



PaT-ID: A tool for the selection of the optimal pump as turbine for a water distribution network

Gabriella Balacco^{a,*}, Gaetano Daniele Fiorese^b, Maria Rosaria Alfio^a, Vincenzo Totaro^a, Mario Binetti^a, Marco Torresi^c, Michele Stefanizzi^c

^a Department of Civil, Environmental, Land, Construction and Chemistry (DICATECh), Polytechnic University of Bari, Via Re David 200, 70125, Bari, Italy

^b Department of Agricultural and Environmental Sciences, University of Bari Aldo Moro, Bari, Italy

^c Department of Mechanics, Mathematics and Management (DMMM), Polytechnic University of Bari, Via Re David 200, 70125, Bari, Italy

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ABSTRACT

In a historical context where renewable energy is increasingly being adopted, the installation of Pumps as Turbines (PaTs) in Water Distribution Networks (WDNs) is gaining relevance in the scientific community. The selection of a PaT to be installed in a WDN is complex, requiring a trade-off between technical and economic aspects. This paper presents a methodology for guiding the selection of a PaT based on the characteristics of the WDN, predicting its characteristic curves, and estimating the daily power generation. The proposed algorithm has been automated in a computer tool called PaT-ID. The innovative aspects of this tool concern its general applicability to any WDN and machine catalogue. It automatically selects the most useful machine considering the input water demand trend and the hydraulic head available for the PaT. In addition, the tool decides on series or parallel layouts if necessary. Finally, in the absence of hydraulic input data, PaT-ID provides a first-level analysis to define the potential of the site for energy production, simulating the flow rate data. The code has been validated with two case studies analysed in previous works.

1. Introduction

In the recent decades, the production of electric power energy through hydropower plants has changed drastically. The construction of new large-scale hydropower plants is practically lacking due to environmental consequences, already exploited water resources and high construction and maintenance costs. Moreover, the share of hydropower in electricity production is decreasing because of climate change and the overall ageing of the plants [1].

Consequently, public attention is addressed to using small-scale hydropower plants [2]. High installation and maintenance costs prevented the development of micro-hydroelectric in the past. However, the possibility of using Pumps as Turbines (PaTs) marked a turning point in this field [3]. Despite these machines show a lower efficiency compared to a conventional turbine, using PaTs in a micro-hydroelectric system is an optimal economic solution [4–7]. Shojaeefard et al. [8] argued that with the installation of PaTs, plant construction and maintenance costs could be cut down. From an environmental point of view, the installation of PaTs makes it possible to recover energy from a part of the hydropower

sector that is not of interest to large hydropower plants. Despite their economic and environmental advantages, pump manufacturers have not yet dedicated commercial catalogues to PaTs.

1.1. State of the art discussion

Installing PaTs in Water Distribution Networks (WDNs) is becoming almost prominent in the scientific community. Indeed, many applications have recently been explored [9–11]. This solution replaces Pressure Reducing Valves (PRVs) with pumps that work in reverse mode. A PaT in a WDN produces energy while regulating pressure simultaneously, such as a PRV [12]. The economic and environmental benefits of using a PaT in a WDN are significant in terms of reduction of CO₂ emissions and water losses at the same time [13].

Actually, the selection of a PaT for a WDN requires a trade-off between technical and economic aspects. Therefore, the choice of a PaT is complex, and for this reason, the research community is currently working on this aspect. Indeed, different research groups focused their work on selecting the proper machine by applying different approaches. For instance, Kandi et al. [14,15] developed a PaT selection

* Corresponding author.

E-mail addresses: gabriella.balacco@poliba.it (G. Balacco), gaetano.fiorese@uniba.it (G.D. Fiorese), mariarosaria.alfio@poliba.it (M.R. Alfio), vincenzo.totaro@poliba.it (V. Totaro), mario.binetti@poliba.it (M. Binetti), marco.torresi@poliba.it (M. Torresi), michele.stefanizzi@poliba.it (M. Stefanizzi).

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Nomenclature	
Symbols	
H_{site}	Average hydraulic head of the reference city [m]
Q_{site}	Average flow rate of the reference city [m ³ /h]
Q_{BEP}	Flow rate of the pump at BEP [m ³ /h]
H_{BEP}	Head of the pump at BEP [m]
η_{BEP}	Efficiency of the pump at BEP [–]
P_{BEP}	Power of the pump at BEP [kW]
$H_{BEP,P}$	Head of the PaT at BEP under pump mode operation [m]
$Q_{BEP,P}$	Flow rate of the PaT at BEP under pump mode operation [m ³ /h]
$H_{BEP,T}$	Head of the PaT at BEP under turbine mode operation [m]
$Q_{BEP,T}$	Flow rate of the PaT at BEP under turbine mode operation [m ³ /h]
$\eta_{BEP,P}$	Efficiency of the PaT at BEP under pump mode operation [–]
$\eta_{BEP,T}$	Efficiency of the PaT at BEP under turbine mode operation [–]
$P_{BEP,T}$	Power in turbine mode at the BEP [kW]
H_T	Hydraulic head of the PaT at time t [m]
Q_T	Flow rate of the PaT at time t [m ³ /h]
P_T	Power generated by PaT at time t [kW]
η_T	Efficiency of the PaT under turbine mode operation at time t [–]
H_{MAX}	Maximum hydraulic head of the catalogue [m]
H_{MIN}	Minimum hydraulic head of the catalogue [m]
Q_{MAX}	Maximum flow rate of the catalogue [m ³ /h]
Q_{MIN}	Minimum flow rate of the catalogue [m ³ /h]
n_T	Rotational speed of the turbine [rpm]
n_P	Rotational speed of the pump [rpm]
$N_{s,T}$	Specific speed of the PaT under turbine mode operation [–]
$N_{s,P}$	Specific speed of the PaT under pump mode operation [–]
h	Head factor [–]
n	Number of pumps [–]
ρ	Density [kg/m ³]
g	Gravity acceleration [m/s ²]
Acronyms	
PaT	Pump as Turbine
BEP	Best Efficiency Point
WDN	Water Distribution Network
PRV	Pressure Reduction Valve

methodology which is based on a genetic algorithm with an objective function which takes into account energy production and two off-design parameters. This method employs the Derakhshan's model developed in 2008 [16] and it is based on four tested PaTs. Moreover, no commercially available machines are considered for the selection. Novara et al. [17] recently proposed a multi-objective software for the PaT selection tool and applied it to install a PaT in a rural WDN in Ireland. Knowing the flow rate and pressure patterns, their approach starts by dividing the Q - H map in discrete points (each of them corresponding to an ideal Best Efficiency Point - BEP). Then, all these BEPs are used as inputs for the Barbarelli's model [18] to calculate the head curve of the machine and to compute the energetic analysis. Despite the proposed methodology currently contemplates only fixed speed operations, it is one of the latest works which reached the installation of a PaT, showing a maximum error of 8% between the predicted pressure drop and the one measured in the field. Mitrovic et al. [19,20] proposed an optimisation-based methodology for selecting PaTs to evaluate different objective functions. Regarding the data set, the work considers 38 real PRVs and the catalogue of a pump manufacturer. Finally, the BEP of each PaT is predicted by means of Yang's model [21].

Morani et al. [22] developed a mixed integer non-linear model to find the best PaT that guarantees the maximum energy output and water savings. Marini et al. [23] proposed a methodology for optimal PaT selection by considering energy production and economic sustainability with both hydraulic and electrical regulation of the machine. They proposed a non-dimensional factor for energy production which assumes a constant value of the PaT efficiency equal to the value corresponding to the BEP instead of considering the η vs. Q curve for the off-design working conditions. Le Marre et al. [24] developed a methodology for water management companies to select the most suitable PaT for a specific WDN by considering both energetic and economics parameters (i.e., the annual energy production and payback period). Their work is based on a database of about 700 pumps, whose performance curves in turbine mode are predicted by means of the Yang's model [21] (for the BEP) and Perez-Sanchez's approach [25] (for the head curves). In addition, the optimal point is found by calculating the maximum annual energy production with the average head value instead of considering its variability. Then, thanks to this optimal operating point, all the PaTs with a BEP within an arbitrary 30% are evaluated. Pugliese et al. [26] developed an operative framework for the

selection of the optimal PaT with the aim to maximise the daily energy production and consider at the same time economic indicators. However, this procedure is applied to a simplified WDN characterised by a daily water demand but three different pressure levels showing no difference between day-time and night patterns. Another approach was presented by Sandoval et al. [27] for selecting a PaT for a specific case, i.e., to recover energy for street lighting and charging stations for e-bikes. The analysis is carried out with a complex objective function, and the net energy production is computed by evaluating the minimum value for the PaT efficiency found in the literature to assess the worst scenario.

