PRELIMINARY ASSESSMENT OF A PUMP USED AS TURBINE IN A WATER DISTRIBUTION NETWORK FOR THE RECOVERY OF THROTTLING ENERGY

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ABSTRACT

Nowadays, the increasing energy demand represents a priority issue to be faced on social, economic, political and technical points of view. For a sustainable development, renewable energy sources should be preferred to the conventional ones. In water distribution networks, Pumps as Turbines (PaTs) can represent a cost-effective alternative to conventional turbines for the recovery of the throttling energy. In this framework, a preliminary assessment of the installation of a PaT in the water distribution network of Casamassima, a town in the Apulia region (Southern Italy), has been conducted. A PaT, suitable for this application, has been tested in both direct and reverse modes at the test rig of the Department of Mechanics, Mathematics and Management of the Polytechnic University of Bari. Then, starting from the analysis of the pressure and flow rate patterns during the day and the night, three installation cases have been evaluated and compared in terms of hydraulic energy harvesting and power output useful to supply an electrical charging station.

KEYWORDS

PUMP AS TURBINE, PAT, WATER DISTRIBUTION NETWORK, HYDROPOWER, ENERGY

NOMENCLATURE

BEP	Best Efficiency Point
C_p	Hydraulic Source Harvesting Coefficient [-]
D_2	Impeller diameter [mm]
DMA	District Metering Area
H	Head [m]
N	Rotational speed [rpm]
$N_{s,P}$	Specific speed of the pump
$N_{s,T}$	Specific speed of the PaT
PaT	Pump as Turbine
PRV	Pressure Relief Valve
Q	Flow rate [m^3/h]
WDN	Water Distribution Network

INTRODUCTION

The stringent environmental policies draw the attention of Industry and Academia to an energy production more oriented to renewable sources. With new enthusiasm the scientific research is attempting to identify new energy sources that can satisfy in a sustainable way the continuously growing energy demand. In hydraulics, the hydroelectric sector counts basically power plants of hundreds of megawatts, where suitable pressure drops and adequate flow rates are available. However, the interest in mini- and micro hydro is gaining relevance. For instance, in water distribution networks (WDNs) is often necessary to insert pressure relief valves (PRVs) in order to regulate flow rates or to reduce leakages, sometimes very high especially during the night, since the drinking water demand is insignificant and consequently the pressure in the network reaches maximum levels. Actually, water management authorities partition the water distribution networks into District Metering Areas (DMAs) and install PRVs in order to control the daily pressure pattern. The replacement of PRVs with mini- or micro-hydropower plants could be a feasible practice to achieve an effective pressure control with throttling energy recovery (Fecarotta et al. 2018). Pumps as Turbines (PaTs) are certainly the best compromise between economic and technical issues when throttling energy recovery is considered, even if pump manufacturers do not provide technical information in terms of performance of their pumps running in reverse mode (Derakhshan and Nourbakhsh, 2008). In the technical literature, some works have been focused on real case studies in order to evaluate the effectiveness of PaT installations. A full-scale PaT application has been implemented into a WDN in Turkey for energy production and pressure reduction (Muhammetoglu et al. 2017), whereas an evaluation of the potential of a PaT installation has been performed for the WDN of Merano (Italy) (Rossi et al. 2016 and Alberizzi et al. 2018). Balacco et al. (2018) considered to replace existing PRVs with a PaT in the WDN of Casamassima (Italy). A horizontal single-stage centrifugal pump was selected and an installation scheme was defined with a hydraulic regulation, constituted by a bypass valve and a control system, which permits the electric regulation by varying the PaT rotational speed. In this work, an empirical correlation from the literature, based on the Best Efficiency Point (BEP) in direct mode, was adopted for the definition of the PaT characteristic curve in order to give the necessary backpressure and satisfy the water demand. It was verified how a PaT system can generate about 160 kWh/day and an average power of 6.6 kW considering a conservative PaT efficiency equal to 0.7. An economic analysis permits to evaluate that a PaT installation is characterized by a payback period of a few years (Caravetta et al. 2018) or sometimes even a few months (Balacco et al. 2018). If compared with a conventional turbine, PaT solution can involve an annual income ranging from 25,000 €/year to 50,000 €/year or more, depending on level of water saving due to pressure reduction in WDN.

The preliminary identification of specific speed of the pump to be used as PaT is fundamental in order to find the best suitable solution. Several works, based on empirical correlations, have been proposed: Barbarelli et al. (2017) proposed a procedure starting from the specific speed requested by the site, Stefanizzi et al. (2017) developed a predictive model to estimate both the flow rate and the head ratios ($q = Q_{BEP,T}/Q_{BEP,P}$, $h = H_{BEP,T}/H_{BEP,P}$), as a function of the specific speed of the pump, $N_{s,P}$. Pugliese et al. (2018) presented a procedure for the preliminary selection of a PaT, based on the design of the main parameters (the head drop and the produced power at the BEP, the impeller diameter and the rotational speed) to maximize the power output and regulate the exceeding pressure. However, the insertion of a PaT must consider the variability of water demand that is fundamentally a stochastic process (Balacco et al. 2017). A similar hydraulic variability in a water distribution network does not permit to define a unique operating point for a PaT and this aspect is a further obstacle for the functional planning of such a system. Generally, the backpressure remains almost constant, as it must be guaranteed the user demand during the day, whereas the upstream pressure depends on the flow rate pattern. For the sake of clarity, while the backpressure is defined by the PRV on adequate values to guarantee the downstream water demand, upstream extremely different conditions can be observed, which are based on the user demand random variability. In order to guarantee the off-design conditions, it is possible to adopt different regulation methods: Hydraulic

Regulation (HR), Electrical regulation (ER) or both modes (Carravetta et al. 2014; Fecarotta et al., 2018).

