Analysis and viability of microturbines in hydraulic networks: a case study
Ángel Mariano Rodríguez-Pérez and Inmaculada Pulido-Calvo

ABSTRACT

The purpose of this study is to examine the use of hydraulic microturbines to make the most of the hydraulic energy available in pressurized water distribution systems. The study was carried out on suitable points of pressurized hydraulic networks, which are managed by Giahsa, a public enterprise responsible for the management of the municipal communities of services (MAS) in the province of Huelva, southwestern Spain. The distribution system situated between the Cabeza del Pasto reservoir in the Andévalo area (Huelva, Spain) and the wastewater treatment plant (WWTP) in the municipality of Puebla de Guzmán (Huelva, Spain) was examined. To obtain the exact amount of energy which reaches the microturbine, the energy conservation equation considering the loss of energy from friction was used. The results show different locations where it is possible to carry out the installation of a Francis turbine, which can generate an annual energy of approximately 280 MWh per year at the selected point, with an approximate investment cost of €20,000 per year, which means a recovery period of this investment of 2 years.

Key words | Francis-type hydraulic turbine, microgeneration, renewable energy, water distribution system

INTRODUCTION

The 2020 European Strategy advocates a sustainable growth defined as the promotion of an economy to make greater and better use of its resources (European Commission 2011). In addition, electrical demand continues to grow worldwide and there is concern about supply security and about fluctuations in the price of fossil fuels, mainly in countries with high external energy dependence. The option of generating electricity from excess and unused hydraulic energy in water distribution systems could comply with the policies of priority energy efficiency and economy. This microgeneration is a good alternative for the reduction of primary energy consumption and to improve the supply security of energy systems (Fernández de Alarcón 2010; Sunderland et al. 2015; Hawkes et al. 2014; Romero-Marrero et al. 2018). In specialized literature, it is possible to find some recent examples of the assessment of the installation of microturbines placed at selected points in hydraulic networks (Kim et al. 2015; Samora et al. 2016a).

In this paper, the source of the water supply is the Andévalo reservoir (Huelva, Spain), where there is a pumping station that lifts the water up to the Cabeza del Pasto pond (Huelva, Spain) (at a height of 236.4 m). From this reservoir the water is channeled by gravity up to the wastewater treatment plant (WWTP) in Puebla de Guzmán (at a height of 186.4 m) (Figure 1), at the entrance of which is a multistream DN300 electrical regulating valve (Multinar). This valve regulates the flow and pressure of water at the entrance of the treatment station. The average flow at the entrance is 120 L/s.
Two alternatives have been considered for the installation of the microturbine in this water distribution network. The first one would be to place it in the space between the Cabeza del Pasto reservoir and the front of the WWTP (Figure 1). The most favorable points are sought, taking into account the slope where the above-mentioned point is, in addition to the distance covered by the flow of water from the reservoir. This is due to the fact that, the longer the distance, the greater the loss of energy from friction. In the 5,600 m which separate the reservoir from the WWTP, four points have been found, which have been examined. The optimal point, without taking into account the energy necessary to take the water from the point to the WWTP, is situated at 1,692 m from the inlet of the pond, and at a height of 157.3 m. This means that there is a slope of 79.1 m with regard to the outlet of the pond. There are two possibilities for the best location. The first option would be to place the microturbine in the same pipeline that has already been installed. The second possibility would be to install it in a parallel position, with a by-pass through a controlling motorized valve (McNabola et al. 2014; Corcoran et al. 2016), allowing variable flow through the turbine providing greater control over the flow. This would also greatly facilitate the maintenance of the turbine, since it would not be necessary to disconnect the main line of supply.

The second alternative would be to place the microturbine in a parallel position (installation with a by-pass) to the reducing valve which is positioned at the inlet of the WWTP. In this type of installation, a motorized valve would be inserted into the microturbine, which would carry out the control. The inlet of the WWTP is situated at a height of 186.9 m, which means that there is a difference in elevation of 49.5 m from the outlet of the reservoir. The main problem concerning this situation is the long distance from the point of outlet of the pond, which results in greater losses due to friction. On the other hand, it is necessary to take into account that the excessive energy with which the water reaches the WWTP is the vital energy needed to be able to use the microturbine. The net head available at any point of the installation would be the same as the one at the entrance of the WWTP since it is the remaining energy in the installation that can be used.

