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Cite as: AIP Conference Proceedings **2191**, 020142 (2019); https://doi.org/10.1063/1.5138875

Published Online: 17 December 2019

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Pump as Turbine for Throttling Energy Recovery in Water Distribution Networks

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Abstract. Nowadays, a great effort is increasingly put by the scientific community into a more sustainable energy management, which requires a higher harvesting of renewable energy sources with respect to conventional ones. In the framework of distributed electricity production, Pumps as Turbines (PaTs), i.e. pumps operated in reverse mode, are becoming more and more tempting, being very cost effective with respect to customized hydro turbines. For instance, Water Distribution Networks (WDNs) are equipped by pressure relief valves (PRVs) in order to regulate flow rates and to reduce leakages. The replacement of PRVs with PaTs could be a feasible practice to achieve both an effective pressure control and a throttling energy recovery. The preliminary identification of specific speed of a pump to be used as a turbine is fundamental in order to find the best suitable solution. However, the insertion of a PaT must consider the variability of water demand and pressure patterns. The 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. In this framework, the present work aims at proposing a methodology to find the more suitable PaT for a specific WDN, starting from the analysis of the pressure and flow rate patterns. The methodology is based on the selection of an existing machine from a pump catalogue. Then, knowing its geometrical information, it is possible to predict the characteristic curve of the pump operating as turbine by using a 1-D performance prediction model. The WDN of a town in the Apulia region (Southern Italy) has been used as a case study, in order to select a PaT useful for throttling energy recovery. Finally, a techno-economic evaluation has been carried out.

INTRODUCTION

In the current global energy scenario, the increasing energy demand represents a priority issue to be faced on social, economic, political and technical points of view. For this reason, after the 2015 United Nations Climate Change Conference (COP21) in Paris, the scientific community and the industry are continuously making a combined effort on a more sustainable energy management, focusing on a higher harvesting of renewable energy sources with respect to conventional ones. According to the latest report by the International Renewable Energy Agency (IRENA) [1], by 2050 electricity could become the central energy carrier, growing from a 20% share of final consumption to an almost 50% share.

The International Energy Agency's renewable energy outlook from 2018 to 2023 points out how the share of renewables in meeting global energy demand is expected to grow by one-fifth in the next five years to reach 12.4% in 2023. During this period, renewables are expected to meet more than 70% of global electricity generation growth, led by solar photovoltaic (PV) and followed by wind, hydropower, and bioenergy [2].

Among all, hydropower is a mature and cost-effective renewable energy technology, having reached the cutting edge of possible energy exploitation in the field of large hydropower. For this reason, it plays an important role in today's electricity mix, contributing to 85% of global renewable electricity. Furthermore, it helps to stabilize

74th ATI National Congress
AIP Conf. Proc. 2191, 020142-1–020142-10; https://doi.org/10.1063/1.5138875
Published by AIP Publishing. 978-0-7354-1938-4/$30.00

fluctuations between demand and supply. This role will become even more important in the next decades, as the shares of variable renewable electricity sources – primarily wind power and solar photovoltaic (PV) – will increase considerably. The future of hydroelectricity seems to consist mainly in the realization of the so-called small hydro plants (SHP), that imply a cost-effective technical commitment, having a very low impact on the environment.

According to the latest World Small Hydropower Development Report by the United Nations [3], the globally installed SHP capacity is estimated at 78 GW in 2016, an increase of approximately 4% compared with data from 2013. SHP represents approximately 1.9% of the world's total power capacity, 7% of the total renewable energy capacity. Europe has the highest SHP development rate, with nearly 48% of the overall potential already installed.

Water Distribution Networks (WDN) are becoming an interesting application area for mini hydro plants with the installation of Pumps as Turbines (PaTs), which represent a cost-effective alternative to conventional turbines for the recovery of throttling energy. Indeed, WDN are equipped with pressure relief valves (PRVs) in order to regulate flow rates and to control the pressure into the network. The replacement of PRVs with PaTs in WDN can be a feasible practice to achieve both an effective pressure control and a green energy recovery. Applying the concept of "*think globally, act locally*", these mini and small hydro power plants could help to create smart grids, or improve the existing ones, for the future electric energy demand.

