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Micro hydro installation analysis in a wastewater treatment plant

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Abstract. This paper introduces the technical and economic viability of a new micro hydro installation solution designed to reduce the power consumption of a medium-sized wastewater treatment plant. The work analyses the hydroelectric potential of the plant and summarizes the turbine-generator design procedure performed to optimize the production. Results demonstrate the viability when energy produced is used for self-consumption.

Key words

Micro hydro, wastewater treatment plant, Kaplan turbine application.

1. Introduction

The importance of water throughout history, not only as a source of life but also as an energy source, has been a constant since the beginning of civilizations. In addition, the consideration of the water as a fundamental resource associated with energy is a matter of particular importance in recent years [1]. So much so that the "International Water Summit", to be held this year in Abu Dhabi (UAE), presents as its motto "*No water, no energy. No energy, no water*", summing up perfectly the two directions of the water-energy relationship.

The Iberian Peninsula has not been out to this reality and, because of its scarce water resources, especially in the south, it has historically developed a strong water policy. From the Romans with their large infrastructure to the current "Agua" Plan, through the large development of ditches and irrigated areas in the Islamic era, the multiple river basins utilization during the Middle Age, the massive development of marshes and large pumping systems made along the 20th century or the "Plan Hidrológico Nacional" repealed and the beginning of 21st century. Nor Castelló, and its surrounding areas, have been oblivious to the need for water use. So, despite not having great rivers in the region, one can find some interesting facilities such as: the old water mills of Ares del Maestre or different water reservoirs with a combined storage capacity of 185 hm^3.

In this context, the importance of an optimized treatment of wastewater from both energetic and public health standpoints is crucial. This task is clearly internalized in all first world countries. Note that the amount of energy used for example in Spain to treat the 3,000 hm^3/year of urban wastewater represents the 1% of the country's total energy consumption [2]. However, there are huge differences in their technological conception between small and large size Wastewater Treatment Plants (WTP). While small and medium-sized WTP sometimes lack of aeration controls and their design is based on the mechanical strength and liability (which implies higher unit costs and consumption), in large WTP the design is optimized to achieve energy consumptions well adjusted. In this sense, while some large WTP are currently operating with consumptions rounding 20-30 kWh/hm^3 throughout the year, the average consumption for the waste water purification park in Spain is around 50 kWh [2]. Therefore, although efforts have been done in this sense [3],[4], there is still room for improvement in the efficiency operation of WTP.

Fig. 1. General view of the wastewater treatment plant.

This work analyses the technical and economic viability of a new solution proposed to improve the energy efficiency of medium-sized WTP. The proposed solution is the introduction of a micro hydro installation to profit the low-head large flow waterfalls existing in a WTP.

The paper structure is as follows. Section II is devoted to perform a brief review of the energy efficiency solutions that are worldwide proposed to improve the energetic efficiency of WTPs. Section III introduces the analysis of the energetic potential that could be obtained in the micro hydro application proposed in this work. Then, the technical solution proposed is described in Section IV. The economic viability of this proposal is analysed in Section V. Finally, some conclusion remarks are introduced in Section VI.

2. Energy efficiency solutions in wastewater treatment plants.

According to [2], the energy optimization of existing WTP can mean an estimated reduction in the total consumption of about 17.5% in average. To achieve that goal, different proposals are introduced in the literature by research groups from all around the globe. These comprehend from the wastewater residual heat reutilization [5],[6], implemented commercially by companies such as the German Urigh Bau [7], to the introduction anaerobic digesters [8],[9], also implemented commercially by lots of companies such as, for instance, the north American Johnson Controls, Inc. [10]. Other proposals deal with the demand side management in a WTP [11], or with multiple interventions derive from energy audits [12]. All these different measures can be grouped in four main categories according to most of the classifications provided by various agencies and institutions involved, such as the American Environmental Protection Agency (EPA). These categories are: equipment and collection system upgrades, operating strategies, energy efficient technologies and renewable energies introduction. Each of them is summarized in the following.

A. Equipment & Collection System Upgrades

This first category comprehends the constant renewal of systems to use new technologies whose efficiency should be higher. Among the solutions or measures that can be included within this group, the following can be highlighted:

- Install variable-frequency drives.
- Upgrade to energy efficient motors and motor systems.
- Heating, cooling, ventilation system upgrades.
- Introduce new energy efficient light technologies.

