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Potential energy exploitation in collective irrigation systems using pumps as turbines: a case study in Calabria (Southern Italy)

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ABSTRACT

The development of efficient energy, water and environment systems is considered a fundamental key to satisfy the principles of cleaner production, energy security and circular economy. The present study aims at investigating the possible energy exploitation of the untapped hydraulic potential in collective irrigation systems by adopting pumps as turbines. These machines are not extensively used to produce electricity due to the lack of information in reverse operation mode and the low efficiency outside the best efficiency point.This study proposesnew correlation rules to obtain more accurate performance of the pumps as turbines and introduces a novel methodology to select the proper hydraulic machines and define the optimal hydropower configuration.The proposed procedure based on a multi-variable optimisation has been applied to the whole collective irrigation networks of Calabria (Southern Italy). Specifically, the energy production,greenhouse gas emissions and investment costs of 114 potential small hydropower plants have been estimated.The results show that the adoption of pumps as turbines in small-scale hydropower plants is a viable, clean and cheap solution for an extensive use in collective irrigation systems. These machines lead to a noticeable decrease in the electro-mechanical costs (-74%) with only a slight reduction (-19%) in the total electric power compared to specific-site designed turbines. Furthermore, the proposed hydropower systems guarantee a significant fall in greenhouse gas emissions (larger than 8800 tons/year) with respect to the conventional Italian electric production. The generated electricity could be used to satisfy a larger share of electric demand coming from collective irrigation agencies and/or agricultural farms with significant improvements in their economic and environmental impact. Overall, the proposed methodology may represent a valid design tool for an extensive exploitation of hydropower sources in rural water systems, in an effort to enhance cleaner energy productions and integrated systems of energy, water and environment.

KEYWORDS: small hydropower plant; renewable energy; collective irrigation system; optimisation; energy efficiency; pumps as turbines.

1. INTRODUCTION

Nowadays, fossil fuels still represent the main energy source worldwide, despite the global concerns on climate change and greenhouse gas (GHG) emissions (Mikulčić et al., 2020). Indeed, the combustion of fossil fuels releases large amounts of carbon dioxide and other harmful emissions to the atmosphere(Viteri et al., 2019). Moreover, fossil fuels are a non-renewable energy source that poses a potential threat in terms of resource depletion(Al-Shetwi et al., 2020).

In a rapidly changing environmental context, there is the need of establishing alternative energy sources and transform energy supply to a cleaner and more sustainable pathway(Li et al., 2020). Renewable energies, including biomass, geothermal, solar, wind and hydropower, are significantly cleaner than fossil fuels and nuclear energy and their usage has increased in the recent years(Fan et al., 2020; Mikulčić et al., 2020). Furthermore, the development of new technologies for energy production from renewable sources provides more sustainable low-carbon emission alternatives, and enables a smoother transition from traditional fossil fuels to hydropower and other renewable sources(Farfan and Breyer, 2017).In particular, hydropower is currently considered among the cheapest and cleanest technology to produce energy (Binama et al., 2017; Serpoush et al., 2017; Zapata-Sierra and Manzano-Agugliaro, 2019). It represents the most mature and diffuse renewable source worldwide (Laghari et al., 2013; Martinez et al., 2019). Hydropower has supplied 16.3% of the world's electricity in 2017 (International Energy Agency, IEA, 2019) and the prospects for the sector are expected to be very positive in the next decades (Feng et al., 2018; Ueda et al., 2019). Large hydropower plants have been widely installed (Farfan and Breyer, 2017; Laghari et al., 2013; Zapata-Sierra and Manzano-Agugliaro, 2019). However, since sites in Europe to develop new large-scale systems are scarce (Butera and Balestra, 2015; Carapellucci et al., 2015), attention has been recently paid to small hydropower plants (SHPs), whose energy production potential has not been completely exploited (Dedić-Jandrek and Nižetić, 2019; Laghari et al., 2013).

Usually, SHPscan convert around 70% of the potential energy into electricity against 80-90% of the largest plants (Okot, 2013; Paish, 2002). Moreover, SHPs are extremely robust and require low maintenance. The peculiar characteristics of SHPs make these systems a suitable option for electricity production in developing countries (Laghari et al., 2013; Paish, 2002) or in rural areas, where grid connection is lacking (Jawahar and Michael, 2017). SHPs are commonly integrated in urban water networks (Berrada et al., 2019; Du et al., 2017). Conversely, less attention has been paid to the irrigation sector (Chacón et al., 2018; García Morillo et al., 2018), where pressurised water networks have a hydropower potential largely unexploited (Butera and Balestra, 2015; García Morillo et al., 2018; Nicotra et al., 2018; Zema et al., 2016). As a matter of fact, the excess water pressure of these networks is often deliberately reduced by valves (García Morillo et al., 2018; Penche, 1998).Therefore, the potential energy is not recovered to generate electricity, but practically wasted. Until now, few studies have been carried out about SHP integration into the existing irrigation plants(Butera and Balestra, 2015; Crespo Chacón et al., 2020). Moreover, the available studies have mainly focused on the SHP functioning at the district and/or farm scales, where usually the water demand fluctuates over time (Adhau et al., 2012; Chacón et al., 2018; García Morillo et al., 2018; Pérez-Sánchez et al., 2018, 2016). SHPs can also be integrated in collective irrigation systems, where the water flows and heads are usually higher and the fluctuations of water demand for irrigation are lower. However, as shown by Zema et al. (Zema et al., 2017, 2016) the installation of SHPs is expensive, due to the high costs of electro-mechanical equipment, which are still a barrier against the SHP larger consolidation worldwide (Jawahar and Michael, 2017; Laghari et al., 2013). It has been estimated that these costs range from 35% to 40% of the total cost in SHPs with peaks of even 70% (Binama et al., 2017).

A possible solution to reduce the investment for the electro-mechanical equipment of SHPs is the use of pumps as turbines (PATs), i.e., pumps operating in reverse mode (Meschede, 2019; Sari et al., 2018; Venturini et al., 2017), instead of the conventional turbines. Beside the lower investment, the use of PATs in water systems allows the reduction of maintenance costs, a simplification of the management and an energy-neutral automation of the monitoring systems(Giudicianni et al., 2020). Usually, the PAT efficiency is lower compared to a conventional turbine (between 0.40 and 0.75 (Pérez-Sánchez et al., 2017)), but its cost may be 10-fold less (Power et al., 2017).Other PAT benefits are: (i) easy availability on markets; (ii) the large size range, suitable for several hydraulic heads and water flows; and (iii) easy installation and maintenance (Sari et al., 2018). However, the PAT adoption in water networks shows two main drawbacks(Laghari et al., 2013): (i) the lack of performance curves of pumps in reverse operation mode (Binama et al., 2017; Venturini et al., 2017); and (ii) the low PAT efficiency, when the machines do not operate at their best efficiency point (BEP) (Pérez-Sánchez et al., 2017). The latter drawback is due to the narrower flow range of PAT functioning compared to a conventional turbine (García Morillo et al., 2018). Therefore, the identification of the most suitable hydraulic machine and the corresponding operating conditions at a particular site is a crucial task for an economically viable installation of PATs(Lydon et al., 2017). Several theoretical and experimental studies have been carried out for predicting PAT performance at the BEP (Liu et al., 2019; Venturini et al., 2017). However, a model to estimate the behaviour of PAT over the entire operation range is not completely established for two reasons:(i) PAT functioning must be experimentally characterised case by case (Venturini et al., 2017); (ii) the selection of the suitable PAT for a specific location has to be based on the possible operation both at design and off-design conditions. The definition of the hydropower configuration should also consider the corresponding investment in order to provide convenient technical and economic operations. Therefore, there is a need for more research to develop an accurate methodology to identify the most suitable hydraulic machines taking into account the real PATs performance under varying conditions (Meirelles Lima et al., 2018; Sari et al., 2018; Venturini et al., 2017).

To satisfy this need, this study proposes a new methodology for PAT selection and optimal hydropower configuration. The PAT selection is based on a comprehensive literature analysis while the optimal hydropower configuration is based on a novel multi-variable optimisation method, considering both the potential electric power of the hydropower system and the corresponding cost of the electro-mechanical equipment. The proposed methodology has been applied to estimate the energy production of small-scale HP systems, the corresponding investment costs, and the greenhouse gas emissions for a real case study. Specifically, the analysis focuses on the possibility to install PATs in the collective irrigation networks of Calabria (Southern Italy).The choice is motivated by the large diffusion of these water networks in the investigated territory and the corresponding highly unexploited energy potential. This methodology may represent a valid design tool for larger hydropower exploitation in rural water systems, in order to enhance the transition of energy production from fossil fuels towards cleaner sources and to develop a low-carbon economy able to mitigate climate changes. This is particularly useful for agriculture, a sector that has increased the demand for energy and water over time(Bórawski et al., 2019) and could benefit from efficiency improvements and reductions in GHG emissions(Yan et al., 2017). An environmentally sound management of agricultural systems, in terms of energy and water, is a crucial objective to foster a more sustainable and efficient use of natural resources(Bere et al., 2017; Giudicianni et al., 2020).

2. MATERIAL AND METHODS

2.1. Study area andhydraulic characteristics of collective irrigation systems

The proposed methodologyhas been applied to evaluate the potential energy achievable by PATs in the Calabria region (Southern Italy) (Algieri et al., 2019), where the irrigation service is provided to farmers by eleven Collective Irrigation Agencies (hereinafter "CIAs") (Figure 1).Explicitly, 106 collective irrigation systems are currently working in Calabria CIAs.

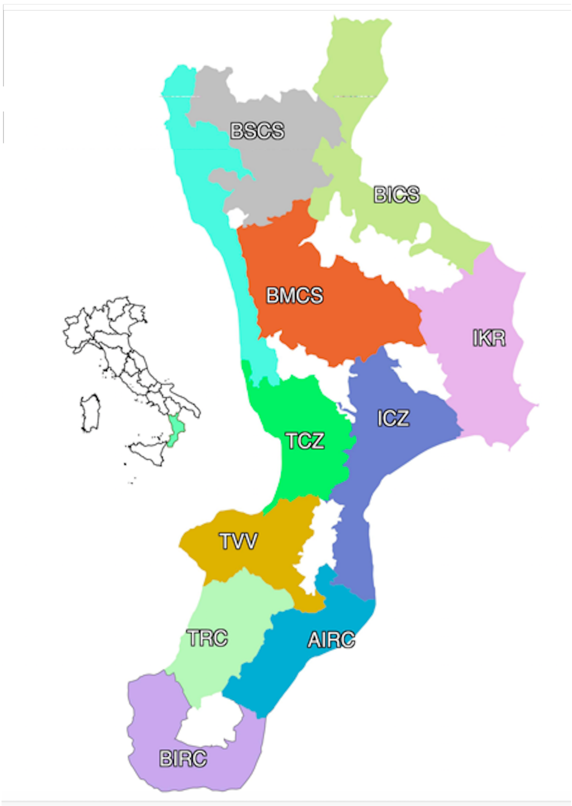


Figure 1 - Map of the eleven Collective Irrigation Agencies of Calabria (Italy).

The total length of the hydraulic networks is about 5300 km (Table 1). In general, the majority ofthe systems are old (60% are 30 years old or older) and small (more than 45% of the total number of systems individually cover an irrigated area of less than 100 ha). Usually the hydraulic network consists of a single conduit feeding distributor pipelines (pressured) or canals (free surface water), which convey and deliver water to farms by hydrants in the downstream irrigation districts. Canals in the hydraulic network are on average 30% of the total number of conduits (Table 1).

