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Energy recovery from rectangular weirs in wastewater treatment plants†

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Abstract: Hydraulic turbines for energy recovery in wastewater treatment plants, with relatively large discharges and small head jumps, are usually screw or Kaplan types. In the specific case of a small head jump (about 3 m) underlying a rectangular weir in the major Palermo (Italy) treatment plant, a traditional Kaplan solution is compared with two other ones: a Hydrostatic Pressure Machine (HPM) located in the upstream channel and a cross-flow turbine located in a specific underground room downstream the same channel.

Keywords: Hydrostatic Pressure Machine; Cross-flow turbine; Low head turbines.

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1. Introduction

WasteWater treatment plants (WWTPs) are industrial systems that require large amounts of electricity for their processes [1]. The awareness that these systems, in order to guarantee compliance with the environmental limits of the threated water, require high quantities of energy, combined with the growing need to make these systems increasingly sustainable, have encouraged research and the use of methodologies for the energy efficiency and partial recovery [2]. The proposed work is placed in this context and aims to investigate, through a case study, the possibility of electrical energy recovery within the water treatment cycle using low-cost hydraulic turbines.

2. Turbine description and selection

In WWTPs many sections of the water treatment lines are usually suitable for hydropower production. In the traditional mosaic diagram discharge and head drop usually fall in the range of low-head turbines, with a weakly variable discharge greater than many hundred l/s and a head drop smaller than 4-5 m. In this field Kaplan turbines have usually the larger efficiencies, along with a significant construction and installation cost. In the following, the performance of a commercial small Kaplan turbine is compared, for a specific case study, with two possible alternatives, recently proposed in literature. The first alternative is a Cross-Flow turbine with horizontal axis, designed according to the procedure proposed in [3-7] The second one is the Hydrostatic Pressure Machine (HPM), proposed in [8-11], which is a "mill" type turbine to be displaced inside an open channel.

2.1. Cross-flow turbine

Cross-Flow turbines are traditionally classified as action turbines, with a good performance in the same field of the more expensive Francis turbines. The water flux enters inside the rotor through the inlet surface of the nozzle in the first stage and leaves it through the exit one. A mobile flap allows a restriction of the inlet area to change the characteristic curve when a discharge reduction occurs, with a minimum efficiency reduction. New design criteria have been proposed in [3-7]. According to these criteria high efficiency values, up to 83%, have been previously obtained both in 3D ANSYS CFX simulations and in lab experiments using standard head drop values [12].

A more extended discussion of the Cross-Flow turbine design and of its management criteria can be found in [3-7].

2.2. Hydrostatic Pressure Machine (HPM)

The Hydrostatic Pressure Machine (HPM) is a novel type of hydropower converter [8] inspired to the ancient water mills. HPM converts only the potential energy of the water flow, without any transformation from the potential to the kinetic form [9].

HPM installation inside a channel requires very little modifications of the existing infrastructure and is a good choice in water flumes with very low available head drop, like irrigation or wastewater channels, where conventional hydraulic or hydrokinetic turbines are inefficient, or just too expensive because of the low power rating [9].

The functional scheme of the HPM is shown in Figure 1.

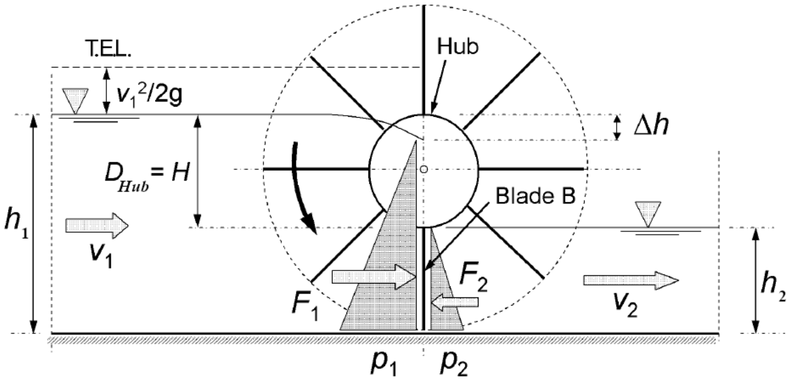

Figure 1. Functional scheme of the HPM

Where:
T.E.L.: Total Energy Level [m];
h_1: the water depth of the upstream channel [m];
h_2: the water depth of the downstream channel [m];
H: the Head difference [m];
v_1: the water upstream velocity [m/s];
v_2: the water downstream velocity [m/s];