Despite the considerable number of methodologies for the PaT selection, no algorithm is more widely used than others; moreover, due to the complexity of many algorithms, it is preferred to use simple selection methods such as the average site flow rate even in high energy availability application as done by Souza et al. [9]. These approaches do not consider an aspect related to the limit curves of the PaT, i.e., the runaway and the blocked rotor curves. Indeed, these curves should be addressed in the selection algorithms, although they are very important since they identify the operating range of the machines, which has to match the operating condition of the installation site. Moreover, there are few and not very robust empirical correlations to predict these two curves [25,28]. For instance, Stefanizzi et al. [29] proposed a new strategy for selecting the operating point by applying a numerical approach to the real data of a WDN and the experimental curves of the PaT. The advantage of this methodology consists in the simplicity of the approach, which is based on the statistical evaluation of both the flow rate and pressure patterns combined with aspects related to the turbo-machines that are not considered in the literature, such as the site selection according to the water management authority needs, operating limits of the PaT imposed by the blocked and runaway curves and the power generation limit of the coupled generator.

Additionally, when PRV installed in series to the PaT is used for off-design hydraulic regulation, some working conditions could be very close to the runaway curve, as explained in Ref. [30]. These conditions should be avoided because they can involve flow separations vibrations, performance losses and local cavitation issues [31,32].

Moreover, the choice of the most suitable installation site for the machine if on the one hand can maximise the energy recovery or minimise costs, on the other hand, it cannot always be a feasible solution for the water management authority, which tends to make the least

number of changes to the network. For instance, the installation site that guarantees maximum power production is not always close to an electric cabin for the grid connection. Thus, in this case, the connection should be created with a considerable increase in capital costs.

Finally, despite all these methodologies showing promising results, their application requires knowledge of the PaT mechanical features and huge computational efforts that complicate the pump selection to be used in reverse mode. In this regard, automatic tools for PaT selection would help designers and technicians and encourage the use of these devices. However, this topic is poorly investigated.

1.2. Research goals

In this framework, with the aim to facilitate the selection process of a PaT, this study provides a tool for selecting a PaT based on WDN characteristics (i.e., water demand pattern and hydraulic head). The novel aspects of this tool regard its general applicability to any WDN and machine catalogues, and the possibility of simulating the water demand pattern in case of unavailable flow rate data of the installation site.

The PaT selection procedure was automated using the open-source software R-studio in a tool called PaT-ID. The input parameters are the hydraulic head available for the PaT and the water demand pattern of the reference site. A methodology for estimating the hourly flow rate of the reference site was also implemented in PaT-ID, in the case of a first

rapid analysis. However, it is necessary to know at least the excess hydraulic load.

A brief description of the paragraphs of this research is reported in the following. In section 2, the work describes the proposed methodology for selecting a PaT, starting from a real water demand pattern or its simulation and the estimation of the daily energy production. Afterwards, the WDNs of two towns in the Apulia region (Southern Italy) are described as case studies to test the PaT-ID algorithm (section 3). Section 4 compares pump selection and daily energy production results with those of previous works. Finally, section 5 discusses the main findings, and section 6 outlines the main conclusions of this study.

2. Materials and methods

Due to water demand fluctuations, a PaT should work with a time-varying flow rate and hydraulic head. Therefore, selecting a PaT for a WDN should refer to an operational range rather than a single operating point. This variable operating condition results in a fluctuating hydro-power potential. PaT-ID can assist the technicians involved in these activities on behalf of water utilities to evaluate the convenience of introducing a PaT in a WDN. The flowchart in Fig. 1 summarises the automatic procedure to select the most suitable centrifugal pump to adopt as turbine.

As shown in Fig. 1, PaT-ID consists of three parts: (i) the definition of

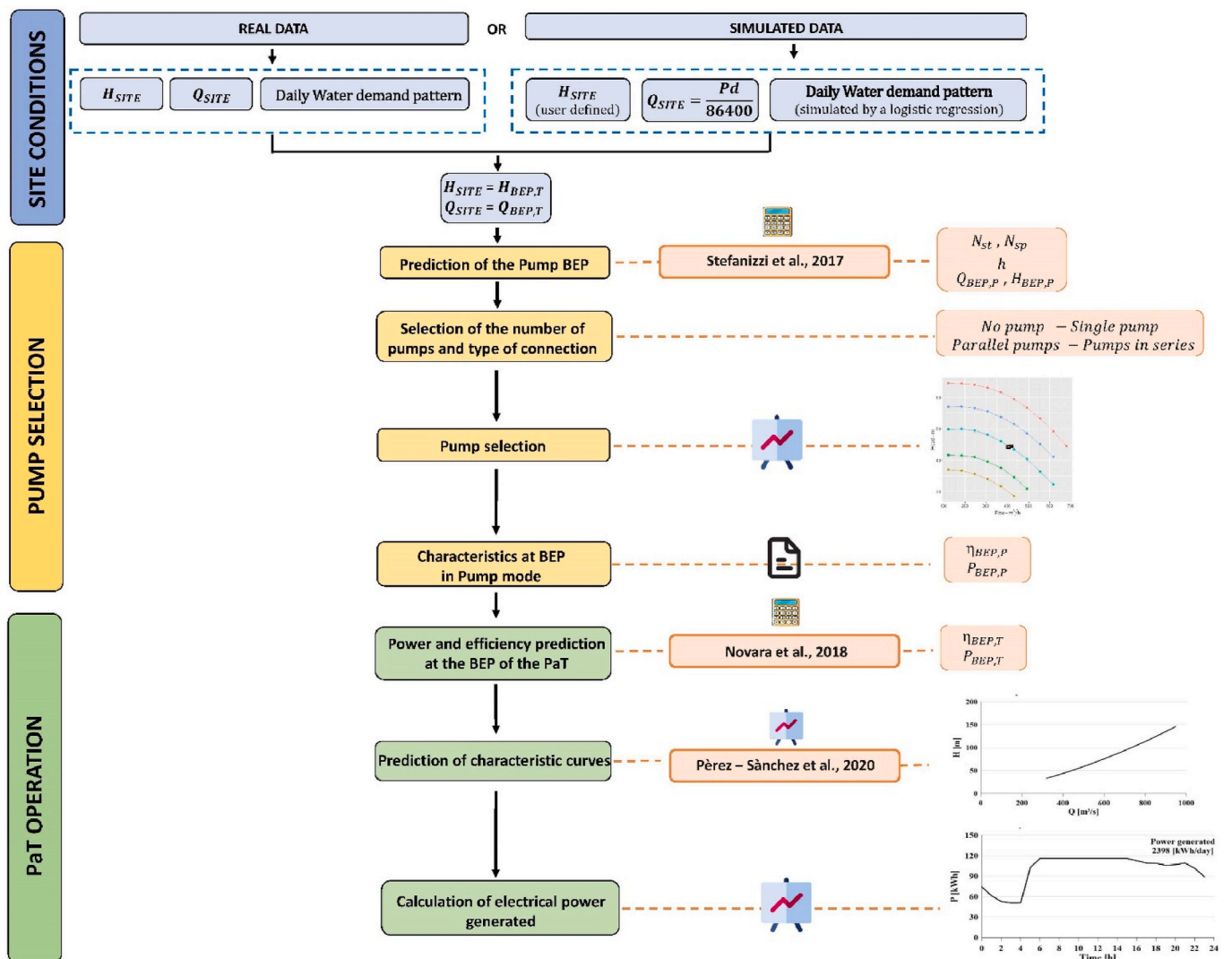


Fig. 1. PaT-ID algorithm.

the site conditions, (ii) the pump selection and (iii) the prediction of the characteristic curves and the daily energy production of the PaT. The input data can be real data entered by the user or simulated data. The first one consists of the daily flow rate and the water head in excess, H_{site} , to be dissipated in the turbine. The second one is an alternative to conducting an initial analysis on a WDN, allowing for a preliminary assessment of daily energy production when flow rate data are unknown to the user. This second option should represent a fast way, without retrieving detailed site information, to decide if a site can be the object of further investigations. Section 2.1 describes a detailed explanation of this second approach. In both cases, the user needs to know the hydraulic head to be dissipated, H_{site} . Regardless of input data, PaT-ID calculates the mean daily flow rate, which represents the Q_{site} for the pump selection. In case of real data, Q_{site} is calculated as the average of the daily water demand pattern. Otherwise, it is calculated using Eq. (17) (Section 2.1). The operating point, represented by ($Q_{site} = Q_{BEP,T}$ and $H_{site} = H_{BEP,T}$), is considered as Best Efficiency Point (BEP) of the machine running as turbine. Then, the pump selection is carried out by using the Xylem company catalogue, which includes 200 centrifugal pumps (coupled with four poles electric machines; thus, characterised by a rotational speed, n_p , equal to 1450 rpm). Before starting the pump selection process, it is important to define its rotational speed in turbine mode. For the same pump, the rotational speed in reverse-mode differs from the rotational speed in pump mode. Indeed, a PaT is coupled with its induction motor powered at 50 Hz with four magnetic poles. Consequently, its synchronous speed is equal to 1500 rpm. Then, it is crucial to consider the slip factor of the electric machine (e.g., 1%), which involves an actual rotational speed equal to 1520 rpm (n_T) [30].

