface area of 31.6 ha. The highest elevated point, where a regulation tank that supplies the water to the irrigation installation is located at 105 m from the sea datum level and the lowest point of this water network profile is at 60 m. The irrigation network is a meshed network, which divides the garden into 12 different main points of demand (Figure 2c).

The proposal developed a hydraulic model to study, analyse and propose solutions to increase the energy efficiency of the irrigation and bike park charging systems (Figure 2c). Once the irrigation system was modelled, a hydraulic recovery solution was examined based on the Epanet Toolkit (Rossman, 2000). This hydraulic model proposed different scenarios based on pumps as turbines (PATs). The calibration of the model considered two values to establish unit irrigation needs. As a result, the water demand for each point was 364000 l/day and 286000 l/day, respectively for summer and winter. The model distributed the water supply-demand patterns for 6 hours, from1:00 to 7:00. During this interval of time, each of the 12 main areas irrigated different internal sections sequentially, maintaining a constant demand without flooding the grass. Consequently, the original demand pattern used for the study, for each point, resulted in a 6 hours constant demand with a value of 13 l/s during the winter and 17 l/s during the summer. Based on the model results for the PATs, these patterns could be modified to optimize energy production. The simulation analysed an extended period analysis of 24 hours to extract the required results for each scenario.

Hydraulic modelling and recovery energy

The water network model was calibrated according to the irrigation demand, the topology area (Step B. Figure 1), the simulation modelling and design for 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 (Step C. Figure 1) were defined. Secondly, an iterative optimization process to design the PATs that would provide the best results to the energy recovery system (Step D. Figure 1) was established.

The first model (Step B) reached a first approach to the PATs possible locations. To obtain as much energy production as possible and it was defined the best locations in the upstream pipes of the three demand points highlighted in Figure 2d, due to their discharge and head values.

Three different model scenarios were created to estimate the energy production capacities in the irrigation system for the nominal demands. In this step, pressure regulation valves (PRVs) were used, considering an outlet pressure consigned of 5 m w.c. The comparison between different scenarios concluded the best alternative for more efficient charging performance was the scenario in which the analysis supposed three PATs installed. This option presented several advantages among the other possible ones. The main reason and most important result was the higher useful flow energy when three PATs operated at the same time. In this case, 9.91 kW of available hydraulic power versus 1.41 kW for one PAT and 5.61 kW for two PATs. Besides, the hydraulic operation was another strong reason to explain the selected solution, since if one or two PATs are installed, the balance of pipes changes considerably because the network is meshed. When one or two recovery systems are installed, the flow resistance induced by the turbine installation locally changes, the energy production decreased and the discharge control was most difficult. If three PATs are considered, the flow control enabled the devices to work in higher pressure drop values and no negatives pressures appeared outlet. In other scenarios, if the pressure drop is incremented, negative pressures appear in some cases, meaning the system would not operate properly.

Once the number of recovery systems is defined, the PAT selection (Step C. Figure 1), as well as the regulation strategy are established (Step D. Figure 1). In this case, an experimental PAT was used, particularly the turbomachine KSB Etanorm 32-160 with a specific speed of 27.88 rpm (m, kW). The BEP corresponded to 0.61 for a flow of 5.4 L/s, head of 21 m w.c. and a rotational speed of 1520 rpm. Although this PAT did not suit to the flow discharge and pressure drop needed for this case study, their experimental data was used to develop the non-dimensional analysis to adapt the characteristic curves to a similar PAT by affinity curves. To develop the non-dimensional analysis, the CCI for the three locations of PATs was defined once the operation points are defined (Figure 3).

Figure 3.

The defined hydraulic simulator based on the EPANET model is possible to represent the available hydraulic energy for pairs of discharge and head values of the CCIs. This analysis showed the best performance characteristic for the design operational curve of the PAT. This point was located in the maximum curve of the hydraulic power (Figure 3). The theoretical maximum recovered power is around 5 kW as a function of CCIs, for a flow of 26.5 L/s and an available head of 18 m w.c..

Using the affinity laws as well as the non-dimensional numbers (q, h, n and t), the characteristic PAT (Etanorm 32-160) defined the behaviour of the recovery system to maintain the geometrical, kinetic and dynamic similarities between the original machine and the adapted one (Carravetta et al., 2014a). Hence, 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 considering CPATs based on the operation flow. The three adapted curves and the efficiency curves obtained are represented in Figure 4.

Figure 4.