$$\Delta h = \frac{{v_2}^2 - {v_1}^2}{2g}; \quad (1)$$

F_1: the force acting on the blade per unit width [N/m];
F_2: the reaction force on the blade per unit width [N/m].

A more extended discussion of the turbine design and management criteria can be found in [8-11].

3. Case study: Acqua dei Corsari wastewater treatment plant

AMAP S.p.A. is responsible for the integrated water service in 35 municipalities of the Metropolitan City of Palermo. The integrated water service also includes the transport of wastewater, its treatment and disposal. The wastewater treatment plant named "Acqua dei Corsari" covers an area of approximately 110 000 m^2 and is located at the south-east end of the city of Palermo, at an average altitude of 10 m above sea level.

In the plant, the wastewater treatment is divided in two different steps: water line and sludge line. The first step includes the coarse and fine grilling processes, sands and oils removal, primary sedimentation, the activated sludge process, final sedimentation and disinfection. The second step includes the pre-thickening, the anaerobic sludge digestion, the chemical conditioning and the sludge mechanical dewatering (Figure 2).

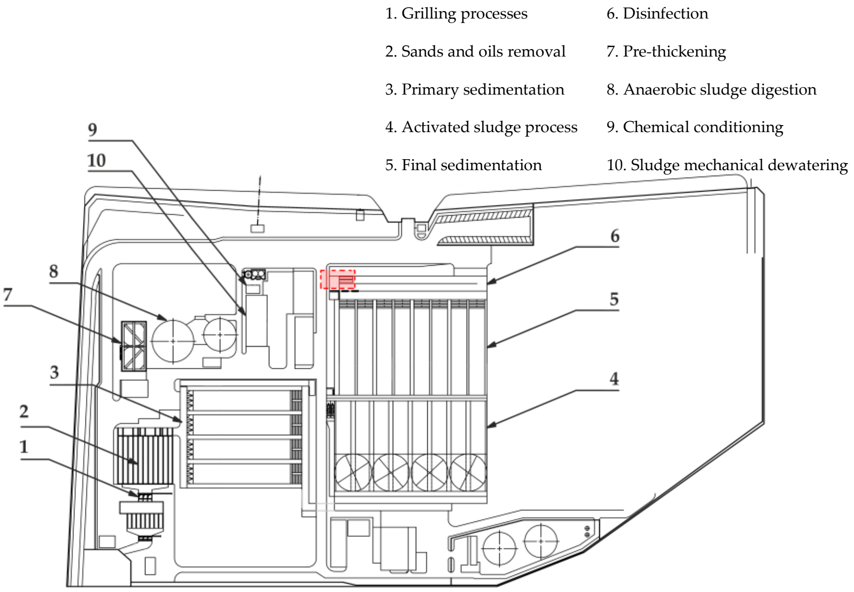

Figure 2. Acqua dei Corsari" WWTP plant.

At the present time the purification plant treats the wastewater produced by 320 000 equivalent habitants (EH) and is expected to increase up to approximately 400 000 EH in two years. At present, the threated discharge Q is about 0.8 m^3/s, but with the planned increment, it should rise up to about 1.0 m^3/s. The water flow clarified from the disinfection channel (number 6 in Figure 2) crosses two rectangular weirs and reaches the discharge channel after a small head jump h_1 of about 3.5 meters. This discharge channel also conveys the water by-passed by the sewage treatment in the case of heavy rain events. AMAP S.p.A. wants to reduce the energy costs linked to the purification process by recovering energy from this head jump with the installation of a hydraulic turbine.