The methodology used to estimate the BEP of the pump is based on the specific speed number, and it was proposed in a series of previous works [30,33,34]. The reason behind this choice is related to the fact that the specific speed number is a dimensionless parameter useful in the turbomachinery field because it correlates the parameters of a machine performance (Q , H and n) with the shape of the impeller, hence to the type of machine. Therefore, the specific speed number is a more useful engineering tool than the dimensional parameters used in other methodologies. As reported in many reviews, several works have been proposed on the BEP and performance prediction of the PaT. However, all these prediction models are still characterised by significant prediction errors on head, power and efficiency of about 15%–20% [5,6,35,36]. In detail, the first empirical correlations allowed to predict the BEP in turbine mode ($Q_{BEP,T}$, $H_{BEP,T}$, $\eta_{BEP,T}$) starting from the corresponding one in direct mode ($Q_{BEP,P}$, $H_{BEP,P}$, $\eta_{BEP,P}$) (e.g., see works by Sharma [37], Williams [38], Derakhshan [16], Singh [39], Nautiyal [40], Yang [21], Tan [41] and Barbarelli [42]). As they are based on a limited number of pumps tested in reverse mode, these prediction models are extremely simple, even though they rarely consider off-design conditions (partial loads and overloads). Indeed, as the number of tested PaTs increased, more sophisticated models have been proposed to predict the entire characteristic curve of the machine to assess the BEP and off-design performance. These models are based not only on statistical correlations (e.g., see Barbarelli et al. [43], Avila et al. [44], Novara et al. [45] and Renzi et al. [46]) but also on more theoretical approaches (e.g., see Gülich [28], Venturini et al. [47], Barbarelli et al. [48], Liu et al. [49], Polak [50], Lin et al. [51], Capurso et al. [52,53]). The latter approach needs specific geometric information that is difficult to retrieve to model velocity diagrams and hydraulic losses inside the machine. Moreover, 3D models using CFD were proposed [54–57]. As a last approach, artificial neural networks (ANN) and Artificial Intelligence (AI) are recently employed, but also in this case, they need to be trained and hence it is essential to tap into a vast database of tested machines [58,59]. Nevertheless, it is difficult for the pump manufacturer to replicate and apply these algorithms in a practical way. For this reason, the BEP prediction method proposed in has been adopted by Stefanizzi et al. [30]. In addition, this method belongs to a methodology developed in

the years by our research group to select a PaT for a WDN, showing a BEP prediction error within 10% [33,34].

Knowing the desired BEP of the PaT (i.e., $Q_{BEP,T}$, $H_{BEP,T}$ and n_T), the tool computes the specific speed of the PaT (Eq. (1)). Hence, following the procedure developed by Stefanizzi et al. [30] for the BEP prediction, Eq. (2) is applied to correlate the specific speed of the PaT, $N_{s,T}$, to that of the pump, $N_{s,P}$. As reported in Stefanizzi et al. [30], the correlation reported in Eq. (2) shows a linear trend between $N_{s,T}$, to that of the pump, $N_{s,P}$ with a high R^2 value of 0.98 for the specific speed ranging from 10 to 80. For the sake of clarity, it is essential to highlight that Eq. (2) correlates the two specific speed numbers by considering the same rotational speed for both reverse and direct modes (in this case, 1520 rpm).

$$N_{s,T} = n_T \frac{\sqrt{Q_{BEP,T}}}{H_{BEP,T}^{0.75}} \quad (1)$$

$$N_{s,P} = \frac{N_{s,T} + 2.6688}{0.9237} \quad (2)$$

Afterwards, the head prediction factor h , defined as $H_{BEP,T}/H_{BEP,P}$, can be evaluated by Eq. (3):

$$h = -0.000023(N_{s,T})^3 + 0.003206(N_{s,T})^2 - 0.145781N_{s,T} + 3.604636 \quad (3)$$

The correlation of Eq. (3) also comes from Stefanizzi et al. [30], based on the same data set used for Eq. (2), showing a R^2 value of 0.82. Hence, using the definition of h and the specific speed number, $N_{s,P}$, the prediction of the pump BEP is obtained by Eqs. (4) and (5), as follows:

$$H_{BEP,P} = \frac{H_{BEP,T}}{h} \quad (4)$$

$$Q_{BEP,P} = \left(\frac{N_{s,P} H_{BEP,P}^{0.75}}{n_p} \right)^2 \quad (5)$$

It must be considered that these equations are valid for a range of specific numbers of centrifugal and mixed flow pumps. In fact, the typical operating conditions of WDNs require machines of this type (see the operating conditions charts reported in Refs. [30,60]). Most of the works presented in the technical literature focused on centrifugal and mixed flow pumps by supporting this aspect. Consequently, all the prediction models are calibrated on this type of machines. Regarding axial machines, the number of works on axial PaTs is lower than those published on centrifugal ones. Then, currently, it is difficult to create a sample of axial machines great enough to develop performance prediction correlations. These works are basically based on numerical investigation of axial pumps running as turbines with the aim of analysing losses inside the machine. Moreover, the area of application is usually rivers, coastal regions or process engineering fields (e.g., see Refs. [61–66]).

As previously mentioned, the obtained working condition (i.e., $Q_{BEP,P}$, $H_{BEP,P}$) refers to a machine with a rotational speed of $n_p = 1520$ rpm, whereas the Xylem catalogue implemented in PaT-ID refers to machines with $n_p = 1450$ rpm. Then, it is necessary to correct the pump BEP by applying affinity laws (see Eqs. (6) and (7)).

$$Q_{BEP,P_{1450}} = Q_{BEP,P} \frac{1450 \text{ rpm}}{1520 \text{ rpm}} \quad (6)$$

$$H_{BEP,P_{1450}} = H_{BEP,P} \left(\frac{1450 \text{ rpm}}{1520 \text{ rpm}} \right)^2 \quad (7)$$

Once obtained the pump BEP at 1450 rpm, PaT-ID compares $Q_{BEP,P_{1450}}$ and $H_{BEP,P_{1450}}$ with the working limits set by the catalogue of the pumps, which are the minimum and maximum hydraulic heads (H_{MIN} , H_{MAX}), and the minimum and maximum flow rates (Q_{MIN} , Q_{MAX}). If the operating point exceeds these limits, the tool can evaluate the number of pumps, n , and their potential connection (series or parallel). This aspect usually is neglected because other works tend to select only one

machine.

Looking at Fig. 2, different cases can be considered. In the first two cases, identified with blue and red zones, respectively, it is impossible to select a pump. The third case is identified in yellow ($H_{MIN} < H_{BEP,P1450} < H_{MAX}$ and $Q_{BEP,P1450} > Q_{MAX}$). In this case, PaT-ID tool provides to consider machines in parallel by keeping constant $H_{BEP,T}$ and dividing the starting $Q_{BEP,T}$ by n , until the new $Q_{BEP,P1450}$ (calculated with the algorithm previously described from Eqs. (1)–(7)) falls within the selection zone (the pink area). In the fourth case, identified in green ($H_{MIN} < H_{BEP,P} < H_{MAX}$ and $Q_{BEP,P} > Q_{MAX}$), PaT-ID tool considers a series installation scheme. Thus, it keeps unchanged $Q_{BEP,T}$, but divides the $H_{BEP,T}$ by n , until the new $H_{BEP,P1450}$ (calculated with the algorithm previously described from Eqs. (1)–(7)) is lower than H_{MAX} by falling within the selection zone (the pink area). Obviously, in the last case identified by the pink zone, PaT-ID selects a single pump ($n = 1$).