Another consideration is the number of microturbines to be installed. Samora et al. (2016b) contemplated the installation of four microturbines in a parallel position. This type of installation allows use of the microturbines depending on the existing demand. It is also necessary to take into account the flow which goes through the microturbine when it is inserted. In order to achieve this, the Gibson method is frequently used (Gibson 1923, 1939; Adamkowski 1998; Urquiza et al. 2007).
The purpose of this study is to assess the possibility of generating energy from a renewable source, that is, the hydraulic energy which is derived from the regulatory valve at the inlet of the WWTP in Puebla de Guzmán (Huelva, Spain). The type of microturbine has been examined as well as the average amount of usable annual energy.

AREA OF STUDY

Figure 1 shows the outline of the pipeline (ductile iron, 500 mm in diameter) from the Cabeza del Pasto reservoir to the WWTP situated in the municipality of Puebla de Guzmán (Huelva, south-western Spain). The possibility of installing a microturbine between the reservoir and the WWTP is being considered. For this purpose, the four most ideal points on the route (1, 2, 3, and 4) have been identified, taking into account only the altitude and distance of each of them with respect to the reservoir (Rodríguez-Pérez et al. 2018), as can be seen in Figure 1. The WWTP would be point no. 5, where the microturbine would be inserted at the inlet, in a parallel position to the regulatory valve.

In Table 1, it is possible to observe the distance in m from each of the selected points to the outflow of water from the reservoir, in addition to the elevation at which each one is situated.

The existing installation is equipped with a multistream DN300 electrical regulating valve (Multinar) situated right at the inlet of the WWTP (Figure 2). The purpose of this valve is to reduce the flow which reaches it, and this descends from 220 L/s, when the valve is open, to 120 L/s, which is the flow normally used in the installation. In this procedure, the valve not only reduces the flow, but also limits the excessive energy which comes with the water. It is this excess energy which will be used. When the microturbine is installed, the water will reach the regulating valve with less force, which will not create a problem provided that the energy dispelled in the microturbine is not greater than the excessive energy with which the water reaches the regulating valve. This problem would not exist if the turbine is placed in a parallel position to the regulating valve (in the WWTP).

The Cabeza del Pasto reservoir has a capacity of 140,000 m³ of water (Figure 2), and serves as a storage and supply tank for the treatment station of potable water (WWTP) in Puebla de Guzmán. This reservoir was built

<table>
<thead>
<tr>
<th>Points examined in the water distribution network for the microturbine installation (Rodríguez-Pérez et al. 2018)</th>
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</thead>
<tbody>
<tr>
<td><strong>Point</strong></td>
</tr>
</tbody>
</table>
|---------------------------------|---------------------------------|---------------------------------
| Cabeza del Pasto reservoir      | 0                               | 236.40                          |
| 1                               | 202.16                          | 188.41                          |
| 2                               | 1,164.30                        | 170.35                          |
| 3                               | 1,691.88                        | 157.27                          |
| 4                               | 1,997.22                        | 156.59                          |
| 5 (Inlet WWTP)                  | 5,632.58                        | 186.90                          |

Figure 2 | Multistream DN300 electrical regulatory valve (Multinar), which controls the flow at the inlet of the WWTP in Puebla de Guzmán (Huelva, Spain) (on the left) and Cabeza del Pasto reservoir which channels water to the WWTP in Puebla de Guzmán (Huelva, Spain) (on the right).
only a few years ago, in 2013, and it was constructed at the highest possible point. This was done so that the water would reach the WWTP by gravitational force, making the use of additional pumps unnecessary.

The Cabeza del Pasto reservoir is supplied by four series of pumps which obtain water from the Andévalo reservoir (Huelva). The individual capacity of each pump is 470 L/s with a height of supplied energy of 53 m. The framework of the operation of this pumping station depends on the amount of water supplied by the Cabeza del Pasto reservoir. When the level of water reaches the established minimum amount, the pumping station starts to operate until the maximum capacity of the reservoir is obtained.