We investigated three different solutions: a commercial Kaplan turbine, a Cross-Flow type turbine and a HPM. All these plants should be located in the area shown in Figure 2.

3.1. *Kaplan turbine solution*

For the commercial solution, we choose the turbine with the design parameters closest to the required ones; namely a flow rate equal to 0.837 m^3/s and a head drop equal to 3.75 m. The actual jump ΔH_k = 3.75 m available for production is given by the difference between the level H_1 of the inlet channel (with respect to the bed of the discharge channel) and the level H_2 of the discharge channel, minus about 0.2 m of head losses H_{losses} estimated in the suction pipe and in the butterfly valve respectively marked with 3 and 4 in Figure 4. The turbine (marked with 6) is put in a specific underground room downstream the plant channel that should be constructed on purpose (marked 5 in Figure 3 and Figure 4).

In case of overflow, the exceeding discharge will bypass the turbine, and will reach the discharge channel through the original rectangular weirs (red dashed arrows). Observe that it is possible to cut off the turbine, and restore the actual layout of the WWTP, just by closing the butterfly valve marked with number 4.

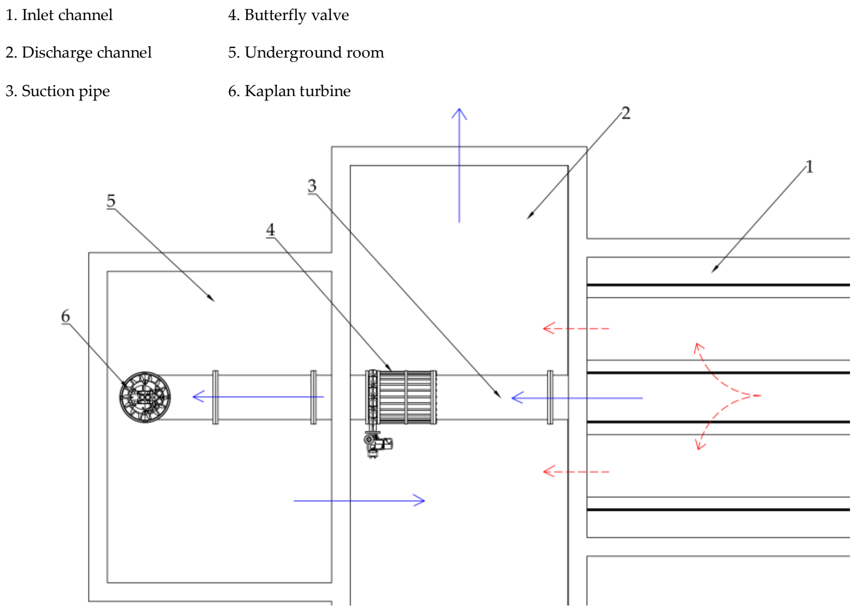

Figure 3. Planimetric view of Kaplan type turbine plant.

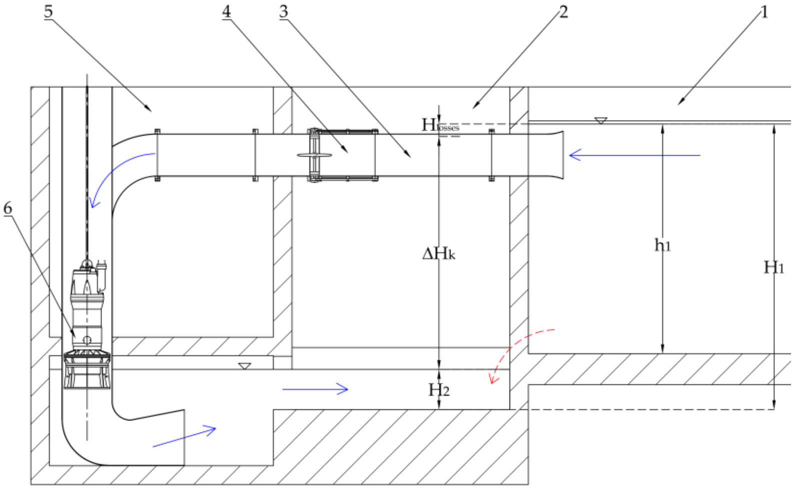

Figure 4. Section view of Kaplan type turbine plant.