The design process is defined based on the following steps:

1. Step 1: BEP was pointed out to the maximum point of available energy obtained with the CCIs: 26.5 l/s of flow discharge and 18 m w.c. conducted to the maximum values of the power generation. However, the pressure outlets have such small values that a slight change in the demand values can create negative pressures. Similarly, it is almost impossible to change the rotational speed to modify the power obtained. If the rotational speed increases, the pressure drops on the PATs, inducing negative pressures at the outlets. So this solution is not suitable due to its lack of operational flexibility.
2. Step 2: BEP transformation into the point of the CCIs for a maximum demand (17 l/s): The main pro achieved in this procedure is 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 a high value of energy recovery due to the losses in the pipes.
3. Step 3: optimization of the previous procedures: the design point used is the maximum amount of energy produced, but with a reduction on the head to widen the range of operation: 26.5 l/s of discharge and 15 m w.c. (instead of 18 m w.c.). It was observed the model ability to reach higher power generation, as good as in

the first step. At the same time, the range of operation has been widened as it is needed.

Once the PAT curve is defined and optimized the energy production, as well as the operation time, irrigation-time conditions and the bikes' use are examined. The irrigation times would be modified to optimize the energy production of the PATs. It would be coupled with the energy demand. This couple defined the final optimized model. Epanet model considered the third curve to get the final results and extract the theoretical power output. The different irrigation scenarios defined the new model to develop a sensitivity analysis based on non-dimensional curves for an electric regulation, varying the change of the rotational speed. Non-dimensional numbers (equation from (1) to (7) defined in the methodology section), four different rotational speeds were chosen for the operation, such as 1180 rpm, 1350 rpm, 1520 rpm, and 1690 rpm. The different scenarios considered the demanded flow and hourly irrigation patterns. Figures 4b and 4c show the head and efficiency curves for the different rotational speeds. These curves enter in the Epanet hydraulic simulator and in the optimization model to analyse all possible scenarios with two energy analysis: (i) the irrigation time was constant and the water demand was variable over time. Table 1 shows the values of energy according to the different demanded flow ranges; (ii) the winter irrigation time was during 6 hours and the summer irrigation time had a duration of 8 hours (corresponding to the same nominal nodal demand of 13 l/s). In these two seasons, the demand is modified to adapt to the changes in the water needs.

Table 1.

When the water needs are constant and the hourly pattern are adapted to values near the bike-charging energy the useful energy is increased (Table 2). In this case, the optimum operating point corresponds to a nodal demand of 14 l/s, considering a rotation speed of 1520 rpm. In these conditions, it’s possible to generate 45.35 kWh in winter and 58.58 kWh in summer.

Table 2.

The energy generation goal of 31.2 kWh to cover the demand easily reached in the majority of the possible operational conditions. Figures 5a and 5b show an example of generated and demanded energy for a winter scenario. Both figures show the distribution of the irrigation hours to supply the demanded energy of the bikes’ park.

Figure 5.

Charging system feasibility and sustainability

The designed power plant can cope with the estimated electric demand of the bikes’ station, based on the official data provided by Gira’s company. Moreover, energy production takes place during the night, while consumption is done for the day. Consequently, there is a need for the system to meet the generation and the consumption and the following solution is proposed in Figure 6, showing the sustainable charging system according to the hydraulic and recovery analysis. This system would synchronize the values of generation and consumption when these values are different using the batteries system, storing or supplying energy as well as injecting energy into the electric grid.

Figure 6.

The proposed system has for the following elements: (i) each PAT generator (1) would be connected to a transformer to normalize the voltage and the intensity generated in alternating current (AC) into direct current (DC) (2). If the system is in the charge phase in the bike station or batteries, a converter (3) is necessary. These converters adapt the current and the voltage to the other components. Besides, it isolates the devices in case of problems. A bidirectional converter was chosen, holding powers up to 9 kW with a smart power tracking point that allows him to reach efficiencies up to 94%. Regarding the inverter, it has the following characteristics: maximum output DC power of 4 kW and maximum efficiency of 99.4%. A set of batteries (4) is necessary to store the excess of recovered energy in the hydraulic system. The storage system should have a capacity of 35 kWh to deal with the demand.

Different analyses were studied according to available technologies, price and maintenance to choose the best storage equipment. Finally, a set of 6 units of 12 V batteries with a total capacity of 36.48 kWh with technology lead-acid was chosen. The lifetime of these batteries was 20 years and 1500 cycles of charging and discharging with a deepness of 80%.

To define the initial investment costs of the sustainable system, all the stages and the resources were considered. For Option 1, with lead-acid batteries, it was an estimated initial investment of 16750 €, while Option 2, lithium batteries, a capital was 28930 €. It has to be considered 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 was up to 133 €/kWh. It included the benefits related to the environmental impact, recycling and waste disposal (Song et al., 2019). Therefore, it considered 4655 € cost every 6 years in Option 1. Regarding the lithium batteries (Option 2), they had 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 to costs values that are being reduced progressively. The estimated cost was 222 €/kWh for the renovation of a lithium battery, resulting in a total of 7770 € every 18 years (Option 2). In addition, an estimated value of 125 €/year was considered for maintenance of the set-ups. Regarding these evaluations, NPV is positive for every estimated value of discount rates, and the IRR is greater than zero (Table 3) as feasible economic indicators requisite.