The Andévalo reservoir has a capacity of 600 hm³, with the possibility of this being increased to 1,025 hm³. This fact makes it the reservoir with the greatest capacity in the whole of the province of Huelva. It was built in 2003 and opened in 2004. It was constructed to satisfy the great need for the pumping of water to the whole of the Andévalo district (urban and irrigation uses).

MATERIALS AND METHODS

Alternative options for the installation of the microturbine

When we decide to carry out our installation, it is necessary to follow several steps. First of all, it is important to study where and how to install the microturbine; in other words, at which point in the pipeline under study, and whether it should be placed in a group or in a parallel position to the outline of the pipeline under study.

In order to obtain the optimum location of the microturbine, three factors need to be taken into account: (a) height: this should be the minimum possible, so that the water pressure would be greater, in spite of gravity; (b) distance between the selected position and the outflow reservoir – this is due to the fact that, the greater the distance, the greater the loss of pressure would be, due to friction with the pipe; and (c) the net jump that we have at each of the points, that is, the energy that reaches the studied points less the need for water to reach the WWTP.

Therefore, the calculations that must be developed are: (a) to calculate the speed \( V \) with which the water reaches the microturbine at any of the points to be studied; (b) to obtain the real energy to be used at each of the points by the microturbine applying the energy conservation equation considering the loss of energy from friction.

Selection of the microturbine type

When the position of the installation has been decided, it is necessary to calculate the speed with which the water fluid would reach the microturbine, in addition to its force. In order to calculate the loss of energy to friction, the Hazen–Williams equation is used because Daugherty & Franzini (1965) and Hwang & Hita (1987) suggest that this equation is applicable for the flow of water in pipes larger than 5 cm and velocities less than 3 m/s (Liou 1998). These conditions are satisfied in the hydraulic installation under study, as shown in the Results section.

Having established the flow, power, and speed with which the water reaches the microturbine, the choice of type is made: turbine type (Pelton, Francis, etc.), the number of nozzles in the turbine (one or several nozzles), and the number of pairs of poles of the asynchronous generator (two, four, or six pairs). When these data are obtained, it is possible to obtain the energy in MWh needed to supply the microturbine each year.

Once the yearly supply has been established, depending on the surplus energy reaching the valve, a test will be made to determine whether it is necessary to install a second microturbine, which will be installed in a series or in a parallel position.

The second installation option, as has been mentioned earlier, would be to place the microturbine in a parallel position to the regulating valve. If this is done, the location of the microturbine would be the inlet of the WWTP. The difficulty incurred with installing it in this position is the huge distance which exists between the outlet of the reservoir and the height at which this point is situated. This is due to the fact that there are other points at a lower level in the connection. What happens is that in the WWTP, the energy with which the water arrives is the net jump, which is inside the WWTP and there is no need for an exit pressure at that point.
RESULTS

Optimum location of the microturbine

First of all, we calculate the speed (V) with which the water reaches the microturbine at any of the points to be studied. Then we take into account the continuous flow (Q) for the whole distance of 0.22 m³/s, and the diameter (D) for the length of the 500 mm pipe:

\[ Q = V \left( \frac{\pi D^2}{4} \right) \Rightarrow V = 1.12 \text{ m/s} \tag{1} \]

After this, we calculate each of the location points to be analyzed. With regard to this, it should be taken into account that the reservoir is situated at a height of 236.40 m. Considering this, we will be able to calculate the difference in height regarding all of the points. In order to calculate the losses to friction, the Hazen–Williams equation is used (Daugherty & Franzini 1965; Hwang & Hita 2011). Finally, with the use of these calculations, it is possible to obtain the real energy contained at each of the points.

The Hazen–Williams equation is:

\[ hf = 10.67 \left( \frac{Q}{C} \right)^{1.852} \frac{L}{D^{1.87}} \tag{2} \]

where \( Q \) = flow rate (m³/s); \( L \) = length of the pipe (m); \( D \) = inside hydraulic diameter (m); and \( C \) = Hazen–Williams coefficient.