We observe in the technical data sheet of the model that the turbine attains the best efficiency equal to 86.7% for a flow rate Q = 0.996 m^3/s and a head drop ΔH = 3.75 m. In the range of flow rates of the WWTP (0.8–1.0 m^3/s) the efficiency reduction is lower than 1%.

3.2. *Cross-flow turbine solution*

Cross-flow type turbines could be implemented in the PRS version [5-7], almost in the same position of the previous Kaplan turbine. PRS turbine has an efficiency usually lower than the traditional Cross-Flow turbine (CFT), which has zero outflow pressure. For this reason we preferred to allocate a CFT in the same underground room of the Kaplan, with its axis above the level of the discharge channel in order to avoid any interaction between the free surface flow in the channel and the turbine blades (Figure 6). This implies a reduction of the net head drop ΔH_c from 3.75 to 2.8 m, due also to head losses H_{losses} equal to 0.2 m in the suction pipe and in the butterfly valve marked with 3 e 4 in Figure 5 and Figure 6, respectively. Following the design criteria can be found in [3-7], we get diameter D and width W equal to 0.83 m and 0.7 m respectively, for a rotational velocity ω equal to 75 rpm.

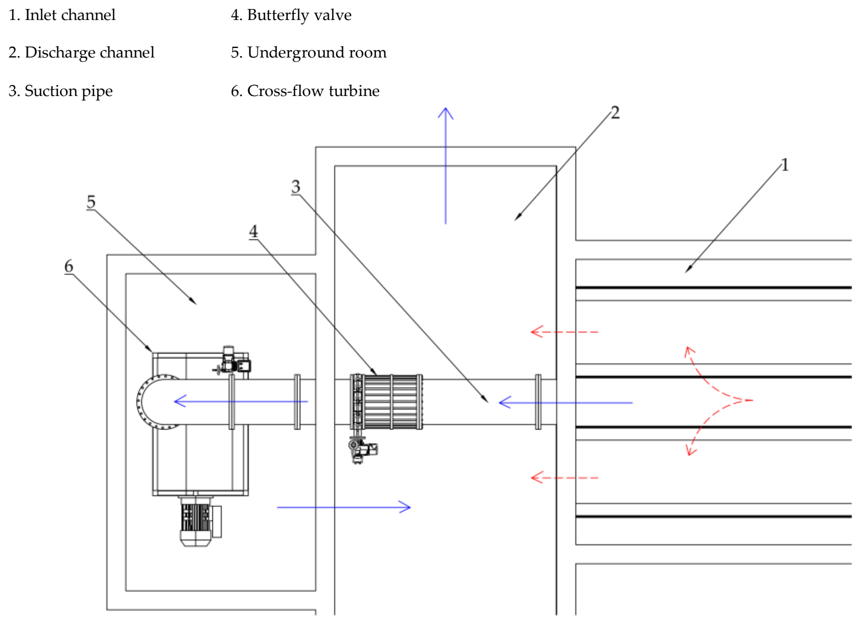

Figure 5. Planimetric view of Cross-flow type turbine plant