Based on the conditions defined by Eqs. (8) and (9), PaT-ID excludes pumps with both head and flow rate greater or less than 10% of the target point. This value has been decided by comparing it with others wider limits found in the literature. Considering, for instance, the latest work by Le Marre et al. [24], all PaTs showing a BEP within 30% of the target value are considered for energetic and economic assessments. The choice of this value is not discussed. In the latest work by Novara et al. [17] that arrived at the installation of the selected machine, a 20% tolerance on the resulting BEP location was considered. Then, in our case, we have selected the 10% to decrease this limit and have fewer machines to be selected. Moreover, the conditions identified by Eq. (10) allow the selection of only those pumps that have operating points with an efficiency greater than 70% preventing excessive performance decay when the pump works in reverse mode.

$$0.90 Q_{BEP,P1450} < Q < 1.10 Q_{BEP,P1450} \tag{8}$$

$$0.90 H_{BEP,P1450} < H < 1.10 H_{BEP,P1450} \tag{9}$$

$$\eta > 0.70 \tag{10}$$

The selected pump is that with the operating point closest to the target point. The main characteristics of the pump can be established i. e., power ($P_{BEP,P}$), and efficiency ($\eta_{BEP,P}$).

PaT-ID calculates PaT efficiency, $\eta_{BEP,T}$, at BEP. Although the literature presents several works proposing performance correlations, the prediction of the BEP turbine efficiency ($\eta_{BEP,T}$) is not often considered. In the first studies, it was considered equal to the BEP efficiency in pump mode, i.e. $\eta_{BEP,T} = \eta_{BEP,P}$ [16]. Actually, from experimental studies on pumps working as turbines, it is possible to notice how the two BEP efficiencies are different [21,39,40,67–74]. Indeed, we have to consider that the losses inside the machine change according to the type of operation. In addition, the aforementioned works have demonstrated that the BEP flow rate in turbine mode is higher than the corresponding BEP flow rate in pump mode.

Another significant consideration is that recent works proposing machine selection models are still based on the model proposed by Derakhshan et al. [16] or Yang et al. [21] (dated in 2008 and 2012, respectively). These empirical correlations are used for modelling the PaTs performances, which are based on four pumps tested in reverse mode without contemplating efficiency. For instance, Tan et al [41] proposed a correlation for the turbine efficiency as a function of the specific speed of the pump, but this correlation was developed on tests carried out on only four machines. A few years later, Renzi et al. [46] proposed a methodology to forecast the main non-dimensional performance parameters of PaTs operating at BEP. In their study, they also suggested a correlation of the prediction of the BEP efficiency in turbine mode as an intricate function of both the specific speed number and efficiency of the pump. However, their best correlation based on 9 PaTs

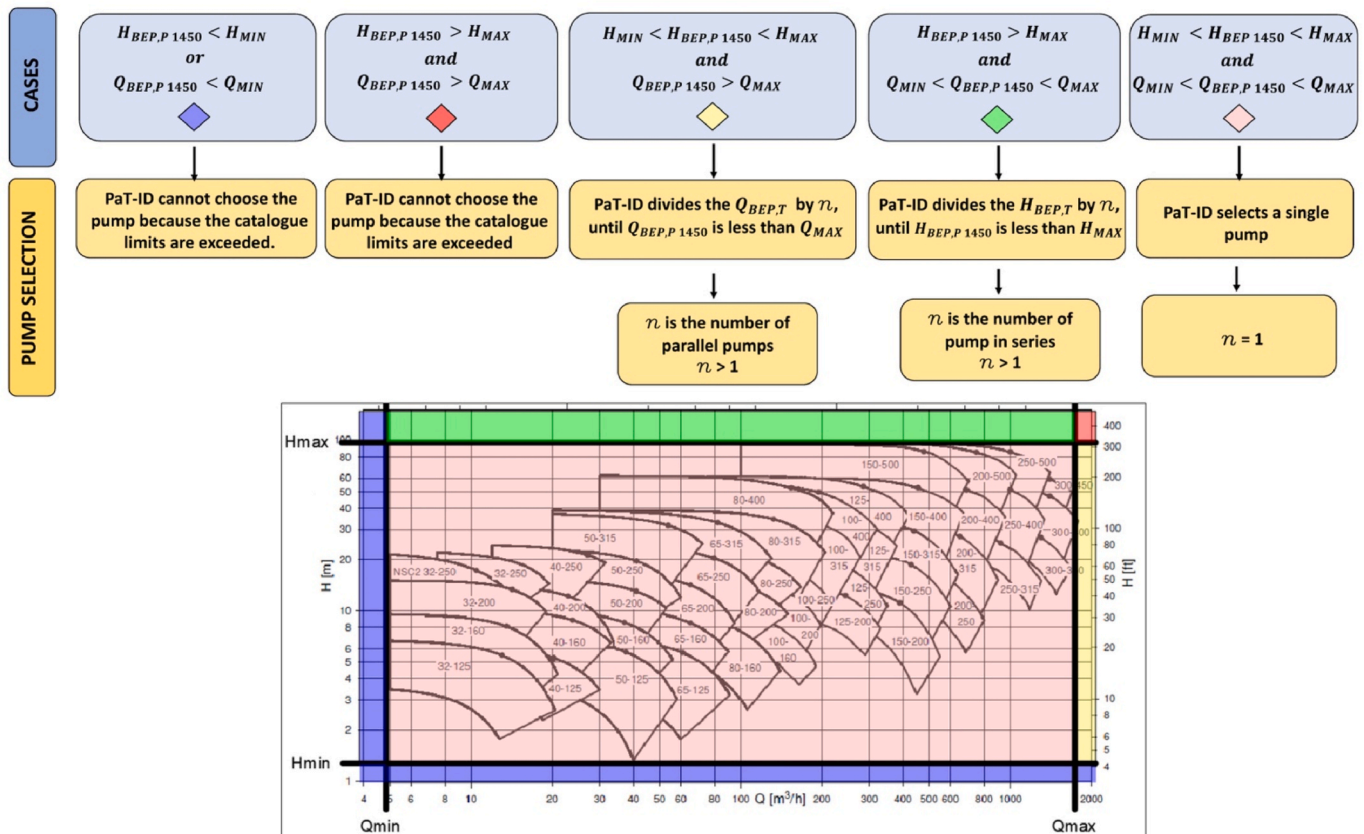


Fig. 2. ABACUS for the pump selection.

showed an R-squared value of 0.78.

Then, although the literature presents several works proposing performance correlations, the proposed methodology considers the correlation proposed by Novara et al. [75] for predicting the BEP efficiency in turbine mode (see Eq. (11)).

$$\eta_{BEP,T} = 0.89 - \left(0.024 / Q_{BEP,T}^{0.41}\right) - 0.076[0.22 + \ln(N_{s,T}/52.933)]^2 \quad (11)$$

Thus, the power generated by PaT at BEP is equal to the following:

$$P_{BEP,T} = \rho g H_{BEP,T} Q_{BEP,T} \eta_{BEP,T} \quad (12)$$

Moreover, the approach developed by Pérez-Sánchez et al. [25] for the characteristic curves (see equations (13)–(15)) has been considered because usually pumps retrieved from catalogues are not yet experimentally tested in turbine mode. Thus, the application of the empirical laws makes it possible to understand how the head, power, and efficiency vary as a function of the flow rate.

$$\frac{H_T}{H_{BEP,T}} = 0.406 \left(\frac{Q_T}{Q_{BEP,T}}\right)^2 + 0.621 \left(\frac{Q_T}{Q_{BEP,T}}\right) \quad (13)$$

$$\frac{P_T}{P_{BEP,T}} = -0.333 \left(\frac{Q_T}{Q_{BEP,T}}\right)^3 + 2.19 \left(\frac{Q_T}{Q_{BEP,T}}\right)^2 - 0.863 \left(\frac{Q_T}{Q_{BEP,T}}\right) \quad (14)$$

$$\begin{aligned} \frac{\eta_T}{\eta_{BEP,T}} = & -1.219 \left(\frac{Q_T}{Q_{BEP,T}}\right)^4 + 6.95 \left(\frac{Q_T}{Q_{BEP,T}}\right)^3 - 14.578 \left(\frac{Q_T}{Q_{BEP,T}}\right)^2 \\ & + 13.231 \left(\frac{Q_T}{Q_{BEP,T}}\right) - 3.383 \end{aligned} \quad (15)$$

In order to perform the calculation of the hourly power generated by the PaT, it is essential to know the daily water demand pattern. If this data is unknown to the user, PaT-ID simulating it through the methodology presented in section 2.1.