B. Operating Strategies

This second category includes strategies that can be introduced in the operation of the WTP in order to improve the energy consumption level during normal functioning of the plant. Among them, the following can be highlighted:

- Managing the electrical load.
- Control of inflows and infiltrations in the sewage.
- Optimizing the operation and maintenance procedures.
- Improving the management of biosolids.

C. Energy Efficient Technology

This category is related to the first one because it is also focused on the use of efficient technologies but, in this case, not for being new but for being really efficient due to their principle of operation. Those in this group are:

- Cogeneration or Combined Heat and Power.
- Cogeneration using landfill gas

D. Renewable Energy

Finally, within the renewable energy category, the measures here enumerated are outstanding thanks to the state of their corresponding technologies:

- Introduction of wind and/or solar power installations.
- Enhance the production of Biogas in the WTP.
- Consider the production of Biodiesel.
- Installing "In Conduit" hydro power or micro turbines that profit some waterfall.

Among all these possible solutions, the latter is the one considered in this work in which a micro hydro installation viability has been analysed for different locations in a WTP.

3. Hydroelectric potential in the plant

In the region of Castelló, there is an extensive network of WTP, almost all of them small and medium-sized. Among them, this work has been developed in a medium-sized WTP located in Vilareal, operated by the company "Fomento Agrícola Castellonense S.A." (FACSA), and directly managed the public entity "Entitat Pública de Sanejament d'Aigües Residuals" (EPSAR). This WTP treats the waste water from Vilareal and its surroundings with the conventional activate sludge system. Thus, the WPT is designed for an equivalent population of 50000 inhabitants, and receives an annual average flow of 9000 m^3/day with rush days of up to 14000 m^3/day (although it could admit up to 20000 m^3/day).

The main reason to choose this WTP is its especial configuration which presents the two waterfalls that can be observed in Fig. 2a) and Fig. 2b) respectively. The first of them correspond to the homogenization lagoon input (in the middle of the process with a variable water head of around 1,5m), and the second one to the chlorination maze output (at the final of the treatment with a fix water head of around 3m). The latter is a very particular location because the water discharge is rarely done to an underground drain which, in this case, provides such a suggestive location for a micro hydro installation.

Therefore, for each of the water falls in the WTP, the hydroelectric potential can be calculated according to (1):

$$P = \eta \cdot Q \cdot \rho \cdot g \cdot H \quad (1)$$

Where:

- η is the efficiency of the micro hydro installation.
- Q is the water flow (in m^3/s).
- ρ is the water density (in kg/m^3).
- g is the gravity acceleration (m/s^2).
- H is the water head (in m).

a)

b)

Fig. 2. Potential locations where the micro turbine could be installed: a) homogenization lagoon input, b) chlorination maze output.

In this way, the maximum electric powers that could be extracted at each location supposing that 70% efficiency can be achieved in the system are:

$$P_1 = 0{,}7 \cdot 0{,}162 \cdot 1000 \cdot 9{,}81 \cdot 1{,}5 = 1{,}67\,kW \quad (2)$$

$$P_2 = 0{,}7 \cdot 0{,}162 \cdot 1000 \cdot 9{,}81 \cdot 2{,}8 = 3{,}1\,kW \quad (3)$$

And considering that the annual average water flow is 105 l/s and that the WTP operates around 8200 hours per year.

$$E_1 = 0{,}7 \cdot 0{,}105 \cdot 9810 \cdot 1{,}5 \cdot 8200 = 8868\,kWh \quad (4)$$

$$E_2 = 0{,}7 \cdot 0{,}105 \cdot 9810 \cdot 2{,}8 \cdot 8200 = 16554\,kWh \quad (5)$$

What, knowing that the WTP is subject to an electric tariff costing 9,5 c€/kWh, would represent an energy saving of 1572 € and 842 €, respectively.

Other in conduit locations of the WTP were also analysed. However the water speed through the conduit was too slow to make the introduction of a vertical axis Darrieus turbine [13] viable.

4. Technical solution proposed

For the two locations of the plant where a certain hydroelectric potential has been obtained, a group turbine + generator proposal has been defined. The selection of the models has been done as follows.