Economic analyses performed on the existing WDNs highlighted the convenience of a PaT instead of a conventional turbine for this kind of application. A PaT installation usually shows a payback period of about 2–3 years compared with a conventional turbine, although PaT hydraulic efficiency is usually reported as being lower. A solution based on a PaT 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. Kramer et al. [4] proposed a new cost classification scheme in order to enable a systematic and generally valid estimation of investment costs of energy recovery plants. Moreover, PaTs are used not only in the hydraulic fields, but also in the process engineering, as described by Stefanizzi et al. [5] and Renzi et al. [6].

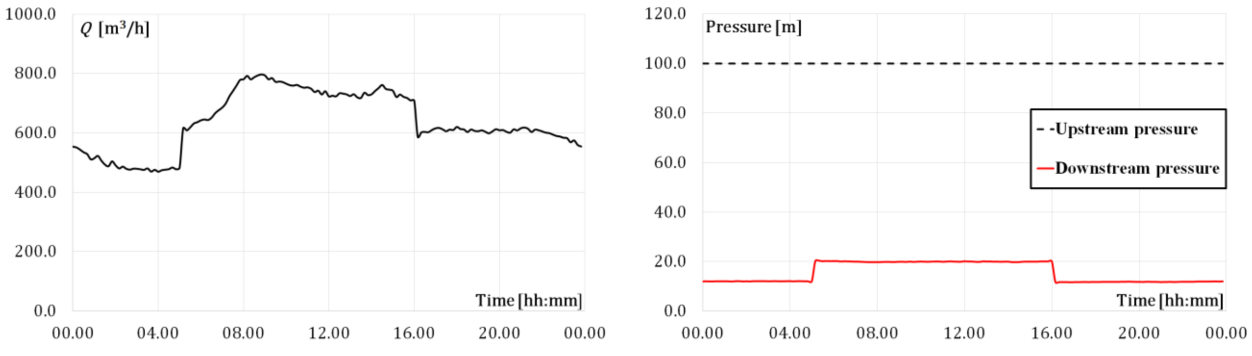
In the technical literature, several works have been focused on real case studies in order to evaluate the effectiveness of PaT installations. Muhammetoglu et al. [7] studied a full-scale PaT application into a WDN in Turkey for energy production and pressure reduction; both Rossi et al. [8] and Alberizzi et al [9] performed an evaluation of the potential of PaT installations for the WDN of different towns in the Northern Italy; Balacco et al. [10] considered to replace an existing PRV with a PaT in the WDN of Casamassima (Italy) to supply a charging station for electric vehicles; Stefanizzi et al. [11] performed a preliminary assessment of a PaT in the same WDN of Casamassima by using experimental characteristic curves of a PaT and evaluating different installation layouts. Finally, Morabito et al. [12] used a PaT for micro Pumped Hydro Energy Storage, integrated in a smart grid. Moreover, in the last year a novel impeller for double suction pumps has been proposed in order to reduce the slip phenomenon and to increase the efficiency [13]. This kind of impeller has been investigated in reverse mode pointing out higher efficiency in a wide range of flow rates compared to a conventional geometry [14].

The insertion of a PaT in a WDN must consider the variability of water demand and pressure patterns, which 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. Moreover, it is difficult to know *a priori* how the PaT could work in the WDN without having its performance curves in reverse mode. Indeed, pump manufactures do not provide experimental curves of their machines running in reverse mode. For this reason, a great effort has been made by the scientific community in order to develop model to predict the performance of a pump used in reverse mode: Barbarelli et al. [15] proposed an empirical procedure starting from the specific speed requested by the site, Stefanizzi et al. [16] 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, $n_{q,P}$. Capurso et al. [17-18] proposed a slip factor correction in a 1-D performance prediction model for PaTs. Venturini et al [19] presented a physics-based model to predict PaT performance curve over the entire range with an optimization procedure to identify model parameters instead of detailed geometrical data.

In this framework, the present work aims at proposing a methodology to find the more suitable PaT for a specific WDN, starting from the analysis of the pressure and flow rate patterns. Indeed, starting from these data, it is possible to evaluate the specific speed range required by the site, in order to understand if the operating field is appropriate for PaTs instead of conventional turbines. The methodology is based on the evaluation of the specific speed of the PaT, hence the specific speed of the pump by means of empirical correlations and its selection from manufacturer's catalogues. Then, based on the geometrical information of the pump, a 1-D performance prediction model is applied in order to predict the characteristic curve of the pump operating as turbine. The WDN of a town in the Apulia region (Southern Italy) has been used as case study, in order to select a PaT useful for throttling energy recovery. Finally, a techno-economic evaluation has been carried out.