Table 3.

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 period of 2 years. Option 2 would create revenues up to 85000 € under the same operating conditions, an IRR value of 34.14 % and a payback period of 3.5 years. In conclusion, both options are feasible, although the lead-acid battery solution may result in a better economic impact. Moreover, apart from economic benefits, the installation would create other positive effects related to urban sustainability and energy recovery, impacting positively the city.

Then, the benefits will be focused on three aspects: (i) green energy, (ii) reduction of greenhouse emissions and (iii) social impacts. Each year, the installation will produce 18980 kWh. This energy will be used based on two different purposes: 67% will be directly used by the charging station, while the rest of generated energy (33%) will be sold to the grid allowing to extract the maximum energy solution benefit. Therefore, the total income received for the energy generation will be of 2480 €/year, approximately. The CO_2 emissions reduction produces input money for several reasons. On the one hand, this reduction is caused by the generation of renewable energy. The recovered energy (1890 kWh/year) is equivalent to reduce the emissions of 13.42 tCO_2e (Epa and Change Division, 2019). On the other hand, the use of this green mobility, an average of 100 users of bikes parked on the studied stations for an urban displacement with a bike is estimated to be 3 km long. Taking into consideration that on average a car emits 0.133 kgCO_2/km it can be concluded 14.56 tCO_2e are reduced due to this green mobility (Defra, 2008). Finally, there is also a fuel consumption reduction of 5110 l/year (Epa and Change Division, 2019), which can be considered as an additional benefit of 6900 €. In total, with energy recovery, CO_2 emissions reduction and fuel source reduction, the project produces 10016 €/year.

The social impact evaluated the effects caused by the economical, technical, cultural, institutional and environmental factors, causing a positive change on the people (Cohen and Martínez, 2005). 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. The reduction of CO_2 emissions to the atmosphere, as well as the incomes created due to renewable electricity generation and green mobility, have significant positive social benefits in a near future.

In addition, the estimated associated benefit of the employment creation is around 44250 €. This project may inspire some new similar green installations, as well as more resembling teams of developers and builders will be needed in the future. Furthermore, the innovation to improve the water irrigation system efficiency together with the bike charging park performance will increase the affordability of water-energy companies in a flexible and efficient nexus.

Conclusions

This strategy established a methodology to implement in the EPANET toolkit, the affinity laws of hydraulic turbomachines, as well as the development of similarity turbines based on existent and tested PATs. This optimization procedure allows the development of sensitivity analysis to reach the maximum recovered energy, which should be coupled to the demanded energy of a bike charging park. The optimization considered the change of irrigation strategies to couple the grid demand to energy generation. The procedure analysed three different scenarios considering one, two or three recovery systems. In each scenario, the energy recovery considered the schedule of the water consumption, the rotational speed of the hydraulic machine and the PAT operational point. The proposal solution generated between 48 and 64 kWh/day as a function of the season (i.e., winter or summer, respectively), estimating an annual demand equal to 18980 kWh/year. This recovered energy enabled managers to supply the electric demand in the bikes station as well as the surplus sold to the grid. This supply must be 31.2 kWh/day.

In addition, since the proposed solutions are renewable and eco-friendly, and environmental analysis provided results about the positive impact of the project. Therefore, a reduction of 27.98 tons of CO_2 will result from renewable electric production and green mobility. Moreover, this green mobility has another positive environmental impact, as it means an estimated reduction of fuel consumption due to urban displacements by car or motorbike of 5510 l/year.

This novel research developed an optimization procedure considering both hydraulic simulations as well as the electric generation and demand. Its application can help to develop smart cities and water managers to improve the sustainable development goals of each city. The proposed model showed if renewable recovery systems are used in public facilities by taking advantage of other opportunities in infrastructures (e.g., water pressurized networks), the generated energy can contribute to supply the energy in other urban activities (e.g, electrical bikes). This improvement contributes to developing non-polluting mobility and promotes a green culture. The application of these methodologies in others cities and locations allow society to reach a step ahead in the reach of the different sustainable development goals. SDG-6 and SDG-7 improve increasing the energy efficiency of the water networks and increasing the generation of clean energy respectively. Finally, SDG-11 improves since the sustainability in the cities increase when other green activities are implemented in the operation of the urban infrastructures. The proposed model can serve as inspiration for other similar projects, public or private. These projects may contribute to eco-friendlier electricity consumption, green mobility consciousness with less pollution, an increase of new employment generation, and news flows, which will increase the circular economy of the city resources.

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