A. Turbine selection

Water turbines are classified into two different groups: impulse turbines and reaction turbines. The first group, which mainly includes Pelton, Turgo and Crossflow (also known as the Michell-Banki), works changing the velocity of a water jet. The water is accelerated prior to enter the turbine using its own pressure but, once the water is flowing over the turbine runner blades the pressure is constant and all the work output is due to the change in kinetic energy of the water. Conversely, reaction turbines such as Francis or Kaplan (Propeller if the blades are non-adjustable ones) types base their functioning on the change in pressure experienced by the water as it moves through the turbine and gives up its energy.

In order to proceed with the selection of a turbine, the criterion is usually based on the available water head, and less so on the available flow rate. Commonly, impulse turbines are more frequently used for high head sites, while reaction turbines are usually used for low head sites. However, note that certain models such as Kaplan turbines, with adjustable blade pitch, are well-adapted to wide ranges of flow or head conditions, since their peak efficiency can be achieved over a wide range of flow conditions. Fig. 3 shows a typical chart which classifies most of the types of turbines according to their range of potential application.

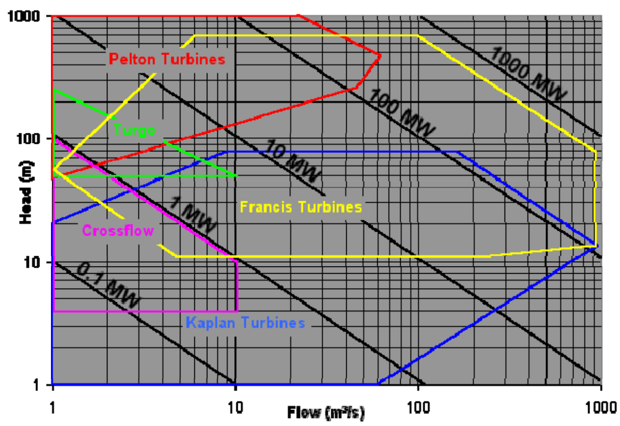

Fig. 3. Turbines selection chart.

Regarding their technical and structural characteristics, small turbines, considering as such those under 10 MW, are usually manufactured with horizontal shafts. On the contrary, large Francis and Kaplan turbines usually have vertical shafts because this makes best use of the available head, and makes the installation of a generator more economical. Finally, Pelton turbines may be installed either vertically or horizontally because the size of the turbine is much less than the available head. Note also that some impulse turbines use multiple water jets per runner to increase specific speed and balance shaft thrust.

Upon all these considerations, and taking into account the head and flow characteristics of the two potential locations where a water turbine could be installed in this WTP, the type of turbine selected in this application is the propeller turbine. For the range of powers defined in Section 3, turbine manufacturers propose different solutions which can be appreciated in Fig. 4.

Not all of them extract the same amount of power from the water flow and prices vary to a large extent. Therefore, for the sake of the economic viability of the project, a good rate quality/price turbine from the Chinese company Guangxi Nanning HeCong Trade Compnay, Ltd. [14] has been selected.

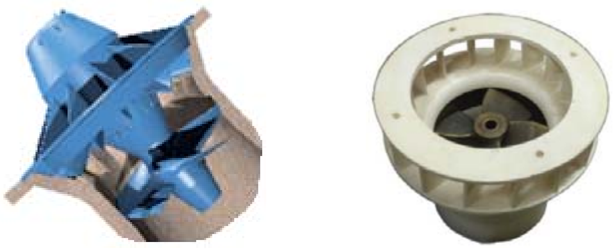

Fig. 4. Turbines models offered by different providers [15],[16].

B. Generator selection

Power generators can be mainly classified into a reduced list of two types: synchronous and induction generators [17]. There are quite a lot of differences among them. In principle, induction generators are simple, robust (requiring minimal maintenance), present an inherent overload protection, and also a small size per generated kW (making them favorable for small power plants). However, they also involve some drawbacks. The main one is that they require reactive power to operate, which is usually fixed by adding a capacitors bank, but also that the small models have not such a good price per kilowatt as the larger central power plants models do (economy of scale). Conversely, synchronous generators are more efficient and can more easily accommodate load power factor variations. However, they present two big handicaps: they require rotor field dc excitation (not in permanent magnet synchronous generators), and they only operate at a constant synchronous speed, while the turbine will vary its rotation speed making the direct connection of this type of generator to the grid impossible.