In this framework a preliminary assessment about the installation of a PaT in a WDN has been conducted. The case study analyzed in this work is the one of Casamassima, a town located in the Apulia region (Southern Italy). Initially a KSB PaT has been selected and tested in both modes at the test rig of the Department of Mechanics, Mathematics and Management of the Polytechnic University of Bari. Then, starting from the analysis of the pressure and flow rate patterns during the day and the night, three installation cases have been evaluated and compared in terms of hydraulic energy harvesting and power output useful to supply an electrical charging station: Case #1) the installation of two different PaTs: the first working at its BEP during the day, whereas the second working at its BEP during the night; Case #2) the installation of two identical PaTs: the first working alone during the night and the second working in parallel to the first during the day; Case #3) the installation of only one PaT.

CASE STUDY

In this study, the Casamassima's WDN is selected as an exemplification of a PaT used as a throttling device. Casamassima counts 19,860 inhabitants and is supplied by a unique tank. Three PRVs subdivide the WDN into three DMAs (Fig. 1). For the sake of clarity, two pressure relief valves (PRV2 and PRV3) are installed at the entrance of the city, though downstream the tank, with the aim to subdivide the water network into the two main DMAs (DIS2 and DIS3). Moreover, one more DMA is located in cascade to DIS2, that supplies several residential buildings and a large golf course (DIS1). In the following analysis, DIS1 has been neglected, due to limited number of inhabitants involved. Balacco et al. (2018) reported flow rate values and pressure patterns measured downstream the tank and downstream the two PRVs (DIS2 and DIS3), as reported in Fig. 2. It can be observed how the two PRVs are set differently because of the different elevation of each DMA. Moreover, each of them is configured according to two different pressure patterns (daily and nightly) to guarantee firstly the necessary daily water demand and then to reduce nightly leaks.