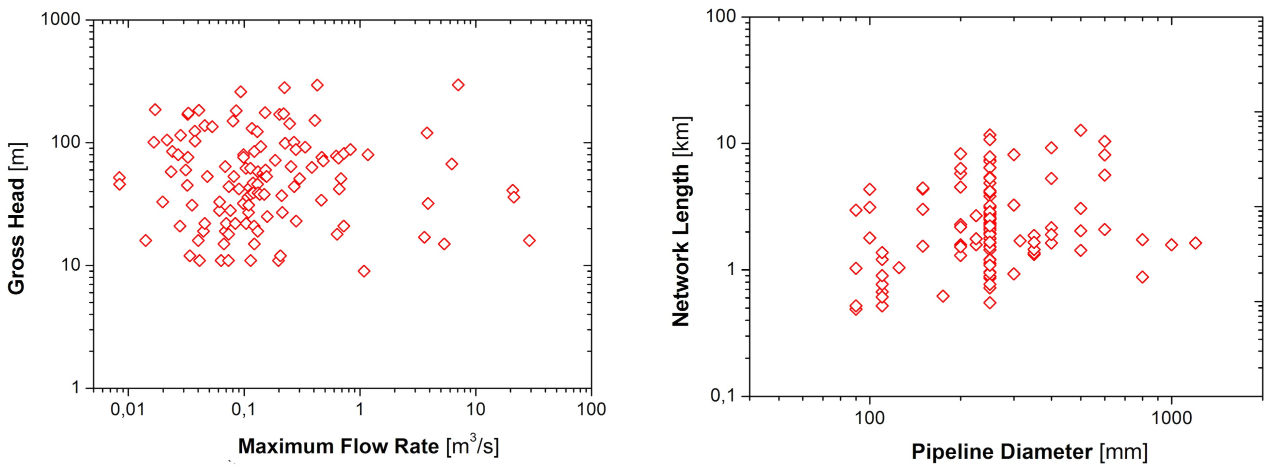
Regarding the irrigation water sources, over 60% of the collective irrigation systems are fed by surface water of torrents, 4% use water stored in lakes and artificial reservoirs, sub-surface water bodies provide irrigation water for 32% of the systems, and in 4% of the latter, groundwater is pumped from wells (Zema et al., 2018).

Table 1 – Number, length and water conveying method of the 106 collective irrigation systems functioning in Calabria (Southern Italy) (Zema et al., 2018).

Collective Irrigation Agency	**System number**	**Length** (km)		**Water conveying method** (%) (*)	
		Feeders	Distributors	Pressured pipelines	Open canals
BSCS	22	52	943	91	9
BTCS	12	53	465	100	0
BMCS	3	0	277	50	50
BICS	10	68	778	58	42
IKR	5	96	656	50	50
ICZ	8	133	167	78	22
TCZ	6	32	246	75	25
TVV	5	45	62	100	0
TRC	7	73	421	29	71
AIRC	9	58	341	78	22
BIRC	19	34	258	64	36
Total	**106**	**644**	**4610**	**70 (**)**	**30 (**)**

Note: (*) percentage on the total number of homogenous (section and material) segments of the irrigation systems; (**) value averaged among all the irrigation systems surveyed.

In this study 114 potential hydropower systems (hereinafter indicated as "PHPS") with a theoretical hydroelectric power lower than 1000 kW have been identified in the 106 collective irrigation networks of Calabria. Table 2 and Figure 2 report the main data of gross head (H_g), maximum available flow rate (Q_{av}), internal diameter (D) of pressured pipelines, and total network length (L) of the 114 PHPS analysed in the study. To summarise, $H_g$range is 9 ÷ 295 m and its average value is equal to 68.4 m, whereas Q_{av} varies from 8 to about 5400 l/s with a mean of 287 l/s. The pressured pipeline D is in the range 90 ÷ 1200 mm and L is between 0.5 and 12.7 km. A more complete characterisation of infrastructures, organisation and management of the CIAs can be found in the literature (Zema et al., 2018, 2015).



a) b)

Figure 2 – Maximum flow rates and gross heads available in the Collective Irrigation Agencies of Calabria (Southern Italy) (a). Internal pipeline diameters and total network lengths (b).

Table 2 – Statistics of the main hydraulic parameters of the 114 potential hydropower sites in the collective irrigation systems of Calabria (Southern Italy).

	Gross head [m]	**Maximum flow rate** [m^3/s]	**Pipeline diameter** [mm]	**Network length** [km]
Minimum	9.0	0.008	90.0	0.5
Maximum	295.0	5.366	1200.0	12.7
Mean	68.4	0.287	276.8	2.9
Standard deviation	58.1	0.704	172.3	2.6

In the 114 PHPSs analysed in this study the net head (H) has been evaluated as a function of the flow rate as:

$$H = H_g - Y \tag{1}$$

where Y is the sum of concentrated (Y_c) and distributed (Y_d) head losses, calculated as follows:

$$Y_c = \sum_{m=1}^{z} \xi_m \frac{Q^2}{2\,g A^2} \tag{2}$$

$$Y_d = \lambda Q^a D^{-b} L \tag{3}$$

where Q is the volumetric flow rate, g is the gravity acceleration,A is the pipeline section area, z is the number of concentrated hydraulic losses and ξ_m represents the generic concentrated loss factor (0.5 for reservoir outlet, 1 for reservoir entrance, $\left(1-D_1^2/D_2^2\right)^2$ for junction of pipelines with diameters D_1 and D_2, 0.1-0.2 for T-branch, and 0.4 for 45°-curve).D and L are the pipeline diameter and length, respectively,and λ, a and b are the coefficients of the formula adopted for the calculation of the hydraulic gradient. The latter has been calculated using Hazen-Williams equation, based on the pipeline diameter and material (plastic or metallic), and discharge(Zema et al., 2016). The calculated λ was in the range 0.0010-0.0015, while the values 4.870 and 1.852 were adopted for a and b coefficients. The total head loss over the analysed water systems was in the range 0.17-104 m. In our study, all the segments of the investigated irrigation systems can be considered as long conduits (L/D > 1000), thus the concentrated head losses can be neglected compared to the distributed losses(Zema et al., 2016). The open channels have not been considered to estimate the hydropower production.

The comparison between the characteristic curve of the hydraulic networks and the characteristics of the hydraulic machines allows the definition of the operating conditions of the SHPs.

2.2. The proposed methodology

The methodology proposed in this study consists of two main steps: (i) PAT selection; and (ii) optimal hydropower plant (HP) configuration.

2.2.1. PAT selection

A comprehensive literature analysis has been carried out to obtain detailed information on the performance of PATs - both in design and off-design conditions - for possible application in small hydropower plants SHPs (Capelo et al., 2017; Carravetta et al., 2018; Tan and Engeda, 2016; Wang et al., 2017). For this purpose, experimental investigations carried out by several researchers in the last years (Barbarelli et al., 2017; Derakhshan and Nourbakhsh, 2008; Singh, 2005; Singh and Nestmann, 2010) have been considered in order to collect accurate and reliable data about the characteristic curves of pumps operating in direct and reverse mode. Specifically, PATs have been selected based on the available flow rate and gross head of the 114 studied PHPSs.The corresponding performance at the BEP in direct and reverse modes and the PAT operating ranges have been analysed in terms of flow rate (Q), head (H), and efficiency (η). Moreover, the related specific rotational speed (n_s) and the PAT conversion factors (q and h) have been considered (Binama et al., 2017; Giosio et al., 2015; Hatata et al., 2019; Yang et al., 2012):

$$n_s = \frac{n Q_{BEP}^{1/2}}{H_{BEP}^{3/4}} \tag{4}$$

$$q = \frac{Q_{t,BEP}}{Q_{p,BEP}} \tag{5}$$

$$h = \frac{H_{t,BEP}}{H_{p,BEP}} \tag{6}$$

where n is the rotational speed, BEP represents the conditions at the best efficient point, while p and t correspond to the pump and turbine operating mode, respectively.

The factors q and h are often adopted to predict the PAT performance at the BEP, when the pump behaviour is known. Table 3 shows the main correlations proposed in the literature in the last decades as a function of the pump efficiency (η_p), turbine efficiency (η_t), and specific rotational speed (n_s) (Barbarelli et al., 2017; Jain and Patel, 2014; Nautiyal et al., 2010).

Table 3 – Literature correlations for PAT performance prediction (Barbarelli et al., 2017; Jain and Patel, 2014; Nautiyal et al., 2010).

	Method	Discharge conversion factor q	Head conversion factor h	Remarks
1	Stepanoff	$1 / \eta_p^{0.5}$	$1 / \eta_p$	Accurate for $n_s = 40 \div 60$
2	Childs	$1 / \eta_p$	$1 / \eta_p$	-
3	Hancock	$1 / \eta_t$	$1 / \eta_t$	-
4	Grover	$2.379 - 0.0264\ n_s$	$2.693 - 0.0229\ n_s$	Accurate for $n_s = 10 \div 50$
5	Sharma	$1 / \eta_p^{0.8}$	$1 / \eta_p^{1.2}$	Accurate for $n_s = 40 \div 60$
6	Schmiedl	$-1.5 + 2.4 / \eta_p^2$	$-1.4 + 2.5 / \eta_p$	-
7	Alatorre-Frenk	$(0.85\ \eta_p^5 + 0.385) / (2\ \eta_p^{9.5} + 0.205)$	$1 / (0.85\ \eta_p^5 + 0.385)$	-
8	Barbarelli et al.	$0.00026\ n_{s,t}^2 – 0.02302\ n_{s,t} + 1.88171$	$-0.00003\ n_{s,t}^3 + 0.00331\ n_{s,t}^2 + 0.15047\ n_{s,t} + 3.68497$	Accurate for $n_s = 10 \div 70$

Furthermore, the flow rate (ϕ) and head (ψ) numbers areused to compare the different hydraulic machines according to the literature(Bozorgi et al., 2013; Jain and Patel, 2014):

$$\varphi = \frac{Q}{n\ d^3} \tag{7}$$

$$\psi = \frac{gH}{n^2\ d^2} \tag{8}$$

where *d* is the outer impeller diameter.

2.2.2. Optimal Hydropower Plant (HP) configuration

The characteristic curves of the selected PATs have been compared to the characteristics of the 114 SHP sites in the CIAs of Calabria, in order to define the most suitable HP arrangements (single, parallel or series installation), the hydraulic machines (model and number), and the consequent operating conditions (flow rate, head and efficiency). To this purpose, a novel method has been proposed using a multi-variable optimisation. The method considers both the potential electric power (P_{el}) of the hydropower system and the corresponding cost of the electro-mechanical equipment (C_{EME}). The "minimum distance" criterion has been used according to the literature (Bellos et al., 2018; Bellos and Tzivanidis, 2018; Dinçer et al., 2018; Zhang et al., 2018). The method suggests adopting the system configuration that minimises the dimensionless distance to the ideal point characterised by the maximum electric power ($P_{el,max}$) and the minimum cost ($C_{EME,min}$), according to:

$$\min\left(\sqrt{\left(\frac{P_{el,\max}-P_{el,i}}{P_{el,\max}-P_{el,\min}}\right)^2+\left(\frac{C_{EME,i}-C_{EME,\min}}{C_{EME,\max}-C_{EME,\min}}\right)^2}\right) \tag{9}$$

where the subscript i refers to the generic i$^{\text{th}}$ HP configuration characterised by the electric power $P_{el,i}$ and the equipment cost $C_{EME,i}$, whereas $P_{el,min}$ and $C_{EME,max}$ indicate the minimum electric power and the maximum cost of the electro-mechanical devices, respectively.