In fact, the micro hydro application here analyzed requires a variable speed generator, what will involve the following advantages: better energy capture than fixed speed generation, mechanical stress reduction of turbine, and acoustic noise reduction. Induction generations have been traditionally used for such an installation [18]. However, the power electronics and microcontroller technologies evolution experienced in the last years have given a decisive boost to the use of permanent magnet synchronous generators (PMSG) also for small scale projects because these enable very advanced and inexpensive types of control that allow the these generators to operate under varying speed regimes. Therefore, a high efficiency PMSG has been selected among those proposed by suppliers, Fig. 5, which usually propose a generator to be integrated with each model of turbine, offering the whole as a pack.

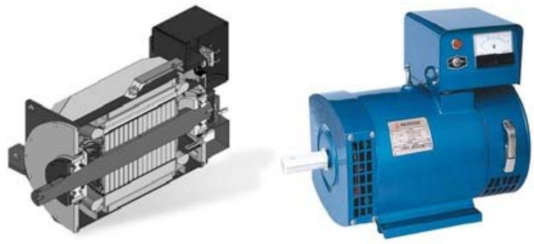

Fig. 5. PMSG models offered by different suppliers.

C. Power electronics required

Once the two main components of the installation have been defined, it is time for the definition and selection of the power electronics stage that will allow the connection of the micro hydro installation to the ac grid of the WTP. Given that the PMSG technology selected cannot control its output frequency, its connection to the grid is not straightforward and requires of some electronic power converter. In the case under consideration, two different connections have been evaluated as possibilities to profit the energy produced by the micro hydro system:

- the possibility of feeding ac loads included within the WTP ac grid. This option implies using a full converter that can modify the frequency to adapt the rotation speed of the generator to the 50Hz ac frequency of the grid.
- the possibility of directly feeding the dc bus of different frequency converters governing the operation of multiples pumps used in the WTP. This solution only requires of a simple rectifier that could transform the ac frequency-varying current produced by the PMSG into dc current.

Among them, the second electric scheme would be cheaper to develop for itself. However, this type of installation would also require a system of batteries, and their corresponding voltage controller, what would increase the cost of it and, then both options would draw near from an economic standpoint. The introduction of batteries would be needed to perform as an energy buffer because the micro turbine installation would be expected to be permanently generating (or at least a great percentage of time throughout the year) and, the frequency converters governing the pumps will only work during certain periods. Therefore, much energy should be lost due to the required disconnection of the turbine to avoid risky situations in the converters cause by a potential overvoltage in their dc buses. Moreover, the parallel connection of different dc buses from different frequency converters is not something that can be taken for granted without problems. If powerful enough, only one converter should be fed in this way, what increases the need for batteries.

In view of the foregoing observations, the first connection schema was selected, Fig. 6. As can be appreciated in the figure, the installation should be connected in ac to the low voltage substation of the plant where its energy will be distributed to the different loads without flowing out to the company distribution grid (self-consumption). Among the commercial converter models that can be used for this application, a SKB-15 rectifier model from Semikron and a Windy Boy 2500 inverter model from SMA have been selected.

These can be also appreciated in Fig. 6. Note that there are not commercial inverter models available for micro hydro applications as the one here analyzed. Nonetheless, the Windy Boy converter is designed to be used in micro wind turbines producing power via a PMSG. Therefore, it will operate perfectly with the generator here selected, what would not be achieved for instance with a solar PV inverter model provided that those implement some algorithms (such as the maximum power tracking) that would make them fail in this precise application.

5. Economic viability of the proposal

The estimated cost of the installation in each of the locations, given the technical solution introduced in the previous section, is around 4500 €. Note that the regional government has a renewables' promotion plan that could provide a non-refundable grant for up to 45% of the cost of the installation. Knowing this, assuming a potential grant of around 30% and taking into account that the maintenance costs can be assumed to be zero, because the WTP already has a maintenance team surveying the plant, and that the energy savings obtained have been estimated in 1572 € and 842 €, respectively, an economic viability analysis of the proposal has been performed. To do so, different investment analysis methods can be used such as: the Payback (PB), the Net Present Value (NPV) and Internal Rate of Return (IRR).