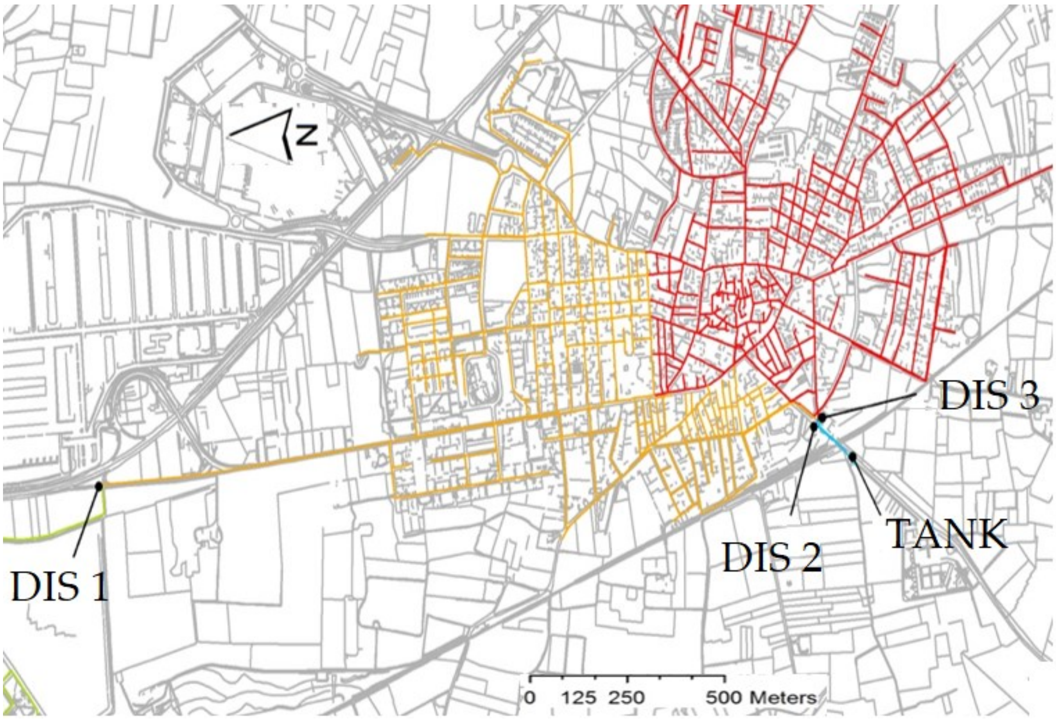

Figure 1: Water Distribution Network of Casamassima (Italy) used as case study

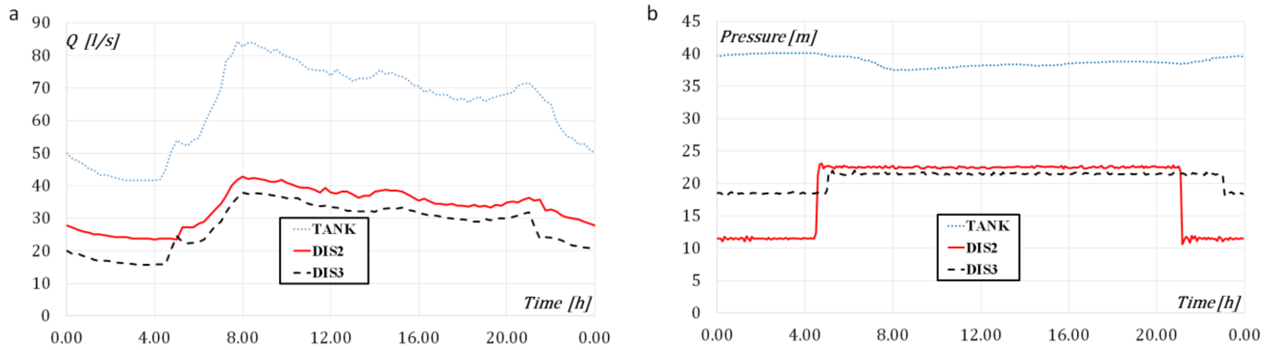

Figure 2: Flow rate measured for the three selected points (TANK, DIS2 and DIS3) (a); Pressure patterns measured downstream the TANK and the PRVs of DIS2 and DIS3 (b)

EXPERIMENTAL CHARACTERIZATION

A KSB Etanorm® 200-150-400 PaT has been tested at the test rig of the Department of Mechanics, Mathematics and Management of the Polytechnic University of Bari (Fig. 3). A detailed description of the test rig can be found in Stefanizzi et al. (2017).

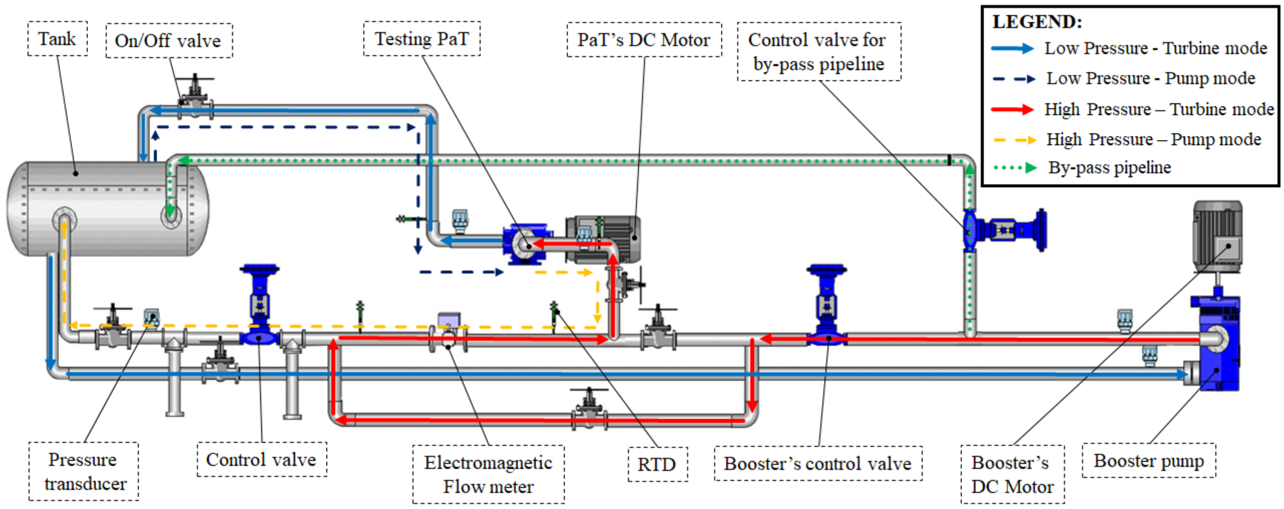

Figure 3: Pump and Turbine mode layouts of the test rig

Fig. 4 and 5 show respectively the experimental head and efficiency curves of the PaT under both operation modes at different rotational speeds: 800 rpm, 1000 rpm, 1200 rpm and 1520 rpm. Moreover, the runway and the blocked rotor curves have been acquired in order to examine the operating range in turbine mode. During pump test, a four-quadrant AC/DC converter automatically maintains constant the rotational speed (0 ÷ 2400 rpm) independently of the flow rate Q. During turbine operation mode, the rotational speed is kept constant by varying the electric motor torque, through the same four-quadrant AC/DC converter. Data were collected for 30 s at a 1 Hz sampling rate, after having reached steady state conditions. The experimental points are provided with their standard deviation bands. The experimental setup is constituted of a series of electronic measurement devices: an electromagnetic flow meter (Siemens Sitrans FM Magflow 3100 – accuracy 0.25% – Q_{max} = 1100 m^3/h), pressure transducers either upstream and downstream the PaT and the booster pump (EH Cerabar – accuracy 0.15%), an HBM T40B torque meter with integrated angular speed encoder characterized by an accuracy class of 0.05% and C_{max} = 3000 Nm. Each pressure measuring section is constituted by three pressure transducers in order to perform pressure measurement replications. Then, the pressure measurement is given by the mean pressure among the three measurements.