The main steps of the procedure for the selection of the proper HP configuration for the generic site s are summarised by the flowchart of Figure 3. For each PAT (j index), different arrangements (k index) are analysed, based on single machine, parallel or series installation (k = 1, 2 or 3, respectively) and on a different number of PATs ($n_k$index). The possible operating points are characterised in terms of flow rate, head and efficiency. Furthermore, the potential electric power of the HP plant and the corresponding cost of the electro-mechanical equipment are evaluated. The procedure is repeated for all the PAT models and all the possible configurations are compared. The result of the comparisons providesthe most suitable hydropower system adopting the multi-objective optimisation based on the proper trade-off between the potential electric power and the corresponding cost of PATs and alternators, according to equation 9.

Figure 3 – Scheme of the adopted procedure to select the proper hydropower configuration for the generic site.

As an example, Figure 4 illustrates a typical scenario in terms of cost and electric power associated to different PATs and system arrangements (blue circles), when the SHP site is defined. The red circle corresponds to the ideal condition, while the black and green squares refer to the HP configurations with the highest power and the lowest cost, respectively. The selected configuration (the blue square) corresponds to the minimum distance from the ideal point and represents the appropriate balancebetween the power that can be installed and the investment cost.

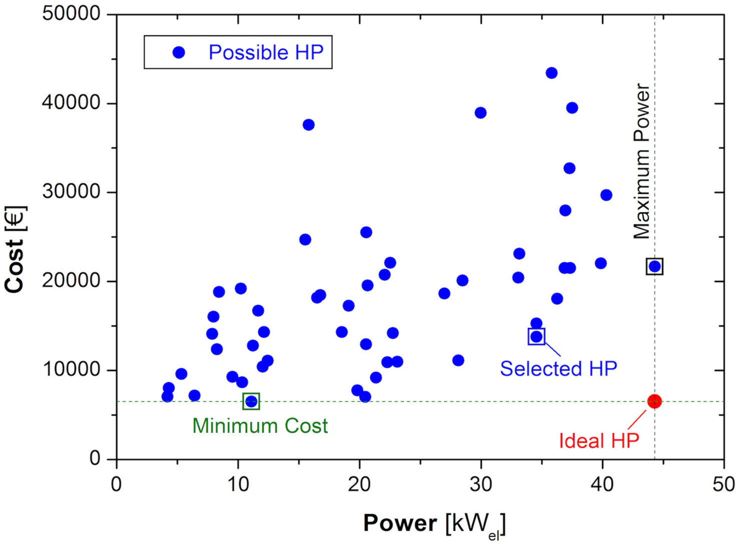


Figure 4 – Example of multi-variable optimisation for the selection of the most suitable PAT and system configuration.

In particular, the HP electric power (P_{el}) is evaluated as:

$$P_{el} = \eta_{el}\, \eta_t\, \rho\, g\, Q\, H \tag{10}$$

where η_{el} is the electric efficiency, η_t is the turbine/PAT efficiency, and ρ is the water density, whereas the cost of the hydraulic and electric machines (C_{EME}) is calculated as the sum of the costs of the PATs (C_{PAT}) and alternators (C_A):

$$C_{EME} = C_{PAT} + C_A \tag{11}$$

Figure 5 reports the cost of the pumps operating as turbines and the cost of alternators as a function of the installed power, as provided by the manufacturers' catalogues (Calpeda, 2018; Grundfos, 2019; Ksb Italia, 2019; Manel Service, 2019; Pedrollo, 2018).

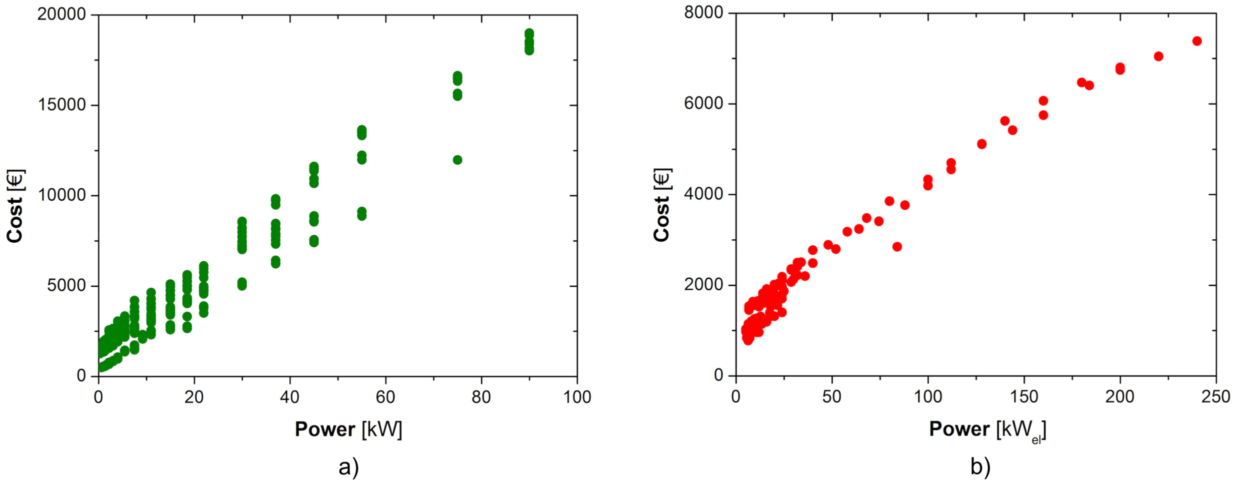


Figure 5 – Influence of nominal power on the cost of pumps (a) and alternators (b) (Calpeda, 2018; Grundfos, 2019; Ksb Italia, 2019; Manel Service, 2019; Pedrollo, 2018).

3. RESULTS AND DISCUSSIONS

3.1. PAT selection

According to the results of the literature analysis, 27 PATs have been identified based on the available flow rate and gross head of the 114 hydraulic networks investigated in the CIAs of Calabria. The corresponding performance at the best efficiency points (BEPs) in direct and reverse modes and the PATs' operating ranges are summarised in Table 4 in terms of flow rate (Q), head (H), efficiency (η), and specific speed (n_s).

For the pumping mode at the BEP, Q and H are in the range 5.28 ÷ 251 l/s and 5.32 ÷ 33.01 m, respectively, with n_s between 9.08 and 94.4 rpm, while η varies between 0.44 and 0.87. When the pump works as a turbine, Q and H at the BEP are in the range 9.72 ÷ 329 l/s and 7.82 ÷ 110 m, respectively, at speeds between 5.09 and 76.9 rpm, while η varies between 0.35 and 0.84. As a consequence, the q factor is on average 1.49 (± 0.22, coefficient of variation of 0.14) and its variability range is 1.14 ÷ 1.90, whereas the mean value of the h factor is 1.78 (± 0.49, coefficient of variation of 0.27) and varies in the range 1.34 ÷ 3.53 (Table 4).

Table 4 – Performance of the selected hydraulic machines at the BEP conditions in direct (pump) and reverse (turbine) mode, operating ranges of PATs, and conversion factors.

	Pump mode				**Turbine mode**						**Conversion factors**	
	BEP				**BEP**				**Operating range**			
PAT	Q_{BEP}	H_{BEP}	η	n_s	Q_{BEP}	H_{BEP}	η	n_s	Q	H	q	h
[-]	[l/s]	[m]	[-]	[rpm]	[l/s]	[m]	[-]	[rpm]	[l/s]	[m]	[-]	[-]
1 *	7.39	33.01	0.44	9.08	13.08	93.28	0.43	5.54	7.5 - 18.0	47.8 - 154.5	1.77	2.83
2 *	7.52	31.41	0.45	9.43	14.11	110.80	0.35	5.09	5.0 - 17.0	38.6 - 150.1	1.88	3.53
3 *	6.97	20.00	0.55	12.82	10.65	43.66	0.51	8.82	4.0 - 16.0	19.3 - 80.9	1.53	2.18
4 *	5.28	12.00	0.55	16.34	9.72	25.50	0.59	12.60	4.0 - 16.0	11.6 - 56.0	1.84	2.13
5 *	16.50	19.30	0.65	20.23	26.02	38.00	0.65	15.28	9.0 - 32.0	19.1 - 51.0	1.58	1.97
6 *	26.77	19.60	0.73	25.43	40.28	33.20	0.73	21.04	14.0 - 46.0	17.1 - 40.0	1.50	1.69
7 *	9.72	8.50	0.67	28.72	15.28	13.10	0.73	26.03	8.0 - 16.0	7.7 - 14.0	1.57	1.54
8 *	24.16	14.52	0.74	30.31	36.52	22.40	0.78	26.91	15.0 - 43.0	11.8 - 28.8	1.51	1.54
9 *	23.19	12.06	0.72	34.11	31.22	17.60	0.76	29.82	13.0 - 41.0	8.1 - 26.7	1.35	1.46
10 *	41.67	12.90	0.76	43.48	50.00	18.80	0.84	35.91	27.0 - 55.0	10.0 - 21.7	1.20	1.46
11 *	57.93	9.59	0.82	53.01	84.33	13.30	0.84	50.04	38.0 - 98.0	6.4 - 17.2	1.46	1.39
12 *	34.95	5.32	0.78	64.07	43.63	7.82	0.70	53.59	25.0 - 48.0	4.0 - 9.2	1.25	1.47
13 **	10.8	14.5	0.77	21.0	19.93	25.80	0.725	18.5	5.8 - 25.5	14.5 - 44.0	1.85	1.78
14**	26.5	21.5	0.78	24.5	50.23	47.37	0.765	18.6	17.9 - 61.2	19.8 - 68.8	1.90	2.20
15**	25.4	12.8	0.785	35.3	33.00	20.66	0.810	28.1	14.3 - 46.3	11.4 - 38.2	1.30	1.61
16**	15.3	8.4	0.744	36.4	23.55	14.42	0.715	30.1	10.3 - 34.3	6.3 - 27.7	1.54	1.72
17**	65.9	19.8	0.850	39.7	88.93	27.80	0.835	35.7	40.6 - 128.8	13.3 - 47.1	1.35	1.40
18**	33.0	10.5	0.800	45.2	45.43	14.72	0.795	41.1	21.2 - 65.8	5.2 - 28.2	1.38	1.40
19**	13.5	5.6	0.760	46.4	17.85	8.74	0.760	38.1	7.8 - 25.3	3.9 - 16.1	1.32	1.57
20**	28.9	6.4	0.720	61.3	44.94	9.32	0.743	57.6	28.1 - 54.7	4.5 - 14.1	1.56	1.46
21**	103.0	10.6	0.840	79.1	130.38	14.64	0.755	70.0	68.1 - 197.1	5.6 - 30.7	1.27	1.38
22 °	251.4	21.5	0.840	72.8	329.41	37.54	0.800	54.9	163.0 - 329.0	11.2 - 37.4	1.31	1.75
23 °	101.4	8.3	0.830	94.4	127.06	12.68	0.830	76.9	72.0 - 162.0	4.3 - 21.4	1.25	1.53
24 °°	8.0	17.8	0.650	14.6	12.46	36.46	0.640	10.9	11.0 - 17.0	26.9 - 60.1	1.56	2.05
25 °°	23.7	20.4	0.760	23.0	37.76	39.81	0.730	17.8	19.0 - 44.0	19.1 - 50.3	1.59	1.95
26 °°	57.2	18.1	0.865	37.6	84.58	31.26	0.740	31.9	31.0 - 96.0	14.6 - 36.8	1.48	1.73
27 °°	107.0	17.5	0.870	55.6	121.97	23.44	0.780	47.5	55.0 - 129.0	12.3 - 27.1	1.14	1.34

Note: *(Barbarelli et al., 2017); **(Singh and Nestmann, 2010); °(Singh, 2005); °°(Derakhshan and Nourbakhsh, 2008).