PUMP SELECTION METHODOLOGY

The preliminary identification of a pump to be used as a turbine is fundamental in order to find the best suitable solution. However, the insertion of a PaT must consider the variability of water demand and pressure patterns. The hydraulic variability in a WDN 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. The interest in PaTs is related to the fact that in WDNs flow rates range from 10 up to 1800 m^3/h and head from 10 up to 100 m, that conventional turbines can difficulty cover. Generally, an urban WDN is characterized by two different conditions (one during the night and another during the day) with different available heads, as depicted in figure 1. Usually, thanks to installation of a PRV the backpressure remains almost constant, as the user demand during the day must be guaranteed, 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 of a PaT, it is possible to adopt different regulation methods: hydraulic regulation with a PRV, electrical regulation by means of a rotational speed control system or both modes [20].



(a) (b)

FIGURE 1. Flow rate measured for the WDN of the case study (a); pressure patterns measured upstream and downstream the PRV (b).

The proposed methodology for the selection of a PaT in a WDN is summarized in the flow chart of figure 2. The first step regards the identification of the machine requirements in terms of flow rate and head for each specific site (Q_{site} and H_{site}), which have to be guaranteed as Best Efficiency Point (BEP) in turbine mode, i.e $Q_{BEP,T}$ and $H_{BEP,T}$. The selection of the operating conditions depends on different aspects, such as the flow rate frequency distributions and the available hydraulic power exploitable. At this point, the PaT specific speed, $n_{q,T}$, can be evaluated. In order to select the proper pump, it is necessary to predict the BEP that the PaT should guarantee in pump mode ($Q_{BEP,P}$ and $H_{BEP,P}$) by applying for instance the empirical model proposed by Stefanizzi et al. [16].

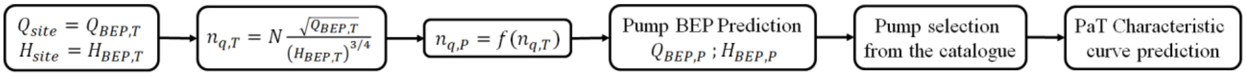
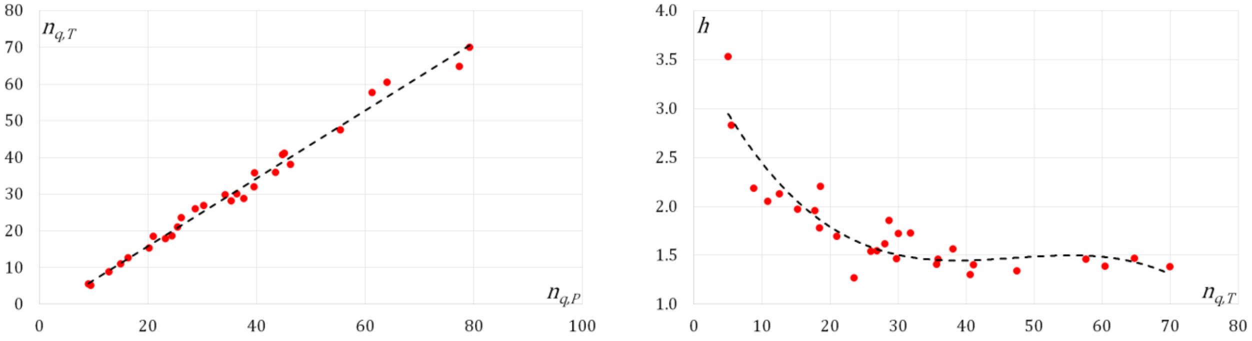


FIGURE 2. Flow chart for the pump selection and PaT characteristic prediction.

As depicted in figure 3, the model is based on empirical correlations which basically correlate the BEP in turbine mode to the BEP in pump mode. Indeed, knowing $n_{q,T}$ it is possible to evaluate $n_{q,P}$ by applying equation 1, which reports the empirical correlation of figure 3a:

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

Afterwards the head ratio $h = H_{BEP,T}/H_{BEP,P}$, hence $H_{BEP,P}$ can be evaluated from figure 3b. Then, the flow rate can be computed by means the definition of specific speed: $Q_{BEP,P} = \left(n_{q,P}\, H_{BEP,P}^{3/4}/N\right)^2$.