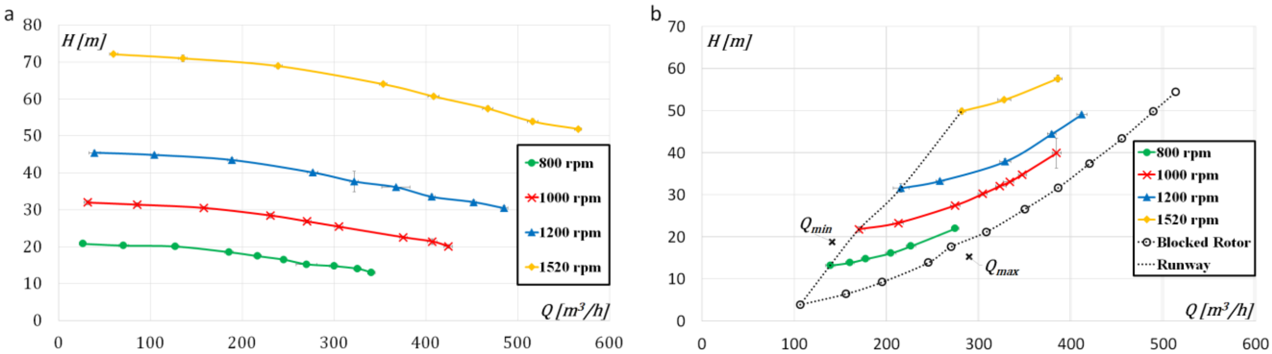

Figure 4: Experimental head, *H*, vs. flow rate, *Q*, under pump (a) and turbine (b) mode; minimum, Q_{min}, and maximum, Q_{max}, operating conditions in WDN of Casamassima plotted on experimental performance chart in turbine mode

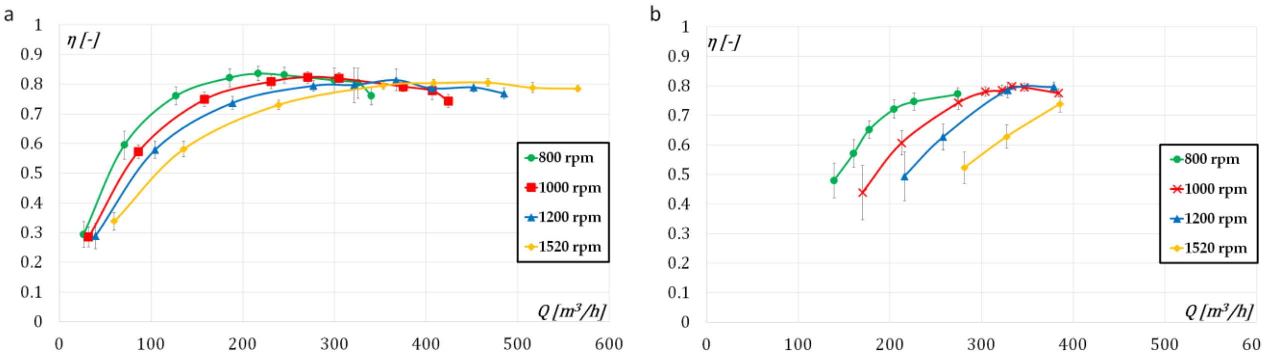

Figure 5: Experimental efficiency, η, vs. flow rate, *Q*, under pump (a) and turbine (b) mode

PRELIMINARY TECHNICAL ASSESMENT

Since there are two different flow conditions (one during the night and another during the day) with different available heads, the specific speed, $N_{s,T}$, must be evaluated at the minimum and the maximum flow rate conditions, $N_{s,T}(Q_{min})$ and $N_{s,T}(Q_{max})$. This allow us to define the machine to be installed. Considering a rotational speed equal to 1500 rpm, the required specific speeds at the minimum and the maximum flow rate are respectively equal to 19.74 and 36.85. Once these two values are known, it is possible to evaluate the specific speeds of the pump to be used as a turbine, according to the correlation proposed by Stefanizzi et al. (2017):

$$N_{s,P} = \left(N_{s,T} + 2.6588\right)/0.9237 \tag{1}$$

In the two different flow conditions, the pump specific speeds are respectively $N_{s,P}(Q_{min}) = 24.2$ and $N_{s,P}(Q_{max}) = 42.8$, which are within the conventional range of applicability of centrifugal pumps and close to the N_s of our PaT.

Having the experimental characteristic curve of the KSB Etanorm® 200-150-400 ($N_{s,T} = 22.06$ and $D_2 = 419\ mm$) used as turbine, the use of this PaT was first considered. Fig. 4b shows the required operating points at the minimum and the maximum flow rate, which are plotted on the PaT performances curves. Unfortunately, both the points are out of the PaT operating range, defined by the runway and the blocked rotor curves.