The hourly power generated by the PaT is equal to:

$$P_T = \rho g H_T Q_T \eta_T \quad (16)$$

where Q_T is the hourly flow rate in a day, i.e., the daily water demand pattern, and H_T is the head, set with variable values during the day. The efficiency η_T is calculated according to Eq. (15).

These correlations have been selected after having compared a series of prediction models found in the technical literature. For the sake of clarity, the comparison of these models has been carried out by applying them to the experimental curves of PaTs tested in a recent work by Delgado et al. [71] and to a PaT tested in our previous work at the laboratory for hydraulic turbomachines of the Polytechnic University of Bari (<https://research.poliba.it/laboratories/hpt-lab>) [29]. The choice of these machines comes from the need to consider a wide range of specific speed numbers in order to have a dataset as general as possible. Specifically, the three machines tested by Delgado et al. [71] are characterised by $N_{s,p} = 21.4$ (PaT 1), 41 (PaT 2) and 67.3 (PaT 3), whereas the machine tested in Ref. [29] shows a $N_{s,p} = 21.9$ (PaT 4).

Regarding the prediction of the maximum efficiency in turbine mode, two models have been compared (i.e., Barbarelli et al. [42] and Novara et al. [75]). To the knowledge of the authors, these two currently propose this kind of correlation as a function of $N_{s,T}$. Table 1 compares

Table 1

– Comparison between prediction models proposed by Barbarelli et al. [43] and Novara et al. [76] in terms of the prediction error of the maximum efficiency in turbine mode.

	$N_{s,p}$	N [rpm]	$\eta_{BEP,T}$ (Experimental)	$err_{\eta_{BEP,T}}$ (Barbarelli)	$err_{\eta_{BEP,T}}$ (Novara)
PaT 1	21.4	1500	68.1%	1.5%	0.5%
PaT 2	41.0	1500	61.1%	27.1%	17.2%
PaT 3	67.3	1500	68.2%	18.9%	13.4%
PaT 4	21.9	800	79.8%	−6.9%	0.8%

the two models in terms of the prediction error of the maximum efficiency, $err_{\eta_{BEP,T}}$, with respect to the experimental value. The model developed by Novara et al. [75] shows lower prediction errors for the range of specific speed numbers under investigation. After all, this model is calibrated on a sample about ten times higher than the one by Barbarelli et al. [42] (i.e., about 280 instead of 27 machines).

Regarding the prediction of the entire characteristic curve of the PaT, three approaches have been compared: Pérez-Sánchez et al. [25], Novara et al. [45] and Fecarotta et al. [76]. Fig. 3 compares the three models in terms of the head and the efficiency curves. For the sake of brevity, the PaT tested in our previous work has been used as a reference (i.e., PaT 4 in this analysis) [29]. It is possible to notice how the four prediction models show a similar trend for the head curve prediction. However, the difference between the aforementioned models can be highlighted by looking at the predicted efficiency curves. Indeed, among them, the one proposed by Pérez-Sánchez et al. [25] shows the lowest prediction errors, above all during part load operating conditions. Furthermore, it must be considered that this model is based on a more significant number of machines (181) than the others (i.e., 113 in Ref. [45] and 5 in Ref. [76]). Finally, the model by Pérez-Sánchez et al. [25] has been considered in this study.

2.1. Simulation of the daily water demand pattern

Sometimes, a water utility could be interested to evaluate the convenience of introducing a PaT in a WDN. PaT-ID permits to conduct a first analysis without the necessity to rebuild the real water demand pattern. This section proposes a methodology to estimate daily water demand trends and give a first estimation of daily energy production. The proposed methodology is based on the availability of daily water demand pattern of 41 Apulian WDNs. These data were provided by the Apulian Integrated Water Company (i.e., Acquedotto Pugliese) in the course of research work already conducted by the authors (see Balacco et al. [77]). The population ranges from a minimum of about 1800 inhabitants to a maximum of about 100,000 inhabitants. Flow measurements recorded for 7–14 days with a sampling time of 10-min were analysed to create the dataset.

For each town in the dataset, PaT-ID selects consecutive days with complete flow measurements of the WDNs and calculates the observed hourly flow rates ($Q_{OBS}(t)$, in Appendix 1). The average theoretical flow rate (Q_{site} , in Appendix 1) is calculated for each one according to Eq. (17), where P [inhabitants] and d [l/(inhabitant per day)] denote population and daily water demand per capita, respectively.

$$Q_{site} = \frac{P d}{86400} [l/s] \quad (17)$$

Specifically, the daily water demand per capita, d , is the water amount for a resident to meet his water and drinking needs.

The population was acquired from the Italian National Institute of Statistics (ISTAT) and referred to the same period of the dataset [78]. The daily water demand per capita of the Apulia region was defined by the latest Plan for the Water Service (2022) [79]. It assumes 200 (l/inhabitant per day) water allocation for each city, plus a rate as a site function (Table 2).

Subsequently, the observed hourly flow rate ($Q_{OBS}(t)$) and the 41

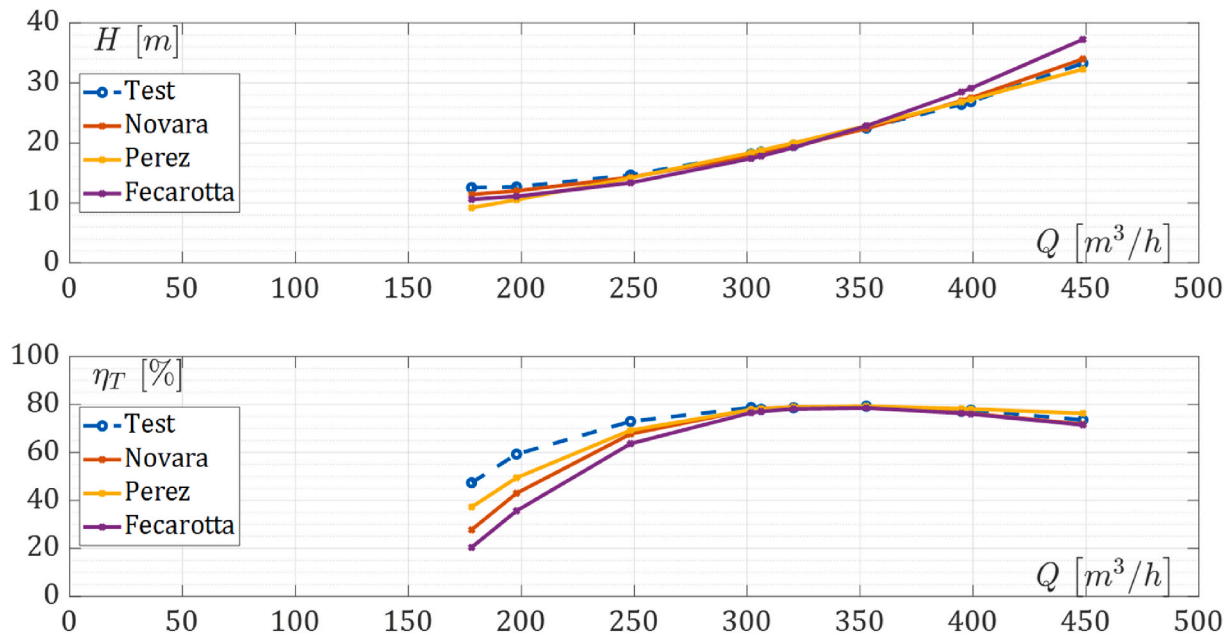


Fig. 3. Comparison between the experimental data [29] and prediction models in terms of head, H vs. Q , (upper) and efficiency, η_T vs. Q , (lower) curves (Pérez-Sánchez et al. [25] in yellow, Novara et al. [45] in red and Fecarotta et al. [76] in purple). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Daily water demand per capita of the Apulian region.