(a) (b)

FIGURE 3. Specific speed number in turbine mode, $n_{q,T}$, vs. specific speed number in pump mode, $n_{q,P}$ (a); head ratio, h, vs. $n_{q,T}$ (b).

Knowing $n_{q,P}$, $Q_{BEP,P}$ and $H_{BEP,P}$, any pump manufacturer could select the machine from own pump catalogue. At this point, having no experimental characteristic curves of the selected pump in reverse mode, it could be possible to predict the characteristic curve of the PaT by using a 1-D performance prediction model. Indeed, this model has been proposed in a previous work [21] for manufacturers in order to predict the entire characteristic of a PaT, by considering detailed geometrical information of the machine (in possession of only manufacturers) and complex phenomena like hydraulic losses. As stated in equation 2, thanks to the knowledge of detailed geometrical data, flow rate, Q, and rotational speed, N, it is possible to accurately calculate the correct velocity triangles and the theoretical head, H_{th}, in reverse mode operation. Afterwards, volute and runner losses are modelled to finally predict the real PaT head, $H_{turbine}$.

$$H_{turbine} = H_{th} + Z_{volute} + Z_{runner} \qquad (2)$$

CASE STUDY

The WDN of a town in the Apulia region (Southern Italy) has been used as case study, in order to select a PaT useful for throttling energy recovery. The town counts approximately 48,000 inhabitants and it is supplied by a unique tank. A PRV is installed at the entrance of the town with the aim to guarantee the necessary daily water demand and to reduce nightly leakages. Figure 1 reports the flow rate values and pressure pattern measured downstream the tank and downstream the PRV in a typical day registered every 10 min. Evident is the double pressure pattern. Indeed, during the night (16:10 – 5:00) the site is characterized by an available pressure drop H_{night} = 90 m , whereas during the daytime (5:10 – 16:00) the available pressure drop is lower, H_{day} = 80 m. In this proposal, the PaT is supposed to be installed in parallel to the existing PRV, as depicted in figure 4. In order to allow the hydraulic regulation, another PRV is installed in series to the PaT.

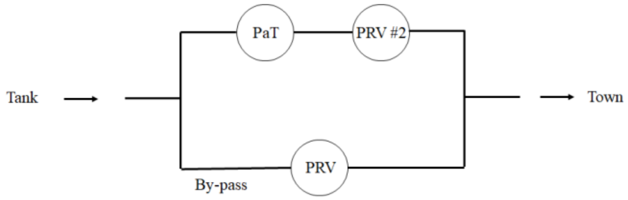


FIGURE 4. Installation scheme of the PaT system.

Following the previously described procedure, the first step of the work regards the pump selection. Since there are two different flow conditions (one during the night and another during the daytime) with different available heads, the PaT specific speed, $n_{q,T}$, must be evaluated in both configurations. Considering the rotational speed $N = 1450$ rpm, $n_{q,T}(Q_{min})$ = 17.91 and $n_{q,T}(Q_{max})$ = 25.5, hence, according to equation 1, the pump specific speed should range in between $n_{q,P}(Q_{min})$ = 22.3 and $n_{q,P}(Q_{max})$ = 30.5. This means that the pump specific speeds are within the conventional range of applicability of centrifugal pumps, in particular mixed flow centrifugal pumps. In order to define a unique specific speed, it has been decided to select the pump based on the daytime head and the average daytime flow rate ($Q_{site} = \bar{Q}$ = 636.5 m^3/h and H_{site} = 80 m). Usually in these kind of applications with a single PaT, the selection of flow rates greater than $\bar{Q}$ involves on one side greater available energy to be harvested, but on the other side the PaT will work with lower efficiency than its BEP for a wide range of flow rates in off-design condition (especially in the night for flow rates lower than the operating point). This causes higher pressure drop, hence a considerable amount of energy dissipated by the hydraulic regulation system with a PRV installed in series to the PaT.