Rather than considering a PaT with the correct N_s, we decided to scale the PaT, in order to guarantee the required operating points of the water distribution network of Casamassima. The scaling has been performed by modifying the outer diameter D_2 and the rotational speed, *N*, as stated in equation 2, where $D_{2,ref} = 419\ mm$ and H_{BEP}^{test} and Q_{BEP}^{test} are respectively the experimental head and flow rate evaluated at the rotational speed N_{ref}, at the BEP conditions.

In order to select the design variables (Q and H) to be used in the right side of the equation 2, a statistical analysis has been performed for each pattern of operating conditions.

$$\begin{cases} Q = \left[Q_{BEP}^{test}\left(\frac{D_2}{D_{2,ref}}\right)^3\right]\left(\frac{N}{N_{ref}}\right) \\ H = \left[H_{BEP}^{test}\left(\frac{D_2}{D_{2,ref}}\right)^2\right]\left(\frac{N}{N_{ref}}\right)^2 \end{cases} \longrightarrow \begin{cases} D = D_{2,ref}\left[\frac{H_{BEP}^{test}}{H}\left(\frac{Q}{Q_{BEP}^{test}}\right)^2\right]^{1/4} \\ N = QN_{ref}\Big/\left[Q_{BEP}^{test}\left(\frac{D_2}{D_{2,ref}}\right)^3\right] \end{cases} \tag{2}$$

The flow rates acquired during the night pattern (23:05 – 4:30) show a mean value $\bar{Q}_{night}$ = 155.2 m^3/h with a standard deviation σ_{night} = 14.38 m^3/h, whereas the day pattern (04:35 – 23:00) is characterized by a mean value $\bar{Q}_{day}$ = 239.4 m^3/h with a standard deviation σ_{day} = 31.21 m^3/h. Fig. 6 depicts the flow rate frequency distributions, f_Q, and the cumulative available hydraulic power, P_{Hydr}, during the night (Fig. 6a) and the day (Fig. 6b). Both of them present the mean values in the range with the highest frequency and the highest available hydraulic power. For this reason, two operative conditions have been chosen: PaT has to work during the night at the BEP with $\bar{Q}_{night}$ = 155.2 m^3/h and H_{night}=19 m, whereas during the day with $\bar{Q}_{day}$ = 239.4 m^3/h and H_{day} = 15 m.

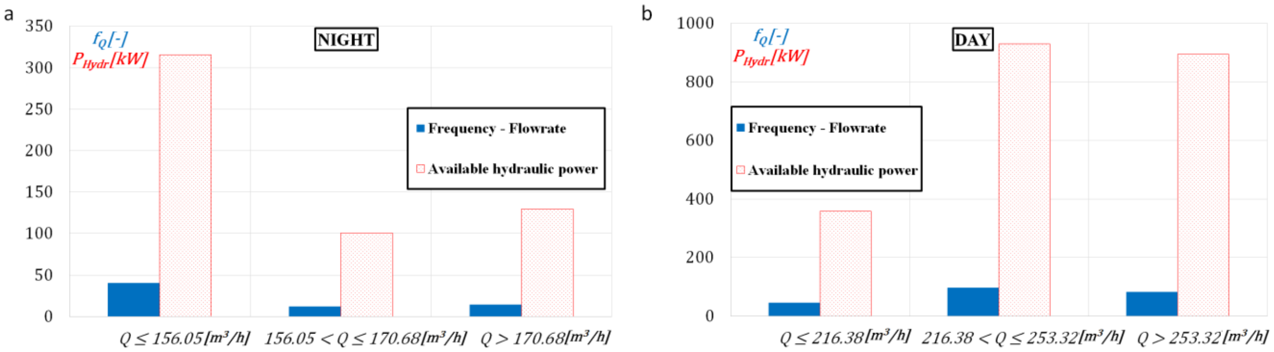

Figure 6: Flow rate frequency distribution and cumulative available hydraulic power during the night pattern (a) and day pattern (b)

Once the operating conditions have been set, it is possible to scale the experimental characteristic by applying equation 2 in order to find the new diameter and the new rotational speed, which guarantee the BEP at the selected operating points. As results, a PaT (PaT #1) with $D_{2,1}$ = 328.2 mm and N_1 = 967.5 rpm is required during the night, whereas a second PaT (PaT #2) with $D_{2,2}$ = 432.7 mm and N_2 = 651.9 rpm is required during the day. Considering the wide range of flow rates, three installation cases have been evaluated and compared in terms of hydraulic energy harvesting and power output useful to supply an electrical charging station. Actuallu, if we would like to identify an existing pump in a manufacturer catalogue (e.g. the KSB Etanorm® catalogue), it can be simply done by knowing the operating conditions. As result, the previous two operating conditions lead to find two machines on the KSB catalogue: a KSB Etanorm® 100-80-315 for the night and a KSB Etanorm® 150-125-400 for the day.