3.2. PAT performance

Figure 6 shows the head number (ψ) and the efficiency (η) as a function of the flow rate number (ϕ) of the selected PATs at the BEP both in direct and reverse operating mode. Lower ψ and ϕ have been recorded when the hydraulic machines work as pumps, according to the literature (Binama et al., 2017; Jain and Patel, 2014). In this configuration, similar ψ values have been found (in the range between 2.5 and 6.3), in spite of the large differences in the device characteristics and performance (Table 4). Conversely, in the turbine mode significant variations of ψ have been noticed, with the highest values ($\psi > 14.3$) found at low flow rate numbers($\phi < 0.02$).

The comparison between the direct and reverse operation shows similar values of the maximum efficiency, with low differences in the performance when the machines work as turbines or pumps (Figure 6b). In particular, the variations are always lower than 12.5%. Furthermore, a progressive η increasewith ϕ has been observed both in pump and turbine operating mode; values higher than 70% have been detected for the selected units, when ϕ is higher than 0.10.

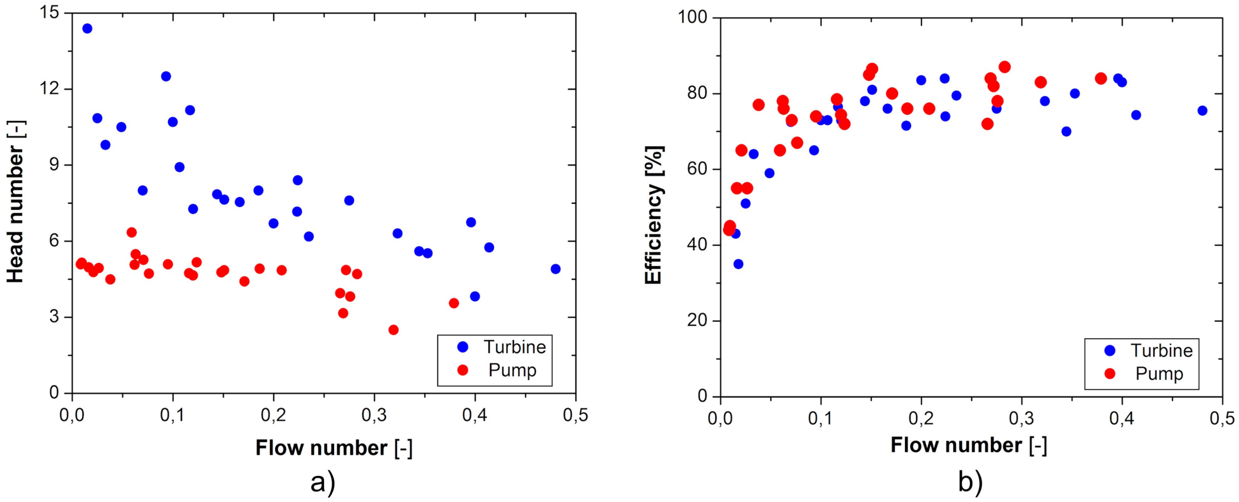


Figure 6 – Head number (a) and efficiency (b) of the selected hydraulic machines at BEP in direct and reverse mode as a function of the flow rate number.

The corresponding q and h conversion factors as functions of n_s at the BEP points for the selected PATs are summarised in Figure 7. BEPs shift towards higher ϕ and ψ when the reverse operation is active, with a mean increase equal to 49% and 78%, respectively. According to the literature, which suggests correlating q and $h$to n_s by second and third order polynomials (Barbarelli et al., 2017), this study proposes new interpolating curves of the conversion factors as follows:

$$q = -0.0002 n_s^2 - 0.0193 n_s + 1.9011 \qquad (12)$$

$$h = -0.000018 n_s^3 + 0.002764 n_s^2 - 0.134384 n_s + 3.540085 \qquad (13)$$

The percentage errors are in range -15.2% ÷ 28.0% for q and -17.1% ÷ 17.2% for h (Table 5). The analysis demonstrates that correlation rules can be adopted to obtain rough information about the PAT performance when the behaviour of the pump is known. However, detailed experimental results in reverse mode are necessary to select the most suitable PAT for each HP installation.

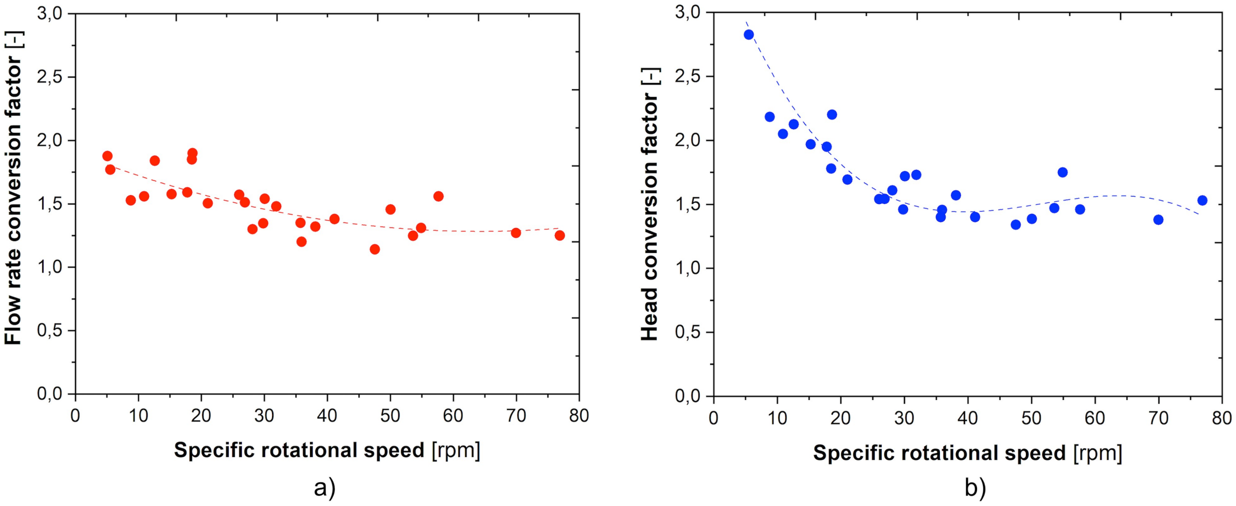


Figure 7 – Discharge (a) and head (b) correction factors as functions of the rotational speed of the selected hydraulic machines at the BEP.

Table 5 – Comparison between measured and calculated discharge (q) and head (h) conversion factors adopting the proposed correlation rules.

PAT	**n_s**	**Measured**		**Calculated**		**Error**	
[#]	**[rpm]**	**q [-]**	**h [-]**	**q [-]**	**h [-]**	**Δq [%]**	**Δh [%]**
1	5.09	1.88	3.53	1.80	2.88	-3.6	-17.1
2	5.54	1.77	2.83	1.75	2.56	1.7	1.8
3	8.82	1.53	2.18	1.71	2.38	14.3	17.2
4	10.9	1.56	2.05	1.69	2.25	9.9	16.1
5	12.60	1.84	2.13	1.65	2.07	-8.2	5.9
6	15.28	1.58	1.97	1.62	1.92	4.8	5.0
7	17.8	1.59	1.95	1.61	1.89	2.0	-1.4
8	18.5	1.85	1.78	1.61	1.88	-12.8	6.0
9	18.6	1.90	2.20	1.58	1.77	-15.2	-14.5
10	21.04	1.50	1.69	1.53	1.60	5.2	4.4
11	26.03	1.57	1.54	1.53	1.57	-2.4	3.6
12	26.91	1.51	1.54	1.52	1.55	1.0	2.1
13	28.1	1.30	1.61	1.50	1.51	16.7	-3.9
14	29.82	1.35	1.46	1.50	1.51	11.7	3.7
15	30.1	1.54	1.72	1.49	1.48	-2.5	-12.3
16	31.9	1.48	1.73	1.47	1.45	0.6	-14.4
17	35.7	1.35	1.40	1.47	1.45	8.7	3.3
18	35.91	1.20	1.46	1.46	1.44	22.2	-0.8
19	38.1	1.32	1.57	1.45	1.44	10.3	-8.5
20	41.1	1.38	1.40	1.44	1.46	4.8	2.6
21	47.5	1.14	1.34	1.44	1.48	25.9	9.3
22	50.04	1.46	1.39	1.44	1.51	-1.3	6.8
23	53.59	1.25	1.47	1.44	1.51	15.4	2.5
24	54.9	1.31	1.75	1.45	1.53	10.3	-13.4
25	57.6	1.56	1.46	1.53	1.50	-6.8	4.8
26	70.0	1.27	1.38	1.60	1.37	20.5	8.9
27	76.9	1.25	1.53	1.80	2.88	28.0	-10.7

Figure 8 highlights the percentage differences between the field test measurements and literature models for the 27 selected PATs. The mean absolute differences are always higher than 11% (Table 6), in line with the findings of several researchers in the last years (Pugliese et al., 2016). The adoption of the new correlations proposed in this study allows a reduction in the absolute mean differences by 10% and in the percentage errors under 30%; however, differences higher than 15%

have been recorded for ten of the 27 selected PATs.