Population	Daily water demand per capita [l/(inhabitant per day)]	Increase daily water demand per capita [l/(inhabitant per day)]
$P < 5000$	200	60
$5000 < P < 10,000$	200	80
$10,000 < P < 50,000$	200	100
$50,000 < P < 100,000$	200	120
$P > 100,000$	200	140

theoretical average flow rates (Q_{site}) were plotted and a regression curve was derived for each hour (Appendix 1). The regression curve is obtained by using the logistic regression model, generally represented by Eq. (18):

$$y(t) = \frac{a(t)}{1 + b(t)e^{-c(t)x}} \quad (18)$$

where a , b and c are constants varying with the considered hour. The common result is that a logistic curve fits data better than other relations with a R^2 coefficient greater than 0.75 for every hour.

Therefore, the hourly flow rate of a site with an unknown water demand model can be estimated. As a first approximation, it can be estimated by using Eq. (18) and by replacing the variable x with the Q_{site} of the case study, which has been calculated with Eq. (17). The parameters a , b , c , of each resulting hourly logistic function are reported in Appendix 1.

Table 3
– Summary of the site conditions for Town 1.

TOWN 1		Real Data	Simulated Data	Hydraulic head	
Inhabitants	Daily water demand per capita [l/(inhabitants per day)]	Q_{site} [m³/h]	Q_{site} [m³/h]	Day-time H_{site} [m]	Night-time H_{site} [m]
50,000	300	636	626	80.0	90.0



Fig. 4. Water distribution network of Town 1 [30].

3. Case studies

Several simulations have been carried out to test the validity of PaT-ID in terms of the ability to obtain similar results with the patterns as close as possible to those obtained with the real patterns. For brevity, only two applications are discussed in the following, whereas Appendix 2 reports the results for every analysed case. The applications assumed the installation of a PaT in two different towns of the Apulian region (Town 1 and Town 2), whose names are omitted for privacy. For each town, two simulations were carried out: the first one with the real

measurements of WDNs, whereas the second one simulates them by PaT-ID for testing the tool without available data.

Town 1 has a population of about 50,000 inhabitants, and its water demand is satisfied by a unique reservoir. This case study was chosen to compare the results with a previous study [30]. The WDN and the installation point of the PaT are shown in Fig. 3.

Table 3 reports input data and simulated ones. The best position to insert the PaT is downstream of the reservoir and at the origin of the WDN, as indicated by a red dot in Fig. 4, where the main PRV is currently installed. In this point, the hydraulic head is equal to 100 m above the land surface. The installation point was chosen in agreement with the water management authority. Then, it was decided that the machine could be installed upstream this PRV to allow the system to return to the original layout in case of PaT maintenance or failure, keeping the integrity and operation of the system. Finally, an electric cabin is close to that zone, allowing the electrical grid connection.

The WDN of Town 1 is regulated by a PRV set at two different patterns. The water head downstream the valve must not exceed 20 m above the land surface during the day-time (i.e., from 06:00 a.m. to 05:00 p.m.). Instead, it must be below 10 m during the night (i.e., from 05:00 p.m. to 06:00 a.m.) [80]. For this reason, the hydraulic head available for the PaT is equal to 80 m during the day and 90 m during the night.

Town 2 counts a population of about 20,000 inhabitants, and the water demand is satisfied by a unique reservoir. The WDN and installation point of the PaT are shown in Fig. 5. It is possible to notice how this WDN is divided into three districts (DIS). Balacco et al. [12] report a description of this town.

Table 4 sums up the input data and simulated ones. Also in this case, a PRV is set to control the pressure in the WDN and reduce the leaks. H_{site} is equal to 17 m during the day and 20 m during the night. The results of Town 2 obtained thanks to PaT-ID were compared with the results of Balacco et al. [12].

4. Results

At the end of each simulation, PaT-ID returns a complete report of the input data used and all the results obtained. It summarises, for each data pair (Q_{site} , H_{site}), the calculated $Q_{BEP,P}$ and $H_{BEP,P}$ values, the selected pump model, the pump operating characteristics, the available hydraulic energy, and the daily energy production. Moreover, the code indicates the number of chosen pumps and whether they are installed in series or parallel. Table 5 reports the results obtained for Town 1 and Town 2.

For the simulation of Town 1 using real data, PaT-ID estimated a $Q_{BEP,P} = 419 \text{ m}^3/\text{h}$ and a $H_{BEP,P} = 44.4 \text{ m}$. The second simulation assessed a $Q_{BEP,P} = 410 \text{ m}^3/\text{h}$ and a $H_{BEP,P} = 44.3 \text{ m}$. For both simulations, PaT-ID selected the same single pump 150–400/750.

For both simulations of Town 2 (using real and simulated data) PaT-ID estimated a $Q_{BEP,P} = 170 \text{ m}^3/\text{h}$ and a $H_{BEP,P} = 10.7 \text{ m}$. For this application, the pump selected from the implemented catalogue Xylem was 100–200/75.

Moreover, it can be noticed that the selected machines for both the real and simulated data are the same for each town. This aspect can be justified by the fact that Q_{site} and H_{site} for both real and simulated cases are very similar. These values are the input values for the algorithm for the BEP conversion (see Fig. 1), which is the same for both the simulated and real. This aspect can be noticed also by looking at Fig. 6, which compares the position of the BEP with the characteristic curves of the pumps listed in the catalogue. The selected pump characteristic curve is the nearest to the BEP point. It allows a visual check of how the code is working.

PaT-ID also returns the characteristic curves of the pumps of the same family. Red and yellow dots indicate, respectively, BEP obtained for the real data and simulated ones. Interestingly, PaT-ID suggests the same pump for both the real and simulated case for both towns.

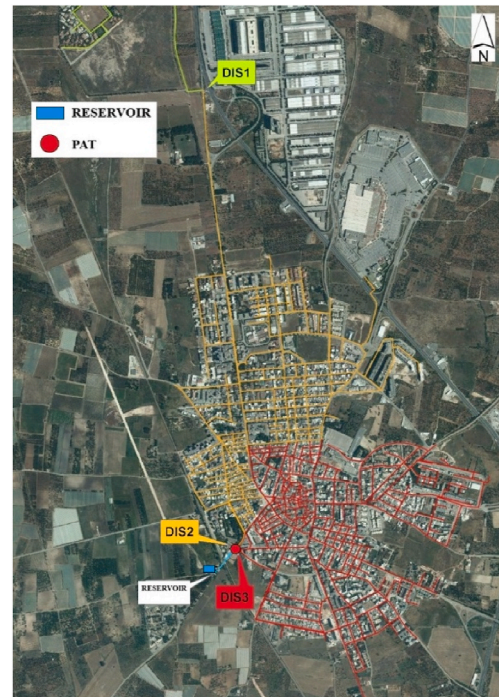


Fig. 5. Water distribution network of Town 2 [12].

Fig. 7 shows the characteristic curves of the resulting pump in reverse mode for both Town 1 and Town 2. It compares the curves obtained with real data (orange dashed line) with those obtained with simulated ones (blue line). The curves relate the hydraulic head, the efficiency, and the power with the flow rate, respectively.

The prediction of the PaT characteristic curves depends on the initial conditions (Q_{site} , H_{site}) and not on the characteristics of the selected pump. In fact, for both Town 1 and Town 2, the pumps selected in the two simulations are the same, but the characteristic curves are almost similar. The small difference is due to a simulated Q_{site} that is slightly lower than the real Q_{site} .

Fig. 8a compares the daily observed and simulated water demand pattern of Town 1, showing a good agreement. Fig. 8b relates the daily power generated by the PaT for the daily observed and simulated water demand pattern. As expected, the trend of the power generated by the PaT follows the daily water demand pattern. A slight difference between the observed and simulated water demand patterns corresponds to a reduction in the daily power produced of 5%.

Fig. 8c compares the daily observed and simulated water demand pattern of Town 2, while Fig. 8d relates the daily power generated by the PaT for the daily observed and simulated water demand pattern. In this case, there is an increase of 7% in the power generated by the PaT between the first and the second simulation. Thus, when the simulated daily water demand pattern is underestimated, the daily power generated is less than that calculated with real data, as for Town 1. Conversely, for Town 2 the overestimation of the simulated daily water demand pattern corresponds to a higher power produced.

Simulations conducted using PaT-ID pursue to define the general convenience or not to introduce a PaT into a WDN. Certainly, in a next phase it will be necessary to input real water daily demand pattern to obtain the “real” energy production. The utility of this instrument is double. From one side, when data are immediately available, it designs the most suitable PaT for maximising energy production. On the other side is a useful instrument for the water utilities to check if one WDN is considerable or not to the insertion of a PaT.