Case #1: PaT #1 during the night and PaT #2 during the day

Fig. 7 shows the layout with PaT #1 and PaT #2 installed in parallel. In order to allow the hydraulic regulation, a PRV is installed in series to each PaT and a by-pass line is contemplated in parallel to the entire PaT system. In this case, it is supposed that PaT #1 works during the night, whereas PaT #2 during the day. Fig. 8 shows the characteristic curve of PaT #1 and the site characteristic with their intersection at the BEP of the machine, highlighted in red ($\bar{Q}_{night}$ = 155.2 m^3/h and H_{night}=19 m). A by-pass line is used when the flow rate exceeds the mean value, $\bar{Q}_{night}$. This solution allows the turbine to work always at its BEP condition. Otherwise, for flow rates lower than the mean value, the

PRV #1 is used to regulate the head. During the day PaT #2 is turned on and works alone during all the daytime pattern. Fig. 8b shows the characteristic curve of PaT #2 and the site characteristic during the day with their intersection at the BEP of the machine, highlighted in red ($\bar{Q}_{day}$ = 239.4 m^3/h and H_{day} =15 m). The regulation is carried out by means of the by-pass line and the PRV #2 with the same logic, as previously discussed.

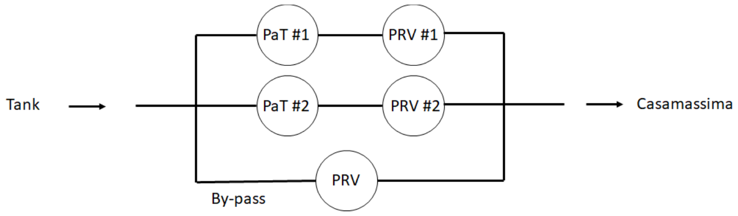

Figure 7: Installation layout of Case #1

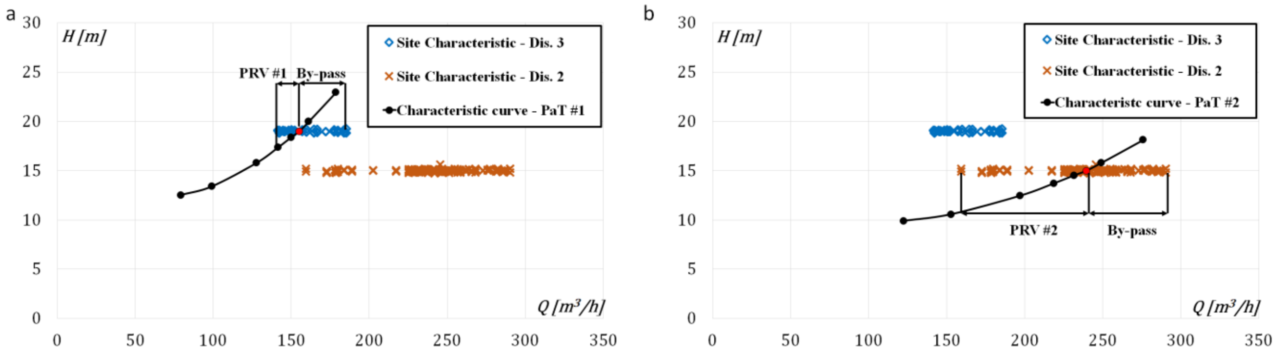

Figure 8: Site characteristic curves with characteristic curve of PaT #1 during the night (a) and characteristic curve of PaT #2 during the day (b) with their regulation methods

Case #2: PaT #1 during the night and Two PaTs #1 in parallel during the day

Fig. 9 shows the layout with two identical PaTs, both equal to PaT #1 installed in parallel. In order to allow the hydraulic regulation, two identical PRVs are installed (one for each PaT) and a by-pass line is installed in parallel to the entire PaT system.

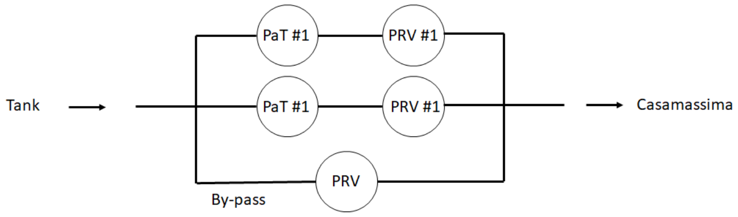

Figure 9: Installation layout of Case #2

In this case, it is supposed that only one machine works during the night, whereas both of them work in parallel during the day. Fig. 10a shows the equivalent characteristic curve of two PaTs #1 working in parallel and the site characteristic. During the day, three types of regulation are considered: the by-pass line is used for flow rates greater than the operating point; both the PRVs operate for flow rates lower than the operating point; furthermore, when the operating points are close to the runway conditions, the system is controlled by means of a speed regulator. The rotational speed is decreased in order to move the runway point towards lower flow rates. At this point, it is possible to use PRVs in order to regulate the head by dissipating the exceeding pressure (Fig. 10b).