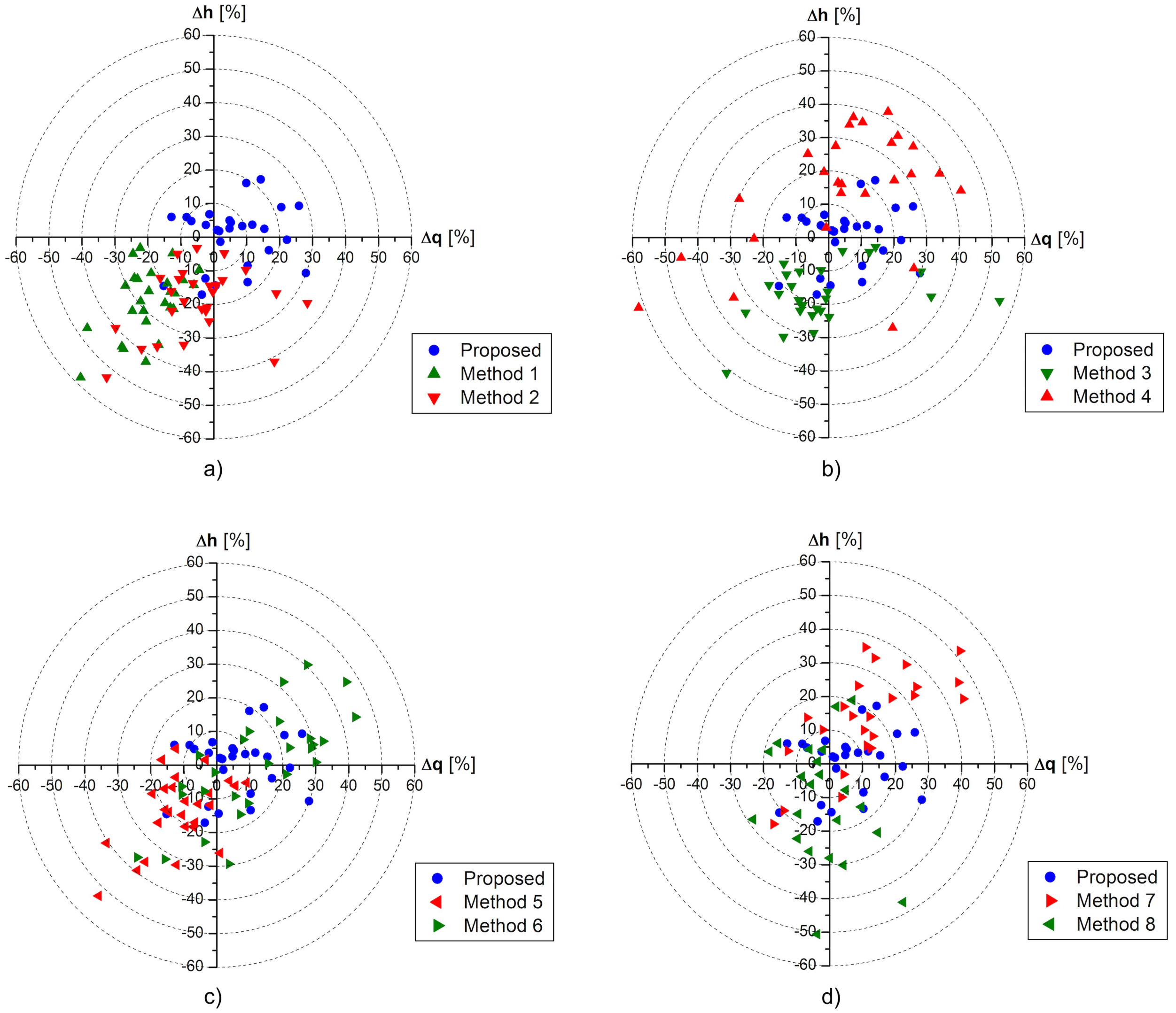


Figure 8 – Percentage errors on discharge and head correction factors for the selected hydraulic machines at the BEP. Comparison between the proposed models and literature methods 1 and 2 (a), 3 and 4 (b), 5 and 6 (c), 7 and 8 (d).

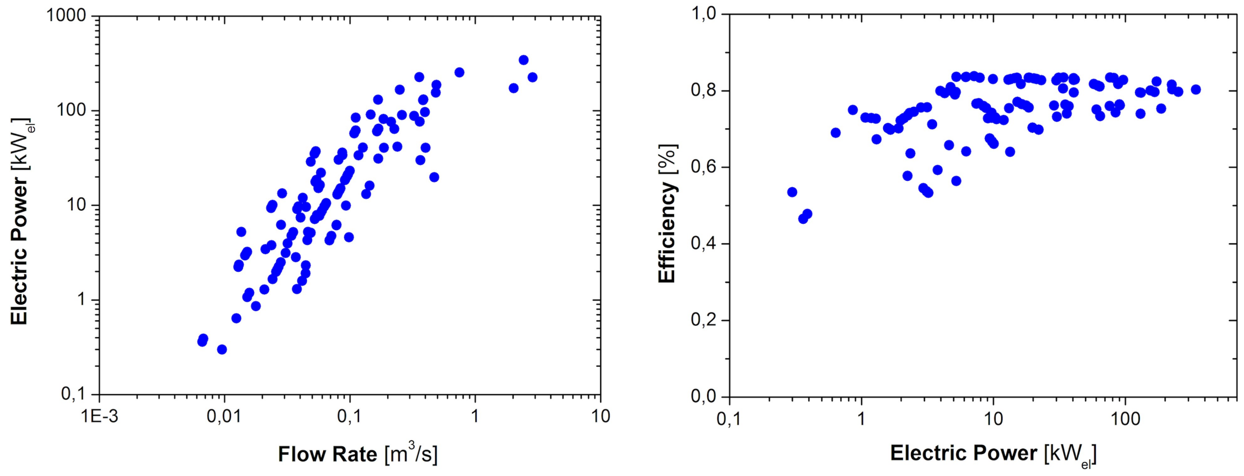
Table 6 – Mean absolute percentage errors on discharge and head conversion factors adopting the proposed and literature correlations (Barbarelli et al., 2017; Jain and Patel, 2014; Nautiyal et al., 2010).

	Author	$\|\Delta q_{mean}\|$ [%]	$\|\Delta h_{mean}\|$ [%]	Notes: investigated PATs
1	Stepanoff	16.6	14.4	PATs with $n_s = 40 \div 60$
2	Child	11.0	19.1	All
3	Hancock	12.9	17.4	All
4	Grover	12.3	23.2	PATs with $n_s = 10 \div 50$
5	Sharma	11.0	11.1	PATs with $n_s = 40 \div 60$
6	Schmiedl	17.5	12.2	All
7	Alatorre-Frenk	25.6	19.2	All
8	Barbarelli et al.	10.6	30.7	PATs with $n_s = 10 \div 70$
9	Proposed rules	9.9	7.4	All

3.3.A practicalapplication: HP potential in Calabria collective irrigation agencies

Figure 9 reports the HP performance for the 114 PHPSs investigated in the CIAs of Calabria, which have been achieved using the novel multi-variable optimisation method proposed in this study. This procedure maximises P_{el} of the HP and minimises C_{EME} of the corresponding electro-mechanical machines that can be installed in a collective irrigation system. The solutions provided by the optimisation method are characterised by mean P_{el} and PAT efficiency equal to 36.8 kW_{el} and 75.2%, respectively. Large differences in the performance of the proposed HP systems have been noticed owing to the significant variations in the characteristics of the different sites (Figure 2). In particular, the nominal P_{el} that can be installed varies between 0.3 kW_{el} and 343.4 kW_{el} with a general progressive increase in the energy potential with the flow rate (Figure 9a). The values of the PAT efficiency in the optimised HPs are in the range 47% ÷ 84% and are always higher than 70% with nominal P_{el} over 13.4 kW_{el} (Figure 9b).

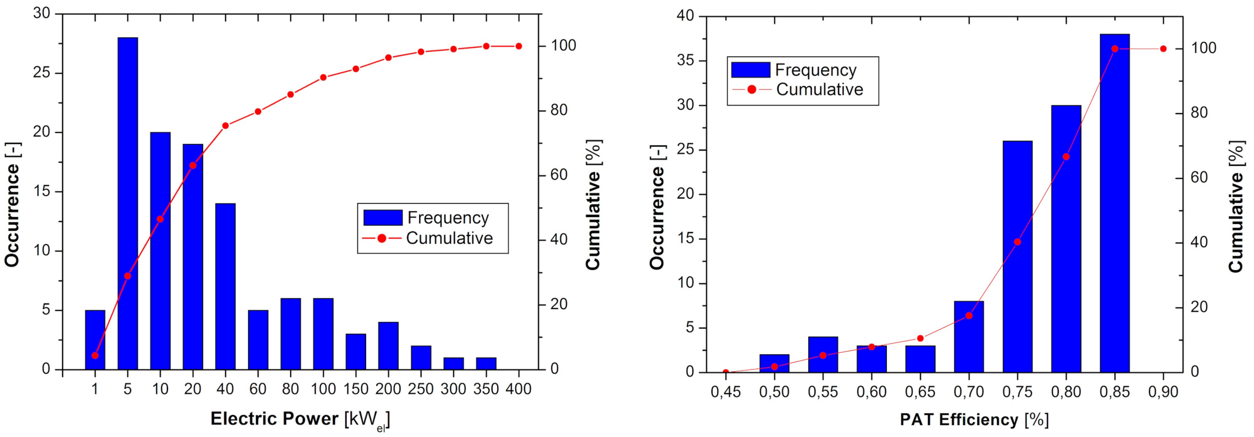
The frequency analysis of the nominal P_{el} distribution (Figure 10a) shows that the characteristics of the potential hydropower systemsof Calabria are suitable for SHPs, since it is possible to install 70 micro HP units (μHP: $5\ kW_{el} \leq P_{el} < 100\ kW_{el}$(Binama et al., 2017; Haidar et al., 2012)), 33 pico (pHP: $P_{el} < 5\ kW_{el}$), and 11 mini (mHP: $100\ kW_{el} \leq P_{el} < 1000\ kW_{el}$) HP plants.



a)

b)

Figure 9 – Potential small hydropower plants in the collective irrigation systems of Calabria (Southern Italy). Electric power (a) and corresponding PAT efficiency (b).



a)

b)

Figure 10 – Cumulative and frequency distribution of HP nominal electric power (a) and PAT efficiency (b).

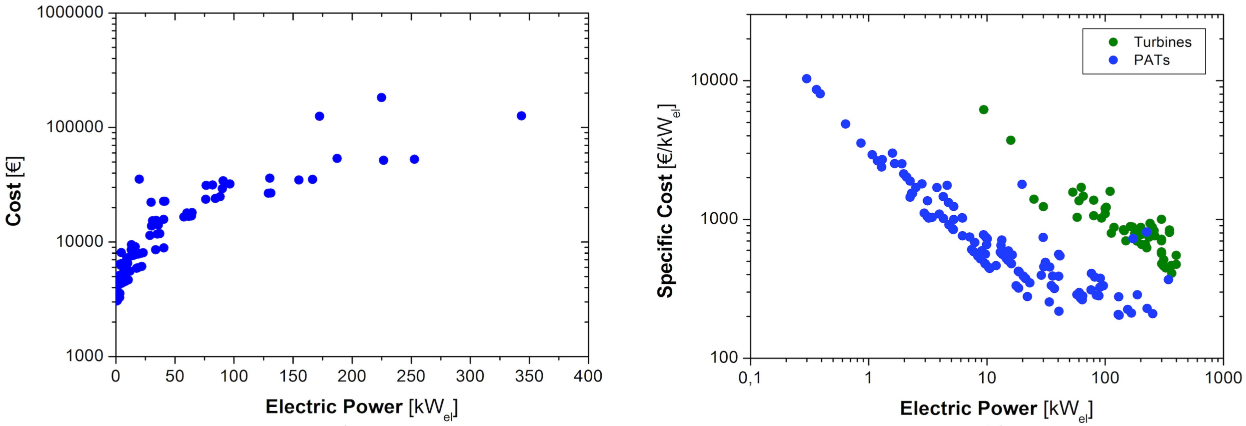
About 95% of the proposed installations have a nominal P_{el} lower than 170 kW$_{el}$ and 50% of the HPs have $P_{el} < 12$ kW$_{el}$. The largest percentages of pico and micro HPs are in the range 1 ÷ 5 kW$_{el}$ (24.6%) and 5 ÷ 10 kW$_{el}$ (17.5%), respectively. A progressive decrease in the frequency with the nominal P_{el} has been found for the mini HPs when P_{el} is higher than 150 kW$_{el}$. Furthermore, the investigation demonstrates that the collective irrigation systems and the selected PATs assure high performance both for μHP and mHP systems (Figure 10b). In fact, about 33% of the potential PATs have values of η higher than 80%, in line with systems on a similar scale adopting purpose-designed turbines. Only 17.5% of PATs operate with η lower than 70%. In particular, the lowest efficiency valueshave been found adopting pico HP plants. The optimisation procedure highlights that 70 HP systems are based on a single PAT installation, while 23 and 15 hydropower plants consist of multiple PATs in parallel and series arrangements, respectively. Six HP sites adopt combined parallel-series installations.

The values of C_{EME} as a function of P_{el} in the optimised HP plants show a global increase with the HP potential (Figure 11a). Conversely, the specific costs (C_s) of PATs and alternators highlight a progressive decrease with the installed P_{el} (Figure 11b). Specifically, when P_{el} and C_s are expressed in $\mathrm{kW_{el}}$ and €/$\mathrm{kW_{el}}$, respectively, the values of C_s can be estimated by the following equation:

$$C_s = 2393.1 P_{el}^{-0.485} \tag{14}$$

with R^2equal to79.9%.