Then, it is possible to evaluate the BEP of the corresponding pump ($Q_{BEP,P}$ and $H_{BEP,P}$) by means of a BEP prediction model, which correlates the BEP in pump mode to the BEP in turbine mode. As result, $Q_{BEP,P}$ = 429.1 m^3/h and $H_{BEP,P}$ = 47.8 m. At this point, knowing $Q_{BEP,P}$ and $H_{BEP,P}$, any pump manufacturer could select the proper machine from own pump catalogue. In this study, thanks to the collaboration with Xylem®, it has been possible to use their pump catalogue in order to have available geometric information of the selected machine. In this study, the calculation led to find the Xylem® NSC 150-400/900, as depicted in figure 5.

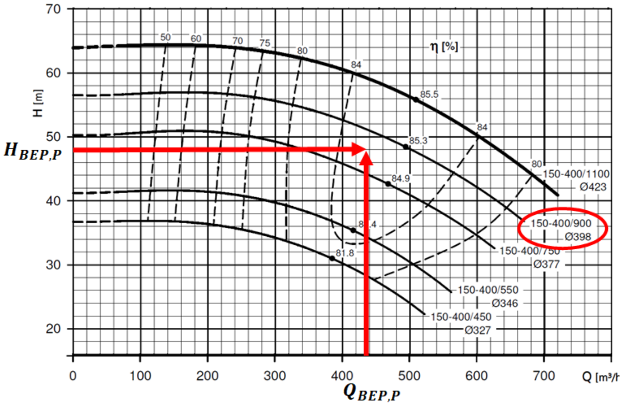
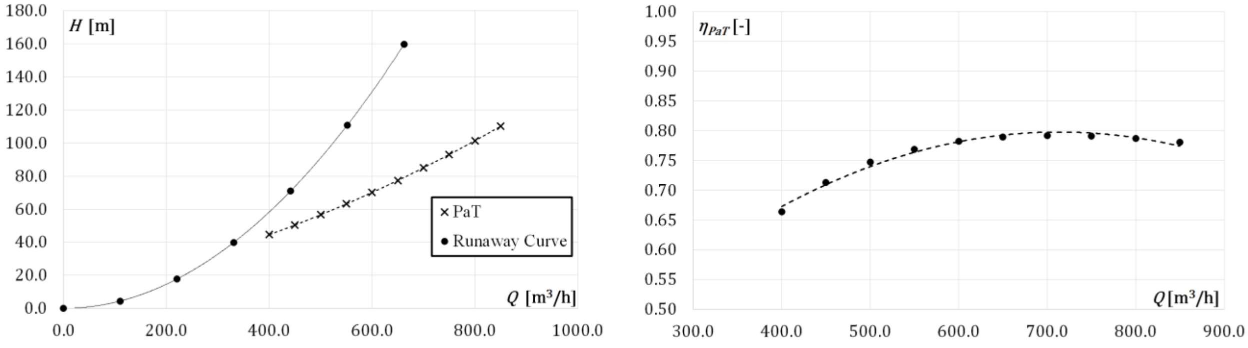


FIGURE 5. Pump selection from the pump selection chart.

Then, knowing its geometrical information, it is possible to predict the characteristic curve of the pump operating as turbine by using the 1-D performance prediction model. Figures 6a and 6b show respectively the predicted characteristic curve of the PaT in terms of head and efficiency. In figure 6a it is also reported the runaway curve, which has been predicted by using correlations proposed by Gülich [22].

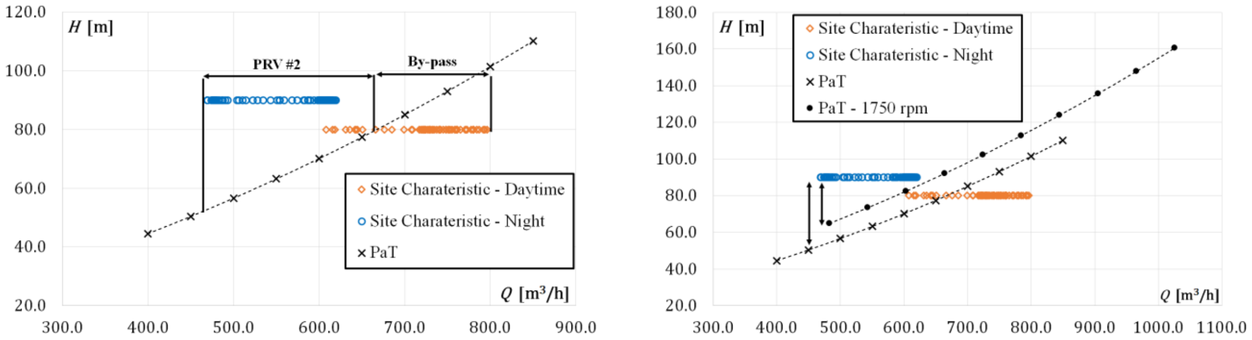


(a)

(b)

FIGURE 6. Predicted characteristic curve of PaT with the runaway curve (a); PaT efficiency curve vs. flow rate (b).