The installation of the microturbine has been analyzed in a water distribution system whose operation began in the year 2013. For this reason, in this simulation, the coefficient of \( C = 110 \) is chosen for ductile iron pipes that are 10 years old (Giles 1962). This value of the Hazen–Williams C (\( C = 110 \)), has been verified using the approximation suggested by Liou (1998) where \( C \) is related to the Reynolds number \( \Re \), the relative roughness \( \epsilon/D \) (in the friction factor \( f \) via the Colebrook–White equation), the pipe diameter \( (D) \) and the cinematic viscosity (\( \nu \)) as:

\[ C = 14.07 f^{-0.54} \Re^{-0.08} D^{-0.01} \nu^{-0.08} \tag{3} \]

Considering a roughness of \( \epsilon = 1 \) mm, a value quite common in aged pipes (Christensen 2000), the solution of Equation (3) in the study case (\( V = 1.12 \) m/s and \( D = 0.5 \) m) is approximately 110. Therefore, the value of \( C = 110 \) is a good approximation.

The calculations for location point no. 1 (Figure 1) are:

\[ \Delta H1 = 236.40 - 188.42 = 47.98 \text{ m} \tag{4} \]

where \( \Delta H1 \) is the difference of height between the outlet of the reservoir and point no. 1 in m.

\[ \text{Losses of power} \Rightarrow hf = 10.67 \left( \frac{0.220}{110} \right)^{1.852} \left( \frac{202.16}{0.5^{1.87}} \right) = 0.63 \text{ m} \tag{5} \]

\[ \Delta h \text{ final} = 47.98 - 0.63 = 47.35 \text{ m} \tag{6} \]

where \( \Delta h \) final is the final difference of height after the losses of power have been eliminated at point no. 1 in m.

The calculation of the loss of energy to friction using the Darcy–Weisbach equation, considering a roughness of \( \epsilon = 1 \) mm, gives similar results to those obtained with Equation (5). In future works, it would be very interesting to estimate the Hazen–Williams coefficient \( C \) for pipe lines by measuring tracer concentrations by using the inverse method and to validate these values for a wide range of operational schemes (Al-Omari & Jamrah 2005).

The results obtained in the other three points being studied can be observed in Table 2. These calculations were obtained in the same manner as for point no. 1.

The real available energy that can be consumed by the turbine is the same at all points of the installation (31.86 m at the entrance to the WWTP, Table 2), because if

<table>
<thead>
<tr>
<th>Point</th>
<th>( \Delta h ) (Difference of height between the outlet of the dam and the point where it is placed in m)</th>
<th>Losses of power (m)</th>
<th>( \Delta h ) final (Final difference of height after the losses of power have been eliminated in m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47.98</td>
<td>0.63</td>
<td>47.35</td>
</tr>
<tr>
<td>2</td>
<td>66.05</td>
<td>3.65</td>
<td>62.40</td>
</tr>
<tr>
<td>3</td>
<td>79.13</td>
<td>5.30</td>
<td>73.83</td>
</tr>
<tr>
<td>4</td>
<td>79.81</td>
<td>6.25</td>
<td>73.56</td>
</tr>
<tr>
<td>5 (Inlet WWTP)</td>
<td>49.50</td>
<td>17.64</td>
<td>31.86</td>
</tr>
</tbody>
</table>
more energy were consumed at an alternative point of the installation, the water would not have enough energy to reach the WWTP. For this reason, the only point that will be studied finally is point 5 which is located at the inlet of the WWTP.

**Characteristics of the microturbine to be installed at the WWTP inlet**

Due to the requirements of flow and net jump of the studied device (0.22 m³/s and 32 m), the turbine recommended by the diagram of selection of hydraulic turbines (flow/jump net) is the Francis type (Castellano 2008). An asynchronous generator with six pairs (p) of terminals is used, for which the synchronism speed (n) is calculated as:

\[
n = \frac{120 f}{p} = 120 \cdot \frac{50}{6} = 1000 \text{ rpm}
\]  

(7)

where \( f \) is the frequency of electric energy in Hz and \( n \) is 1,000 rpm.