The results of the study demonstrate that the adoption of PATs in small-scale HP plants is a viable alternative to specific site-designed hydraulic turbines owing to the significant reduction in the investment costs of the electro-mechanical devices and to the high efficiencies. To this purpose, Figure 11b depicts the specific cost of turbines for some micro and mini HP plants installed in Europe (Italy, Spain, Portugal, France, Belgium) and North Africa (Morocco) in the last years (Ogayar and Vidal, 2009). It is worthy to notice that for μHP installations (5 ÷ 100 $\mathrm{kW_{el}}$) the specific costs of PATs are about 25% of costs of turbines (Table 7). In particular, the costs of PATs and alternators for micro HP systems range between 218 and 1790 €/$\mathrm{kW_{el}}$ with a mean value of 532 €/$\mathrm{kW_{el}}$, while the corresponding average cost for turbines is 1926 €/$\mathrm{kW_{el}}$. The adoption of PATs to replace turbines in mHP systems allows more than halving C_{EME}: the mean value shifts from 760 €/$\mathrm{kW_{el}}$ of turbines to 341 €/$\mathrm{kW_{el}}$ of pumps operating as turbines. The maximum costs of PATs and alternators in pico HP (pHP) are about 10,500 €/$\mathrm{kW_{el}}$. These costs become lower than 3000 €/$\mathrm{kW_{el}}$ when the installed P_{el} is higher than 1 $\mathrm{kW_{el}}$.



a) b)

Figure 11 – Influence of the installable HP size on global (a) and specific costs (b) of optimised electro-mechanical machines.

Table 7 – Comparison of specific costs of PATs and turbines for pico, micro, and mini hydropower plants.

	Specific cost [€/kW$_{el}$]					
	Investigated PATs			**Turbines** (Ogayar and Vidal, 2009)		
	Min	Max	Mean	Min	Max	Mean
Pico HP	914.7	10323.5	2575.4	n.a.	n.a.	n.a.
Micro HP	218.2	1787.0	532.0	1021.5	6170.2	1926.0
Mini HP	204.0	812.4	341.2	410.0	1591.0	760.4

3.4. Cleaner electric production and GHG mitigation

In order to evaluate the potential electric production, the installation costs, and the amount of greenhouse gas emissions generated by the proposed small hydropower plants, the estimated electric power and costs of electro-mechanical equipment have been aggregated for the 11 CIAs of Calabria (Figure 12). In particular, the exploitation of the hydraulic energy in CIAs allows the installation of a total P_{el} equal to 4.2 MW$_{el}$; the total investment for the electro-mechanical devices (PATs and generators) in the optimised HPs is always lower than 750 €/kW$_{el}$. In a previous study (Zema et al., 2016) in the same sites of Calabrian collective irrigation agencies, a total electrical power of 5.1 MW$_{el}$and a total cost of 6.6 M€ were estimated using conventional turbines with an efficiency of 85% (the specific cost corresponds to about 1300 €/kW$_{el}$). The comparison between the data of Zema et al. (2016) and the results of this work confirms that the adoption of PATs and the optimisation procedure provide a significant decrease (-74.2%) in the total cost of electro-mechanical equipment (the investment corresponds to 1.7 M€ for the optimised PATs) whereas a slight reduction in the global SHP electric power is noticed (-18.5%).

In all the agencies P_{el} is larger than 100 kW_{el} and the highest energy potential has been found in the provinces of Cosenza, Reggio Calabria, and Vibo Valentia, where BSCS, BIRC, and TVV agencies provide nominal power between 794 and 642 kW_{el}.

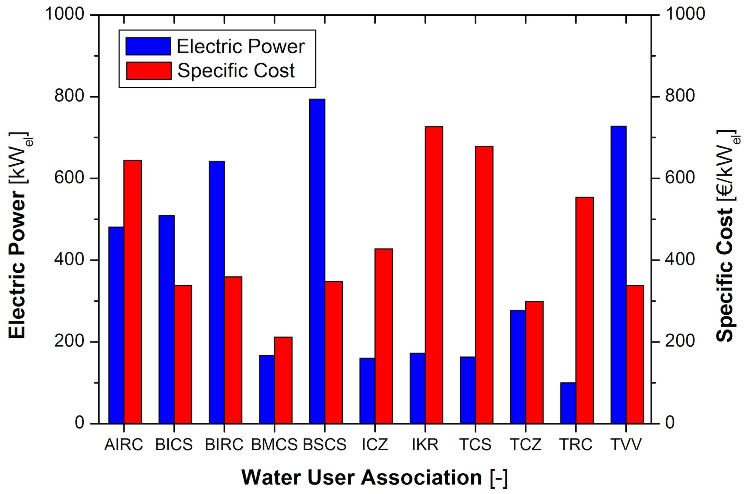


Figure 12 – Potential electric power and corresponding specific cost of electro-mechanical machines in CIAs of Calabria (Southern Italy).

The corresponding annual electric productions for the 11 CIAs are reported in Table 8. By this estimation, the HPs are supposed to work throughout seven months per year, since the irrigation period in Calabria usually lasts five months and the hydraulic systems cannot be simultaneously used for energy purposes (Zema et al., 2016).

The analysis demonstrates that all the investigated collective irrigation systems could provide an important share in the electric production, considering that the mean yearly consumption of CIAs in Calabria is equal to 856 MWh_{el}/year (Fabiani, 2014). The minimum electric generation capacity has been found in the TRC agency, which is 58.9% of the average annual electric demand, whereas values higher than 94% have been detected for the other CIAs. A positive difference between the electric production and demand has been estimated in seven CIAs.This surplus can be used to increase the revenues of irrigation and land reclamation services, thus improving the economic performance of the agencies. As an alternative, the electricity generated by the hydraulic sources in existing collective irrigation systems that currently are not exploited could satisfy a share of the electric demand of farms associated to the CIAs. Specifically, the latter could fulfil the electric load of about 2800 farms (almost 15% of the total at the regional scale), considering that the annual demand of farms in the Calabria region is on average 7.6 MWh (Terna, 2019).

Improving the energy efficiency and increasing local production of electricity from hydropower can represent the cornerstones to reduce emissions from electricity consumptions (Martire et al., 2018), especially in the agriculture sector, taking into account that agricultural products appear among the most GHG emission intensive products in the European Union (Yan et al., 2017). In this context, Table 8 illustrates that the exploitation of the untapped energy potential of Calabria CIAs provides a significant decrease in terms of CO_2 and GHG emissions, expressed as tons of CO_2 and tons of CO_2 equivalent, respectively. To this purpose the standard and LCA approaches are adopted (Cerutti et al., 2017; Koffi et al., 2017). The latter is obtained by adding the emissions from the supply chain to the standard emissions values.

In Italy the emission factors for the electricity consumption are equal to 0.343 t_{CO2}/MWh and 0.344 $t_{CO2,eq.}$/MWh when the standard approach is considered. The GHG emissions are 0.424 $t_{CO2,eq.}$/MWh for the LCA approach (Cerutti et al., 2017; Koffi et al., 2017). The corresponding emission factors for hydropower systems are zero for the standard method and 0.004 $t_{CO2,eq.}$/MWh when the lifecycle is considered. It is worthy to notice that main infrastructures (pipework, block and hatched sections) are already present in the investigated irrigation agencies and, as a consequence, the lifecycle GHG impact of the optimised SHPs is expected to be also lower than 4 $g_{CO2,eq.}$/kWh, according to the literature (Gallagher et al., 2015). The analysis demonstrates that the proposed SHPs provide significant environmental benefits compared to conventional electric production based on the Italian energy mix with renewable and non-renewable sources. In fact, the global reduction in the CO_2 emissions is larger than 7250 tons per year and more than 8800 tons of GHG emissions are avoided considering the complete supply chain.

Table 8 – Potential annual energy production and reduced emissions of CIAs of Calabria (Southern Italy).

CIAs	***HP plants***	***Electric Performance***		***Reduced emissions of***		
				CO_2	***GHG***	
		Power	***Production***	***Standard Approach***	***Standard Approach***	***LCA Approach***
[-]	[-]	[kW$_{el}$]	[MWh$_{el}$]	[t$_{CO2}$]	[t$_{CO2, eq}$]	[t$_{CO2, eq}$]
AIRC	16	480.6	2422.4	830.9	833.3	1012.6
BICS	11	508.9	2564.9	879.8	882.3	1072.1
BIRC	22	642.0	3235.8	1109.9	1113.1	1352.6
BMCS	1	166.5	839.2	287.8	288.7	350.8
BSCS	16	794.1	4002.1	1372.7	1376.7	1672.9
ICZ	6	160.1	807.1	276.8	277.6	337.4
IKR	1	172.5	869.2	298.1	299.0	363.3
TCS	20	163.3	823.2	282.4	283.2	344.1
TCZ	2	277.4	1398.2	479.6	481.0	584.4
TRC	9	100.1	504.4	173.0	173.5	210.8
TVV	10	727.6	3667.1	1257.8	1261.5	1532.8
Total	**114**	**4193.2**	**21,140.6**	**7251.2**	**7272.4**	**8836.8**

The investigation demonstrates that the proposed approach may represent a viable solution for a larger exploitation of hydropower in rural water systems. In this way, it is possible to promote an integrated development of energy, water and agricultural systems for the diffusion of cleaner energy production. Furthermore, the efficient use and the proper management of water systems can provide economic, environmental and social benefits especially in remote and isolated areas, where water and energy facilities may be particularly expensive (Giudicianni et al., 2020). The proposed methodology, developed for the Calabria region and its irrigation networks, may be easily extended and adapted to other geographic areas and different water infrastructures, with significant benefits in terms of cost reductions and environmental protection.

4. CONCLUSIONS

A new methodology for PAT selection and optimal hydropower configuration is proposed and verified in collective irrigation systems of Calabria (Southern Italy). To develop the procedure, 27 PATs have been identified to exploit the energy potential of the 106 collective irrigation systems operating in the region. The performance of the hydraulic machines has been analysed at the BEP both in direct and reverse operating mode, detecting similar values of the maximum efficiency when the machines work as turbines or pumps.

The results of this study have both theoretical and practical implications. From a theoretical point of view, two new interpolating curves for discharge and head corrections factors have been proposed. These relations permit a reduction in the errors, i.e., the distance between the observations and the simulations, compared to other models currently used in the literature. However, the analysis has demonstrated that, although correlation rules can be adopted to obtain information about the PAT performance when the behaviour of the pump is known, detailed experimental results in reverse mode are necessary to select the most suitable PAT for each HP installation. The proposed multi-variable optimisation method helps the selection and configuration of the proper PAT for each specific hydro-site, ensuring high efficiencies both in design and off-design conditions, and low costs. Moreover, the developed methodology can facilitate a larger production and use of the common hydraulic machines, with relevant advantages for pump manufacturers in the industrial sector. Furthermore, the proposed methodology could provide useful information to water network managers in order to evaluate the power and the energy recovery potential in irrigation systems, define the optimal configuration of the hydropower plants, and quantify the installation costs of electro-mechanical equipment.