Then, two installation cases have been evaluated and compared in terms of hydraulic energy harvesting and power output: Case #1 is characterized only by a hydraulic regulation system with a PRV installed in series to the PaT and a by-pass line; Case #2 considers also an electrical rotational speed regulation in order to reduce the pressure drop during the night. Figure 7a shows the predicted performance curve and the site characteristics with hydraulic regulation methods (Case #1). A by-pass line is used when the flow rate exceeds the operating point. This solution allows the turbine to work always at its BEP condition. Otherwise, for flow rates lower than the mean value, the PRV #2 is used to regulate the head. Moreover, 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 1450 rpm to 1750 rpm), as depicted in figure 7b (Case #2). In this case, the turbine works with lower efficiency than its BEP, but a considerable amount of energy, otherwise dissipated by PRV, is recovered, as it will be shown in the next section.



(a) (b)

FIGURE 7. Case #1: site characteristic curves with the characteristic curve of PaT at constant rotation speed with hydraulic regulation methods (a); Case #2: site characteristic curves with the characteristic curves of PaT at different rotation speed (b).

ENERGY PRODUCTION

Table 1 summarizes the daily available energy that could be theoretically exploited, equal to 3520.3 kWh/day. This information can be useful to evaluate the amount of energy that the PaT system can harvest. For this reason, a Hydraulic Source Harvesting Coefficient has been introduced, C_E, as the ratio between the total hydraulic energy produced by the PaT and the total hydraulic energy available from the site (equation 3).

$$C_E = \frac{E_{produced}}{E_{available}} \tag{3}$$

Table 2 compares the two cases in terms of C_E. During the night, Case #1 shows a decrease of 10% of C_E with respect to Case #2, which is characterized by the rotational speed regulation. This decrease is understandable because considering only one PaT, all the available energy in the night is no more exploitable because of the hydraulic regulation by means of only the PRV. During the daytime both cases show the same value of C_E because of the same by-pass regulation. However, since during the night Case #2 performs better, the overall increase of the total energy production of Case #2 with respect to Case #1 is equal to 7% (from 2241.2 kWh/day to 2414.1 kWh/day).

TABLE 1. Daily Available Energy.

Night [kWh/day]	Daytime [kWh/day]	Total [kWh/day]
1778.3	1742.0	3520.3

TABLE 2. Comparison of the two proposed cases in terms of C_E.

ID CASE	C_E (Night)	C_E (Daytime)	$C_{E,TOT}$ (Entire day)	Energy Production [kWh/day]
CASE #1	0.56	0.72	0.64	2241.2
CASE #2	0.66	0.72	0.69	2414.1

Figure 8 shows respectively the effective produced power ($P_{eff} = \eta_{PaT}\,\rho g H Q$) during the entire day for both cases. The rotational speed regulation allows to obtain a higher power output than the case with only the hydraulic regulation. Indeed, during the day it could be possible to obtain on overall increase of the power output equal to 17%. However, it can be observed how Case #2 permits only a margined energy production which does not justify the cost of a frequency converter and for this reason this second case has been neglected in the following.

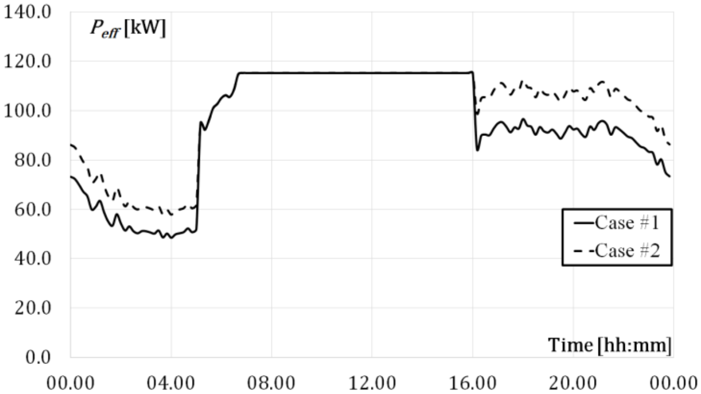


FIGURE 8. Comparison of the two proposed cases in terms of effective power output, P_{eff}.