This way the calculation of the specific speed is as follows:

\[
P_{\text{WWTP}} = (0.87) \cdot 9810 \cdot (0.22) \cdot (31.86) = 59.82 \text{kW} = 80 \text{CV}
\]

(8)

\[
N_s = n P u^{1/2} H n^{-5/4} = 1000 \cdot 80^{1/2} \cdot (31.86)^{-5/4} = 117 \text{ rpm}
\]

(9)

with \( P u \) = useful absorbed power and \( H n \) = net height.

Therefore the energy generated by the microturbine would be:

\[
P = \gamma \eta Q H n
\]

(10)

where \( \gamma \) is the yield from the microturbine and in this case will be 0.87 (87%); \( \eta \) is the specific weight = water density \( \cdot \) gravity = 1,000 kg/m³ \( \cdot \) 9.81 m/s² = 9,810 N/m³.

Since the microturbine would be working an average of 14 hours a day during the whole year, the total amount of energy it would generate for the year would be:

\[
\text{Energy} = \text{hours per year} \cdot P
\]

(11)

\[
\text{Hours per year} = 14 \text{ hours} \cdot 365 \text{ days} = 5,110 \text{ hours}
\]

(12)

\[
\text{Energy per year for the WWTP} = 5,110 \cdot 5,8454 = 298.70 \text{ MWh per year}
\]

(13)

The Francis turbine type depends on \( N_s \), in our case for \( N_s \) we have a Francis medium turbine, and \( N_s \) is between 110 rpm and 200 rpm (low speed Francis (\( N_s < 110 \)), medium speed Francis (110 < \( N_s < 200 \)), fast speed Francis (200 < \( N_s \))).

According to the results obtained, the ideal microturbine to be installed would be the following:

- A medium speed Francis turbine
- Raw height (\( H b \)): 49.50 m
- Net height (\( H n \)): 31.86 m
- Flow (\( Q \)): 0.22 m³/s
- Specific speed of the turbine (\( N_s \)): 117 rpm
- Power: 59.82 kW = 80 CV
- Estimated number of hours of workload: 14 hours per day, 5,110 hours per year
- Energy: 59.82 kW·5,110 h = 305.68 MWh per year
- An asynchronous generator with six pairs of terminals at 1,000 rpm.

**Installation budget**

With corresponding data to the hydraulic installation at study, in Table 3 is shown the approached investment costs proportioned by some sector companies.

On the other hand, we have the cost of assembly and installation, which we estimate at €19,500, which would mean a total cost of €40,000.

To calculate the annual energy generated, it is necessary to take into account the efficiency of the generator, which is 91%, since we only took into account the efficiency of the turbine:

\[
\text{Energy} = 59.82 \text{ kW} \cdot 5,110 \text{ h} \cdot 0.91 = 278.17 \text{ MWh per year}
\]

(14)

This equates to more than €20,000 per year, which means that the investment is recovered in 2 years. With the requirements of flow and net height of the hydraulic network in the study, a Pelton turbine was also evaluated but the total costs were higher than with the Francis turbine with a recovery period of this investment of 5 years (Rodríguez-Pérez et al. 2018).
DISCUSSION

This study has, as a main objective, the evaluation of the viability of the installation of a microturbine in a water supply pressure network. The results show that the amount of usable energy is significant. The microturbine chosen is the Francis type, due to the fact that it is the one which possesses greater efficiency for this water flow. As has been observed, the characteristics of the microturbine vary, depending on the point chosen for its insertion. More exactly, what varies is the number of pairs and revolutions per minute at which the microturbine works.

One of the most important aspects of the study is the insertion of the microturbine, in our case, the WWTP inlet has been chosen. When the position has been decided, it was necessary to determine how to insert the microturbine, whether in a series or in a parallel position with the pressure reducing valve (Figure 3). In this regard, the latter alternative was chosen. This consists of placing the microturbine in a parallel position (with the installation of a by-pass) to the pressure reducing valve if the position chosen were the inlet of the WWTP (Figure 3(a)).