From a practical point of view, the application of this new methodology to the case study has allowed the identification of the optimal hydropower configurations for the 106 collective irrigation systems operating in the CIAs of Calabria. This methodology maximises the electric power and minimises the costs of the electro-mechanical equipment that can be installed in a collective irrigation system. In the analysed CIAs, it is possible to install 70 micro, 33 pico, and 11 mini HP plants, with high performance (efficiency > 80%) both for μHP and mHP systems. The case study has also demonstrated that the adoption of PATs in small-scale HP plants represents an interesting solution for sustainable production and a viable alternative to specific site-designed hydraulic turbines. The total electric power that the 11 CIAs of Calabria can guarantee by installing PATs is equal to 4.2 MW_{el}. A 74.2% decrease in the electro-mechanical costs has been estimated when PATs are adopted to replace specific-site designed hydraulic turbines. Conversely, only a slight reduction (-18.5%) in the global electric power is registered when PATs are installed. The proposed small-scale HPs can provide a positive surplus compared to the electric demand of seven CIAs and/or satisfy a share of the electric load required by about 15% of the farms in Calabria. Furthermore, the optimised SHP systems guarantee a yearly electric production larger than 21 GWh_{el} and an interesting decrease in the GHG emissions (higher than 8800 tons/year) compared to the conventional electric generation based on the Italian energy mix.

Overall, from this study it can be deduced that, when sufficient water resources are available and important water systems are present, hydroelectricity can be produced at low cost using common hydraulic machines, as the pumps (operating as turbines). The electricity could be used to satisfy a share of the electric demand of collective agencies and/or agricultural farms. This provides significant economic and environmental benefits avoidingwasting the available hydraulic energy, as currently happens. The surplus energy may be injected into the electric grid; thus, the CIAs may become industrial producers of renewable energy. On a broader points of view, the larger use of small-scale and cheap hydropower plants in agricultural areas can be also a contribution to both the development of rural territories and to the transition of energy production from fossil fuels towards cleaner sources in a sector with large requirements of water and energy.

NOMENCLATURE

Symbols

A	*Area;*
a	*Coefficient of Hazen-Williams equation;*
b	*Coefficient of Hazen-Williams equation;*
C	*Cost*
D	*Pipeline diameter;*
d	*Pump impeller diameter;*
H	*Head;*
h	*Head conversion factor;*
g	*Gravity acceleration;*
L	*Network length;*
n	*Rotational speed;*
n_k	*Number of PATs;*
P	*Power;*

Q	*Flow rate;*
q	*Flow rate conversion factor;*
s	*Generic hydropower site;*
Y	*Head losses.*

Greek symbols

ξ	*Concentrated loss factor;*
ϕ	*Dimensionless flow rate;*
λ	*Coefficient of Hazen-Williams equation;*
η	*Efficiency;*
ψ	*Dimensionless head.*

Subscripts

A	*Alternator;*
av	*Available;*
c	*Concentrated;*
d	*Distributed;*
el	*Electric;*
EME	*Electro-mechanical equipment;*
g	*Gross;*
i	*Generic hydropower configuration;*
imp	*Impeller;*
j	*Generic PAT model;*
k	*Generic PAT arrangement;*
max	*Maximum;*
min	*Minimum;*
p	*Pump;*
s	*Specific;*
t	*Turbine.*

Acronyms

BEP	*Best efficient point;*
CIA	*Collective irrigation agency;*
HP	*Hydropower plant;*

PAT	*Pump as turbine;*
PHPS	*Potential hydropower site*
SHP	*Small hydropower plant;*

Acronyms of the Collective Irrigation Agencies in Calabria (Southern Italy)

AIRC	*Alto Ionio Reggino;*
BCSC	*Bacini Settentrionali del Cosentino;*
BICS	*Bacini dello Ionio Cosentino;*
BIRC	*Basso Ionio Reggino;*
BMCS	*Bacini Meridionali del Cosentino;*
BTCS	*Bacini del Tirreno Cosentino;*
ICZ	*Ionio Catanzarese;*
IKR	*Ionio Crotonese;*
TCZ	*Tirreno Catanzarese;*
TRC	*Tirreno Reggino;*
TVV	*TirrenoVibonese.*

REFERENCES

Adhau, S.P., Moharil, R.M., Adhau, P.G., 2012. Mini-hydro power generation on existing irrigation projects: Case study of Indian sites. Renew. Sustain. Energy Rev. 16, 4785–4795. https://doi.org/10.1016/j.rser.2012.03.066

Algieri, A., Andiloro, S., Tamburino, V., Zema, D.A., 2019. The potential of agricultural residues for energy production in Calabria (Southern Italy). Renew. Sustain. Energy Rev. 104, 1–14. https://doi.org/10.1016/j.rser.2019.01.001

Al-Shetwi, A.Q., Hannan, M.A., Jern, K.P., Mansur, M., Mahlia, T.M.I., 2020. Grid-connected renewable energy sources: Review of the recent integration requirements and control methods. J. Clean. Prod. 253, 119831. https://doi.org/10.1016/j.jclepro.2019.119831

Barbarelli, S., Amelio, M., Florio, G., 2017. Experimental activity at test rig validating correlations to select pumps running as turbines in microhydro plants. Energy Convers. Manag. 149, 781–797. https://doi.org/10.1016/j.enconman.2017.03.013

Bellos, E., Tzivanidis, C., 2018. Multi-objective optimization of a solar driven trigeneration system. Energy 149, 47–62. https://doi.org/10.1016/j.energy.2018.02.054

Bellos, E., Vellios, L., Theodosiou, I.-C., Tzivanidis, C., 2018. Investigation of a solar-biomasspolygeneration system. Energy Convers. Manag. 173, 283–295. https://doi.org/10.1016/j.enconman.2018.07.093

Bere, J., Jones, C., Jones, S., Munday, M., 2017. Energy and development in the periphery: A regional perspective on small hydropower projects. Environ. Plan. C Polit. Space 35, 355–375. https://doi.org/10.1177/0263774X16662029

Berrada, A., Bouhssine, Z., Arechkik, A., 2019. Optimisation and economic modeling of micro hydropower plant integrated in water distribution system. J. Clean. Prod. 232, 877–887. https://doi.org/10.1016/j.jclepro.2019.06.036

Binama, M., Su, W.-T., Li, X.-B., Li, F.-C., Wei, X.-Z., An, S., 2017. Investigation on pump as turbine (PAT) technical aspects for micro hydropower schemes: A state-of-the-art review. Renew. Sustain. Energy Rev. 79, 148–179. https://doi.org/10.1016/j.rser.2017.04.071

Bórawski, P., Bełdycka-Bórawska, A., Szymańska, E.J., Jankowski, K.J., Dubis, B., Dunn, J.W., 2019. Development of renewable energy sources market and biofuels in The European Union. J. Clean. Prod. 228, 467–484. https://doi.org/10.1016/j.jclepro.2019.04.242

Bozorgi, A., Javidpour, E., Riasi, A., Nourbakhsh, A., 2013. Numerical and experimental study of using axial pump as turbine in Pico hydropower plants. Renew. Energy 53, 258–264. https://doi.org/10.1016/j.renene.2012.11.016

Butera, I., Balestra, R., 2015. Estimation of the hydropower potential of irrigation networks. Renew. Sustain. Energy Rev. 48, 140–151. https://doi.org/10.1016/j.rser.2015.03.046

Calpeda - www.calpeda.com, 2018. Price List.

Capelo, B., Pérez-Sánchez, M., Fernandes, J.F.P., Ramos, H.M., López-Jiménez, P.A., Branco, P.J.C., 2017. Electrical behaviour of the pump working as turbine in off grid operation. Appl. Energy 208, 302–311. https://doi.org/10.1016/j.apenergy.2017.10.039

Carapellucci, R., Giordano, L., Pierguidi, F., 2015. Techno-economic evaluation of small-hydro power plants: Modelling and characterisation of the Abruzzo region in Italy. Renew. Energy 75, 395–406. https://doi.org/10.1016/j.renene.2014.10.008

Carravetta, A., DerakhshanHoureh, S., Ramos, H.M., 2018. Pumps as Turbines, Springer Tracts in Mechanical Engineering. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-67507-7

Cerutti, A.K., Duerr, M., Iancu, A., Janssens-Maenhout, G., Koffi, B., Kona, A., Covenant of Mayors & Mayors Adapt Offices, European Commission, Joint Research Centre, 2017. Covenant of Mayors for Climate and Energy: default emission factors for local emission inventories : version 2017.

Chacón, M.C., Rodríguez-Díaz, J.A., Morillo, J.G., Gallagher, J., Coughlan, P., McNabola, A., 2018. Potential Energy Recovery Using Micro-Hydropower Technology in Irrigation Networks: Real-World Case Studies in the South of Spain. Proceedings 2, 679. https://doi.org/10.3390/proceedings2110679

Crespo Chacón, M., Rodríguez Díaz, J.A., García Morillo, J., McNabola, A., 2020. Hydropower energy recovery in irrigation networks: Validation of a methodology for flow prediction and pump as turbine selection. Renew. Energy 147, 1728–1738. https://doi.org/10.1016/j.renene.2019.09.119

Dedić-Jandrek, H., Nižetić, S., 2019. Small scale archimedes hydro power plant test station: Design and experimental investigation. J. Clean. Prod. 231, 756–771. https://doi.org/10.1016/j.jclepro.2019.05.234

Derakhshan, S., Nourbakhsh, A., 2008. Experimental study of characteristic curves of centrifugal pumps working as turbines in different specific speeds. Exp. Therm. Fluid Sci. 32, 800–807. https://doi.org/10.1016/j.expthermflusci.2007.10.004

Dinçer, İ., Rosen, M., Ahmadi, P., 2018. Optimization of energy systems. John Wiley & Sons, Chichester, West Sussex, UK.

Du, J., Yang, H., Shen, Z., Chen, J., 2017. Micro hydro power generation from water supply system in high rise buildings using pump as turbines. Energy 137, 431–440. https://doi.org/10.1016/j.energy.2017.03.023

Fabiani, S., 2014. Il potenziale di efficientamento energetico nei Consorzi di Bonifica.(in Italian) https://doi.org/10.13140/RG.2.1.4062.5127

Fan, Y.V., Chin, H.H., Klemeš, J.J., Varbanov, P.S., Liu, X., 2020. Optimisation and process design tools for cleaner production. J. Clean. Prod. 247, 119181. https://doi.org/10.1016/j.jclepro.2019.119181

Farfan, J., Breyer, C., 2017. Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. J. Clean. Prod. 141, 370–384. https://doi.org/10.1016/j.jclepro.2016.09.068

Feng, Z., Niu, W., Cheng, C., 2018. Optimizing electrical power production of hydropower system by uniform progressive optimality algorithm based on two-stage search mechanism and uniform design. J. Clean. Prod. 190, 432–442. https://doi.org/10.1016/j.jclepro.2018.04.134

Gallagher, J., Styles, D., McNabola, A., Williams, A.P., 2015. Life cycle environmental balance and greenhouse gas mitigation potential of micro-hydropower energy recovery in the water industry. J. Clean. Prod. 99, 152–159. https://doi.org/10.1016/j.jclepro.2015.03.011

García Morillo, J., McNabola, A., Camacho, E., Montesinos, P., Rodríguez Díaz, J.A., 2018. Hydro-power energy recovery in pressurized irrigation networks: A case study of an Irrigation District in the South of Spain. Agric. Water Manag. 204, 17–27. https://doi.org/10.1016/j.agwat.2018.03.035

Giosio, D.R., Henderson, A.D., Walker, J.M., Brandner, P.A., Sargison, J.E., Gautam, P., 2015. Design and performance evaluation of a pump-as-turbine micro-hydro test facility with incorporated inlet flow control. Renew. Energy 78, 1–6. https://doi.org/10.1016/j.renene.2014.12.027

Giudicianni, C., Herrera, M., di Nardo, A., Carravetta, A., Ramos, H.M., Adeyeye, K., 2020. Zero-net energy management for the monitoring and control of dynamically-partitioned smart water systems. J. Clean. Prod. 252, 119745. https://doi.org/10.1016/j.jclepro.2019.119745

Grundfos - https://www.grundfos.com, 2019. Price List 2019 (in Italian).