Table 4

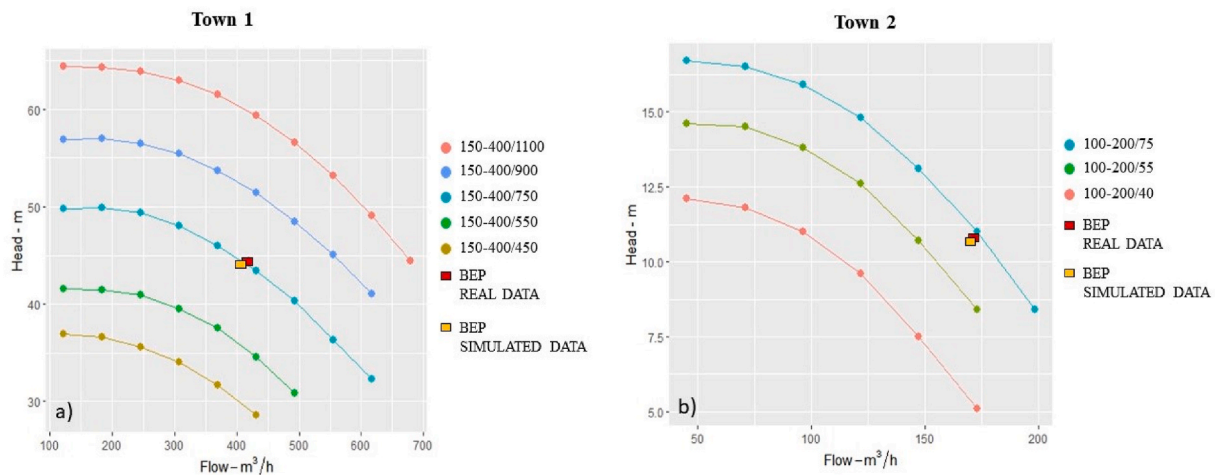
– Summary of the site conditions for Town 2.

TOWN 2		Real Data	Simulated Data	Hydraulic head	
Inhabitants	Daily water demand per capita [l/(inhabitants per day)]	Q_{site} [m^3/h]	Q_{site} [m^3/h]	Day-time H_{site} [m]	Night-time H_{site} [m]
20,000	300	238	237	17.0	20.0

Table 5

– Summary of the results shown by PaT-ID at the end of each simulation.

TOWN 1											
Data	Q_{site} [m^3/h]	H_{site} [m]	$Q_{BEP,P}$ [m^3/h]	$H_{BEP,P}$ [m]	Model	Q_{BEP} [m^3/h]	H_{BEP} [m]	η_{BEP} [%]	Available hydraulic energy [kWh/day]	Daily energy production [kWh/day]	Config.
Real	636	80.0	419	44.4	150-400/750	470	43.0	85	3521	2294	Single pump
Simulated	626	80.0	410	44.3	150-400/750	470	43.0	85	3467	2188	Single pump
TOWN 2											
Data	Q_{site} [m^3/h]	H_{site} [m]	$Q_{BEP,P}$ [m^3/h]	$H_{BEP,P}$ [m]	Model	Q_{BEP} [m^3/h]	H_{BEP} [m]	η_{BEP} [%]	Available hydraulic energy [kWh/day]	Daily energy production [kWh/day]	Config.
Real	238	17.0	170	10.7	100-200/75	140	15.0	84	262	170	Single pump
Simulated	237	17.0	170	10.7	100-200/75	140	15.0	84	284	184	Single pump

**Fig. 6.** Characteristic curves of the pump selected for (a) Town 1 and (b) Town 2 for the two simulations. BEP indicates the operating point.

5. Discussion

The results confirmed that the proposed methodology implemented in PaT-ID tool could be worthy of interest in selecting a pump to be installed in reverse mode in a WDN for producing electrical power. For Town 1, the results of this tool were compared with those obtained by Stefanizzi et al. [30]. Despite the methodology adopted for the selection of the most appropriate pump to use as turbine is slightly different concerning [30], PaT-ID selects a pump that belongs to the same family. Indeed, instead of the pump named 150–400/900, it selects the closer and inferior one (150–400/750). The difference between the two machines regards the nominal power of the coupled electric motor.

Results obtained by PaT-ID have been compared with respect to the ones from Ref. [30] in terms of daily energy production. Specifically, PaT-ID returns 2294 kWh/day (for real water demand pattern) and 2188 kWh/day (simulated water demand pattern) instead of 2241

kWh/day estimated in Ref. [30]. This result is crucial because it demonstrates the goodness and generality of the developed tool. Moreover, the performance curve of the machine selected in Ref. [30] is based on a theoretical model which requires very detailed geometrical data, usually known only by pump manufacturers. Instead, PaT-ID overcomes this limit by employing performance prediction correlations selected among literature methodologies, as previously discussed in Section 2.

For Town 2, the results obtained were compared with Balacco et al. [12]. Before comparing PaT-ID results with [12], it is essential to make a foreword. In Ref. [12] the authors used the methodology proposed by Pugliese et al. [81] to estimate the BEP of the pump in reverse mode and to select the machine. Moreover, the PaT in Ref. [12] was selected assuming a cautionary PaT efficiency equal to 0.70. This assumption has driven the authors to estimate a theoretical daily energy production and not a real one.

Considering these differences, it is possible to compare now the

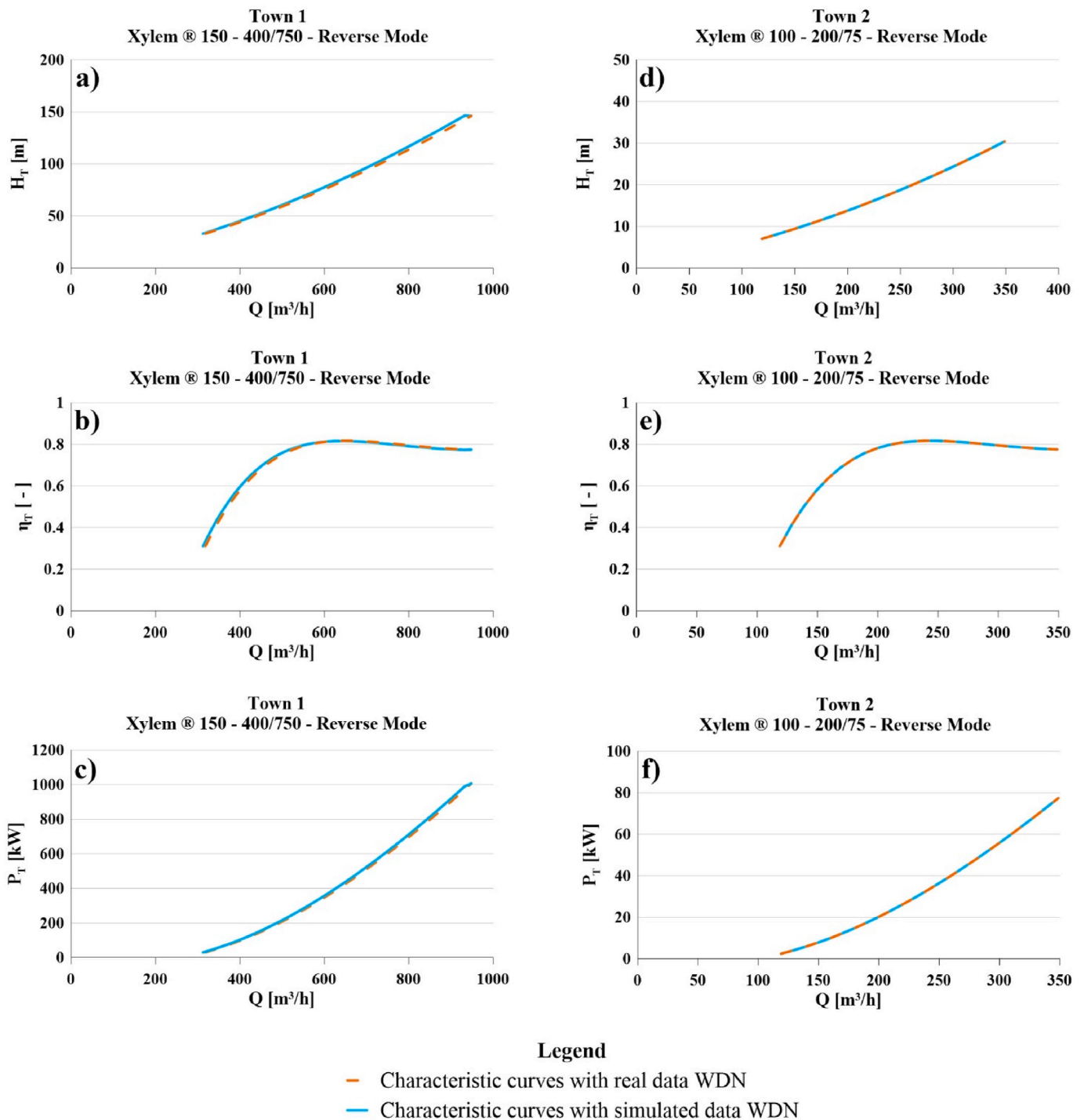


Fig. 7. Comparison between the approaches with real and simulated data in terms of characteristic curves (H_T vs. Q , η_T vs. Q and P_T vs. Q) of the PaT selected for Town 1 (a, b, c) and Town 2 (d, e, f).