The PB is one of the simplest methods used to analyze investments and is defined as the time required to recover the investment by means of the annual savings derived from that investment. Therefore, it can be simply calculated by the following equation.

$$PB = Net\_Cost / Saving \tag{6}$$

For this proposal, a PB is equal to 2,1 years. It is important to note that this period is shorter than the concession period of the WTP, whose operating license has to be renewed every four years, being this time a key parameter taken into consideration by FACSA for the final investment decision.

On the other hand, the NPV can be described as the "difference amount" between the sums of discounted: cash inflows and cash outflows. It compares the present value of money today to the present value of money in the future, taking inflation and returns into account. It can be calculated according to:

$$NPV = \sum_{t=1}^{n} \frac{V_t}{(1+k)^t} - I_0 \tag{7}$$

In this case, the NPV obtained at the 4th year is equal to 2660 €, and for 20th year, considering this period as the expected life of the installation, is equal to 20048€. Note that every investment getting a positive value of NPV is normally accepted.

And finally, the IRR which represents the money return rate that would make the NPV equal to zero after a certain period of time. The equation used to calculate it is as follows:

$$I_0 = \sum_{t=1}^{n} \frac{V_t}{(1+IRR)^t} \tag{8}$$

The IRR results in this analysis equal to 35% for a four-year period. Given that the decision criterion in this case is based on comparing the resulting IRR with the expected bank return rate throughout the period, and accepting the investment in case the IRR is larger, it can be stated that this installation is economically profitable.

Therefore, the proposal of installing the introduced micro hydro system at the location shown in and Fig. 2b) is clearly viable in economic terms. Conversely, this viability is marginal if installed at the location shown in Fig. 2a), at least for a four-year time horizon.

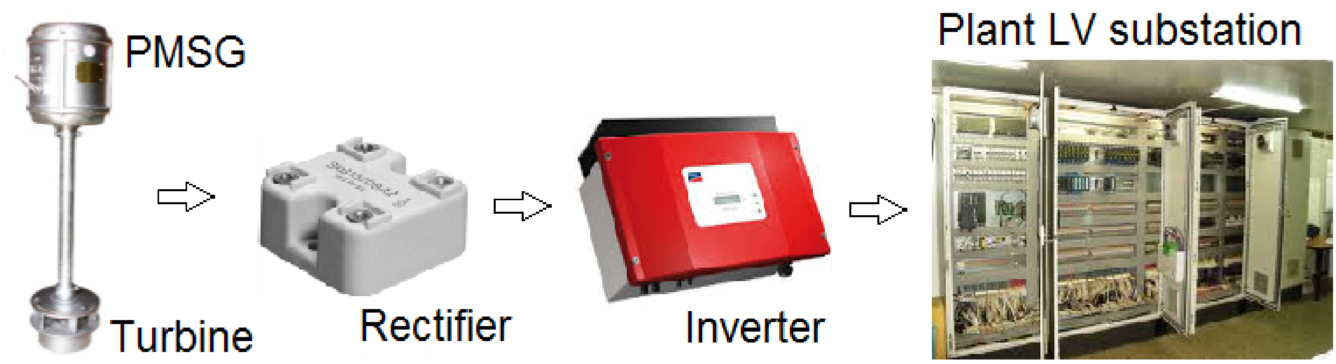

Fig. 6. Main components of the whole micro hydro installation proposed in this work.

6. Conclusion

In this paper, the technical and economic viability of introducing a turbine-based micro hydro installation in a wastewater treatment plant is discussed. The goal of such an installation is to cooperate in the reduction of the energy consumed by the plant, i.e. improving its energy efficiency.

The different procedures or measures worldwide proposed to improve the efficiency in a wastewater plant have been reviewed. Micro hydro installations are quite an original solution. The design methodology, including the turbine and generator selection and the power electronics definition, has been presented. This is mainly based in the water flow-water head relationship which, in this case, returns a propeller Kaplan-type turbine.

The analysis of the results show that an acceptable power production can be obtained by introducing the proposed installation. Therefore, although there are certain important uncertainties in the renewable regulations in Spain, what can have strong influences on the revenue of this installations, its use for self-consumption presents positive enough economic parameters to say it would be viable from an economic point of view.

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