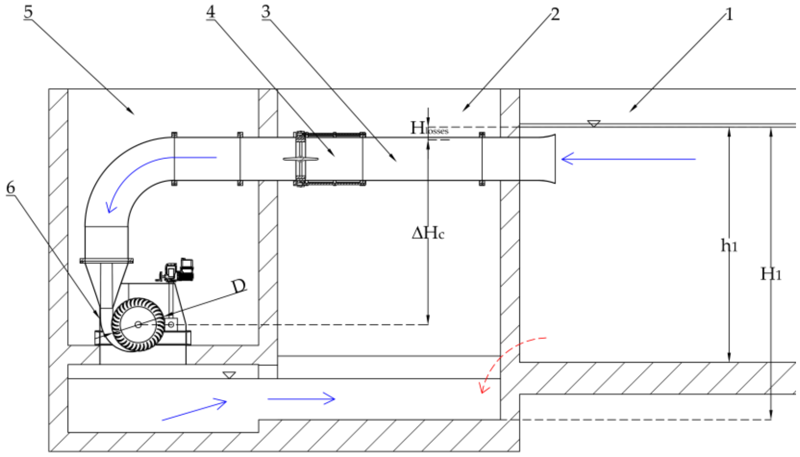

Figure 6. Section view of Cross-flow type turbine plant.

According to [12] we assume an efficiency up to 83%, for this solution.

3.3. HPM turbine solution

The use of HPM turbine requires a downstream water depth greater than zero, with a water level H_2 equal to the level of the inlet channel bed plus a water depth h_2= 0.75 m (Figure 7). According to design and management criteria can be found in [8-11], the diameter of the hub D_{Hub} is equal to ΔH_H = 2.75 m, the height of the blades is equal to h_2, and the outer diameter D is equal to 4.25 m, 10 diagonal blades were fixed on the hub [11]. For this diameter and mass flow rate, the efficiency attains a maximum for an upstream velocity v_1 equal to 0.3 m/s, corresponding to a width of the wheel W equal to 0.76 m and an angular velocity equal to 7 [rpm]. HPM turbine is located in one of the two original rectangular weirs of width W_c equal to 1 m, in order to to respect the ratio 1:1.3 between wheel width and width of rectangular weir suggest in [8, 10]. In case of overflow, the exceeding discharges crosses the other original rectangular weir to directly reach the discharge channel (red dashed arrows in Figure 7).

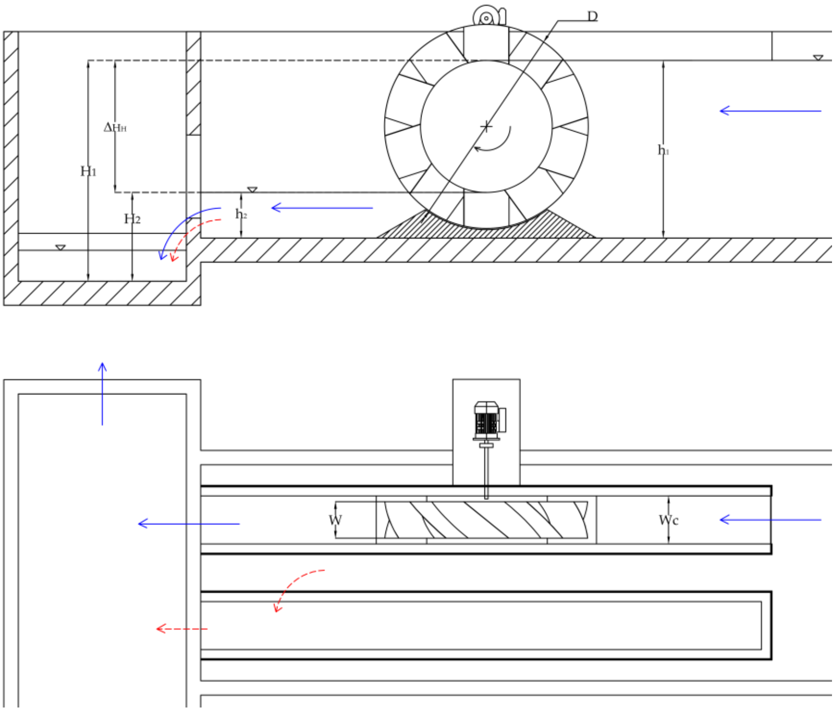

Figure 7. Planimetric and Section view of HPM plant.