Case #3: One single PaT #3

A third case has been considered in order to simplify the system with only one machine, PaT #3, one PRV and a by-pass line, as shown in Fig. 11. The KSB PaT has been scaled in order to guarantee the mean flow rate required daily and nightly ($\bar{Q} = 219.55$ m^3/h and $\bar{H} = 15$ m). As results, the machine requires $D_2 = 414.4\ mm$ and $N = 680\ rpm$. In this case with a $N_{s,P} = 26.8$, it would have been possible to choose from the catalogue a KSB Etanorm® 150-125-400.

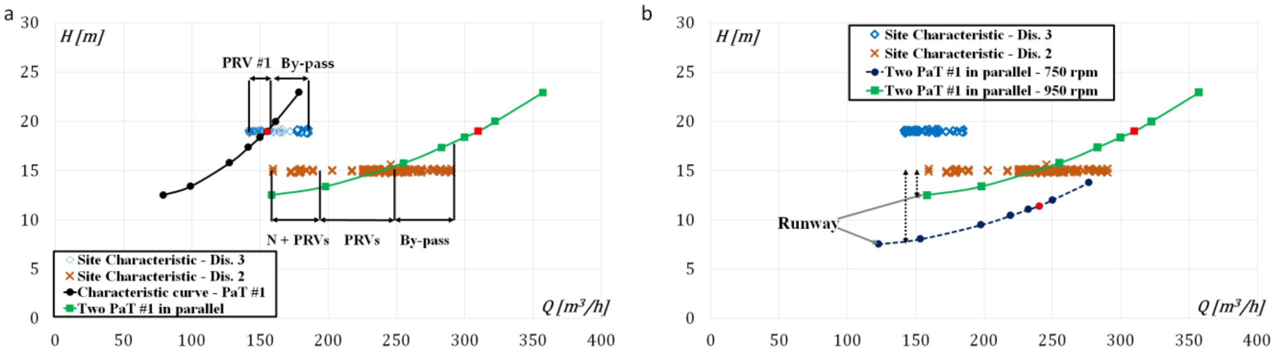

Figure 10: Characteristic curve of PaT #1 during the night (in black) and characteristic curve of two PaT #1 in parallel during the day (in green) (a) with their regulation methods; Particular of the speed regulation method during the day (b)

In this way, the by-pass line is used for all the flow rates greater than the BEP condition (highlighted in red), whereas a PRV can be used for flow rates lower than the BEP condition. In order to guarantee a lower pressure drop during the hydraulic regulation in the night, it is possible to increase the rotational speed of the turbine (from 680 rpm to 750 rpm), as depicted in Fig. 12b.

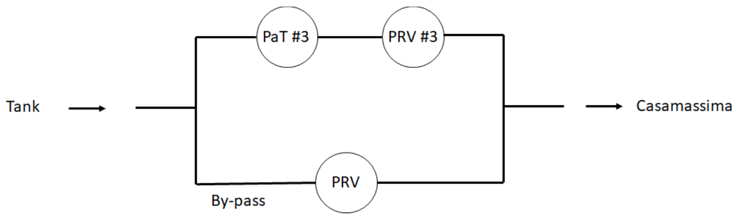

Figure 11: Installation layout of Case #3

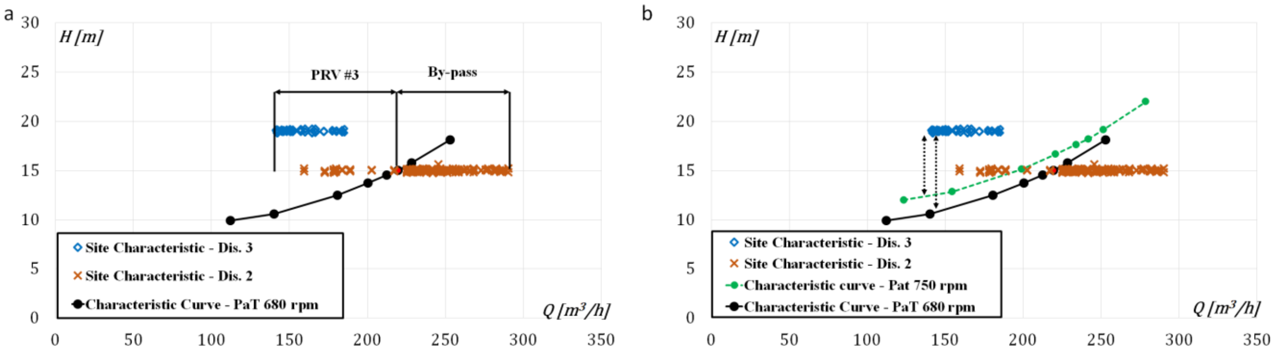

Figure 12: Characteristic curve of a single PaT during the day (a) and the night (b) with its regulation methods

RESULTS AND DISCUSSIONS

In order to evaluate which solution can be more suitable for the case study, a Hydraulic Source Harvesting Coefficient has been introduced, C_P, as the ratio between the total hydraulic power obtained by the PaT and the total hydraulic power available from the site (equation 3).