Haidar, A.M.A., Senan, M.F.M., Noman, A., Radman, T., 2012. Utilization of pico hydro generation in domestic and commercial loads. Renew. Sustain. Energy Rev. 16, 518–524. https://doi.org/10.1016/j.rser.2011.08.017

Hatata, A.Y., El-Saadawi, M.M., Saad, S., 2019. A feasibility study of small hydro power for selected locations in Egypt. Energy Strategy Rev. 24, 300–313. https://doi.org/10.1016/j.esr.2019.04.013

International Energy Agency (IEA), 2019. Electricity Statistics. https://www.iea.org/statistics/electricity/ (accessed 20 October 2019).

Jain, S.V., Patel, R.N., 2014. Investigations on pump running in turbine mode: A review of the state-of-the-art. Renew. Sustain. Energy Rev. 30, 841–868. https://doi.org/10.1016/j.rser.2013.11.030

Jawahar, C.P., Michael, P.A., 2017. A review on turbines for micro hydro power plant. Renew. Sustain. Energy Rev. 72, 882–887. https://doi.org/10.1016/j.rser.2017.01.133

Koffi, B., Cerutti, A.K., Duerr, M., Iancu, A., Kona, A., Janssens-Maenhout, G., 2017. CoM Default Emission Factors for the Member States of the European Union - Version 2017.

Ksb Italia - www.ksb.it, 2019. Pump Catalogue Price List 2019 (in Italian).

Laghari, J.A., Mokhlis, H., Bakar, A.H.A., Mohammad, H., 2013. A comprehensive overview of new designs in the hydraulic, electrical equipments and controllers of mini hydro power plants making it cost effective technology. Renew. Sustain. Energy Rev. 20, 279–293. https://doi.org/10.1016/j.rser.2012.12.002

Li, H.X., Edwards, D.J., Hosseini, M.R., Costin, G.P., 2020. A review on renewable energy transition in Australia: An updated depiction. J. Clean. Prod. 242, 118475. https://doi.org/10.1016/j.jclepro.2019.118475

Liu, M., Tan, L., Cao, S., 2019. Theoretical model of energy performance prediction and BEP determination for centrifugal pump as turbine. Energy 172, 712–732. https://doi.org/10.1016/j.energy.2019.01.162

Lydon, T., Coughlan, P., McNabola, A., 2017. Pressure management and energy recovery in water distribution networks: Development of design and selection methodologies using three pump-as-turbine case studies. Renew. Energy 114, 1038–1050. https://doi.org/10.1016/j.renene.2017.07.120

Manel Service, 2019. Alternators (in Italian). https://www.manelservice.com/shop/ (accessed 20 October 2019).

Martinez, J.J., Daniel Deng, Z., Klopries, E.-M., Mueller, R.P., Scott Titzler, P., Zhou, D., Beirao, B., Hansten, A.W., 2019. Characterization of a siphon turbine to accelerate low-head hydropower deployment. J. Clean. Prod. 210, 35–42. https://doi.org/10.1016/j.jclepro.2018.10.345

Martire, S., Mirabella, N., Sala, S., 2018. Widening the perspective in greenhouse gas emissions accounting: The way forward for supporting climate and energy policies at municipal level. J. Clean. Prod. 176, 842–851. https://doi.org/10.1016/j.jclepro.2017.12.055

Meirelles Lima, G., Brentan, B.M., Luvizotto, E., 2018. Optimal design of water supply networks using an energy recovery approach. Renew. Energy 117, 404–413. https://doi.org/10.1016/j.renene.2017.10.080

Meschede, H., 2019. Increased utilisation of renewable energies through demand response in the water supply sector – A case study. Energy 175, 810–817. https://doi.org/10.1016/j.energy.2019.03.137

Mikulčić, H., Baleta, J., Klemeš, J.J., 2020. Sustainability through combined development of energy, water and environment systems. J. Clean. Prod. 251, 119727. https://doi.org/10.1016/j.jclepro.2019.119727

Nautiyal, H., Varun, Kumar, A., 2010. Reverse running pumps analytical, experimental and computational study: A review. Renew. Sustain. Energy Rev. 14, 2059–2067. https://doi.org/10.1016/j.rser.2010.04.006

Ogayar, B., Vidal, P.G., 2009. Cost determination of the electro-mechanical equipment of a small hydro-power plant. Renew. Energy 34, 6–13. https://doi.org/10.1016/j.renene.2008.04.039

Okot, D.K., 2013. Review of small hydropower technology. Renew. Sustain. Energy Rev. 26, 515–520. https://doi.org/10.1016/j.rser.2013.05.006

Paish, O., 2002. Small hydro power: technology and current status. Renew. Sustain. Energy Rev. 6, 537–556. https://doi.org/10.1016/S1364-0321(02)00006-0

Pedrollo - www.pedrollo.com, 2018. Price List 2018 (in Italian).

Penche, C., 1998. Laymańs Guidebook on How to Develop a Small Hydro Site.

Pérez-Sánchez, M., Sánchez-Romero, F., Ramos, H., López-Jiménez, P., 2017. Energy Recovery in Existing Water Networks: Towards Greater Sustainability. Water 9, 97. https://doi.org/10.3390/w9020097

Pérez-Sánchez, M., Sánchez-Romero, F., Ramos, H., López-Jiménez, P., 2016. Modeling Irrigation Networks for the Quantification of Potential Energy Recovering: A Case Study. Water 8, 234. https://doi.org/10.3390/w8060234

Pérez-Sánchez, M., Sánchez-Romero, F.J., López-Jiménez, P.A., Ramos, H.M., 2018. PATs selection towards sustainability in irrigation networks: Simulated annealing as a water management tool. Renew. Energy 116, 234–249. https://doi.org/10.1016/j.renene.2017.09.060

Power, C., Coughlan, P., McNabola, A., 2017. Microhydropower Energy Recovery at Wastewater-Treatment Plants: Turbine Selection and Optimization. J. Energy Eng. 143, 04016036. https://doi.org/10.1061/(ASCE)EY.1943-7897.0000383

Pugliese, F., De Paola, F., Fontana, N., Giugni, M., Marini, G., 2016. Experimental characterization of two Pumps As Turbines for hydropower generation. Renew. Energy 99, 180–187. https://doi.org/10.1016/j.renene.2016.06.051

Sari, M.A., Badruzzaman, M., Cherchi, C., Swindle, M., Ajami, N., Jacangelo, J.G., 2018. Recent innovations and trends in in-conduit hydropower technologies and their applications in water distribution systems. J. Environ. Manage. 228, 416–428. https://doi.org/10.1016/j.jenvman.2018.08.078

Serpoush, B., Khanian, M., Shamsai, A., 2017. Hydropower plant site spotting using geographic information system and a MATLAB based algorithm. J. Clean. Prod. 152, 7–16. https://doi.org/10.1016/j.jclepro.2017.03.095

Singh, P., 2005. Optimization of the Internal Hydraulic and of System Design in Pumps as Turbines with Field Implementation and Evaluation.

Singh, P., Nestmann, F., 2010. An optimization routine on a prediction and selection model for the turbine operation of centrifugal pumps. Exp. Therm. Fluid Sci. 34, 152–164. https://doi.org/10.1016/j.expthermflusci.2009.10.004

Tan, X., Engeda, A., 2016. Performance of centrifugal pumps running in reverse as turbine: Part Ⅱ - systematic specific speed and specific diameter based performance prediction. Renew. Energy 99, 188–197. https://doi.org/10.1016/j.renene.2016.06.052

Terna, 2019. Statistical Publications. https://www.terna.it/en/electric-system/statistical-data-forecast/statistical-publications (accessed 20 October 2019)

Ueda, T., Roberts, E.S., Norton, A., Styles, D., Williams, A.P., Ramos, H.M., Gallagher, J., 2019. A life cycle assessment of the construction phase of eleven micro-hydropower installations in the UK. J. Clean. Prod. 218, 1–9. https://doi.org/10.1016/j.jclepro.2019.01.267

Venturini, M., Alvisi, S., Simani, S., Manservigi, L., 2017. Energy Production by Means of Pumps As Turbines in Water Distribution Networks. Energies 10, 1666. https://doi.org/10.3390/en10101666

Viteri, J.P., Henao, F., Cherni, J., Dyner, I., 2019. Optimizing the insertion of renewable energy in the off-grid regions of Colombia. J. Clean. Prod. 235, 535–548. https://doi.org/10.1016/j.jclepro.2019.06.327

Wang, T., Wang, C., Kong, F., Gou, Q., Yang, S., 2017. Theoretical, experimental, and numerical study of special impeller used in turbine mode of centrifugal pump as turbine. Energy 130, 473–485. https://doi.org/10.1016/j.energy.2017.04.156

Yan, Q., Yin, J., Baležentis, T., Makutėnienė, D., Štreimikienė, D., 2017. Energy-related GHG emission in agriculture of the European countries: An application of the Generalized Divisia Index. J. Clean. Prod. 164, 686–694. https://doi.org/10.1016/j.jclepro.2017.07.010

Yang, S.-S., Derakhshan, S., Kong, F.-Y., 2012. Theoretical, numerical and experimental prediction of pump as turbine performance. Renew. Energy 48, 507–513. https://doi.org/10.1016/j.renene.2012.06.002

Zapata-Sierra, A.J., Manzano-Agugliaro, F., 2019. Proposed methodology for evaluation of small hydropower sustainability in a Mediterranean climate. J. Clean. Prod. 214, 717–729. https://doi.org/10.1016/j.jclepro.2018.12.327

Zema, D.A., Angelo Nicotra, Vincenzo Tamburino, Santo Marcello Zimbone, 2017. Energy production by small hydro power plants in collective irrigation systems of calabria (southern italy). Chem. Eng. Trans. 58, 523–528. https://doi.org/10.3303/CET1758088

Zema, D.A., Nicotra, A., Tamburino, V., Zimbone, S.M., 2016. A simple method to evaluate the technical and economic feasibility of micro hydro power plants in existing irrigation systems. Renew. Energy 85, 498–506. https://doi.org/10.1016/j.renene.2015.06.066

Zema, D.A., Nicotra, A., Tamburino, V., Zimbone, S.M., 2015. Performance Assessment Of Collective Irrigation In Water Users' Associations Of Calabria (Southern Italy):

Performance Of Collective Irrigation In Southern Italy. Irrig. Drain. 64, 314–325. https://doi.org/10.1002/ird.1902

Zema, D.A., Nicotra, A., Zimbone, S.M., 2018. Diagnosis and Improvement of the Collective Irrigation and Drainage Services in Water Users' Associations of Calabria (Southern Italy): Collective irrigation and drainage in Calabrian WUAs (Southern Italy). Irrig. Drain. 67, 629–644. https://doi.org/10.1002/ird.2276

Zhang, Y., Deng, S., Zhao, L., Lin, S., Ni, J., Ma, M., Xu, W., 2018. Optimization and multi-time scale modeling of pilot solar driven polygeneration system based on organic Rankine cycle. Appl. Energy 222, 396–409. https://doi.org/10.1016/j.apenergy.2018.03.118

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