ECONOMIC ANALYSIS

Generally, reliable information about costs and benefits of a particular renewable energy technology are an essential phase for the assessment of which renewable energy technology is the most appropriate for a particular circumstance [23]. Considering a WDN application, a micro-hydro o rarely a mini-hydro plant is an obvious choice if the final goal is the recovery of throttling valve waste energy. Despite promising development in terms of scientific research, currently installation plants of PaT into real WDNs are a few, since the initial distrust of water management authorities, that prefer installations of PRVs to reduce and control water pressure into the system, and the economic return of this type of installation.

However, a correct approach to this problem must take into account the incontrovertible environmental benefit that follows by converting pressure in excess into a WDN rather than waste it, but above all considering that even if the consequent economic benefit could be modest, it is available energy otherwise lost.

Economic analysis of a PaT installation plant can be conducted adopting several methods and evaluating several parameters. Usually, an economic analysis is achieved comparing costs and revenues for the lifetime of the hydraulic machine at least, otherwise it is necessary to take into account reinvestments for the refurbishment of mechanical and electrical equipment.

In this study the cost analysis has been conducted for a useful life of the project estimated in 15 years and equal to the mechanical and electrical equipment lifetime. Costs were subdivided into capital costs, that sum all the equipment costs necessary to realize the plant, and annual cost, due to the little maintenance and operational costs of every devices and civil works, estimated respectively equal to 0.5% and to 2.5% of the capital costs [23] (table 3). In details the hydraulic equipment consists in the by-pass, valves and pipes, whereas the electrical equipment consists in the measurement devices with their SCADA connections. Repositioning costs related to the substitution of the equipment were considered equal to zero since the defined economic life of the system.

A cost-benefit analysis was conducted using both the statistical method, evaluating the definition of Payback Period (PP) and Return of Investment (ROI), and the dynamic approach, thanks to Net Present Value (NPV) and Internal Rate of Return (IRR). The latter, unlike the former, take into account the total costs and benefits for the entire useful life of the equipment and the moment when the cash inflows occur.

Annual energy production by the PaT system was estimated at 818,028 kWh/year and the annual revenue for this produced energy was computed as 127,612 €/year, considering a complete feed-in of the produced electricity and a reference sales price fixed by the Italian Energy Manager (GSE) in 2019. Italian Regulatory Authority for Energy, Networks and Environment (ARERA) has indicated GSE like the unique authority to whom the energy producers turn to stipulate the agreement that regulates the commercial withdrawal of the electricity fed into the network. Actually, GSE is the responsible of the minimum guaranteed sales price for energy produced by small power generating systems with renewable energy plants with the aim to encourage energy production from renewable sources.

Economic analysis results, summarized by Table 4, are rather encouraging even considering only the economic benefit due to the produced energy revenue. Based on the capital costs and the economic revenues, the Payback Period was estimated of about 24 months and the amount of return on the investment respect to the investment cost (ROI) is equal to 49 %. The Benefit/Cost Ratio (B/C), that compares actual values of benefit and costs amounts to 4.50 in this case, while Net Present Value (NPV), defined as the sum of the actual values of all the costs and revenues associated to the project, amounts to 876,797 €. Finally, the Internal Rate of Return (IRR), the discount rate that makes the NPV of all cash flows from a particular project equal to zero, is equal to 19.29%.

TABLE 3. Costs for the PaT plant.

Items	Cost (€)
PaT	13,000 €
Hydraulic equipment	181,760 €
Electrical equipment	22,800 €
Civil works	30,000 €
Total cost	*262,895 €*

TABLE 4. Economic analysis results.