results between PaT-ID and the previous one. In this case, the selected PaT differs from that of [12] in terms of pump family. Nevertheless, the daily energy production is comparable. Using real data, PaT-ID returns a daily energy production equal to 170 kWh/day, while it gives 184 kWh/day using simulated ones. Instead, the daily energy production in Ref. [12] was 157 kWh/day. In the case of the real and simulated data, PaT-ID returns a daily energy production 7% and 17% higher than [12], respectively.

This result is of great interest because, considering the assumptions highlighted, and the limitations of a simulated water demand curve,

PaT-ID effectively simulates the potential of the WDN, the survey site.

However, it is necessary to highlight the difference between real and simulated data is highly dependent on the hydraulic input data of the WDN. This happens because many houses have private tanks that collect water at night. As a result, a higher average water flow is recorded at night. Thus, a slight overestimation of the night-time flow rate by the water demand pattern is obtained. Nevertheless, the simulated water demand pattern assessment is affected by an error that could overestimate or underestimate the real pattern with consequent overvalues or losses of electrical power generated. This is because the water flow

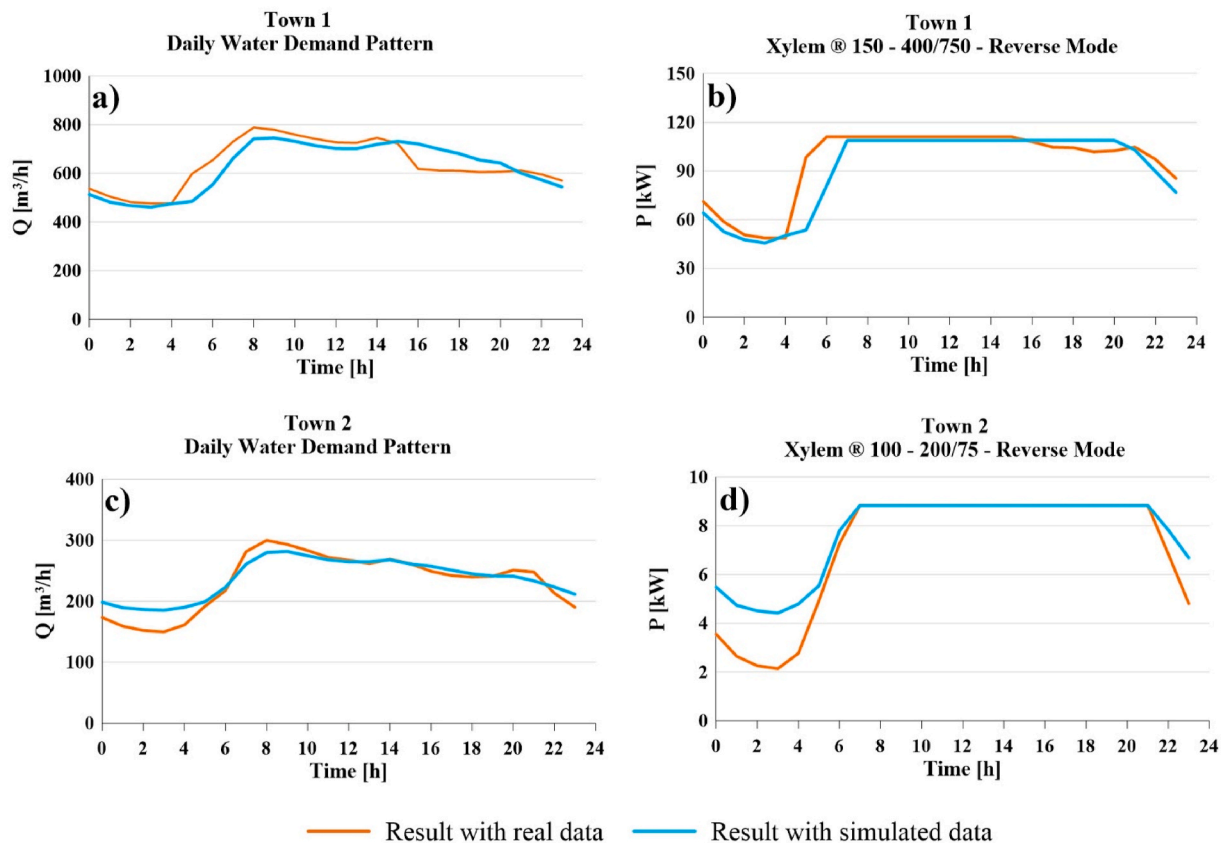


Fig. 8. Comparison between the approaches with real and simulated data in terms of daily water demand pattern (a) and daily power generated by the PaT installed in Town 1 (b); Daily water demand pattern (c) and daily power generated by the PaT installed in Town 2 (d).

rate depends on numerous factors besides the number of inhabitants. Some cities implemented in the dataset, for example, supply manufacturing or industrial areas with consequent water flow rates higher than that theoretically necessary for the number of inhabitants. Moreover, as explained above, the daily water flow rates are sensitive to the presence of autoclaves in the urban water distribution, which collect water during the night with consequent higher water demand with respect to normal conditions. The procedure implemented in PaT-ID for estimating the daily water demand pattern could be a useful instrument for a qualitative assessment of the energy recovered by the PaT.

6. Conclusions

This paper proposes a methodology for automatically selecting the most suitable pump to be used in reverse mode, predicting its performance, and estimating the potential daily power generated. It is automated by a computer tool called PaT-ID. This code could be a useful and interesting decision-making tool for future action planners.

This tool shall represent a helpful instrument for public utilities that would like to explore the energy potentialities of a WDN before deciding to install a PaT and, eventually, to replace an existing PRV.

In this preliminary tool version, the unique necessary parameter to insert into PaT-ID is the hydraulic head available for the machine. PaT-ID will simulate the hourly flow rate using the regression curves defined thanks to the dataset from several cities widespread in the Apulian territory.

The results obtained from the two case studies, also in case of unknown daily water demand pattern, are quiet the same obtained with a different methodological approach ([12,30]). They show that the code has an excellent potential and can facilitate decision-makers in their work and reduce the time-to-market.

The code proposed in this paper is a preliminary version of PaT-ID. Currently, it contains only one methodology for selecting and predicting PaT operating curves. Future developments may lead to implementing other methods and analyses to maximise the energy produced by the PaT. The database of pumps can be augmented by using different catalogues from other manufacturers. However, it is essential to note that the pumps currently implemented in PaT-ID cover many operating points and a good market range.

Additionally, further development of the code may be the implementation of economic analysis. By entering the cost of pumps, piping, and the price of electricity into PaT-ID, it may be possible to calculate the payback period. This update would be critical to the code because it would allow the feasibility of the construction to be evaluated in a few simple steps.

Credit author statement

Gabriella Balacco: Conceptualization, Methodology, Investigation, Writing - review & editing, Methodology, Supervision; **Gaetano Daniele Fiorese:**Methodology, Formal analysis, Investigation, Data curation, Writing - original draft; **Maria Rosaria Alfio:**Methodology, Formal analysis, Investigation, Data curation, Writing - review & editing; **Vincenzo Totaro:** Methodology, Formal analysis, Investigation; **Marco Torresi:** Writing - review & editing; **Mario Binetti:** Supervision; **Michele Stefanizzi:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - review & editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.energy.2023.128366>.

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