The final decision to place the microturbine in the WWTP inlet is that at the exit of the turbine we do not

Table 3  | Budget for the turbine + excitation device + generator + packing fee + valve

<table>
<thead>
<tr>
<th>Technical parameters</th>
<th>Euros</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net head: $H_r$</td>
<td>32 m</td>
</tr>
<tr>
<td>Flow rate: $Q$</td>
<td>0.22 m$^3$/s</td>
</tr>
<tr>
<td>Capacity: $P$</td>
<td>60 kW</td>
</tr>
<tr>
<td><strong>Turbine</strong></td>
<td></td>
</tr>
<tr>
<td>Rated rotating speed $r$</td>
<td>1,000 rpm</td>
</tr>
<tr>
<td>Efficiency of turbine $\eta_f$</td>
<td>87%</td>
</tr>
<tr>
<td>Rated discharge $Q_r$</td>
<td>0.22 m$^3$/s</td>
</tr>
<tr>
<td><strong>Generator</strong></td>
<td></td>
</tr>
<tr>
<td>Rated efficiency of generator $\eta_f$</td>
<td>91%</td>
</tr>
<tr>
<td>Rated voltage of generator $V$</td>
<td>400 V</td>
</tr>
<tr>
<td>Rated rotating speed $r$</td>
<td>1,000 rpm</td>
</tr>
</tbody>
</table>

**Product price**

<table>
<thead>
<tr>
<th>Name of commodity</th>
<th>(pcs)</th>
<th>Euros</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>1</td>
<td>11,500</td>
</tr>
<tr>
<td>Generator</td>
<td>1</td>
<td>3,400</td>
</tr>
<tr>
<td>Excitation device</td>
<td>1</td>
<td>2,170</td>
</tr>
<tr>
<td>Governor</td>
<td>1</td>
<td>1,080</td>
</tr>
<tr>
<td>Valve</td>
<td>1</td>
<td>1,350</td>
</tr>
<tr>
<td>Packing fee</td>
<td>1</td>
<td>1,000</td>
</tr>
<tr>
<td><strong>Total amount</strong></td>
<td></td>
<td>20,500</td>
</tr>
</tbody>
</table>

Figure 3  | Diagram showing the installation of the microturbine at the inlet of the WWTP: (a) parallel position (with the installation of a by-pass) to the pressure reducing valve and (b) series position to the pressure reducing valve.
need the water to come out with a certain force and therefore we can take advantage of all the energy that reaches it. Therefore, at the input of the WWTP the water derived from Cabeza del Pasto reservoir is distributed to a treatment pond with height sufficient to run the water through all of the WWTP.

This means that the most adequate position for generation is not an ideal one due to inadequate pressure to reach the WWTP. The position chosen is to place it in a parallel position to the regulating valve which is situated at the inlet of the WWTP. Thus the problem is avoided, but the energy generated would be less. The results obtained for the annual energy generation are less than in the ideal position. However, in order to calculate the installation, the most unfavorable data have been used. This guarantees that obtaining the annual energy calculated is assured and this could possibly increase.

Having made the necessary calculations for its placement, a medium speed Francis turbine and an asynchronous generation with six terminals functioning at 1,000 rpm has been selected for the position.

CONCLUSIONS

This paper shows how effective the installation of a microturbine in a hydraulic network can be, and how energy can be generated by a renewable source. This type of installation has been studied with great interest in the last few years, since it could be ideal for many urban and irrigation water distribution systems. This generated energy could be added directly to the electricity network, but perhaps the best option would be to use it as self-consumption in the water distribution network (for example, for the energy requirements in control devices such as motorized valves, for the illumination of the WWTP, etc.).

In this particular case study, the best alternative is the insertion of a microturbine in a parallel position with a regulating valve at the inlet of the WWTP. Some rather interesting results have been obtained due to the large flow available, and it has been possible to compensate losses from friction due to the long distance covered by the water between the reservoir and the WWTP. This is due to the significant height difference between the Cabeza del Pasto reservoir and the input to the WWTP where the microturbine must be installed.

This paper presents an approach for technicians and managers of water distribution systems who, with a good knowledge of the operating schemes of their hydraulic network, are aware of the significant contribution of energy that could be achieved at certain points with the installation of a microturbine. In order to quantify this energy potential in certain locations of water distribution networks, with complex operation schemes that depend on the time of day and month of the year, this work could be useful as a methodological guide for the optimum location of microturbines and for the selection of the type of microturbines to install.

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