According to [11] we assume an efficiency up to 80%, for this solution.

4. Cost/Benefit analysis

We split the costs in three main groups:

- Civil work costs: they include the cost for the required modification of the existing infrastructures: the upstream channel section for the HPM and the cost for excavation and building of a specific underground room downstream the plant channel for Kaplan and Cross-Flow type turbines.
- Machine costs: these include the cost of the turbine, the gearbox, electrical generator of the asynchronous type, belts if necessary.
- Control system and installation costs: these include the cost of control system for regulation and management of the turbine, and cost of installation.

In Table 1 a summary of design parameters, efficiencies and costs for each energy recovery plant is proposed.

Table 1. Comparison of electrical energy recovery costs.

Parameters	Kaplan	Cross-flow	HPM
Design Head ΔH [m]	3.75	2.8	2.75
Design Flow rate Q [m^3/s]	0.837	0.820	0.800
Hydraulic Efficiency	0.864	0.830	0.800*
Gearbox / belts / generator efficiency	0.887	0.887	0.870*
Global efficiency	0.766	0.736	0.696
Nominal Power ($P_{Electrical}$) [kW]	23.6	16.6	15.0
Civil works [€]	20 000	20 000	5 000
Hydropower System [€]	165 000	50 000	55 900*
Control system and installation [€]	40 000	40 000	40 000*
Total (C_i) [€]	225 000	110 000	100 900
Specific cost [€/kW installed]	9 534	6 627	6727
Total producible energy [MWh]	186.912	131.472	118.800
Average cash flows (C_f) [€/year]	29 700	20 891	18 877
Payback period (n_y) [year]	7.58	5.27	5.35

* According to [11].

In compliance with the resolution n° 280/07, the Italian Regulatory Authority for Energy, Networks and Environment (ARERA) sets guaranteed minimum prices p_{MWh} for the sale of energy from renewable power generation.

For hydropower plants with a nominal power up to 1 MW and produced energy up to 250 MWh/year, the guaranteed minimum prices p_{MWh} for the 2022 is equal to 158.9 €/MWh [13].

Assuming the hydropower plant working 24 hours a day, 330 days a year, the total producible energy over a typical year and the average cash flows for each solution are calculated (Table 1).

With the known cost of investment C_i and the average cash flows C_f for each solution, we can calculate the payback period n_y for a preliminary estimation of amount of time it takes to recover the cost of investments.

$$n_y = \frac{C_i}{C_f} \text{ [years]} \quad (2)$$

Cross-flow turbine plant is the solution with the shorter payback period (Table 1). A more detailed cost analysis could also analyze the ordinary and extraordinary maintenance costs, and also take into account the temporal variation of the money value.

Regarding the analysis of benefits, in Kaplan turbine the net available head jump is the higher of the three solutions, but the water flow in the diffuser could reach negative pressure with the risk of cavitation. This problem is not present in HPM and Cross-flow turbines.

HPM and Cross-flow turbines are both much cheaper than the Kaplan one. Efficiency of Cross-flow is higher than HPM. On the other hand, the HPM requires very little modifications of the existing infrastructure and it does not require a specific underground room like the Kaplan and the Cross-Flow turbines.

HPM and cross-flow turbines represent a valuable choice due their constructive simplicity with respect the Kaplan one. In Kaplan and Cross-flow turbine plants it is possible to exclude the turbine and restore the actual layout of the plant in any moment, only by closing a butterfly valve.

A brief summary and comparison of benefits for each solution is reported in Table 2

Table 2. Benefit comparison of solutions.