$$C_P = \frac{\sum P_{Hydr}^{obt.}}{\sum P_{Hydr}^{available}} \tag{3}$$

Tab. 1 compares all the three investigated cases in terms of C_P. Case #1 represents the best solution in terms of hydraulic energy harvesting because the two specific PaTs have been chosen in order to guarantee BEPs in different operating conditions, during the nightly and daily patterns. However, this solution can involve high costs in terms of the purchase of two different machines, three different PRVs and civil works. Case #2 shows a decrease of 3% of C_P in daily working condition. This is understandable because the intersection between the daily site characteristic and the characteristic in parallel is not at the BEP, as illustrated in the Case #1. Although this decrease of C_P, this solution is more suitable with respect the first case in terms of costs because it requires the purchase of two identical machines and PRVs. Finally, Case #3 shows a decrease of C_P in the night whereas a lower decrease in the day. Indeed, considering only one PaT, all the available energy in the night is no more exploitable because of the hydraulic regulation by means of the PRV. Despite of this reduction of C_P, this solution minimizes costs because it shows the simplest layout with one PaT, one PRV and the by-pass line.

ID Case	**C_p (Night)**	**C_p (Day)**
Case #1	0.7621	0.8987
Case #2	0.7621	0.8743
Case #3	0.6842	0.8644

Table 1: Comparison of the three proposed cases in terms of C_p

Fig. 13 shows respectively the effective produced power ($P_{eff} = \eta_{PaT} P_{Hydr}^{obt.}$) during the day and the night for each proposed case. The power required by the recharging point is a design constrain and it is equal to 3.7 kW (Balacco et al. 2018). Case #1 shows the highest power output during the day with the by-pass regulation because of the highest flow rate with a pressure drop as equal as to the other cases, whereas Case #3 shows the highest power output with the pressure regulation by PRV. Moreover, during the night, Case #1 and Case #2 show the same power output because in both cases the same PaT works (PaT #1), as showed in Fig. 13b. During all the night, these two solutions presents power output greater than 3.7 kW. Case #3, due to the head reduction with the PRV, shows a lower power output level than the Case #1 and Case #2 during the night. Moreover, some operating points are below the constrain of 3.7 kW and electric batteries could be used to store the surplus power obtained during all the other moments of the day. Although Case #3 does not show the maximum power output, it represents a good compromise in terms of power generation and cost installation.

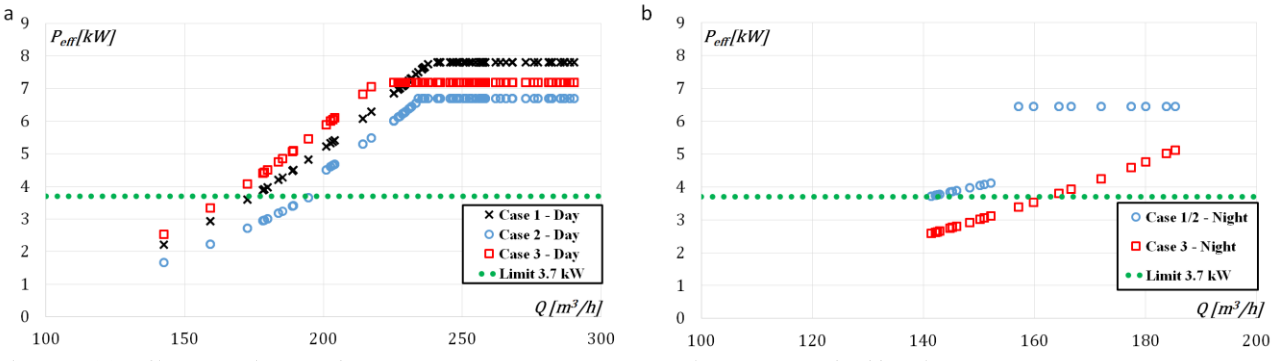

Figure 13: Comparison of the three proposed cases in terms of effective power output, P_{eff}, during the day (a) and the night (b); in green the power required by the electrical charging system

CONCLUSIONS

In this framework a preliminary assessment about the installation of a PaT in the Casamassima's water distribution network has been conducted. Starting from the analysis of the pressure and flow rate patterns during the day and the night, a KSB PaT has been selected and tested in both modes at the test rig of the Department of Mechanics, Mathematics and Management of the Polytechnic University of Bari. The experimental characteristic curves have been scaled in order to define three different pumps, geometrically similar to the Etanorm® 150-125-400. However, it could be possible to select the specific machine from the manufacturer catalogue of the KSB Etanorm® family, even if in this work they were not taken into account. Then, three installation cases have been evaluated and compared in terms of hydraulic energy harvesting and power output useful to supply an electrical charging station: Case #1) the installation of two different PaTs, each of them works alone during the day and the night; Case #2) the installation of two identical PaTs: the first works alone during the night and the second works in parallel to the first during the day; Case #3) the installation of only one PaT, which works during the day and the night. Although Case #1 and Case #2 are better than Case #3 in terms of hydraulic energy harvesting, Case #3 can be considered a practical solution to be implemented because it shows the simplest layout with one PaT, one PRV and the by-pass line. Also in terms of power output, Case #3 represents a good compromise in terms of power generation and cost installation. Obviously, further economic analysis has to be performed in order to have a more detailed assessment of the installation of a PaT in the real water distribution network of Casamassima.

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