Economic indicators	Value considering only electrical economic revenues	Value considering environmental benefits
Payback Period	1.93 years	0.19 years
ROI	49%	525%
B/C	4.50	52
NPV	876,797 €	12,753,498 €
IRR	19.29%	150%

However, a comprehensive cost-benefit analysis must also include the estimation of environmental benefits and consequently revenues derived from the use of a PaT into a WDN. Mainly, the use of a PaT into a WDN, converting pressure in excess into electric energy, is very close to a PRV installation. The WDN analysed is very old and pipes are largely corrupted, for this reason water management authority has installed recently a PRV on the main pipe and after this water leakages have been drastically reduced with a consequent water savings volume of about 1.57 Mm^3/year and a full-recovery cost of water of about 1,261,440 €/year. Moreover, a similar power generating system with renewable energy involves a carbon dioxide (CO_2) reduction [24]; the evaluation of the total reduction in CO_2 emissions due to green energy production has been estimated in 327.211.044 gCO_2/year, considering an emission factor of 400 g/kWh obtained by Italian national data for the last ten years [25].

TABLE 5. Environmental benefits and revenues of the PaT system.

Item	Environmental benefits	Revenues (€)
Annual energy production by the PaT system (kWh/year)	818.028	127.612 €
Reduction of CO_2 emissions from energy saving (g CO_2/year)	327.211.044	71.986 €
Water saving due to pressure reduction by the PaT system (m^3/year)	1.576.800	1.261.440 €

Results of this second scenario are summarized in the same Table 5. Clearly, significant economic revenues due to the water saving can be observed and in this case the Payback Period was estimated of about 2.5 months, a very short time compared with the first scenario and with classical turbine application. ROI amounts to 553% and B/C results equal to 55. While NPV amounts to 13,430,548 € and, finally, IRR for this study is equal to 150%.

For the sake of clarity and comparing results obtained by the economic analysis for the two scenarios, it is obvious that a correct and complete costs analysis must take into account also the environmental benefits because the first goal of a renewable energy plant is indeed that of preserving the environment and producing energy from renewable and available sources such as the actual pressure in a WDN.

CONCLUSIONS

In this work a methodology to select a PaT for a specific WDN has been proposed. The WDN of a town in the Apulia region (Southern Italy) has been used as case study, in order to select a PaT useful for throttling energy recovery. In this proposal, the PaT is supposed to be installed downstream the tank and in parallel to the existing PRV at the entrance of the town. Starting from the analysis of the pressure and flow rate patterns, it is possible to evaluate the specific speed range required by the site, in order to understand if the operating field is appropriate for PaTs instead of conventional turbines. The methodology is based on the selection of an existing machine from a pump catalogue. Then, knowing its geometrical information, it is possible to predict the characteristic curves of the pump operating as turbine by using a 1-D performance prediction model.

For this application, the main value of the flow rates supplied during the day has been chosen as working condition. This value of flow rate and its corresponding head value have been selected as the turbine BEP operating condition. Afterwards, it is possible to evaluate the BEP of the corresponding pump ($Q_{BEP,P}$ and $H_{BEP,P}$) by means of a BEP prediction model, which correlates the BEP in pump mode to the BEP in turbine mode. At this point, knowing $Q_{BEP,P}$ and $H_{BEP,P}$, it is possible to select the proper machine from pump catalogues. In this study the Xylem® Catalogue has been considered and the calculation led to find the Xylem® NSC 150-400/900. Then, knowing its geometrical information, it is possible to predict the characteristic curve of the pump operating as turbine by using the 1-D performance prediction model.

Then, two installation cases have been evaluated and compared in terms of hydraulic energy harvesting and power output: Case #1 is characterized only by a hydraulic regulation system with a PRV installed in series to the PaT and a by-pass line; Case #2 considers also an electrical rotational speed regulation in order to reduce the pressure drop during the night. Case #2 permits marginal energy production increase (7%) and for this reason this second case has been finally neglected.

Finally, an economic analysis has been carried out in order to assess the cost-effectiveness of this application. Annual energy production by the PaT system has been estimated at 818,028 kWh/year and the annual revenue for this produced energy is equal to 127,612 €/year, considering a complete feed-in of the produced electricity. The analysis has showed results in terms of Payback Period of about 24 months and the ROI is equal to 49 %. The Benefit/Cost Ratio amounts to 4.50 in this case, while Net Present Value (NPV) amounts to 876,797 €. Finally, the Internal Rate of Return (IRR)is equal to 19.29%. Actually, all these results are based only on the capital costs and the economic revenues. Indeed, the same results become better if the estimation of environmental benefits, like the reduction of CO_2 emissions and the water saving, can be observed. In this case the Payback Period has been estimated of about 2.5 months, a very short time compared with the first scenario and with classical turbine application.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support received for this research from Xylem and Saint-micheGobain.

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