	Kaplan	Cross-flow	HPM
Net available head jump	✓	✗	✗
Risk of cavitation	✗	✓	✓
Payback period	✗	✓	✓
Nominal power	✓	✗	✗
Building a specific underground room	✗	✗	✓
Constructive simplicity of the turbine	✗	✓	✓
Possibility to exclude turbine and restore the actual WWTP layout	✓	✓	✗

5. Conclusions

In natural or artificial channels the best turbine for hydropower plants with low ultra-low head jumps is usually deemed to be the Kaplan one. In the analyzed study case it is shown the HPM or Cross-Flow turbines can also be an attractive alternative. Cross-Flow turbines have also a very simple device for hydraulic regulation, while the Kaplan type require the rotation of all the blades in the rotor and in the guide vane. The main advantage of the Kaplan turbine is the pressurized outflow, which allows the recovery of the entire available head jump. In the present study allocation of the PRS type turbine has not been investigated, but it could provide a competitive performance due to the same advantage of the Kaplan pressurized outflow.

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References

1. Molinos-Senante M., Maziotis A. Evaluation of energy efficiency of wastewater treatment plants: The influence of the technology and aging factors. *Applied Energy* **2022**, *310*, 118535.
2. Sabia G., Petta L., Avolio F., Caporossi E. Energy saving in wastewater treatment plants: A methodology based on common key performance indicators for the evaluation of plant energy performance, classification and benchmarking. *Energy Conversion and Management* **2020**, *220*, 113067.
3. Picone C.; Sinagra M.; Aricò C.; Tucciarelli T. Numerical analysis of a new cross-flow type hydraulic turbine for high head and low flow rate. *Engineering Applications of Computational Fluid Mechanics* **2021**, 15:1, 1491-1507. https://doi.org/10.1080/19942060.2021.1974559.
4. Sammartano, V.; Morreale, G.; Sinagra, M.; Tucciarelli, T. Numerical and experimental investigation of a cross-flow water turbine. *Journal of Hydraulic Research* **2016**, 54(3), 321-331. https://doi.org/10.1080/00221686.2016.1147500.
5. Sinagra, M.; Sammartano, V.; Morreale, G.; Tucciarelli, T. A new device for pressure control and energy recovery in water distribution networks. *Water* **2017**, 9(5), 309. https://doi.org/10.3390/w9050309.
6. Sinagra, M.; Picone, C.; Aricò, C.; Pantano, A.; Tucciarelli, T.; Hannachi, M.; Driss, Z. Impeller Optimization in Crossflow Hydraulic Turbines. *Water* **2021**, 13, 313. https://doi.org/10.3390/w13030313.
7. Sammartano, V.; Sinagra, M.; Filianoti, P.; Tucciarelli, T. A Banki-Michell turbine for in-line hydropower systems. *Journal of Hydraulic Research* **2017**, 55(5), 686-694. https://doi.org/10.1080/00221686.2017.1335246.
8. Senior, J.; Saenger, N.; Müller, G. New hydropower converters for very low-head differences, *Journal of Hydraulic Research* **2010**, 48:6, 703-714. https://doi.org/10.1080/00221686.2010.529301.

9. Pienika, R.; Usera, G.; Ramos, H.M. Simulation of a Hydrostatic Pressure Machine with Caffa3d Solver: Numerical Model Characterization and Evaluation. *Water* **2020**, 12, 2419. https://doi.org/10.3390/w12092419.
10. Schneider, S.; Müller, G.; Saenger, N. *HYLOW Project Report: Converter Technology Development—HPM and HPC*; Internal Task Report 2.3; Not published.
11. Senior, J.; Wiemann, P.; Müller, G. The Rotary Hydraulic Pressure Machine for Very Low HEAD Hydropower Sites. Available online: http://www.hylow.eu/knowledge/all-download-documents/ (accessed on 7 August 2020).
12. Sinagra, M.; Sammartano, V.; Aricò C.; Collura, A. Experimental and Numerical Analysis of a Cross-Flow Turbine. *Journal of Hydraulic Engineering* **2016**, 142, 1. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001061.
13. Italian Regulatory Authority for Energy, Networks and Environment (ARERA). Prezzi minimi garantiti per l’anno 2022, 18 January **2022**, https://www.arera.it/it/comunicati/22/220118.htm.